IMPROVING FACILITIES LIFECYCLE MANAGEMENT USING RFID LOCALIZATION AND BIM-BASED VISUAL ANALYTICS

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ABSTRACT

Improving Facilities Lifecycle Management Using RFID Localization and BIM-Based Visual Analytics

Ali Motamedi
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Indoor localization has gained importance as it has the potential to improve various processes related to the lifecycle management of facilities, such as the manual search to find assets. In the operation and maintenance phase, the lack of standards for interoperability and the difficulties related to the processing of large amount of accumulated data from different sources cause several process inefficiencies. For example, identifying failure cause-effect patterns in order to prepare maintenance plans is difficult due to the complex interactions and interdependencies between different building components and the existence of the related data in multiple, fragmented sources.

Building Information Modelling (BIM) is emerging as a method for creating, sharing, exchanging and managing the information throughout the lifecycle of buildings. Radio Frequency Identification (RFID), on the other hand, has emerged as an automatic data collection technology, and has been used in different applications for the lifecycle management of facilities. The previous research of the author proposed permanently attaching RFID tags to assets where the memory of the tags is populated with their accumulated lifecycle information taken from a standard BIM database to enhance various lifecycle processes. This thesis builds on this framework and investigates several methods for supporting lifecycle management processes of assets by using BIM, RFID and visual analytics. It investigates the usage of location-related data that can be retrieved from a BIM and are stored on RFID tags. It also investigates the usage of RFID technology for indoor localization of RFID-equipped assets using handheld readers. The research proposes using the location data saved on the tags attached to fixed assets to locate them on the floor plan. These tags also act as reference tags to locate moveable assets using received signal pattern matching and clustering algorithms. Additionally, the research investigates extending BIM to incorporate RFID information. It provides the opportunity to interrelate BIM and RFID data using predefined relationships. For this purpose, a requirements' gathering is performed to add new entities, data types, relationships, and property sets to the BIM. Moreover, the research investigates the potential of BIM visualization to help facilities managers make better decisions in the operation and maintenance phase of the lifecycle. It proposes a knowledge-assisted BIM-based visual analytics approach for failure root-cause detection in facilities management where various sources of lifecycle data are integrated with a BIM and used for interactive visualization exploiting the heuristic problem solving ability of field experts.

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DEDICATION

To My parents, Forough Asfa and Mehdi Motamedi and my brother Mohammad who made all of this possible, for their endless encouragement and support.

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LIST OF ABBREVIATIONS (NOMENCLATURE)

Abbreviation	Description
AEC/FM	Architecture, Engineering, Construction, and Facilities Management
A-GPS	Assisted GPS
ANN	Artificial Neural Network
AoA	Angel of Arrival
API	Application Programming Interface
BIM	Building Information Modeling
BSA	BuildingSMART Alliance
CAD	Computer-Aided Design
CAFM	Computer Aided Facilities Management
CAS	Condition Assessment Systems
CMMS	Computerized Maintenance Management System
CMTL	Cluster-based Movable Tag Localization
COBIE	Construction Operations Building Information Exchange
DoD	Department of Defense
DOM	Document Object Model
EAM	Enterprise Asset Management
EAS	Electronic Article Surveillance
EPC	Electronic Product Code
ERP	Enterprise Resource Planning
FM	Facilities Management
FMVAS	FM Visual Analytics System
GPS	Global Positioning System
HF	High Frequency

HVAC	Heating, Ventilation and Air Conditioning
IAI	International Alliance of Interoperability
IFC	Industry Foundation Classes
IFF	Identity Friend or Foe
INS	Inertial Navigation Systems
IoT	Internet of Things
ISO	International Organization for Standardization
kNN	k-Nearest Neighbors
LBS	Location-Based Services
LED	Light Emitting Diode
LF	Low Frequency
LoS	Line-of-Sight
MVD	Model View Definition
NBIMS	National Building Information Model Standard
NIBS	National Institute of Building Sciences
O&M	Operation and Maintenance
PDA	Personal Digital Assistant
PLM	Product Lifecycle Management
PoA	Phase of Arrival
PSet	Property Set
RF	Radio Frequency
RFID	Radio Frequency Identification
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RTLS	Real-Time Location System
RToF	Reverse Time of Flight

SCM	Supply Chain Management
SMP	Smallest M-vertex Polygon
STEP	Standard for the Exchange of Product model data
SVM	Support Vector Machine
TdoA	Time Difference of Arrival
ToA	Time of Arrival
UHF	Ultrahigh Frequency
UWB	Ultra Wide Band
VA	Visual Analytics
WLAN	Wireless Local Area Network
XML	Extensible Markup Language

CHAPTER 1 INTRODUCTION

1.1 GENERAL BACKGROUND

The Operation and Maintenance (O&M) is the longest and the most costly phase of facilities' lifecycle. The cost for the O&M constitutes 75 percent of the total cost of ownership (Singh et al., 2009). Facility managers are responsible for major corporate assets that often accounts for 35 to 50 percent of an organization's balance sheet (Jordani, 2010). The costs can be reduced by utilizing new methods and technologies to improve the efficiency of existing processes.

Singh et al. (2009) stated the cost-saving potential in the O&M phase of the life cycle when all the information is collected and made available in early planning and design phases and continues to accumulate to mine maximum savings. The NIST Interoperability Study (Gallaher et al., 2004) indicated that two-thirds of the estimated $15.8 billion lost are due to inadequate interoperability during the O&M phases (Rundell, 2006; Jordani, 2010).

Building Information Modeling (BIM) has been developed in order to tackle the problems related to interoperability and information integration by providing effective management, sharing and exchange of a building information throughout its entire lifecycle (Isikdag et al., 2008). A BIM database contains information about the geometry of the building as well as the lifecycle data of its components. Therefore, owners and operators can mitigate their portion of the cost associated with the lack of interoperability by using the high-quality building information from a BIM during the longer, more expensive O&M phase of the building's lifecycle (Rundell, 2006).

The framework developed in our previous research has proposed adding structured information taken from the BIM database to Radio Frequency Identification (RFID) tags attached to building assets (Motamedi and Hammad 2009a, 2009b). RFID is a type of automatic identification technology in which radio frequencies are used to capture and transmit data (Aimglobal, 2008). RFID based systems have been used in different applications in construction and maintenance, such as component tracking, inventory management, equipment management, progress management, facilities and maintenance management, tool tracking, material management, and quality control (for example, Jaselskis and El-Misalami, 2003; Song, 2005; Motamedi and Hammad, 2007; Ergen et al., 2007a; and Kiziltas et al., 2008). Based on our previous research (Motamedi and Hammad, 2009a), RFID tags are permanently attached to assets at an early stage of lifecycle and the stored information on tags is beneficial for several lifecycle processes and is used by various stakeholders. Having tags attached to assets results in a massive tag cloud in the building which can be used for localizing RFID-equipped assets and people.

1.2 PROBLEM STATEMENT AND RESEARCH GAPS

The key problem of facilities O&M process inefficiencies can be attributed to the following main issues: (1) The existence of wasteful manual operations, such as manual search to find assets, (2) The lack of standards for interoperability between various systems, and (3) The difficulties related to the processing of large amount of accumulated data from different sources in the O&M phase. The details of the above-mentioned issues are presented as follows:

(1) Regarding the first issue of manual operations to locate assets; the productivity of labor can be improved by minimizing the time they spend searching for critical assets and equipment. For example, a study done in a typical hospital building showed that the location of 15 to 20 percent of assets is unknown and the time spent searching for these assets equates to $1900 per nurse (Cisco, 2007). To tackle this problem, the users can be provided with locations of assets in order to decrease their search time. Location information can be used by occupants unfamiliar with a building to navigate and find their destinations. Hence, indoor location information is especially valuable as it has the potential to improve the utilization and maintenance of facilities. The Global Positioning System (GPS) technology provides solutions for outdoor localization. However, so far no single indoor localization solution has been universally adopted (Li and Becerik-Gerber, 2011). Although several radio frequency-based methods have been introduced to provide accurate indoor localization, these methods suffer from the lack of precision and accuracy, inability to adapt to changes in the environment, and high implementation cost due to the need for fixed infrastructure (Li and Becerik-Gerber, 201; Papapostolou and Chaouchi, 2011).

RFID technology has been employed for localization in indoor environments in various research projects (e.g., Hightower and Borriello, 2001; Ni et al., 2003). However, the main shortcoming of RFID based localization is the interference of the environment of the building on radio frequency, which makes it sensitive to changes in the environment resulting in inconsistent performance (Papapostolou and Chaouchi, 2011). The RFID tag localization methods introduced by various research projects mainly require fixed infrastructure of RFID readers (e.g., Ni et al., 2003; Zhen et al., 2008). This infrastructure imposes high implementation cost and low flexibility for localization as the system can only detect tags that are within the covered areas by fixed readers. With the advent of mobile computing, there is a need for localization methods that utilize handheld devices (such as Personal Digital Assistants (PDAs) and smartphones) equipped with RFID readers for localization of tagged assets. Moreover, using handheld devices to localize assets brings flexibility to users and enables them to look for assets anywhere in the facility without relying on the presence of localization infrastructure in certain covered areas. Additionally, most of RFID tag localization techniques that operate based on converting the radio signal strength to distance values perform poorly in the noisy and cluttered indoor building environments (Xu et al., 2012). As the result, there is a need to investigate new RFID-based indoor localization methods that consider the above-mentioned problems.

(2) Regarding the second issue on the lack of standardization; the BIM database is mandated to contain data related to all aspects of the facility (e.g., geometry, mechanical systems, construction scheduling) that are accumulated throughout the lifecycle. Currently, BIM standards are evolving and various BIM-compatible applications are introduced in the market. Consequently, various types of data that are useful for building's stakeholders are required to be defined and added to available standards. On the other hand, RFID based systems are used in various applications in construction, operation and maintenance of facilities. The use of RFID tags attached to building components to store their lifecycle information has been proposed by Motamedi and Hammad (2009a). However, there is no formal definitions of RFID systems in the BIM

yet. Consequently, there is a need to incorporate the definitions of this technology into available standards.

(3) Regarding the third issues on the difficulties of processing large amount of fragmented data; decisions on maintenance-related tasks are usually made based on various types of accumulated historical data, such as design drawings, inspection records, and sensing data (Chen and Wang, 2009). Most of these data are text-based which makes the process of correlating information time-consuming and less intuitive. For example, discovering the root-cause of a problem based on the data recorded in a Computerized Maintenance Management System (CMMS) is difficult and prone to failure. This is due to the complexity of interrelations between various building components and systems (Ahluwalia, 2008), multiplicity of building components and various changing environmental factors. Although BIM is emerging as the main repository of information for the lifecycle of buildings, the use of BIM data in the O&M phase of building's lifecycle is limited. Becerik-Gerber et al. (2012) performed interviews with Facilities Management (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 the chances of errors and increases efficiency. BIM has the potential to help improving the quality of FM by visualizing the large amount of lifecycle data that is available. The visualization potentials of BIM for finding root cases of problems or trends has not been fully explored. This is due to the fact that lifecycle information about building assets and systems are fragmented and are hosted in several different applications (e.g. CMMS, Computer Aided Facilities Management (CAFM), and Enterprise Asset Management (EAM)) that are not tightly interconnected. Hence, there is a research gap in the area of

integrating various sources of building's data and knowledge. Additionally, there is a research gap in using these knowledge and data sources with the native BIM visualization capabilities for problems' root-cause detection. This is possible by providing experts with various types of background knowledge and data, and a flexible visualization tool that allows them to utilize their cognitive and perceptual reasoning for problem solving.

1.3 RESEARCH VISION AND OBJECTIVES

This research investigates the usage of available mass of RFID tags in a building for indoor localization of RFID-equipped assets during the operation phase of facilities. It investigates a framework to store location-related data on the RFID tags attached to various assets in the building. The aim is to propose an asset localization method that is tailored to operate within buildings and adapt to requirements and conditions of facility management personnel. Hence, the proposed method should operate in noisy and cluttered environment with the possibility of frequent layout changes.

The research also proposes extending the BIM standard to incorporate the definitions of RFID technology in order to map the data to be stored on RFID memory to associated entries in a BIM database. This can be done by identifying relationships between RFID tags and building assets to provide the opportunity to interrelate BIM data and RFID data using predefined relationships. Eventually, the data related to objects that are required to be saved on RFID tags can be automatically selected using defined relationships in a BIM.

Finally, the research proposes a knowledge-assisted BIM-based Visual Analytics (VA) approach for failure root-cause detection in FM where CMMS inspection and maintenance data can be integrated with a BIM and used for interactive visualization exploiting the heuristic problem solving ability of field experts.

The specific objectives of the current research are: (1) to explore the possibility of using RFID tags attached to assets for localization purpose and to investigate new methods for localizing various types of RFID-equipped assets during the O&M phase; (2) to perform requirements' gathering and to extend BIM by defining RFID system components, their properties, and their relationships with other building elements; and (3) to investigate the potential of knowledge-assisted BIM-based VA for the failure root-cause detection scenario by considering the BIM as the primary data source for information related to building lifecycle; and (4) to investigate the applicability of the proposed methods using several case studies.

1.4 THESIS ORGANIZATION

This study will be presented as follows:

Chapter 2 Literature review: This chapter reviews the concepts, techniques, major technologies and standards that are used in the research. The literature review comprises the information about RFID technology, the concepts of ubiquitous computing and intelligent products, Real-Time Location System (RTLS) technologies, context aware information delivery, BIM technology, and other building knowledge sources. Our previously proposed approach for lifecycle management of assets using RFID and BIM technologies is reviewed in detail. Complimentary to the BIM, the literature related to visual analytics techniques to support O&M activities in the building for the purpose of failure root-cause detection is reviewed.

Chapter 3 Overview of the proposed methodology: In this chapter the idea of lifecycle location management using RFID technology is discussed. It includes examples of location-related data that can be saved on RFID tags and can be used during the lifecycle of the asset. This chapter also briefly discusses the different modules of the proposed methodology including the motivations and brief overview for each module. It contains a summary figure that shows various modules and their relationships to the literature review contents.

Chapter 4 Localization of RFID-equipped assets during the operating phase of facilities: This chapter elaborates on the proposed approach to use RFID technology to localize various types of assets that are equipped with RFID tags. The main focus of this chapter is on the localization of movable assets using a mobile RFID reader. The chapter includes various case studies that have been performed in order to validate the approach.

Chapter 5 Incorporating information of RFID tags attached to building components to the BIM: This chapter elaborates on the proposed approach to incorporate definitions of RFID tags into the BIM. The chapter includes, requirements' gathering, model view definition (MVD), and a case study related to the discussed topics.

Chapter 6 Knowledge-assisted BIM-based visual analytics for failure root-cause detection in facilities management: This chapter elaborates on the proposed approach to utilize BIM and other building knowledge sources for providing customized visualizations to help facility operators find the root-causes of failures. The chapter includes a case study to demonstrate how the proposed approach can be applied.

Chapter 6 Summary, Conclusions, and Future Work: This chapter summarizes the present research work, highlights its contributions, and suggests recommendations for future research.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter, major technologies and standards related to RFID, ubiquitous computing RTLS, BIM, building knowledge sources, and visual analytics are introduced and related literature is discussed. The literature review comprises the history of RFID technology, its components and details about different tag types and operating frequencies. It elaborates on the concepts of ubiquitous computing and intelligent products, their relation to RFID technology and an insight of future developments. Reviewing localization methods and RTLS technologies is another major part of the literature review. This part focuses on the methods that utilize RFID technology for localization. BIM technology is also covered in this chapter, including data storage/exchange/sharing models, Industry Foundation Classes (IFC), and projects related to extending the IFC. Our previously proposed approach for lifecycle management of assets using RFID and BIM technologies is reviewed in detail. Complimentary to BIM and lifecycle management, the literature related to various knowledge sources that support the O&M processes of the buildings are explained. Furthermore, the applications of visual analytics to support O&M activities in the building are reviewed.

2.2 RADIO FREQUENCY IDENTIFICATION (RFID)

RFID has emerged as an automatic data collection and information storage technology and has been used in different applications in construction and maintenance (Domdouzis et al., 2007; Motamedi and Hammad, 2009a; Wang et al., 2007), such as component tracking, inventory management, equipment monitoring, progress management, facilities and maintenance management, tool tracking, material management, and quality control (e.g., Jaselskis and El-Misalami, 2003; Song, 2005; Ergen et al., 2007a; and Kiziltas et al., 2008). An RFID tag is a memory storage device for storing a certain amount of data (e.g., the product ID, price and manufacturing date) that can be read wirelessly providing the ability to access large volumes of multiple data sets from multiple tags simultaneously (Chao et al., 2007; Domdouzis et al., 2007). Similar to barcodes, RFID is a technology for identifying and tracking objects. However, RFID technology introduces several advantages over barcoding in that its operation does not require line-of-sight and clean environments, and the stored data are modifiable. RFID has been identified as one of the ten greatest contributory technologies of the 21st century (Chao et al., 2007). An increasing variety of enterprises are employing RFID to improve their efficiency of operations and to gain a competitive advantage (Chao et al., 2007).

2.2.1 A BRIEF HISTORY OF RFID

Ernst F.W. Alexanderson in 1906 showed how the first radio wave can be continuously generated and how radio signals can be transmitted (Landt, 2005). During World War II, the British wanted to distinguish between their own returning aircrafts and those of the enemy. They installed radio transponders on their aircrafts which were able to respond appropriately to interrogating signals from base stations. This was called the Identity Friend or Foe (IFF) system which is widely considered the first use of RFID (Dittmer, 2004; Domdouzis et al., 2007).

Harry Stockman (1948) published a paper entitled “Communication by Means of Reflected Power”. In 1964, R.F. Harrington examined the electromagnetic theory related to RFID in a paper entitled “Theory of Loaded Scatterers”. In the late 1960s, two companies called Sensormatic and Checkpoint together with another company called Knogo, developed the Electronic Article Surveillance (EAS) equipment to prevent the theft of merchandise (Landt, 2005; Domdouzis et al., 2007).

The first commercial application of RFID was developed in Norway in 1987 and was followed by the Dallas North Turnpike in the United States in 1989. During the 90s, a number of American states adopted a traffic management system which was based on the use of readers that could detect RFID tags (Domdouzis et al., 2007). Later on, several companies were involved in the development of a common standard for electronic tolling applications. More recently, much smaller RFID tags have been developed. RFID tags are built in the form of labels and placed on the objects which are going to be managed (Domdouzis et al., 2007).

2.2.2 RFID TECHNOLOGY COMPONENTS

RFID technology is a wireless technology based on the detection of electromagnetic signals (McCarthy et al., 2003). A basic RFID system consists of three components: an antenna, a transceiver with a decoder (*RFID reader*) and a transponder (*RFID tag*) electronically programmed with information. The emission of radio signals by the reader's antenna activates a tag to read or write data from/to it. The transceiver is responsible for the data acquisition and communication. The antenna can be packaged with the transceiver and decoder in order to become a *reader*. The reader can be configured either as a handheld or a fixed-mount device. It can be part of other mobile computing and communication devices, such as cell phones or PDAs. If an RFID tag is placed in the electromagnetic zone produced by the reader's antenna, it detects the activation signal and responds by sending the stored data in the form of electromagnetic waves. The reader decodes the data which are encoded in the Integrated Circuit (IC) of the tag and passes them to the host computer system for processing (Domdouzis et al., 2007; Aimglobal, 2008). A typical RFID system is shown in Figure 2-1.

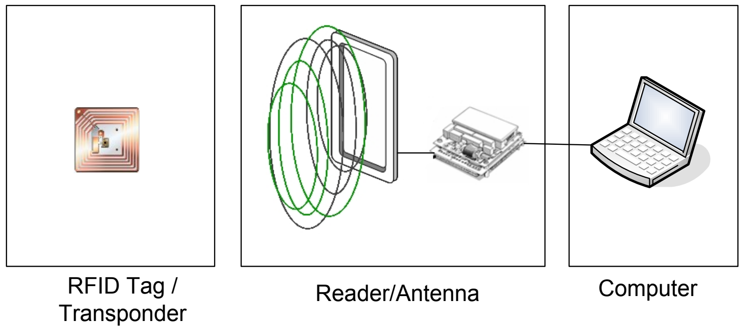


Figure 2-1 RFID system (Motamedi et al., 2009)

2.2.2.1 Tag Types

Two major types of RFID tags are available: *active* and *passive*. Active RFID tags are powered by an internal battery. The memory size of an active tag varies and some tags have more than 1 MB of memory (Scansource, 2008). The power supplied by the internal battery of an active tag generally gives it a longer read range. Active tags are usually bigger and more expensive than passive ones and have a limited operational life which may yield a maximum of 10 years, depending on operating temperatures and battery type (Aimglobal, 2008).

Passive RFID tags do not need any external power source and obtain operating power generated from the reader. Passive tags are consequently much lighter than active tags, less expensive, and offer a virtually unlimited operational lifetime. The trade-off is that they have shorter read ranges than active tags (Scansource, 2008).

2.2.2.2 Operating Frequencies

RFID systems currently operate in the Low Frequency (LF), High Frequency (HF) and Ultrahigh Frequency (UHF) bands. Each frequency has advantages and disadvantages relative to its capabilities. Generally a lower frequency means a lower read range and slower data read rate, but better capabilities for reading near or on metal or liquid surfaces compared with higher frequencies (Scansource, 2008).

2.2.2.3 RFID Standards

Standards are critical for RFID applications in areas, such as payment systems and Supply Chain Management (SCM). There are RFID standards related to the *air interface protocol* (communication details between tags and readers), *data content* (the way data are organized or formatted), *conformance* (ways to test that products meet the standard) and *applications* (how standards are used on shipping labels, for example) (Violino, 2005).

The International Organization for Standardization (ISO) and the Electronic Product Code (EPC) Global have both been leading the standardization debate. The ISO has introduced the 18000 standard and the EPC Global Center has introduced the EPC standard. The standardization situation was complicated by the fact that the Auto-ID Center, which developed EPC technologies, chose to create its own air interface protocol for tracking goods through the international supply chain (Violino, 2005). Wal-Mart decided to use the EPC standard, where the Department of Defense (DoD) uses the EPC for general purposes, but uses the ISO standard for air interface, which puts pressure on the ISO and EPC to come to an agreement (Scansource, 2012).

The Auto-ID Center developed its own UHF protocol. Originally, the center planned to have one protocol that can be used to communicate with different classes of tags. Each successive class of tags would be more sophisticated than the one before it. The classes changed over time, but the following is what was originally proposed (Violino, 2005). More details on tag class definitions can be found in GS1 (2007).

- *Class 1*: a simple, passive, read-only backscatter tag with one-time, field-programmable non-volatile memory.
- *Class 2*: a passive backscatter tag with up to 65 KB of read-write memory.
- *Class 3*: a semi-passive backscatter tag, with up to 65 KB read-write memory; essentially, a Class 2 tag with a built-in battery to support increased read range.
- *Class 4*: an active tag that uses a built-in battery to run the microchip's circuitry and to power a transmitter that broadcasts a signal to a reader.
- *Class 5*: an active RFID tag that can communicate with other Class 5 tags and/or other devices.

In 2004, EPCglobal began developing a second-generation protocol (Gen 2). The aim was to create a single, global standard that would be more closely aligned with ISO standards. Gen 2 was approved in December 2004 and RFID vendors that had worked on the ISO UHF standard also worked on Gen 2 (Violiono, 2005). The RFID Network (RFIDNet, 2012) has assembled a quick reference list that contains a complete and updated list of ISO standards related to RFID.

2.2.3 UBIQUITOUS COMPUTING AND INTELLIGENT PRODUCTS

Friedewald and Raabe (2011) defined ubiquitous computing as "countless very small, wirelessly intercommunicating microprocessors, which can be more or less invisibly embedded into objects". Such objects have a quality that they *know*, for example, where they are, which other things are in the vicinity and what happened to them in the past. It is predicted by Friedewald and Raabe (2011) that ubiquitous computing can pervade all spheres of life, such as increasing comfort in the private home area, improving energy efficiency, increasing work productivity and monitoring the health of the user (Aarts and Encarnaçao, 2005).

The new technologies have contributed to the development of systems that can autonomously communicate with each other, such as *smart objects* (Mattern, 2003; Siegemund, 2004; Kortuem et al., 2010; SEC, 2008; Khoo, 2010). The *smart objects (intelligent products)* are one of the technologies to watch with a time-to-adoption horizon of four to five years (HorizonProject, 2012). McFarlane et al. (2003) defined an *intelligent product* with the following properties: (1) Possession of a unique identification; (2) Capability of communicating effectively with its environment; (3) Retaining or storing data about itself; (4) Deploying a language to display its features, production requirements, etc.; and (5) Capability of participating in or making decisions relevant to its own destiny. Based on this definition, Wong et al. (2002) have defined a product with Level 1 intelligence when the product covers points 1-3. Kärkkäinen et al. (2003) stated that the fundamental idea behind an *intelligent product* is the inside-out control of the supply chain deliverables and of products during their lifecycle by: (1) Possession of a globally unique ID; (2) Linkage to information sources about the product across organizational border; and (3) Communicating with information systems and users when needed. Similar to the classification of McFarlane et al. (2003), this classification is mainly focused on the use of RFID technology. Ventä (2007) provided a definition that focuses on decision-oriented products by extending point five of the first definition and point three of the second definition and is more focused on products with sufficient embedded computing power (Meyer et al., 2009).

Intelligent Products were first analyzed in an after-sales and service context. Later the idea of integrating intelligence and control into the product spread to manufacturing (McFarlane et al., 2003) and supply chain control (Kärkkäinen, 2003).

Internet of Things (IoT)

The IoT can be defined as "Things having identities and virtual personalities operating in smart spaces using intelligent interfaces to connect and communicate within social, environmental, and user contexts" (EpoSS, 2008). A fundamental enabler would be the identity knowledge, of the *self* and of the others. Enabling the object to know *itself* and its common properties, such as creation, recycling, transformation, ownership change, or use for different purposes will allow common objects to interact actively and decisively with the environment.

Based on the review of the literature related to IoT (e.g., Brock, 2001; Gershenfeld et al., 2004; Huvio et al., 2002) by Meyer et al. (2009), they concluded that in many contexts, such as the SCM, the IoT concept tends to focus on product identification technologies, information storage and information exchange rather than on the intelligence of the products.

2.2.4 RFID AND INTELLIGENT PRODUCTS

In manufacturing and supply chain application domains, Auto Identification (Auto-ID) technologies (such as RFID) provided the possibility of tracking and tracing of products throughout the entire supply chain. Meyer et al. (2009) suggested that we would enter the realm of *Intelligent Products*, in case any individual product in a logistic or production setting is given a traceable individuality, the associated content, and possibly the delegated decision power. They stated that information needs to be represented at the item level and communicated between different organizations for such tracking and tracing in the supply chain. Moreover, RFID has the potential to enable machines to identify objects, understand their status, and communicate and take action if necessary, to create *real-time awareness* (Welbourne et al., 2009; Yan et al., 2008; Khoo, 2010).

The mobile devices have a huge penetration in the market covering the needs of both consumers and industry due to the processing power and communication facilities they provide (Tesoriero et al., 2010). In the field of microelectronics, it can be assumed that, according to Moore's Law (Swanson, 1998), in the coming years, logic and memory elements will become smaller, more powerful and cheaper at the same time. New materials, such as semi-conducting polymers help to ensure that electronic systems will be embedded in almost all conceivable objects and require less energy to operate (Chalasani and Conrad, 2008; Alcañiz and Rey, 2005; Friedewald and Raabe, 2011).

Open standards and interoperability are key enablers for the success of the RFID deployments in the near future and the viability of the IoT in the long term. Moreover, the integration of smart devices into packaging and products, and the support for different communication and security standards and protocols that operate at different frequencies are enablers for the success of IoT (EpoSS, 2008; ITU, 2005). The barriers in implementing the idea of IoT, such as governing authority, acceptance by states, companies, trade organizations and the common people should be considered. Also the privacy and security has a major importance and the public acceptance for the IoT will happen only when strong security and privacy solutions are in place (EpoSS, 2008).

2.3 LOCALIZATION AND RTLS

2.3.1 IMPORTANCE OF LOCATION DATA

Location data are essential for many processes related to SCM, FM, and Product Lifecycle Management (PLM) as many applications need to know where objects are located (Khoury and Kamat, 2009a; Zhao et al., 2007). They are is central to personalized applications in different areas and they are the basis for the delivery of personalized and Location-Based Services (LBS) (Li and Becerik-Gerber, 2011). Moreover, the accurate location data of objects are used for several applications (Zhou and Shi, 2009), such as finding items in a warehouse (Hariharan, 2006), locating equipments in construction sites (Song, 2007), avoiding collision between vehicles (Tong, 2007), and rescuing victims in underground mines (Zhang, 2006). In the area of construction management, effective monitoring of personnel movements, material locations, and construction equipment helps successfully manage projects (Ko, 2010; Ibn-Homaid, 2002; Fan et al., 2008; Yagi et al., 2005; Grau et al., 2009).

Indoor location data provide the basis for context awareness within the building, which involves an automatic recognition of the user's location and activity (Zhao et al., 2007; Papapostolou and Chaouchi, 2011; Aziz et al., 2005). Context-aware information can automate the delivery of information to on-site mobile personnel allowing them to locate specific targets, such as building components, equipment, tools and themselves to access target-specific information.

Li and Becerik-Gerber (2011) stated that indoor location information is especially valuable as it has the potential to improve the utilization and maintenance of facilities by: (1) Helping unfamiliar users of a building by providing them with information to navigate around and find their destinations; (2) FM personnel can be provided with locations of building components or equipment they need to maintain or repair; (3) Locations of tools and on-site FM personnel and the length of time they spend at each location can be analyzed to monitor the work procedures and improve productivity; and (4) Changes in building occupancy can be detected in real-time through location sensing, and energy conservation measures, such as adjustment of lighting and air conditioning, can be automated.

Location tracking systems provide the potential for achieving savings depending on the selected technology (Kelepouris and McFarlane, 2010). RTLS technologies (e.g., Ultra Wide Band (UWB)) are capable of providing real-time location information of assets in facilities, such as production floors or commercial buildings (Daek et al., 2012). However, providing RTLS infrastructure inside the building is costly because of the need of fixed infrastructure, which imposes tremendous amount of hardware, technical design and implementation costs.

2.3.2 LOCALIZATION LEVELS

Papapostolou et al. (2011) defined the localization problem as the process of determining the current position of a user or an object within a specific region, indoor or outdoor. However, a position can be expressed in several ways (e.g., coordinate, region, cell, hierarchical) depending on the application requirements or the positioning system specifications.

Razavi and Haas (2011) identified two approaches to localization: *fine-grained* localization using detailed information and *coarse-grained* localization using minimal information. Minimal techniques are easier to implement and more likely to involve fewer resources and lower equipment costs, but they provide a lower degree of accuracy than detailed localization techniques. However, fine-grained localization uses measurement techniques (Razavi and Haas, 2011). Coarse-grained node localization uses range-free or connectivity-based localization algorithms that do not use any measurement. In this category, some sensors, have a priori information about their own location. The locations of other sensors are estimated based on connectivity information, such as which sensor is within the communication range of which other sensors (Bulusu et al., 2000; Simic et al., 2002; Song et al., 2006). The presence of an object within a specific range is usually determined by monitoring physical phenomena that have limited range, e.g., physical contact with a magnetic scanner, or communication connectivity to access points in a wireless cellular network (Razavi and Haas, 2011). Our proposed method for localizing movable assets (Explained in Chapter 4) follows fine-grained approach for localization as it uses measurement techniques to calculate the exact location of RFID tags.

2.3.3 CONTEXT-AWARE INFORMATION DELIVERY

Location-aware computing has significant potential to improve manual processes and supporting important decision making tasks in the field (Khoury and Kamat, 2009a). The context-aware information delivery (Aziz et al., 2005) has the potential to create a user-centered mobile dynamic indoor and outdoor work environment, which has the ability to deliver relevant information to on-site mobile users in order to help them take more informed decisions (Schilit and Want, 1994). Providing this wide range of information that forms the basis of context awareness in construction and FM, leads to improvement in project safety, schedule, cost (Caldas et al., 2006) and decision-making (Li and Becerik-Gerber, 2011).

For example, instead of browsing through detailed drawings and other paper based media, contextual project information can be automatically retrieved and visualized by continuously and accurately tracking mobile users' three-dimensional spatial context (i.e. position and orientation) (Khoury and Kamat, 2009b). Navigation information, as demonstrated in Rueppel and Stuebbe (2008), is an example of information that can be delivered to mobile users (Li and Becerik-Gerber, 2011).

Li and Becerik-Gerber (2011) listed the areas for future research on applying information delivery mechanism to multiple areas including: (1) Execution and management of construction activities, e.g., assembly instructions are delivered to the workers; (2) Safety and security, e.g., locations of workers are monitored in real-time to avoid collisions, or alerts are sent when assets are removed without authorization; (3) Supporting FM personnel, e.g., a worker is located and his/her context analyzed, so that information, such as maintenance history, work orders, or inspection records is delivered to him/her; and (4) Smergency response, e.g., rescuers are guided inside a building.

2.3.4 INDOOR LOCALIZATION

The GPS technology provides solutions for outdoor localization. However, so far no single indoor localization solution has been universally adopted (Li and Becerik-Gerber, 2011). Li and Becerik-Gerber (2011) listed technologies that have been proposed and tested for indoor localization as follows:

- *Indoor GPS*: GPS-based solutions have been introduced to extend the use of GPS to indoor environments, such as high-sensitivity GPS that uses highly signal-sensitive receivers developed for weak-signal conditions (Schon et al., 2008), and Assisted GPS (A-GPS) (Diggelen, 2002).
- *Inertial Navigation Systems* (INS) using sensors, such as accelerometers and gyros (Mezentsev et al., 2005).
- *Infrared-based solutions,* such as Active Badge (Want et al., 1992), use portable infrared beacons and fixed infrared sensors to provide zone-level localization.
- *Ultrasound,* such as the Cricket Location Support System (Priyantha et al., 2000) and Active Bat location system (Harter et al., 1999). They compare the time of arrival of ultrasonic signals with that of Radio Frequency (RF) signals to determine the distance between the signal transmitter and the receiver.
- *UWB-based solutions* use very short pulses for communication between tags and receivers, and provide a high accuracy localization using fixed infrastructure (Becker, 2008; Cho et al., 2010).

- *Wireless Local Area Network (WLAN)-based solutions*, such as the RADAR system (Bahl et al., 2000), can be easily set up and require few base stations.
- *Bluetooth and Zigbee-based solutions* (Cruz et al., 2011; Huang and Chan, 2011; Shen et al., 2008).
- *RFID-based solutions:* is further discussed in detail in Subsection 2.3.5.

Li and Becerik-Gerber (2011) provided a comparison chart that compares indoor localization solutions that is presented in Table 2-1.

Indoor Localization Challenges

The indoor radio propagation is site and environment specific. The changes of signal in indoor environments are difficult to predict because of dense environment and radio propagation effects, such as reflection, diffraction and scattering (Bekkali et al., 2007). Moreover, indoor environments exhibit severe multi-path effects and low probability of line-of-sight (LoS) signal propagation between the transmitter and the receiver (Pahlavan and Levesque, 2005) and makes accurate indoor positioning very challenging (Papapostolou and Chaouchi, 2011).

Table 2-1 Comparison of indoor localization techniques (Li and Becerik-Gerber, 2011)

Technology	Accuracy (m)	affordability ($/m2)	No line of sight required	Wireless Communication	Context Independent	On-board data storage	Built-in power supply	Wide application in building industry
GPS	0.01-0.02	380	X	X	X	√	√	√
INS	1.10-4.15	20	√	X	√	√	√	X
Infrared	0.30-0.50	17	X	√	X	X	X	X
UWB	0.06-0.50	140	√	√	X	X	X	X
WLAN	4.53-6.89	3	√	√	X	X	X	√
RFID	1.55-3.11	25	√	√	X	√	X	√

2.3.5 RFID-BASED INDOOR LOCALIZATION

RFID technology has been employed for localization in indoor environments in various research projects. However, the main shortcoming of RFID is the interference among its components, and the interference among RFID components and some materials (Papapostolou and Chaouchi, 2011). The proximity of liquids and metals significantly affects the readability range and data transfer rate of the RFID system.

2.3.5.1 RFID Localization Methods

Several researchers categorized RF-based localization methods and provided surveys and comparisons among various projects for RFID tag and reader localization (e.g, Fuchs et al., 2011; Liu et al., 2007; Li and Becerik-Gerber, 2011; Papapostolou and Chaouchi, 2011; and Zhou and Shi, 2009). The RF localization methods can be categorized in five major groups: (1) *Trilateration*: it uses the distances of the target to at least three points with known positions. The distance is estimated based on RF properties using the following techniques: Time of Arrival (ToA), Time Difference of Arrival (TDoA), Phase of Arrival (PoA), signal attenuation (Received Signal Strength (RSS)-based), Reverse Time of Flight (RToF), and hop-based; (2) *Angulation*: it determines the location of an object from the measured angles to at least two fixed points with known locations (e.g., Angel of Arrival (AoA)); (3) *Proximity*: it uses the approximate communication area to detect whether the target node is in a region or not (Zhou and Shi, 2009). It relies upon a dense grid of antennas, each having a known position. When a mobile target is detected by an antenna, it is considered to be collocated with it (Liu et al., 2007); (4) *Fingerprinting (scene analysis):* it requires an offline phase for learning the radio signal behavior within a specific area under study to build a radio map database. It estimates the location of a receiver based on the similarity of its current signal strength measurements with the closest a priori location fingerprints in the radio map using the following techniques: Support Vector Machine (SVM), Artificial Neural Network (ANN), Smallest M-vertex Polygon (SMP), and probabilistic methods; and (5) *neighbourhood:* it uses RF properties to measure nearness to a known set of points. In this method, an RFID tag or a reader is attached to a target and communicates with the readers or tags with known locations deployed in the environment through radio waves. The observed signal strength or time of arrival are used to measure the nearness of reference positions. The measured nearness, along with the corresponding known locations, are used to estimate the location of a target. Figure 2-2 shows various methods used for RF localization based on the abovementioned categorization. The RFID tag localization method introduced in this research (explained in Subsection 4.6), utilizes the LANDMARC method, which is a specific neighborhood method, for the localization of mobile RFID tags. The LANDMARC method is briefly explained in the Subsection 2.3.5.3.

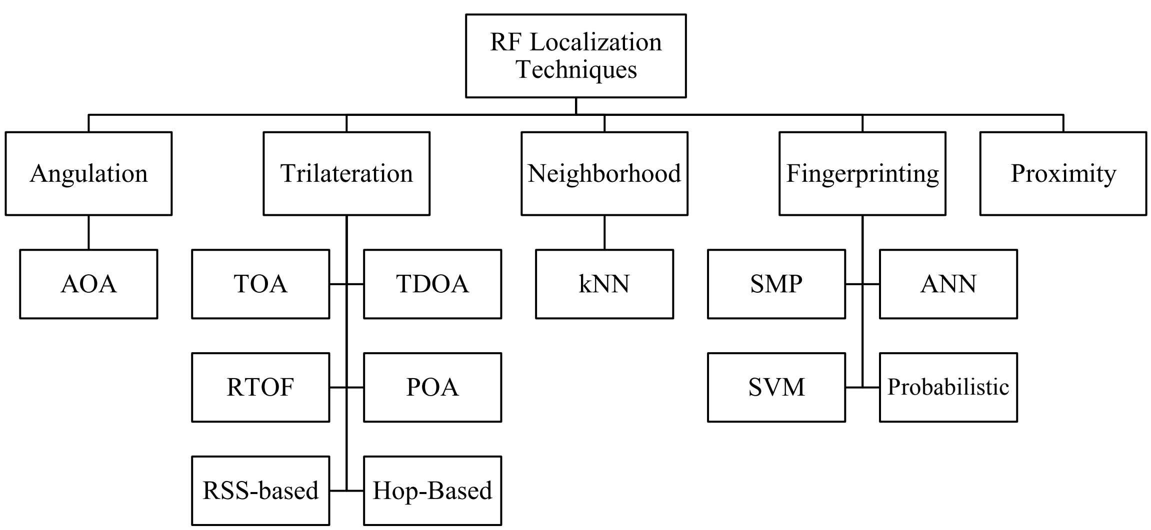


Figure 2-2 RF localization hierarchy (Motamedi et al., 2013)

2.3.5.2 RFID Localization Targets

In RFID-based localization systems, *tags* or *readers* can be the targets for localization (Sanpechuda and Kovavisaruch, 2008). In *tag localization*, the RFID tag is attached to the target component for localization (e.g., Hightower et al., 2000; Ni et al., 2003; and Bekkali et al., 2007). In most of the settings, in order to track the target tag, readers or reference tags are deployed as reference points and a positioning technique is applied for estimating the location of a tag. In *reader localization*, usually reference tags are deployed as reference points for localization of the reader (e.g., Lee and Lee, 2006, Yamano et al., 2004, and Wang et al., 2007). Papapostolou and Chaouchi, (2011) listed some of tag and reader positioning systems that are summarized in Table 2-2.

Table 2-2 Tag and reader localization (adopted from Papapostolou and Chaouchi, 2011)

Target	System	Reference	Deployment	Approach	Accuracy
Tag	SpotOn	Hightower et al. (2000)	Readers	RSS trilateration	3m
	LANDMARC	Ni et al. (2003)	Readers and tags	RSS scene analysis	1-2m
	Simplex Passive	Wang et al. (2007)	Readers and tags	RSS proximity and optimization	0.3-3ft
	Kalman	Bekkali et al. (2007)	Readers and tags	RSS mean squares/ Kalman Filtering	0.5-5m
Reader	Lee	Lee et al. (2006)	Tags (dense)	RSS proximity	0.026m
	Han	Han et al. (2007)	Tags (dense)	Training and RSS proximity	0.016m
	Paysian	Xu and Gang (2006)	Tags	Proximity and Bayesian inference	1.5m
	Simplex Active	Wang et al. (2007)	Tags	RSS proximity and optimization	0.2-0.5ft

2.3.5.3 LANDMARC Method for RFID Tag Localization

LANDMARC (Ni et al., 2003), has been a foundation for many RFID tag localization solutions. LANDMARC-based methods have advantage over trilateration methods in adapting to complex and dynamic environments (Li and Becerik-Gerber, 2011).

LANDMARC uses active tags that are attached to the target assets (*target tags*). In this method, a grid of fixed reference tags with known locations is placed in the sensing area in order to provide reference locations. The Received Signal Strength Indicator (RSSI) values received from all RFID tags are recorded by fixed readers. The system measures the nearness of the reference tag to the target and identifies the nearest reference tags to the target. It uses weighted averaging in order to locate the target tag using an empirical formula. Equation 2-1 shows the weighted averaging method where x and y are the coordinates of the target tag and x_i and y_i are the coordinates of the k-nearest neighbors (kNN) reference tags. The weights are calculated using Equation 2-2 where E_i is the Euclidean distance in signal strengths (Ni et al., 2003).

$$(x, y) = \sum_{i=1}^{k} w_i (x_i, y_i) \qquad \text{Equation 2-1}$$

$$w_i = (1/E_i^2) / \left(\sum_{j=1}^{k} (1/E_j^2)\right) \qquad \text{Equation 2-2}$$

Ni et al. (2003) performed field tests in an area of 5 m × 10 m with a grid of 16 reference tags and four fixed readers. Results showed the accuracy of within 1 m with 50% probability and within 2 m with 90% probability. Their research adopted the use of four nearest reference tags for optimal positioning (Ni et al., 2003). It is also noted that increasing the number of reference tags and readers improves the accuracy of the results. Technological constraints for available RFID systems at the time, such as inability to provide direct signal strength by readers, long time intervals of emitting signals from tags, and variations in the behaviour of tags are introduced as limitations.

2.4 BUILDING INFORMATION MODELING (BIM)

BIM is emerging as a method of creating, sharing, exchanging and managing the information throughout the lifecycle between all the building stakeholders. It has been developed in order to tackle the problems related to interoperability and information integration by providing effective management, sharing and exchanging of a building information through its entire lifecycle (Isikdag et al., 2008). The BIM database will contain data related to all aspects of the facility (e.g., geometry, mechanical systems, construction scheduling) that are accumulated throughout the lifecycle. Currently, BIM standards are evolving and various BIM-compatible applications are introduced in the market. Consequently, various types of data that are useful for stakeholders are required to be defined and added to available standards.

2.4.1 DEFINITION AND SCOPE OF BIM

According to Associated General Contractors Guide (AGC, 2005), BIM is a data-rich, object-oriented, intelligent and parametric digital representation of facilities. Views and data appropriate to various users' needs can be extracted and analyzed to generate information that can be used to make decisions and improve the process of delivering a facility.

NBIMS (2007) described the scope of BIM within the following relationships: (1) BIM as a product or intelligent digital representation of data about a capital facility; (2) BIM as a collaborative process which covers business drivers, automated process capabilities, and open information standards use for information sustainability and fidelity; and (3) BIM as a facility lifecycle management tool of well understood information exchanges, workflows, and procedures which stakeholders use throughout the building lifecycle as a repeatable, verifiable, transparent, and sustainable information based environment. BIM acts as an enabler of interoperability and is a facilitator of data sharing and exchange between software applications. Furthermore, BIM is extensible, open and vendor neutral (Isikdag et al., 2008).

2.4.2 BIM DATA STORAGE, EXCHANGE AND SHARING MODELS

BIM data can be stored as a digital file or in a database, and can be shared and exchanged between several applications. The difference between data sharing and data exchange is related to the ownership and centrality of data. In the data exchange model, while the master copy of data is maintained by one software, the snapshots of data are exported to others to use. The ownership is assumed by the software that imports the exchanged data. In the sharing model, there is a centralized control of ownership and there is a master copy of data. The data sharing model facilitates the revision control issue associated with the data exchange model (Isikdag et al., 2007; Vanlande et al., 2008).

Isikdag et al. (2007) explored five different methods for the storage and exchange of BIMs: (1) Data exchange by using physical files where the files are transferred using physical mediums (e.g., CD/DVD) or computer networks (e.g., Internet); (2) Data sharing by using Application Programming Interfaces (APIs) where the BIM physical file can be accessed through proprietary or standard API based on the type of BIM in use. In case the physical file is an Extensible Markup Language (XML) file, the model can be shared using appropriate XML interfaces (i.e. APIs supporting Document Object Model (DOM)); (3) Data sharing by using a central database that allows multiple applications to access the data and use database features, such as query processing and business object creation; (4) Data sharing by using federated project databases where multiple distributed but synchronized databases can be accessed through single unified view; and (5) Data sharing by Web services where a Web service interface provides access either to the central project database where the BIM is stored, or to an API which provides access to a physical BIM file or to the domain specific views of the model.

2.4.3 INDUSTRY FOUNDATION CLASSES (IFC)

The IFC standard developed by BuildingSMART Alliance (BSA) has matured as a standard BIM in supporting and facilitating interoperability across the various phases of the construction lifecycle (Isikdag et al., 2008). It is developed as a means to exchange model-based data between model-based applications in the Architecture, Engineering, Construction, and Facilities Management (AEC/FM) industry, and is now supported by most of the major Computer-Aided Design (CAD) vendors as well as by many other applications (IFC, 2013; Khemlani, 2004). The IFC model represents both tangible building components (e.g., walls, doors, beams) and more abstract concepts (e.g., schedules, activities, spaces, organization, and construction costs) in the form of entities. Each entity can have a number of properties, such as name, geometry, materials and relationships (Liebich, 2009).

The IFC standard is similar to another International Standards Organization (ISO) collaborative representation standard known as STandard for the Exchange of Product model data (STEP) (Pratt, 2001). STEP was focused on defining standards for the representation and exchange of product information in general, and continues to be used in various design disciplines, such as mechanical and product design. Researchers from the building industry realized that a more domain-specific model was needed for representing building data. Hence, the BSA used their experience to define a specific industry-based standard (i.e., IFC) (Khemlani, 2004; Laakso and Kiviniemi, 2012).

2.4.3.1 IFC Architecture

The current IFC standard currently covers nine domains (e.g., structural elements, electrical elements) (IFC, 2013). Several commercial and open source application software packages support the IFC standard. Hence, the data exchange among their relevant products can be realized. However, the IFC standard can support only a limited number of use cases in the AEC/FM industry and more developments are required (Weise et al., 2008; Ma et al., 2011).

The IFC standard has a hierarchical and modular framework. Its data schema architecture defines four conceptual layers, i.e. resource layer, core layer, interoperability layer and domain layer (Figure 2-3). Each layer comprises a number of modules that contain various entities, types, enumerations, property and quantity sets. The modular design is intended to make the model easier to maintain and grow, to allow lower-level entities to be reused in higher-level definitions, and to make a clearer distinction between the different entities so that the model can be more easily implemented in individual discipline-specific applications (IFC, 2013; Khemlani, 2004).

2.4.3.2 Extending IFC

The IFC standard is an object oriented approach by assigning entities to objects with predefined attributes that can be inherited by all related entities. Utilizing inheritance reduces the effort to redefine content as it can be inherited from the super entity. Hence, the description of both the entities and their inheritance relationships is required in the information model to give a full picture of the use of related entities (Ma et al., 2011).

The IFC specification is written using the EXPRESS data definition language which has the advantage of being compact and well suited to include data validation rules within the data specification. Additionally, an ifcXML specification is provided as an XML schema 1.0 (BuildingSMART, 2012).

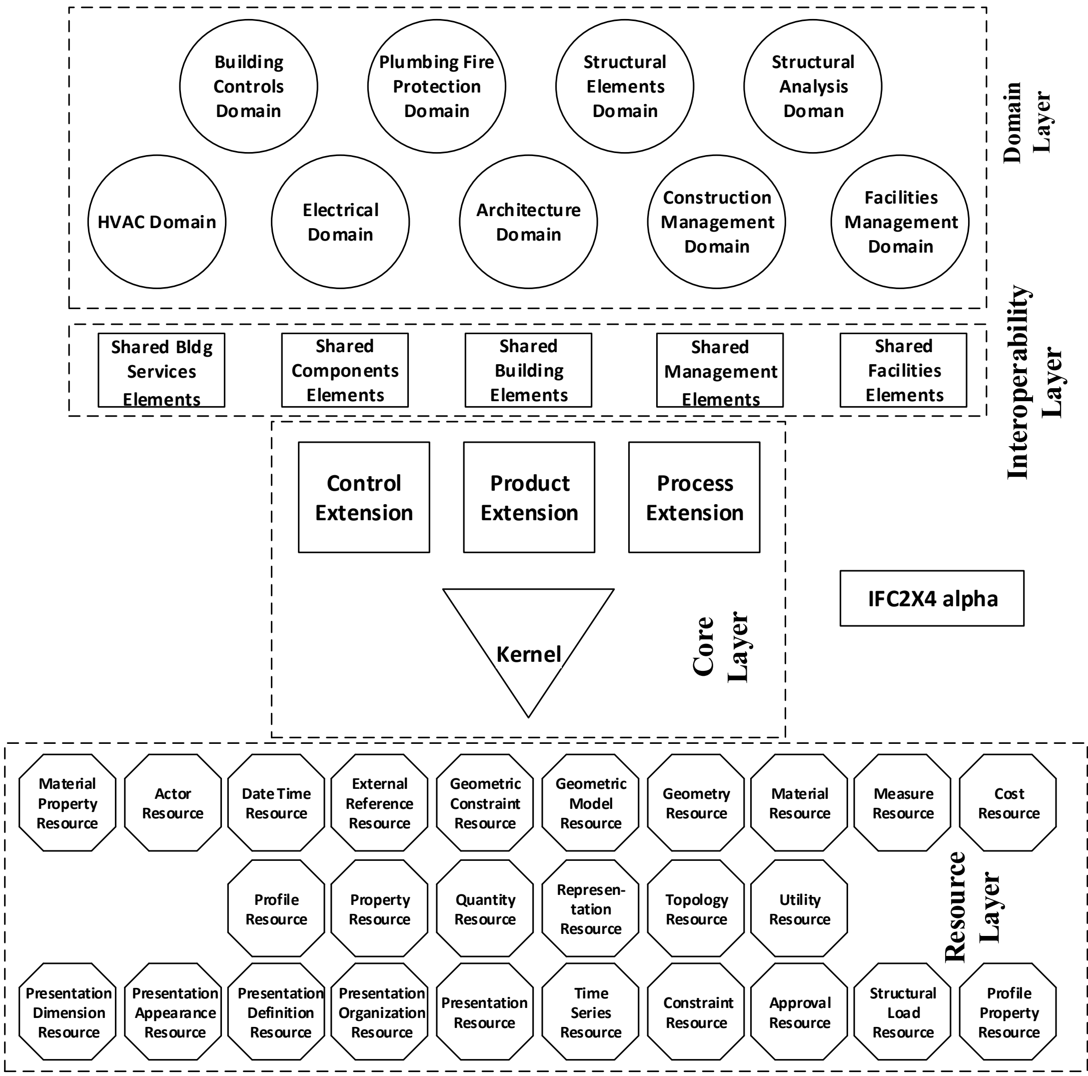


Figure 2-3 The overall architecture of the IFC model (IFC, 2013)

There are three mechanisms to extend the IFC standard: (1) New entities or types definitions; (2) Using *proxy elements*; and (3) Using the property sets or types (Weise et al., 2008). Ma et al. (2011) noted that defining new entities or types is the best way to extend the IFC standard among the three alternatives since the newly defined entities and types can then be used in the same way as the existing ones. However, it normally takes at least two years to define new entities by the BSA (Weise et al., 2008). For the other two alternatives, additional implementation agreements about the definition of the property sets and proxy elements are required, if they are used to share data with other application software. In our proposed BIM extension to incorporate the definitions of the RFID technology (Explained in Chapter 5), new entities and types together with their property sets are proposed.

2.4.3.3 Related Research on Extending IFC for FM

Froese et al. (1999a, 1999b) analyzed the IFC classes related to project management including project planning and cost estimation. Their implementation and testing confirmed the applicability of the overall approach of the IFC model and provided recommendations for potential improvements. Weise et al. (2000) proposed an extension for the structural engineering domain which was not supported in the IFC standard at the time. The same group further suggested an IFC extension for structural analysis (Weise et al., 2003) that contained the conceptual modelling and the envisaged actors and usage scenarios leading to data exchange views. Fu et al. (2006) presented a holistic architecture of nD modelling tools based on IFC. They have also developed an IFC-viewer as a central interface of nD modelling tools. Ma and Lu (2010) discussed an approach for representing information resources by analyzing available IFC entities and relationships. Ma et al. (2011) presented an IFC-based information model for construction cost estimation for tendering in China. Their research included information requirement model for construction cost estimating for tendering in China, and an IFC extension for representing the model. However, there is no research aiming to propose an extension for RFID systems to IFC.

2.4.4 NATIONAL BUILDING INFORMATION MODEL STANDARD (NBIMS)

Completion of the IFC model facilitated the development of exchange standards. In 2005, the Facility Information Council of the National Institute of Building Sciences (NIBS) formed the NBIMS group. According to its charter (NBIMS, 2007), the vision of NBIMS is "an improved planning, design, construction, operation, and maintenance process using a standardized machine-readable information model for each facility, new or old, which contains all appropriate information, created or gathered about that facility in a format useable by all throughout its lifecycle." One of the objectives of NBIMS group is to speed the adoption of an open-standard BIM through the definition of information exchange standards based on the IFC model (East and Brodt, 2007). However, new proposals to extent IFC standard are required to be submitted to the BSA.

2.4.5 FACILITIES LIFECYCLE MANAGEMENT USING BIM

The managerial emphasis has shifted from planning, design, and construction, to the operational stage in terms of the cost of the building life cycle (Dunston and Williamson, 1999). Owners and operators shoulder almost two-thirds of that cost as a result of ongoing facility operation and maintenance (Rundell, 2006). The cost-saving potential at the O&M stage of the life cycle is highest when all the information is collected and made available in early stages during planning, design, and construction. However, continuous accumulation of information is necessary to mine maximum savings and reduce the total lifecycle costs of ownership (Singh et al., 2009).

In order to tackle the problem of information exchange between the construction and the operation phases of the lifecycle, the Construction Operations Building Information Exchange (COBIE) standard is introduced. The COBIE standard provides facilities managers with some of the required data for O&M and for project handover (East, 2013). COBIE data can be created and exchanged using simple spreadsheets.

CAFM (Watson et al., 2011) and CMMS (Sapp, 2011) are essential tools for managing facilities during the O&M phase. These systems do not contain all the data related to the operation and maintenance of a facility and are often not interoperable with other software applications. Owners and operators can use the high-quality building information from a BIM design during the longer, more expensive O&M phase of the building's lifecycle (Rundel, 2006).

Becerik-Gerber et al. (2012) performed 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 the chances of errors and increases efficiency. Hassanain et al. (2001) proposed an IFC-based data model for integrated maintenance management for roofing systems. Later on, Hassanain et al. (2003) presented a general object-oriented schema for asset maintenance management that supports information exchange and interoperability among different domain areas. However, they did not consider BIM visualization potentials for improving maintenance activities.

In 2005, a case study has been performed for BIM modeling of Sydney Opera House (SOH) aiming to utilize the potentials of BIM for FM (Sabol, 2008). The resulting model includes the information about the physical structure of the building, service, maintenance (such as maintenance tasks and schedule), cost, and data fields for *Building condition indices.* Visual reporting is provided using queries based on these attributes in the BIM and color coding techniques. Retrieving all objects with a certain performance index is an example of visual queries that were used (CRCCI, 2007; Sabol, 2008). However, the relationships between assets and the knowledge related to failure causes were not included in this study.

2.5 LIFECYCLE MANAGEMENT USING RFID AND BIM

The lifecycle of a building can be divided into different stages where each stage is generally managed independently while exchanging partial information with other stages (EPCglobal, 2008). The information related to each component should be tracked separately throughout the lifecycle. Furthermore, the information should be in a convenient format and stored at a suitable location to enable all the stakeholders to efficiently access throughout the lifecycle (Ergen et al., 2007b). This need has resulted in various BIM standards, such as NBIMS as discussed in Subsection 2.4. Centrally stored information that is accessible over a computer network is a solution for data access. However, having real-time access to information can be difficult since reliable connections to the central data storage may not be always available.

Our previous research proposed adding structured information taken from BIM database to RFID tags attached to the components (Motamedi and Hammad, 2009a; Motamedi et al., 2011). The original data is saved in a BIM database and the required parts of the data are copied on tags. In all operations, the aim is to synchronize data on the tag with the original BIM data. Having the essential data related to the components readily available on the tags provides easy access for whoever needs to access the data regardless of having real-time connection to the central database or having a local copy of the required information on a portable device.

The ability to store information in digital format on assets can provide “level one product intelligence” for the components (Ergen et al., 2007b). Since an RFID tag can be used to store the above information and is capable of communicating wirelessly with the environment, it is considered to be capable of adding such intelligence to the component. Moreover, this distributed memory space of the tags can store information not only related to the component itself but also related to processes or environment data, and can function as a distributed database.

Based on the proposed approach, RFID tags were attached to a selection of building components, such as Heating, Ventilation and Air Conditioning (HVAC) control units, boilers, etc. It is assumed that the RFID tags can be sensed from relatively long distance and can store several kilobytes of data. The data to be stored on the tags are derived from a BIM database, based on the size of memory and the stage of the component in its lifecycle (Motamedi and Hammad, 2009a; 2009b).

2.5.1 SYSTEM INTERACTION DESIGN

In our previously proposed approach, every component is a potential target for tagging. Having standard tags attached to components would result in a massive tag cloud in the building. While having tags attached to all components would not happen in the immediate future, in order to benefit from the concept of having identity and memory tags on a mass of objects, the subset of components to be tagged can be selected based on the scale of the project, types and values of the components, specific processes applied to these components, and the level of automation and management required by the facility owners.

The system design, including the data structure model and data acquisition method, is general for all components. The target components are tagged during or just after manufacturing and are scanned at several points in time. The scan attempts are both for reading the stored data, or modifying the data based on the system requirements and the stage at which the scan is happening. The scanned data are transferred to different software applications and processed to manage the activities related to the components. The memory of the tag contains a subset of BIM information. While the BIM database is being populated by information by different software applications throughout the lifecycle, the tag memory space is modified and updated as the component is scanned. Details about the relationship between BIM and data on RFID tags are discussed in Motamedi and Hammad (2009a).

2.5.2 DATA CAPTURE METHODS

The structured data stored on the tags should be read, updated and changed during the lifecycle. These modifications are executed by different types of RFID readers (stationary or mobile). In order to identify the suitable type of readers for each scan attempt, the detailed process requirements should be captured, such as the readability range, data transfer rate and portability.

The data stored on the tags can be read from different distances. The maximum readability distance depends on various factors, such as the power level of the reader, antenna type and size, frequency range and environmental factors. In some applications, it is desirable that the data be read from a far distance. Hence, the system can detect the tag even if it is hidden or not visible. Other applications may require shorter readability. For example, if the tags are used to facilitate inspection activities, having short read/write range would guaranty that the inspector was in the required proximity of the component. In the proposed approach, RFID tags are fixed to components; therefore, tags should be designed to have the maximum possible range and protection from noise and interference. However, it is always possible to control the read/write range of the reader based on the process requirements.

2.5.3 CONCEPTUAL DATA STRUCTURE

Considering the limited memory of the tags, the subset of BIM data stored on the tags has to be chosen based on the requirements. Because data on a tag are changing during the lifecycle of the component and different software applications use and modify the data with different designated access levels (Motamedi et al., 2011), the memory of the tag should be virtually partitioned in a structured fashion based on predefined data types. It is proposed to virtually partition the memory space into the following fields, as shown in Figure 2-4:

ID: In order to look up the component in the BIM database, there is a need to have a none-changeable, unique identifier for each component (e.g., EPCglobal Tag Data Standards (EPCglobal, 2008)).

Specifications: This field is dedicated to specifications of the component derived from the design and manufacturing stage of the lifecycle. Safety related information and hazardous material information are examples of these specifications.

Status: Status field identifies the current main stage (e.g., in service, installed, and assembled) and sub-stage (e.g., in service: waiting for inspection) of lifecycle of the component. The status information is used to decide which software application can use and modify the data in the process data field.

Process data: This field is relatively large compared to the other fields and is designed to store the information related to the component's current stage of the lifecycle. The data to be stored on the tags related to different processes are different and should be changed during the lifecycle. For example, assembling instructions are used only in the assembly stage. Therefore, the process data field contains only information related to the current lifecycle stage taken from BIM database. Moreover, the ownership (ability to read, modify or change) of the process data, should be restricted to one or a group of applications (e.g., inspection management software, installation management software) that are involved in that specific stage. The ownership of the process data field is decided based on the status field as explained above. Figure 2-4 provides an overview of our integration scheme where different lifecycle software applications use the central BIM database as the information source and communicate with RFID tags. The figure also shows that different software applications modify the process data field using the same memory space at different lifecycle stages.

History data: This field is designated for storing the history data used during the lifecycle for maintenance and repair purposes. The history records are derived from BIM and accumulated during the lifecycle to be used in forthcoming stages.

Environment data: This field is designated for storing environment specific data, such as the location or the functionality and specifications of the space (e.g., floor plan). Environment data is also taken from BIM and contains all the information that is not related to the component itself.

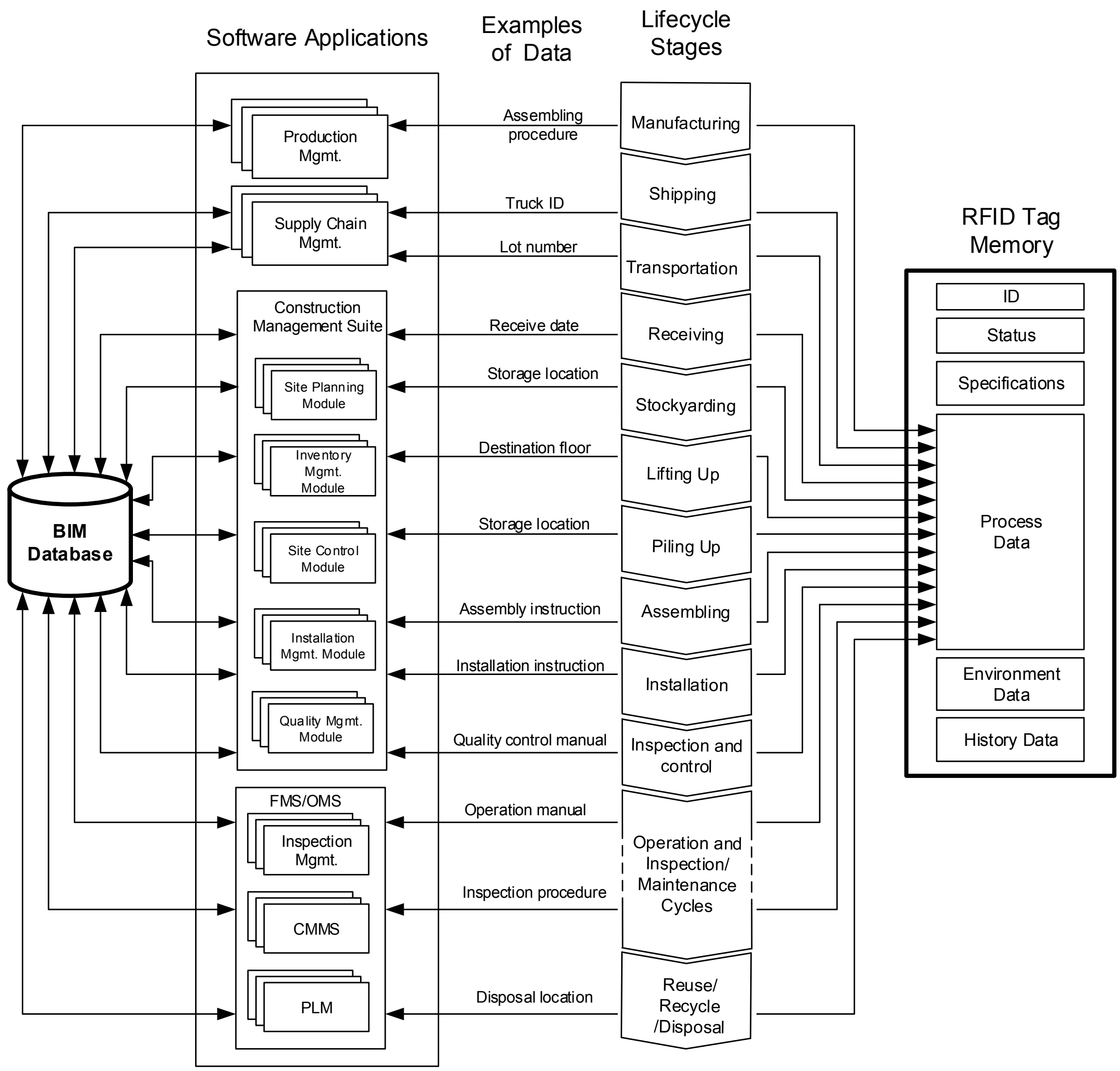


Figure 2-4 Process data update (Motamedi and Hammad, 2009a)

Figure 2-5 shows how the data stored on the tag can be used in the *O&M* phase by different users. During the normal operation of a component, information, such as user manual, occupant names, map and locations, can be used by regular facility users. During fire incidents, other types of stored data (such as hazardous materials in the area or evacuation procedure) can be used by fire fighters and other first respondents. Furthermore, the data on the tag can be used by FM personnel to facilitate the process of inspection or maintenance.

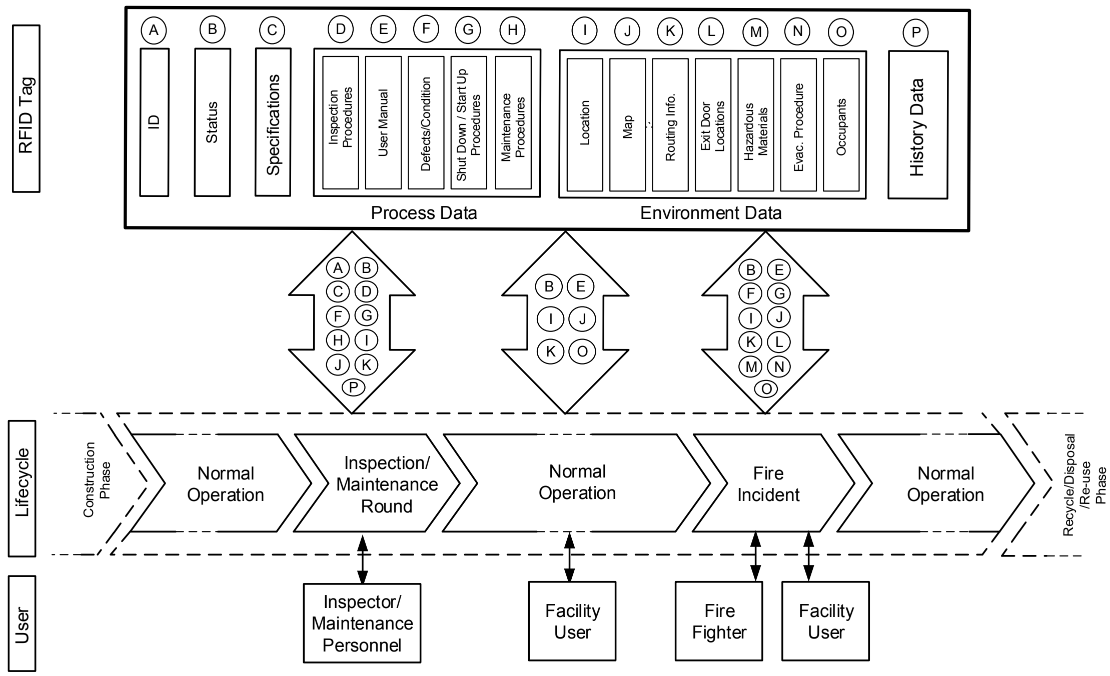


Figure 2-5 Example of tag-data usage in the operation phase (Motamedi et al., 2011)

2.6 BUILDING KNOWLEDGE SOURCES

There are various sources of knowledge related to building assets and systems. Various software applications and databases host this information that are briefly introduced in this section.

2.6.1 ASSET/SYSTEM HIERARCHIES

An asset hierarchy is a means to classify and cluster building components in different categories. The grouping of components into a branch in the hierarchy can reflect similar characteristics (e.g., materials) or similar inspection needs (Ahluwalia, 2008; Uzarski and Burley, 1997). The IFC schema provides a logical hierarchy of building elements through the definitions of various domains (IFC, 2013). Ahluwalia (2008) conducted a review of the literature related to asset hierarchies and analyzed five main elemental classification systems used for data exchange.

2.6.2 SYSTEM MODELING AND OPERATIONAL PROCEDURES

There are various standard techniques to formally model systems and the interaction between their components (e.g., Petri-Nets and SysML) (Andrade et al., 2009). These methods are used for modeling building systems, such as HVAC, drainage, water supply, and building control. Additionally, contractors provide facilities managers with operation manuals for assets and systems. These manuals include procedures, such as start-up/shut down, maintenance/repair, and safety. Moreover, facility managers develop their own procedures for inspection and preventive maintenance that are considered as operation knowledge of the facility.

2.6.3 FM EXPERT SYSTEMS

Expert systems apply artificial intelligence methods to real-world problems. They are referred to as knowledge-based or decision-support systems with a heuristic component that use knowledge to make recommendations, draw conclusions, and/or propose a hypothesis (Kaetzel et al., 1995).

Chang et al. (2007) used the problem-oriented medical record adopted for the medical diagnosis of human diseases and designed a Building Medical Record (BMR) to enable maintenance engineers, building managers, and contractors of a school building to access information for making evaluations and maintenance suggestions. Chang and Tsai (2013) proposed an extension of BRM called Building Diagnosis Navigation System to support on-site managers during the diagnosis of the facility when making decisions about treatment options. However, their system did not use BIM data management capabilities.

Chen et al. (2013) reviewed several studies on the development of expert systems in different areas. They concluded that, for building facilities, the predictive method based on maintenance data has not yet been studied. Moreover, they concluded that the reviewed expert systems generally provide text-based forms and 2D graphical user interfaces for receiving users' inputs and presenting analytical results. They developed an expert system which utilizes visualization, databases, reliability, and optimization technologies to provide predictive information based on accumulated FM data to facilitate decision making. They used OpenGL (OpenGL, 2013) to create a 3D model as the interface for accessing various maintenance data. However, their method did not use BIM to support failure analysis.

2.6.4 CONDITION ASSESSMENT SYSTEMS (CAS)

Condition assessment is the basis for determining the level of preventive maintenance that is needed for building's systems and components (Ahluwalia, 2008; NCES, 2003, Hegazy et al., 2010). Ahluwalia (2008) listed various definitions presented in the literature and current CASs for buildings in practice. Her analysis shows that the number of reactive maintenance work orders of an asset is a good indicator of its condition. Amani and Hosseinpour (2012) provided a survey of current CASs. Some of the reviewed CASs utilize various reliability/serviceability analysis methods including deterioration modeling to estimate the condition of assets. For example, Myrefelt (2004) provided a study on the reliability and functional availability of HVAC systems that includes mathematical modeling together with empirical results.

2.6.5 FAULT/FAILURE MODELING

Current CAFM and CMMS applications use failure class/codes for categorizing the causes for failures. Table 2-3 shows sample failure codes with their description. These systems also use *problem codes* to categorize the symptoms of failures. The codes are entered into CMMS work orders and used for providing statistics about equipment failures (PEMMS, 2003). *Failure Classes* are higher level classification of failure codes in the failure hierarchy.

Table 2-3 Sample failure code table (PEMMS, 2003)

CODE	DESCRIPTION
ARLK	Air Leak
CALB	Calibration Problem
DIRT	Dirt or Foreign Matter Problem
JAMD	Equipment Jammed
XLUB	Excessive Lubrication
LLUB	Lack of Lubrication
WIRE	Loose or Broken Connection or Wire
ALIN	Misalignment
NAIR	No Air
NPWR	No Power
OLLK	Oil Leak
OPER	Operator Error
XHOT	Overheating or Smoking
BROK	Part of Equipment is Physically Broken
SHRT	Short Circuit
VNDL	Vandalism
WTLK	Water Leak

Figure 2-6 shows a part of a failure hierarchy for a centrifugal pump (MRG, 2009). The failure hierarchy describes the failure of the equipment, the possible cause for the failure and recommended remedies for correcting the failure. They include dictionaries of templates that contain the class and subclass of assets, their possible failure modes, causes and remedies (MRG, 2009).

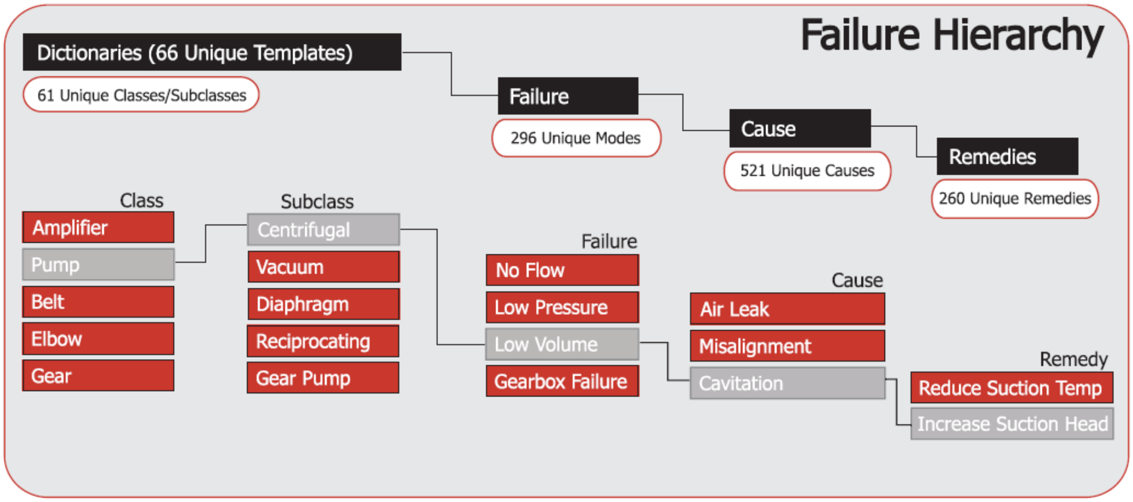


Figure 2-6 Sample failure hierarchy for a centrifugal pump (MRG, 2009)

Deductive fault models are used to deduce the causes of an undesired event by identifying events and modeling their causes. The event is resolved into its immediate causal events using appropriate logic. This process proceeds until the basic causes are identified. The major deductive fault models are:

(1) Root-cause analysis (RCA): RCA is a structured evaluation method that identifies the root-causes for an undesired outcome and the adequate actions to prevent recurrence. The objective of RCA is to identify the root-cause(s) in order to eliminate or modify latent failures and to prevent future occurrences of similar problems or mishaps (NASA, 2003).

(2) Fault tree analysis (FTA): A FTA is a graphical tool for analyzing possible causes of a failure. It can be used as a prevention tool or as a diagnostic tool. A fault tree is constructed to model the logical relationships of events and to provide a framework for qualitative and quantitative evaluation of the undesired events. This method exhaustively identifies the causes of failure and prioritizes the contributors to this failure. Using the data about the probabilities of the causes, the probability of system failure can be determined. Failure probability sources include: manufacturers data, industry standards, historical evidence, simulation and testing, and Delphi estimates (Vesely, 2013).

Hessian et al. (1990) used FTA to model failure modes of an HVAC system control room of a large production facility. They analyzed various failure combinations that any of which can cause system failure for design and/or procedural modifications in order to enhance system availability. Wong (2000) collected time-to-failure and failure modes data for the HVAC of large buildings over a period of six years to quantify the reliability of the system using fault trees. Khan and Haddara (2003) proposed a comprehensive methodology for risk-based inspection and maintenance. Probabilistic failure analysis is conducted for HVAC systems using FTA together with components' failure data and human reliability data for the determination of the frequency of occurrence of an accident.

2.7 VISUALIZATION FOR FM

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 spatial distribution of the 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. Akcamete et al. (2010) added the maintenance and repair work orders to the BIM model manually because of the lack of interoperability between the CMMS and the BIM software. They used symbols and color codes for visualizing work order's data and identified some patterns that can help in planning maintenance activities. Akcamete et al. (2011) visualized work orders' information in a 3D model to perform spatiotemporal analysis and to find the trends of abnormalities. However, they did not consider the relationships between components and did not include other types of data and lifecycle knowledge.

Rad and Khosrowshahi (1997) and Khosrowshahi and Banissi (2001) demonstrated a 4D visualization of some components for building maintenance where the life expectancy of components is mathematically calculated. Hallberg and Tarandi (2011) used Revit (Autodesk, 2011) to represent lifecycle information of the exterior part of a hospital by adding additional object properties, such as *date of inspection* and *condition class* to the 3D model. They also used degradation 4D models to visualize performance-over-time of windows and the concrete structure. Chen and Wang (2009) proposed a 3D visual approach for the 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. However, none of above-mentioned research explored the relationships between components to generate visualizations for failure root-cause detection.

2.7.1 VISUALIZATION METHODS

There are several methods used by different studies to visualize components information. These methods include: (a) Icons/symbols: This method is usable to visualize the states (e.g., installed and replaced), conditions (e.g., good and bad), and properties (e.g., humidity). Akcamete et al. (2010) used symbols in their research to show the assets and their conditions where the symbols show the condition of components and the patterns show the components (Figure 2-7). As the graphical patterns are limited and there are many components in a building, this visualization method can be confusing and prone to errors; (b) 3D components: Hammad and Motamedi (2007) used color coding of 3D assets for the visualization of asset conditions during the construction and operation phases. Figure 2-8 shows the visualization of components' status during the O&M phase. This method is useful for remarkable-sized components, such as boilers, cooling towers, chillers, etc.; and (c) Color-coded spaces: The color-coding of spaces and zones is another method to visualize different spaces according to their functionality, condition and status. This type of visualization is more useful for space management (Autodesk, 2011). Additionally, it can be envisioned that the above-mentioned techniques can be combined to use color coding of assets/spaces together with icons/symbols to visualize multiple attributes simultaneously.

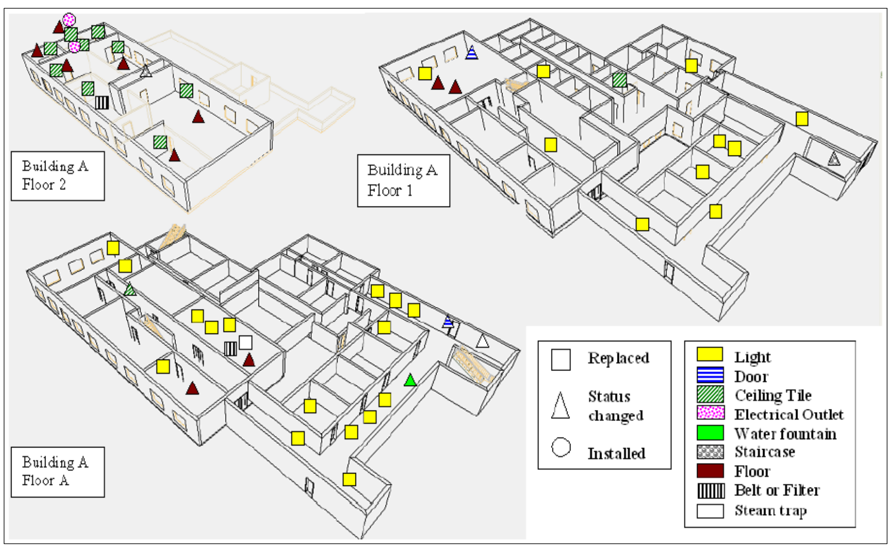


Figure 2-7 Symbols used to show maintenance and repairs of components (Akcamete et al., 2010)

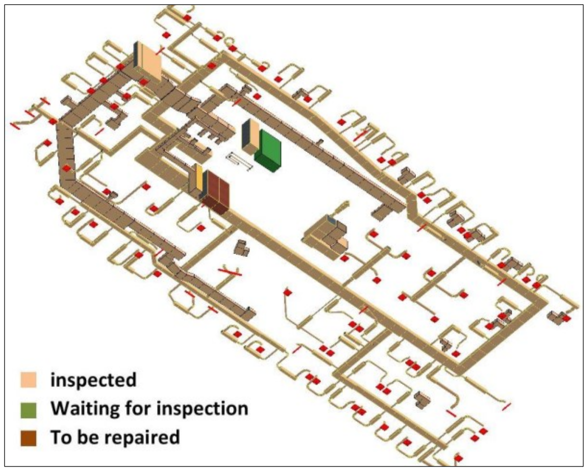


Figure 2-8 HVAC 3D drawing of one floor during the maintenance phase (Hammad and Motamedi, 2007)

2.7.2 VISUAL ANALYTICS (VA)

VA is an emerging discipline which aims to make the best possible use of a huge amount of information by appropriately combining the strengths of intelligent automatic data analysis with the visual perception and analysis capabilities of the human user (Kohlhammer et al., 2011). An early definition of VA was “the science of analytical reasoning facilitated by interactive human-machine interfaces” (Thomas and Cook, 2005). Keim et al. (2010) provided a more specific definition: “Visual analytics combines automated analysis techniques with interactive visualizations for an effective understanding, reasoning and decision making on the basis of very large and complex datasets”.

Recently, knowledge-assisted visualization, which integrates and utilizes domain knowledge to produce effective data visualization, has been a fast growing field. It provides the experts with the insights and reasoning artifacts that make them more capable of performing complex analytical processes (Wang et al., 2009).

2.8 SUMMARY AND CONCLUSIONS

This chapter reviewed the concepts, techniques, major technologies and standards that are used in the current research. The literature review covered the review of RFID technology, including components and details about different tag types, operating frequencies and standards. Furthermore, it elaborated on the concepts of ubiquitous computing and intelligent products, their connection to RFID technology and the insight of future. RTLS technologies and context aware information delivery was discussed and RFID based localization techniques are elaborated in detail. BIM was also covered in this chapter, including data storage/exchange/sharing models, IFC, NBIMS and new standard data handover models in the AEC/FM industry. The approach for lifecycle management of assets using RFID technology was elaborated in detail. Moreover, various sources of building knowledge that are used for the purpose of failure root-cause detection were discussed. Additionally, different visualization methods and the concepts related to visual analytics to support O&M activities in buildings were elaborated.

Based on the reviewed literature, it is concluded that RFID technology is emerging and several applications are being developed in AEC/FM industry. Although the use of RFID technology for localization has been proposed by several research projects, the accuracy and precision of localization systems are still low in indoor environments. Moreover, various opportunities exist to utilize BIM technology for lifecycle management of facilities. Hence, the standards related to the BIM need to be further developed and interoperability issues of BIM-based software need to be solved. Furthermore, the usage of BIM visualization for visual analytics is still in its early stage and several applications can be designed to utilize the integration of visualization software and CMMS data.

CHAPTER 3 OVERVIEW OF THE PROPOSED METHODOLOGY

3.1 INTRODUCTION

This chapter provides an overview of the proposed methodology. The proposed methodology can be segmented in three different but interlinked modules. As mentioned in Subsection 1.2, this research aims to improve the processes related to the O&M phase of the lifecycle of facilities. BIM technology is central to all modules of the research as it is considered to be the main repository of building's lifecycle information that can be used for location management, tracking of RFID tags in the building, and visual analytics for failure's root-cause detection.

This chapter starts by extending our previously proposed framework (Motamedi and Hammad, 2009a), explained in Subsection 2.5, by elaborating on the location-related data that can be retrieved from a BIM and are stored on RFID tags (Subsection 3.2). Storing location-related data on RFID tags that are attached to assets can provide context-aware information inside the building and has the potential for several process improvements throughout the lifecycle of the building. The main focus of the research in the area of location management is the localization of assets in the O&M phase of the lifecycle (First module - Subsection 3.3). The second module (Subsection 3.4), focuses on extending BIM to incorporate the definitions of RFID tags. The definition of RFID as an extension to BIM provides the opportunity to interrelate BIM data and RFID data using predefined relationships. BIM can also be used as the main repository of information related to the facility throughout its lifecycle. This chapter also provides an overview about the proposed knowledge-assisted BIM-based visual analytics approach for failure root-cause detection in FM (Third module - Subsection 3.5). In our approach, the CMMS inspection and maintenance data are integrated with a BIM and are used for interactive visualization exploiting the heuristic problem solving ability of field experts. Finally, this chapter discusses the link between our proposed RFID-tagged environment with the concepts of intelligent products, ubiquitous computing and IoT (Subsection 3.6).

Figure 3-1 shows the relationships between the contents of the thesis. It shows how the sections in the literature review are related to subsequent chapters.

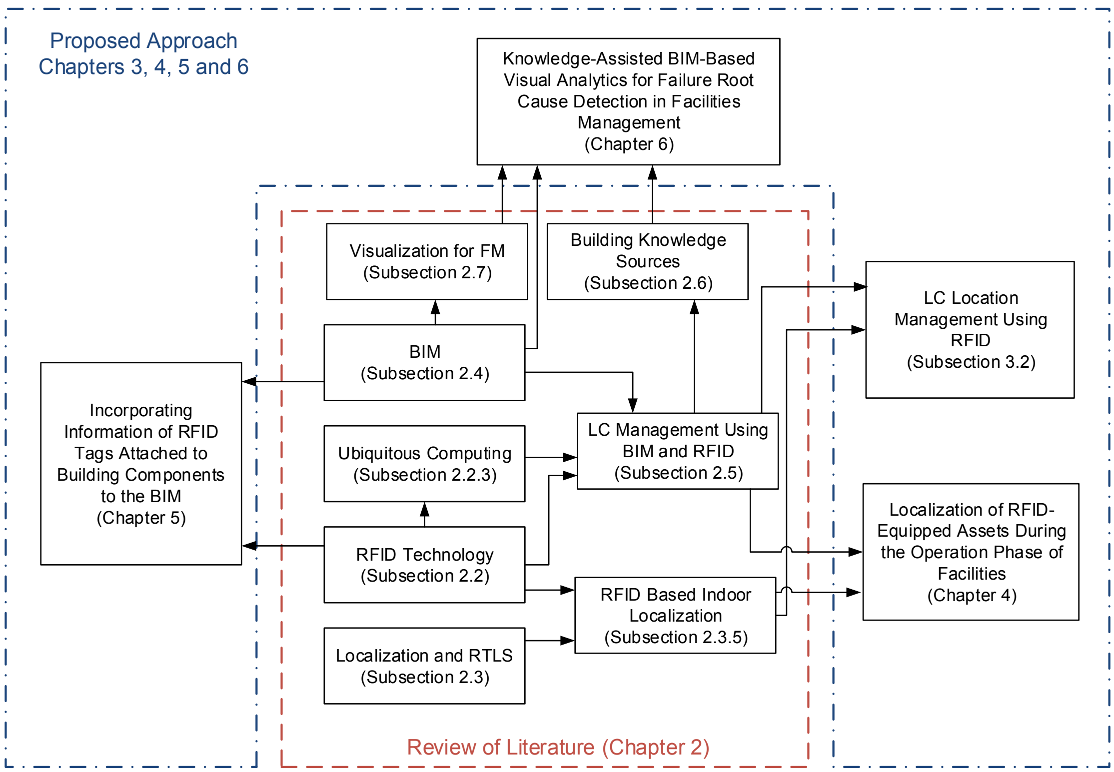


Figure 3-1 Thesis structure and content relationships

3.2 LIFECYCLE LOCATION MANAGEMENT USING RFID

Several location-related data (e.g., current location, temporary location, destination site, and disposal location) can be stored on the RFID memory of the tags attached to building components or assets. These data can be read and updated during the lifecycle to facilitate several processes. In our previously proposed framework (Subsection 2.5), components that are equipped with RFID tags are scanned and the data on the tags are updated before each stage or sub-stage for several purposes. Consequently, the location-related data can be updated during the same data update event.

The location information is available, or would be added, to a BIM and can be used by different software applications, such as Enterprise Resource Planning (ERP), project management, inventory management, CMMS, SCM, and PLM. The location information can facilitate operations, such as locating components, warehouse management, shipping and transportation, assembling and installation, supply chain visibility, site management, quality control, dismantling, repair, and navigation.

The location information are determined either based on the design (e.g., final location, location of attached parts, location of subcomponents) or decided during the lifecycle (e.g., temporary location, lot number, destination site) by systems, such as operation management, construction management, site management and SCM software. This information is usually included in *process-related* data, which is managed by different software applications and is process-specific.

As explained in Subsection 2.5.3, the *process data* field contains information related to a specific lifecycle stage, and the data recorded in this field are changing during the lifecycle. Hence, the suggested location-related data in the *process-related data* field is only present at the required stage and are managed by the related software that has the ownership of process data field.

At the design phase, the ID and the *final location* of the fixed assets are created in the CAD modeling software and communicated with the manufacturer in the ordering process. While the *final location* information is written on the tag at an early stage in the lifecycle, a variety of *temporary location* information is stored and used at various stages. Thus, in order to use relevant location information, a series of read/write events have to be executed during the lifecycle. Figure 3-2 shows some of the possible location-related data that can be stored on a tag attached to a generic fixed component. The required location information is determined based on the type of component and the processes involved in its lifecycle. The figure also shows the lifecycle phases where the location data can be used. The white, shallow-grey and dark-grey colors show whether the data is updated, read or written, respectively, on the tags' memory at that specific lifecycle phase. The location information that can be stored on RFID tags are:

A: ***Final location*** is defined at the design phase for *fixed components* and recorded on the tags at the manufacturing phase. This information is considered as an unchangeable property of the component and is placed in the *specification* section of the memory.

B: ***Subcomponents' locations*** are the information about the parts inside the component, e.g., mechanical parts, electronic parts, controllers and power units. These data can be used in the assembly line to help operations, such as welding and part installation. These data are also useful to help detaching the faulty part for repair purposes and finally it can be used to dismantle the component at the end-of-life.

C: ***Attached parts' locations*** are the data about ports and connection points that connect the component to its adjacent units (e.g., HVAC ducts). These data are most useful at the assembling and installation stages and can also be used at the operation phase where the component it detached for repair or maintenance purposes.

D: ***Temporary location*** is one of the main location-related data that can be recorded on RFID tags and are useful at various stages. The *temporary location* is basically any location that the component may be stored at other than its *final location* in the building. The components are stored in various locations (e.g., storage, yard, shelf, floor, and warehouse) during their supply chain and the temporary storage location can be recorded on tags to help moving the components.

E: ***Delivery lot information*** is a subset of *temporary location data* that can be stored and used at shipping and transportation stages and managed by SCM software. The data can be also used for inspection and quality control purposes.

F: ***Destination site*** is a subset of *temporary location data* and is used at the transportation and receiving stages where the components are transported and delivered to designated locations. There might be several destination sites during the supply chain stream, where their information can be stored and read during transportation.

G: ***Disposal location*** can be recorded on the tag based on the environment factors decided by the product management software. The data is used to ensure that the component is disposed at the right location

H: ***Current location*** data recorded on long-range RFID tags can be used to locate components. This data can be accessed by facility users or emergency responders as well as inspectors and maintenance staff. This field of memory is further discussed in Subsection 4.5 for *fixed assets* localization. The content of this field (i.e., coordinates) recorded on the *reference tags'* memory, are used for locating movable assets in our proposed approach for the localization of RFID tags (explained in Subsection 4.6).

I and J: ***Navigation data*** *(e.g., predefined routes, floor plans/maps)* can be used for navigational purposes. The FM personnel, emergency responders or general facility users can use this data to download the floor plan and navigational aid information. Parts of a floor plan can be stored on adjacent tags in the building and the user application can get the floor plan by extracting and combining those parts.

K: ***Locations of other component*** include the relative or absolute locations of other components that do not have tags attached to them or have tags with short readability range. This field of memory will be further discussed in Subsection 4.5.1.

L: ***Previous locations*** is the history of important previous locations of a component. These locations are managed by the PLM system.

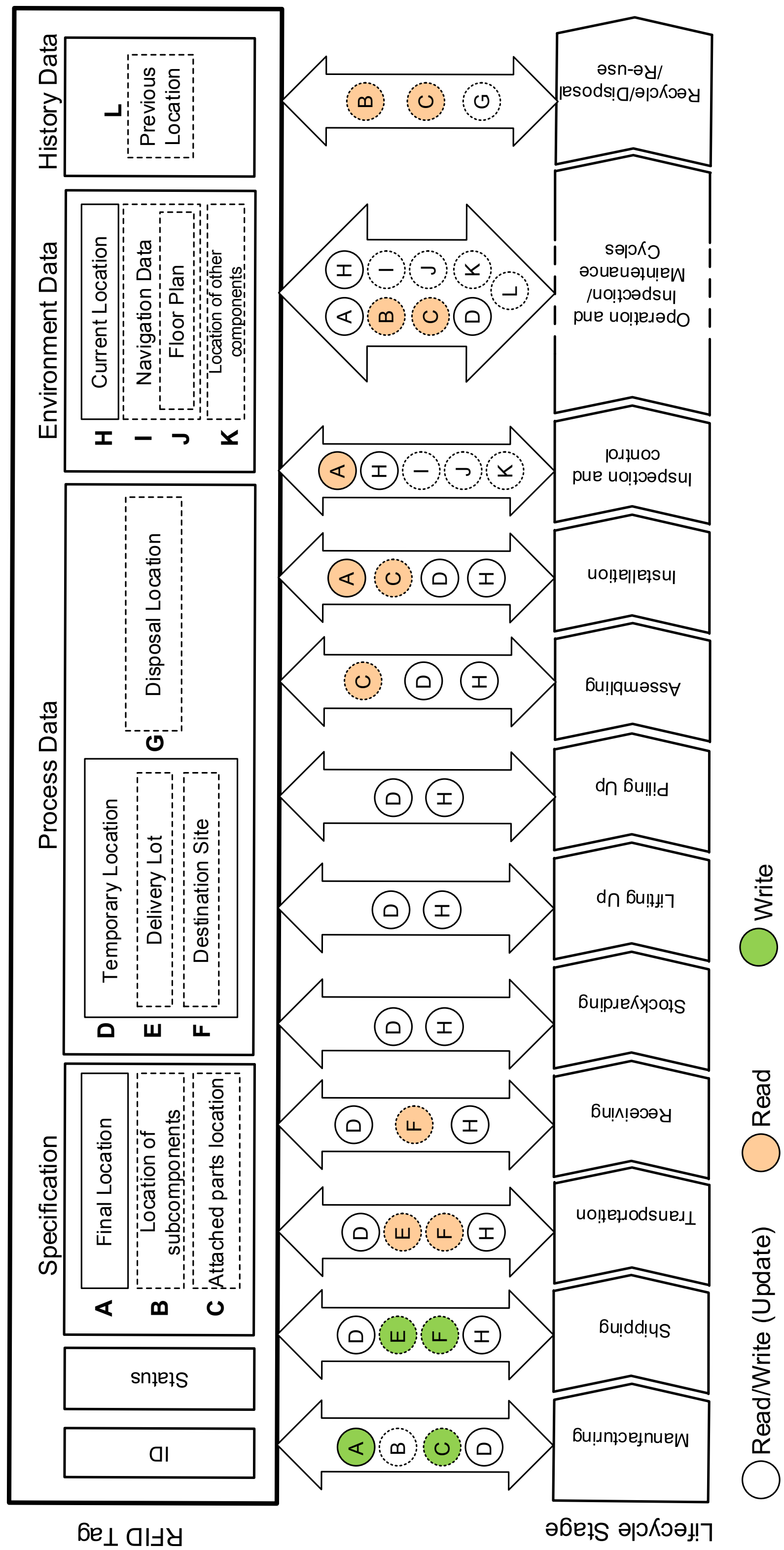


Figure 3-2 Examples of lifecycle location-related data on the RFID tag

3.3 LOCALIZATION OF RFID-EQUIPPED ASSETS DURING THE OPERATION PHASE OF FACILITIES

As explained in Subsection 2.3.1, location data is essential for many processes related to SCM, FM, and PLM. Location tracking systems provide the potential for achieving savings depending on the selected technology (Kelepouris and McFarlane, 2010). Although RTLS technologies are capable of providing real-time location information of assets, providing RTLS infrastructure inside the building is costly and imposes tremendous amount of technical design and implementation issues.

In our previous research (as described in Subsection 2.5), a framework is proposed where RFID tags are attached to components at an early stage of their lifecycle and the memory on tags is used to store various types of data. This research aims to utilize the available mass of RFID tags in the building for localization purposes. In our approach, the user who is searching for assets is equipped with a handheld RFID reader and is able to read the data of the tags from a distance. This approach is based on the assumption that relatively long-range RFID tags are attached to building components. Hence, the tags are not solely used for locating purpose, and their memory is used during the lifecycle for various applications.

First, a method is proposed to save current location data (e.g., coordinates) on tags attached to fixed assets. Consequently, an FM personnel is able to read a tag from a distance and locate the fixed assets on a floor plan. Fixed tags with known locations act as *reference tags* for RFID reader localization techniques (e.g., trilateration, scene analysis and neighborhood). In this scenario, the user can also estimate his/her location by scanning the surrounding tags. Additionally, information, such as floor plans and navigational aids can be stored on these tags.

Second, the research investigates a new method to locate moveable assets (e.g., tools). In this method, radio signals received from tags attached to fixed assets help the user estimate the location of the target tag attached to a movable asset based on received RSSI pattern matching and clustering techniques. This method introduces several improvements to available techniques as it incorporates the dynamics of the environments since the target tag and surrounding reference tags are affected by the same environment. Furthermore, this method does not require calibration since it uses RF signal data without converting them into distance information. As a result, a user equipped with an RFID reader is able to estimate his/her location, as well as to obtain the location information of target assets, without having access to any RTLS infrastructure. The details of the proposed methods for locating the user and locating fixed and movable assets are given in Chapter 4.

3.4 EXTENDING BIM TO INCORPORATE INFORMATION OF RFID TAGS ATTACHED TO BUILDING ASSETS

There is an evident need for a standard data model to be used as the basis for computer-aided design, planning, construction and maintenance. As explained in Subsection 2.4.1. BIM is emerging as a method of creating, sharing, exchanging and managing the information throughout the lifecycle to tackle the problems related to interoperability and information integration. The IFC standard developed by BSA (formerly known as International Alliance of Interoperability (IAI)), has matured as a standard BIM in supporting and facilitating interoperability across the various phases of a building lifecycle (Isikdag et al., 2008) (described in Subsection 2.4.3). IFC is an object-oriented, non-proprietary building data model. However, modelling all objects related to the building industry is extremely complex. Therefore, the BSA introduced an incremental development of the IFC model by providing an extensible architecture for extending IFC in various domains.

Based on the assumption that the RFID tags are permanently attached to building components, the tags can be considered as components of the building. Consequently, there is a need to formally define these RFID tags and their associated properties in the building's data model. The data in the model are essential for tracking and maintaining the RFID components throughout the lifecycle of the building. Moreover, due to the fact that RFID memory is populated with BIM data, defining RFID as an object in the model facilitates the data linkage and management. The data interrelation can be achieved by defining the RFID system components (e.g., tags and readers) as objects in a BIM together with their logical and physical relationships to other objects.

The research goal is to propose adding the definitions of RFID technology components to the BIM standard and to map the data to be stored on RFID memory to associated entries in a BIM database. A requirements' gathering are performed to add new entities, data types, and properties to the BIM. Furthermore, the research identifies relationships between RFID tags and building assets. It provides the opportunity to interrelate BIM data and RFID data using predefined relationships. Eventually, the data related to objects that are required to be saved on RFID tags can be automatically selected using defined relationships in a BIM. The details of the approach are given in Chapter 5.

3.5 KNOWLEDGE-ASSISTED BIM-BASED VISUAL ANALYTICS FOR FAILURE ROOT-CAUSE DETECTION IN FACILITIES MANAGEMENT

Decisions on maintenance-related tasks are usually 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 the process of correlating information time-consuming and less intuitive. In the current status of practice, FM technicians add inspection and maintenance data to the database of a CMMS. The CMMS application provides managers and technicians with various reports related to maintenance and repair issues. As explained in Subsection 2.4.5, BIM has the potential to help improving the quality of FM by visualizing the large amount of lifecycle data.

On the other hand, discovering the root-cause of a problem based on the data in a CMMS is difficult and prone to failure. This is due to the complexity of the relationships between various building components and systems (Ahluwalia, 2008), multiplicity of building components and various changing environmental factors. Finding the root-cause of a problem or trends in the operation of the facility can be assisted by providing experts with various types of background knowledge and a flexible visualization tool that allows them to utilize their cognitive and perceptual reasoning for problem solving. VA can apply the expert cognitive capabilities and judgment for the following scenarios: (1) Visualizing possible causes of a certain problem based on available lifecycle knowledge and the relationships between elements in a BIM. The visualization of all known possible causes provides the opportunity for heuristic problem solving to find the main cause of the detected problem; (2) Analyzing the temporal and spatial distribution of problems to infer patterns and trends by visualizing this distribution and the occurrence frequency of the problems in the past and present situations; and (3) Visualizing the chain of effects caused by changing the status/condition of a certain component (e.g., failure or temporary shutdown of a mechanical component) in order to simulate resulting effects using relationships between assets. This can be used to plan for redundancy, to help developing incident management plans, and to prepare tasks related to change management plan.

In this research the potential of knowledge-assisted BIM-based VA for the above-mentioned failure root-cause detection scenario is investigated. The BIM is considered to be the primary data source for information related to building lifecycle. BIM data is linked to data stored in FM software applications (e.g., CAFM, EAM, and CMMS). The proposed approach provides customized visualization through the interaction with the FM technicians in order to assist failure root-cause detection using their cognitive and perceptual reasoning. The details of the approach are given in Chapter 6.

3.6 RELATIONSHIP WITH INTELLIGENT PRODUCTS, IOT AND UBIQUITOUS COMPUTING

Our proposed framework for lifecycle management (Subsection 2.5), lifecycle location management (Subsection 3.2), and RFID localization (Chapter 4), will eventually lead to having assets with embedded or attached RFID tags. This would provide data storage capacity as well as unique identification of assets. Several definitions of an object's intelligence are proposed as explained in Subsection 2.2.3. Wong et al. (2002) have defined a product with Level 1 intelligence as a product that possesses a unique identification, has the capability of communicating with its environment, and is able of retaining or storing data about itself. Based on this definition, an RFID-equipped asset can be categorized as a product with Level 1 intelligence. Moreover, an RFID-equipped asset can be categorized as an intelligent product by Kärkkäinen et al. (2003) definition that is centered on the control of the supply chain deliverables and of products during their lifecycle. Based on their definition, the possession of a globally unique ID, the linkage to information sources about the product across organizational borders, and communicating with information systems and users when needed are considered as defining properties of intelligent products. An RFID-equipped asset possesses the abovementioned properties except for the fact that current RFID technology does not perform proactive actions due to the lack of processing power on the RFID tag. Finally, RFID-equipped assets have some degree of intelligence based on Meyer et al. (2009) due to their *Information handling* ability.

As explained in Subsection 2.2.3, a ubiquitous computing environment comprises objects that have embedded wirelessly intercommunicating microprocessors that can be coupled with sensors. In our previously proposed environment (explained in Subsections 2.5), the assets are equipped with embedded RFID tags. Although available RFID tags lack processing power, they are able to communicate their stored information wirelessly and can be coupled with sensors to record their environment characteristics. Moreover, the proposed environment comply with some of the characteristics of ubiquitous environments introduced in the literature, such as decentralization or modularity of the systems and networking, the mobile support for users to access information services anywhere and anytime, and context awareness.

Furthermore, since the identity knowledge, of the *self* and of the others is considered as fundamental enabler for the IoT, our proposed RFID tagged environment is aiming towards the vision of the IoT which will connect and enable intelligent interaction between objects around the world.

3.7 SUMMARY AND CONCLUSIONS

This chapter provides an overview of the proposed methodology of this thesis. It also contains details on the proposed approach to use RFID memory to store various location-related data that can be used during the lifecycle of the building. The example of location data that was explained in this chapter showed some of the possible location-related information to be stored on the tag. Moreover, the availability of tags in the building provides localization opportunities for the O&M stage that is explained in the following chapter.

CHAPTER 4 LOCALIZATION OF RFID-EQUIPPED ASSETS DURING THE OPERATION PHASE OF FACILITIES

4.1 INTRODUCTION

As explained in Subsection 2.3.1, indoor localization has gained importance as it has the potential to improve various processes related to the lifecycle management of facilities and to deliver personalized and LBSs. RFID-based systems, on the other hand, have been widely used in different applications in construction and maintenance (Subsection 2.2). This chapter investigates the usage of long-range RFID technology for indoor localization of RFID-equipped assets during the O&M phase of facilities. As explained in Subsection 3.2, the location-related data on RFID tags attached to assets are extracted from a BIM and can provide context-aware information inside the building which can improve FM processes. In this chapter, it is proposed to use the current location of the assets saved on the tags attached to *fixed assets* for locating them on a floor plan (Subsection 4.5). Fixed tags with known positions act as *reference tags* for RFID reader localization techniques. In this scenario, the user can also estimate his/her location by scanning the surrounding reference tags (Subsection 4.7). Furthermore, this chapter investigates new approach to locate *moveable assets* using received signals from available reference tags in the building based on pattern matching and clustering algorithms (Subsection 4.6). As a result, a user equipped with an RFID reader is able to estimate his/her location, as well as the location of target assets, without having access to any RTLS infrastructure. Several case studies are used to demonstrate the feasibility of the proposed methods (Subsection 4.9).

This chapter has the following objectives: (1) to explore the possibility of using RFID tags attached to assets for localization purposes; (2) to investigate new methods for localizing various types of RFID-equipped assets during the O&M phase without having an RTLS infrastructure; and (3) to investigate the applicability of the proposed methods using several case studies.

4.2 OVERVIEW OF PROPOSED METHOD

As explained in Subsection 2.5, in our previous research, a framework is proposed where RFID tags are attached to components at an early stage of their lifecycle and the memory on tags is used to store various types of data. The present research aims to utilize the available mass of RFID tags in the building for localization purposes. In our approach, the user who is searching for assets is equipped with a handheld RFID reader and is able to read the content of the tags from a distance to locate *fixed* and *movable* assets. The approach is based on the assumption that relatively long-range RFID tags are attached to assets. The tags are not solely used for the localization purpose, and their memory is used during the lifecycle for various applications.

4.3 LOCATION INFORMATION SOURCE

There are two major information sources for providing the current location of the assets:

(1) Location is sensed by RTLS infrastructure: As shown in Figure 4-1, in this method the current location of the assets is provided by the RTLS technology that scans and detects target assets in the area of coverage. The users hence, need to have access to the RTLS system (e.g., web service access, middleware access, and software application) to query and retrieve the location of a specific asset. Locations of assets are sensed by RTLS system using various position estimation techniques, such as angulation, lateration and finger printing explained in Subsection 2.3.4. In this method, the system is not dependent on the data that are stored on RFID tags attached to target assets for finding their locations.

(2) Location data is available on the tags: As shown in Figure 4-2, in this method *current location* data (explained in Subsection 3.2) are stored on RFID tags attached to assets. Using this method, the user can read the location data from a long distance and locate the asset even if it is hidden, obstructed or stored in closed areas. The current research focuses on this technique for location tracking of *fixed assets*. Moreover, this research uses *current location* data on tags attached to *fixed assets* for localizing *movable assets*. However, the location data on RFID tags should be recorded and updated to reflect the accurate position of the asset to users who read the data. The following various methods are used to update the location data:

(a) Updated by FM personnel: the location data (e.g., coordinates) can be recorded on assets' tags when installed and updated after they are moved by FM personnel. In this method, FM personnel can acquire the location of assets while updating the location data of tag from an RTLS (e.g., GPS/UWB) or by taking coordinates from the original design plans reflected in a BIM file.

(b) Updated automatically: in this method the location data on the RFID tag are saved and updated automatically. *Location-Aware RFID Tags* that have embedded location sensors (i.e. GPS receivers) (e.g., RFIDJournal, 2007) can be used in this method. Another technique for updating the location data on the tags is the usage of fixed RFID readers or magnetic loops infrastructure that automatically write the location information on tags as tags pass close to them (e.g., Identec, 2011).

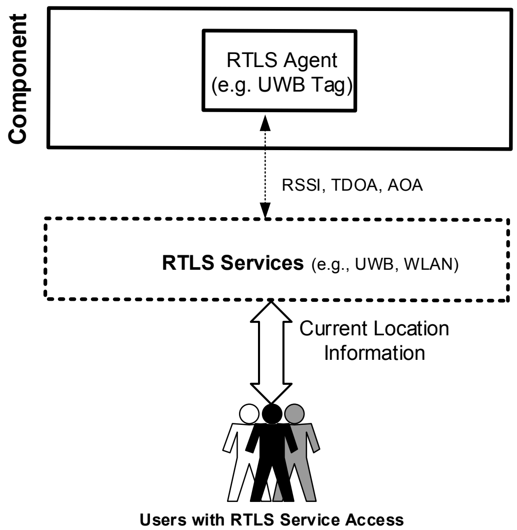


Figure 4-1 RTLS-based location tracking

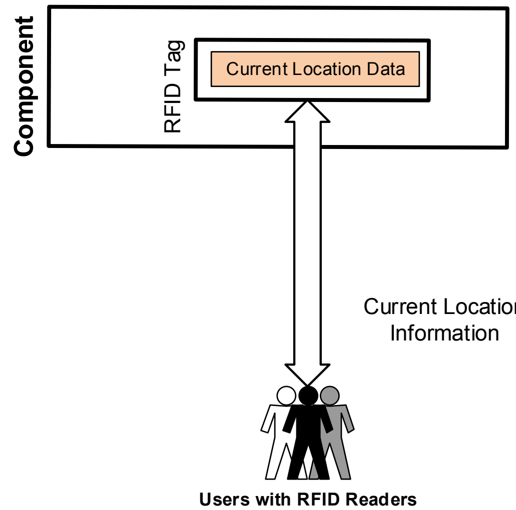


Figure 4-2 Location tracking based on RFID data

4.4 ASSET CATEGORIZATION

In order to use appropriate localization technique for various types of building assets, they are categorized as follows:

(1) Fixed assets: Those are assets that do not move and remain in their initial position after installation. The locations of these assets are decided at the design stage and are available in a BIM. These assets may be moved during the building lifecycle for maintenance and repair purposes. However, they should be installed back in their original location. Assets, such as boilers, walls, doors, and HVAC ducts are examples in this category,

(2) Semi-fixed assets: Those are assets that are moved infrequently. The locations of these assets are recorded in a BIM database. The movement can be *planned,* where a asset is moved by FM personnel and is recorded (e.g., fire extinguisher, furniture) or, *unplanned* where an asset is moved per use by users based on special needs (e.g., computer or a lab equipment).

(3) Movable assets: Those are assets that are frequently moved. Moving these assets does not require special permission from the FM department and their locations in BIM and FM software do not need to be updated per move (e.g., shared ladder, cart, containers).

(4) Temporary Assets: Those are assets are not owned by building owners. Their information is not available in BIM and they are used in the building for a limited period of time (e.g., scaffolding, tools of a contractor).

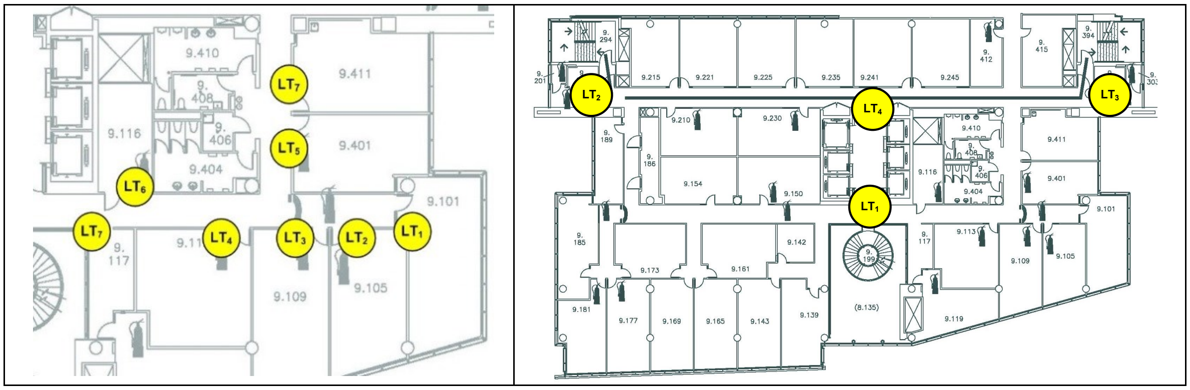
4.5 FIXED ASSETS LOCALIZATION

The real-time localization of fixed assets, that constitute a large portion of available assets, is unnecessary. The FM software and the BIM database contain location information of fixed assets on floor plans or in asset databases. In our proposed approach, the memory of tags attached to these assets contains the exact location data taken from a BIM. Consequently, by accessing the memory content of these tags from a distance, the location of the associated assets can be identified. Having the location data together with a digital floor plan, the personnel are able to find the asset even if it is obstructed or hidden without having access to any RTLS infrastructure. In this method, the location data on a tag are updated in advance and are not real-time. Hence, this method is not suitable for locating movable assets. Therefore, another method for locating moveable assets is explained in Subsection 4.6.

4.5.1 LOCATION TAGS

Attaching long-range tags with large memory to all fixed assets may not become financially feasible in the near future. In order to benefit from the proposed method, specific long-range tags called *location tags* can be attached to selected assets to store location information related to a set of assets in the neighboring area. Consequently, when a user tries to locate an asset, the location tags data are read from a distance. These data contain the locations (e.g., coordinates) of all assets in that area including the target asset. These data are recorded in the *environment data* section of the tag's memory as explained in Subsection 3.2.The location data are updated on location tags when a fixed asset is installed in that specific area.

The location tags are proposed to be placed based on predefined rules to facilitate finding these tags. In scenarios where there are various target assets in each room (e.g., a university building), the location tags can be placed *per room* at the exterior side of the entrance to each room in the common area (e.g., hallway). Figure 4-3(a) shows a sample floor plan of a building where location-tags are assigned per room. These tags can contain information related to the assets that are located inside each associated room. The tags are placed at the exterior to provide maximum data accessibility and read range for users who are navigating in the common areas. In scenarios where the target assets are spread in various locations on the floor (e.g., commercial office space with cubicles or production floor), the location tags can be placed at the entrances to the floor (e.g., near elevators, in the lobby). Figure 4-3(b) shows the location tags that are attached close to the main entrances of the floor. These tags contain information about the important assets in the associated floor. Moreover, the tags can contain floor plans and occupants' data for each floor. Consequently, the user will be able to retrieve the data related to each floor as soon as he/she enters the floor.



(a) Location-tags assigned per room (b) Location-tags assigned per floor

Figure 4-3 Location-tags placement

The location tags require more memory storage than regular asset tags. Moreover, it is desirable to employ long-rang tags with maximum readability in common areas. Directional antennas on the tags should be used for areas, such as corridors to provide maximum readability. These tags should be placed at visible locations and use high-visibility materials and colors (e.g., retroreflective material) to attract the attention of the users.

4.5.2 PROCESS OF FIXED ASSET LOCALIZATION

Figure 4-4 shows the process flowchart for fixed asset localization: (1) The user scans the area to look for the target RFID tag; (2) The handheld's reader detects surrounding tags and reads their IDs and data; (3) The software application queries for the ID/property of target asset amongst detected tags. The queries can be based on the unique ID of a specific tag or a property of an asset (i.e., condition=require maintenance, type=boiler, status=faulty); (4, 5) If the target tag is found, the application reads the location data from the memory, locates the appropriate floor plan and shows the asset on the floor plan; (6)

In case the target tag is not found in the scanned area, the application starts an exhaustive search among all detected location tags to find the data related to the target tag; (7, 8) In case a location tag is detected, the reader reads the data and queries for the target tag; (9) In case the target tag information is found on location tags, the application reads the data and shows the location of the target tag on the floor plan; (10) If the target tag's data are not found on the location tag, the application prompts that the target assets cannot be found and advises the user to move and change his/her location and rescan. The location tags are placed in the building based on predefined rules (as described in Subsection 4.5.1) that can assist users finding them on the floor.

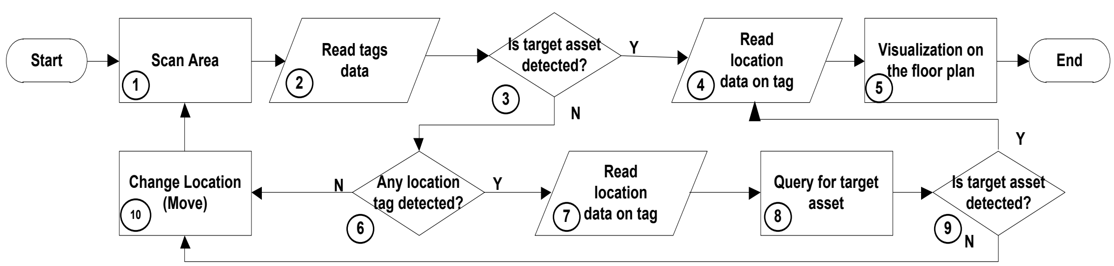


Figure 4-4 Process flowchart of fixed asset localization

4.6 MOVEABLE ASSETS LOCALIZATION

In the proposed method, it is assumed that fixed and movable target assets are equipped with long range, omnidirectional and identical tags. RFID tags that are attached to fixed assets contain their exact location coordinates and are available throughout the building. Moreover, it is assumed that the target tags are stationary for the period of localization and the user equipped with a handheld reader is moving within the facility to collect RSSI values and locate assets.

The proposed method can be categorized under neighbourhood-based localization techniques (explained in Subsection 2.3.5.1) where *fixed* assets are used as *reference* *points* to help locating *moveable* assets. The similarity of received RSSI between target tags and fixed-assets' tags (reference tags) is used for localization. The RSSI received from reference tags and from target tags are logged by a handheld RFID reader at several locations and processed to determine the similarity between signal strength patterns. Tags that show similar signal patterns are considered to be spatially adjacent. This similarity of patterns stems from the fact that the radio signals are affected by similar environmental effects for neighbouring tags. This method does not use RSSI values to estimate the distance between the reader and tags due to the unreliability of this conversion in indoor environments. The proposed method is called *Cluster-based Movable Tag Localization (CMTL)* throughout the thesis.

4.6.1 PROCESS OF MOVABLE TAGS LOCALIZATION

As shown in Figure 4-5, a user equipped with a handheld RFID reader moves in the building and collects the RSSI values from all surrounding tags at different locations (e.g., L_1, L_2, and L_3 in Figure 4-5). Recorded RSSI values are those received from reference tags (R_i) attached to *fixed* assets that have their locations and from a tag attached to a movable asset with no location information (T). In this method the received RSSI values from the target tag are compared with those received from the reference tags at different data collection steps. By using a pattern matching algorithm, the reference tags that exhibit similar signal patterns to those of the target tag are identified. Finally, a group of reference tags is selected and their coordinates are used for localizing the target tag as explained in the following sections.

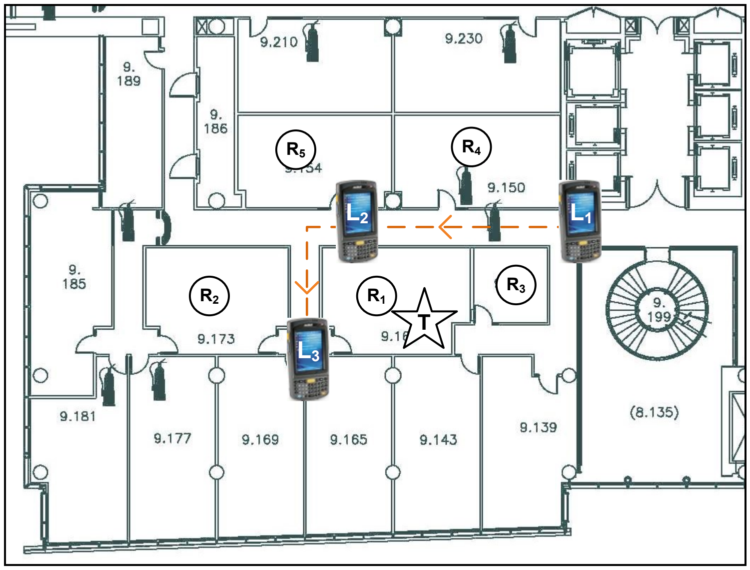


Figure 4-5 Sample scenario of localization process

Figure 4-6 shows the process flowchart to locate a specific movable asset: (1) The user scans the area to detect the tag that is attached to the target asset; (2) If the target tag is not in the range of the RFID reader, the user needs to change his/her location to be able to detect the tag; (3) As soon as the target tag is detected by the reader, the user starts logging the RSSI received from surrounding tags. The user remains stationary during data collection for a short time period of Δt; (4) The logged data are processed by the data processing module which includes: **filtering logged RSSI values** to eliminate the values that are out of range as the result of sudden noises, errors in recording data, hardware errors, etc.; **data averaging and pattern matching** to compare the pattern of the RSSI of the target tag with all reference tags using a pattern matching algorithm; and **clustering** to group reference tags considering the result of pattern matching and their spatial distribution; (5) The location of the target asset is estimated based on the result of the pattern matching, clustering and other information, such as spatial constraints; (6, 7) If the logged data are not adequate for accurately estimating the location, the user is prompted to move to a new location and to continue logging data; (8) After estimating the location of the target tag, it is shown on the floor plan.

The method can also be used to locate a group of movable assets by collecting RSSI values for all target tags while moving in the facility. The data are then processed to calculate the locations of all target tags. The details of filtering, averaging, pattern matching, clustering and localization are given in the following sections.

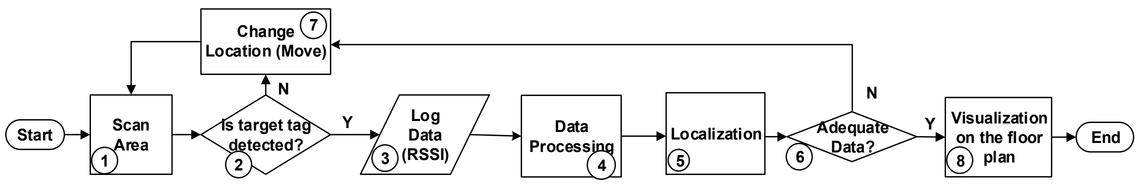


Figure 4-6 Process flowchart of localizing a specific movable target asset

4.6.2 FILTERING AND AVERAGING

At each data collection step, several RSSI values from various tags are sensed and logged by the reader. Data collection happens when the user is stationary for a short duration of Δt. As the tags and the reader are not moving for the period of data collection, the received RSSI value from each tag is expected to be constant. However, variations in the received values result from small changes in distance, ambient noise, multi-path effects and several other changing environment factors. On the other hand, some received values can be outside the expected range and show systematic errors, such as recording errors and sudden signal blockage. These values should be filtered out from the logged data and then the average RSSI value for each data collection step should be calculated to be used for the pattern matching. In case these values are not filtered out, the average value will be affected, and consequently the results of data processing will be distorted. There are two major sources of errors that should be filtered as follows:

Removing outliers: The purpose of this operation is to remove the RSSI values that are out of range and are evidently the result of errors in recording data, signal spikes and measurement malfunctions.

Reducing multi-path and signal blockage effects: Analyzing RSSI values collected from our testing in indoor environment, explained in Subsection 4.9.1, shows that the received signals in an obstacle-free area have random variations around the mean (Figure 4-7(a)). In noisy environments with large multi-path effect, the variation of the signal is high and the standard deviation of the dataset is large (Figure 4-7(b)). The effect of the signal blockage is a sudden decrease of the RSSI mean value over time due to the absorption of energy by objects that are blocking the signal (Figure 4-7(c)). Figure 4-7(d) shows the pattern of the signal when there is a sudden blockage or temporary noise in a noisy area with large multi-path effects.

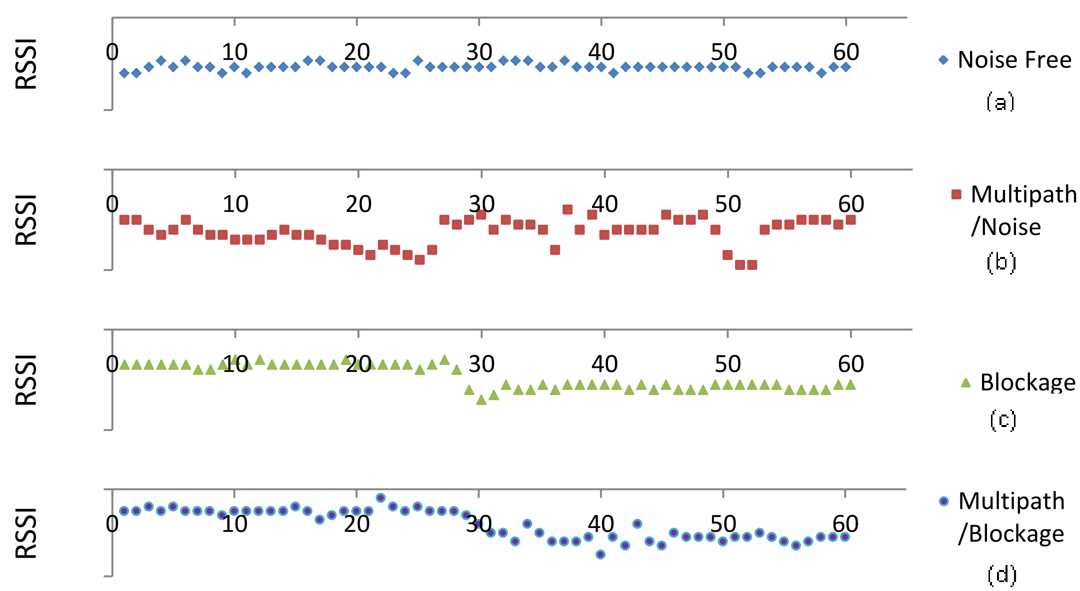
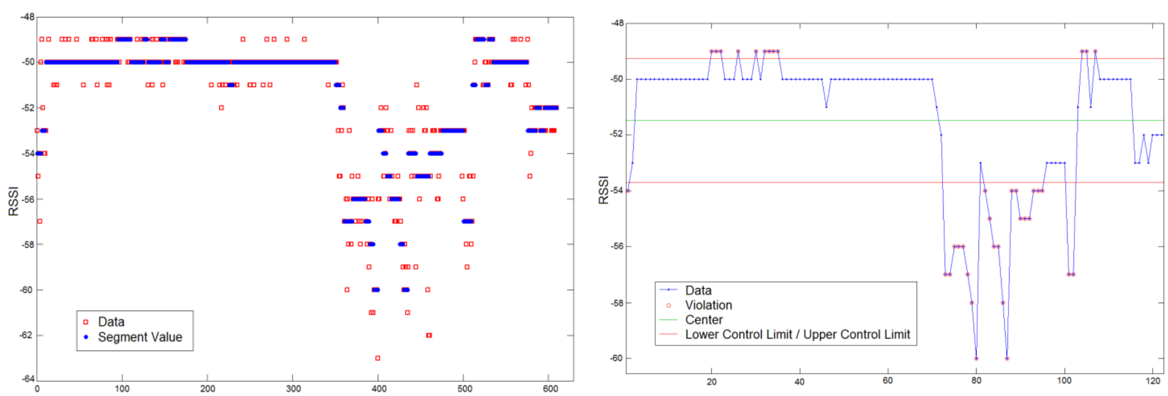


Figure 4-7 Various types of RSSI patterns

Static segmentation of the signal data (with fixed number of data points) for each tag is used at each data collection step. After the segmentation of the signal data, the median value for each segment is chosen as the representative value of the segment. This operation automatically removes outliers in each segment. As shown in Figure 4-8(a), the sample logged data are segmented and the median value for each segment is selected to replace the individual readings. Shewhart individuals control chart (Montgomery, 2005) is also used to identify the segments that are showing big variations that are most likely the result of signal blockage or temporary noise. Figure 4-8(b) shows the individuals control chart for the median values of each segment extracted from Figure 4-8(a). As shown in this figure, some points are out of the control limits (CLs). After removing those segments, the median values are averaged considering the number of remaining segments and the number of readings in those segments.



(a) Logged data and median values

(b) Control chart for each segment median values

Figure 4-8 Sample logged data and control chart

During the data collection, it is assumed that there are *n reference tags* and *p target tags* in the building. R_i $[i \in (1, n)]$ denotes the i^{th} reference tag. T_j $[j \in (1, p)]$ denotes the j^{th} target tag. Data collection happens at *m* different data collection steps.

$RSS_s^{R_i}$ denotes the averaged RSSI value for the i^{th} reference tag at the s^{th} data collection step calculated using Equation 4-1. $RSS_{s,x}^{R_i}$ denotes a single logged RSSI value recorded from the i^{th} reference tag at the s^{th} data collection step; where $z_s^{R_i}$ is the total number of recorded RSSI values for the i^{th} reference tag at the s^{th} data collection step after filtering. $RSS_{s,x}^{T_j}$ denotes a single logged RSSI value recorded from the j^{th} target tag at the s^{th} data collection step; where $z_s^{T_j}$ is the total number of recorded RSSI values for the j^{th} target tag at the s^{th} data collection step after filtering.

$$\boldsymbol{RSS_s^{R_i}} = \left[\sum_{x=1}^{z_s^{R_i}} \boldsymbol{RSS_{s,x}^{R_i}}\right] / \boldsymbol{z_s^{R_i}} \quad , \quad \boldsymbol{RSS_s^{T_j}} = \left[\sum_{x=1}^{z_s^{T_j}} \boldsymbol{RSS_{s,x}^{T_j}}\right] / \boldsymbol{z_s^{T_j}} \qquad \text{Equation 4-1}$$

4.6.3 PATTERN MATCHING ALGORITHM

A data collection step time series, L_s $[s \in (1, m)]$, is a series of averaged RSSI values recoded where the reader is stationary for the period of data collection (Δt). The s^{th} instance of L_s is composed of all $RSS_s^{R_i}$ and all $RSS_s^{T_j}$.

$L_s = \{ RSS_s^{R_i}, RSS_s^{T_j} : i \in (1, n), j \in (1, p)\}$,

P^{R_i} and P^{T_j} denote the *signal patterns* received from the i^{th} reference tag and the j^{th} target tag respectively, for m data collection steps.

$P^{R_i} = \{RSS_s^{R_i} : s \in (1, m)\}$

$P^{T_j} = \{RSS_s^{T_j} : s \in (1, m)\}$

The goal of pattern matching is to determine which reference tags (R_i) show similar signal patterns to the signal pattern received from the target tag (T_j).

The least square difference method is employed to calculate the similarity of reference tags to the target tag. $\beta_{R_j}^{T_i}$ is the *distance indicator (pattern dissimilarity)* value between the i^{th} reference tag and the j^{th} target tag after m data collection steps (Equation 4-2). The matrix of β (Equation 4-3) is constructed using the calculated values from Equation 4-2.

$$\beta_{R_i}^{T_j} = \sqrt{\sum_{s=1}^{m} \left(RSS_s^{R_i} - RSS_s^{T_j}\right)^2} \qquad \text{Equation 4-2}$$

$$\beta = \left[\beta_{R_i}^{T_j}\right]_{i=1,..n;j=1,..p} \qquad \text{Equation 4-3}$$

The β values in the j^{th} column of the matrix indicate the distance indicators for each reference tag to the j^{th} target tag. The least β value in each column shows the reference tag that is assumably closer to the associated target tag.

4.6.4 IDENTIFYING THE TARGET AREA BY CLUSTERING REFERENCE TAGS

There are cases that some reference tags which are not spatially close to the target tag show similar signal patterns to that target tag. This can happen randomly or can be caused by the movement pattern of the user while collecting data and the layout of the building due to the symmetry of the distribution of reference tags with respect to the data collection path. For example if the user walks in a corridor where the rooms are located on two sides, there might be cases that reference tags located in different rooms across the corridor show similar signal patterns due to symmetry. Figure 4-9(a) shows an example layout of several reference tags and a target tag. Figure 4-9(b) shows the similarity of each reference tag represented by a circle where the diameter of the circles is inversely proportional to the β value. LANDMARC method (Ni et al., 2003) selects the best k reference tags based on the β values sorting and uses weighted averaging to position the target tag. However, this technique may select reference tags that are far from the target. Therefore, the localization based on LANDMARC method suffers from a large error as shown in Figure 4-9(c).

The solution to this problem is to form clusters of reference tags that are spatially close. The target localization can be performed within the selected cluster, as shown in Figure 4-9(d). However, clustering of reference tags based only on spatial closeness (nearness) of the tags does not necessarily lead to the best results. For example, Figure 4-10(a) shows a case where spatial clustering will not lead to the optimum selection of reference tags for localization.

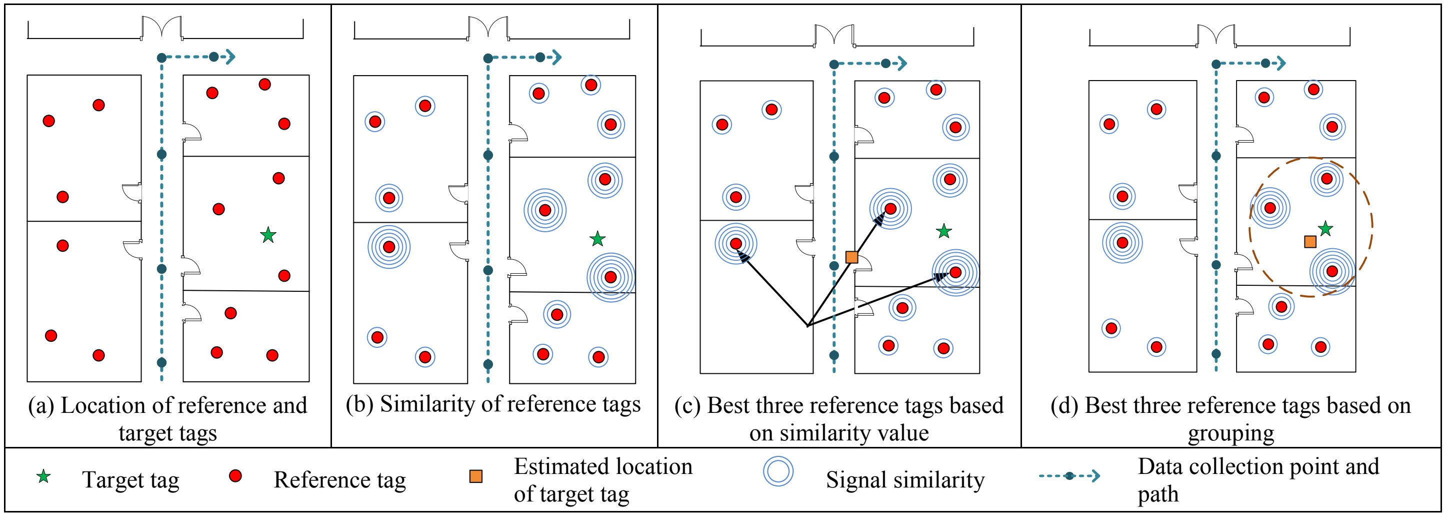


Figure 4-9 Reference tags clustering

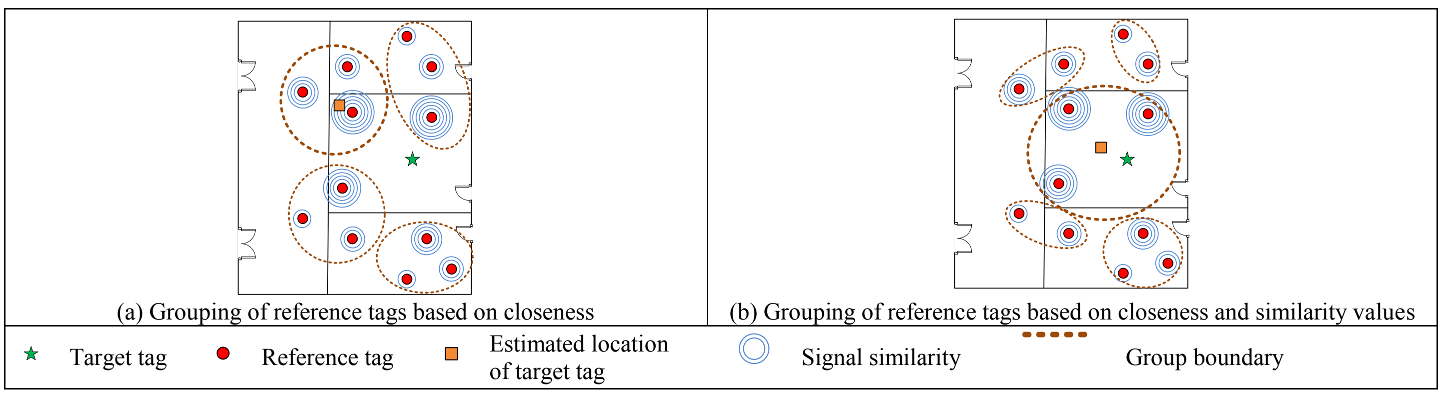


Figure 4-10 Multi criteria clustering vs. single criterion

There are several methods to form clusters. Clustering of tags can be *static* using a predefined fixed number of tags or can be *dynamic*. Moreover, the clustering can be uni-dimentional (e.g., closeness) or multi-dimensional (e.g., closeness and similarity) (Chen et al., 2012). The proposed method for clustering uses combination of two criteria for selecting members of each cluster: (1) *Closeness of reference tags*: by selecting the reference tags that are spatially close to each other using algorithms, such as k-means (Kanungo et al., 2002); and (2) *Similarity of reference tags to the target*: by selecting tags that have similar signal pattern to that of the target tag using β values. Consequently, by using the proposed CMTL method, target tags that show similar signal pattern to the one of the target and at the same time are in close proximity of each other are chosen as the target cluster. Figure 4-10(b) shows how this clustering method chooses a group of tags that is spatially close and at the same time shows high signal pattern similarity. The steps to form clusters and chose the target cluster are as follows:

Calculating spatial closeness of clusters members

It is assumed that there are z clusters available in the environment. G_r *[$r \in (1, z)$]* denotes the r^{th} cluster and o_{G_r} denotes the total number of reference tags in the cluster. First, the x and y coordinates of the centroid point for each group are calculated. $x^C_{G_r}$ and $y^C_{G_r}$ denote the coordinates for the centroid point of r^{th} group. $x_{R_e^{G_r}}$ and $y_{R_e^{G_r}}$ denote the coordinates of the e^{th} member of the group. The total of the distances of each group member to the centroid of the group is calculated using Equation 4-4 and normalized using Equation 4-5.

$$D_{G_r} = \sum_{e=1}^{o_{G_r}} \sqrt{\left(x_{R_e^{G_r}} - x^C_{G_r}\right)^2 + \left(y_{R_e^{G_r}} - y^C_{G_r}\right)^2} \quad \text{Equation 4-4}$$

$$\acute{D}_{G_r} = D_{G_r} / Max\ \{D_{G_r}\}$$ Equation 4-5

Calculating the signal pattern similarity of members

In this stage the average signal pattern dissimilarity (β) of each member of the group ($R_e^{G_r}$) to the target tag (T_u) is calculated using Equation 8 and the value is normalized using Equation 9.

$$\beta_{G_r}^{T_u} = (\sum_{e=1}^{o_{G_r}} \beta_{R_e^{G_r}}^{T_u}) / o_{G_r}$$ Equation 4-6

$$\acute{\beta}_{G_r}^{T_u} = \beta_{G_r}^{T_u} / Max\ \{\beta_{G_r}^{T_u}\}$$ Equation 4-7

Selecting the target cluster

The target cluster is selected based on two values calculated using Equations 4-5 and 4-7. K_{G_r} denotes the score of each multi-dimensional cluster based on two criteria (i.e., spatial closeness of members and the signal pattern similarity of members to the target) as shown in Equation 10. The weights, w_D and w_β, can be adjusted based on the layout of the building, density of tags and their spatial distribution. The best cluster with the smallest score is chosen as the *target cluster* using Equation 4-9.

$$K_{G_r} = w_D \times \acute{D}_{G_r} + w_\beta \times \acute{\beta}_{G_r}^{T_u}$$ Equation 4-8

$$K_{G_r}^{Best} = Min\ \{K_{G_r}\}$$ Equation 4-9

4.6.5 POSITIONING BASED ON CLUSTERING RESULTS

As mentioned in Subsection 2.3.5.2, LANDMARC uses weighted averaging of selected reference tags coordinates to calculate the location of the target tag. The weights are calculated based on an empirical function using the distance indicators (Equation 2-1). In our method, the same empirical function is utilized. However, the selected reference tags that belong to the best cluster are used for weighted averaging calculations.

4.6.6 ACCURACY CALCULATION

Once the target cluster is selected (G_r^{Best}), the closest reference tag (the one with the most similar signal pattern) within the cluster is chosen ($R_{Closest}^{G_r^{Best}}$). In order to estimate the accuracy of the localization, the chosen reference tag is localized using the same method. Since the coordinates of the reference tags are known, the distance between the estimated location and the actual location can be calculated. The distance shows the error of localization for the closest reference tag. It is assumed that this value approximates the accuracy of localization in the target area.

4.7 USER LOCALIZATION

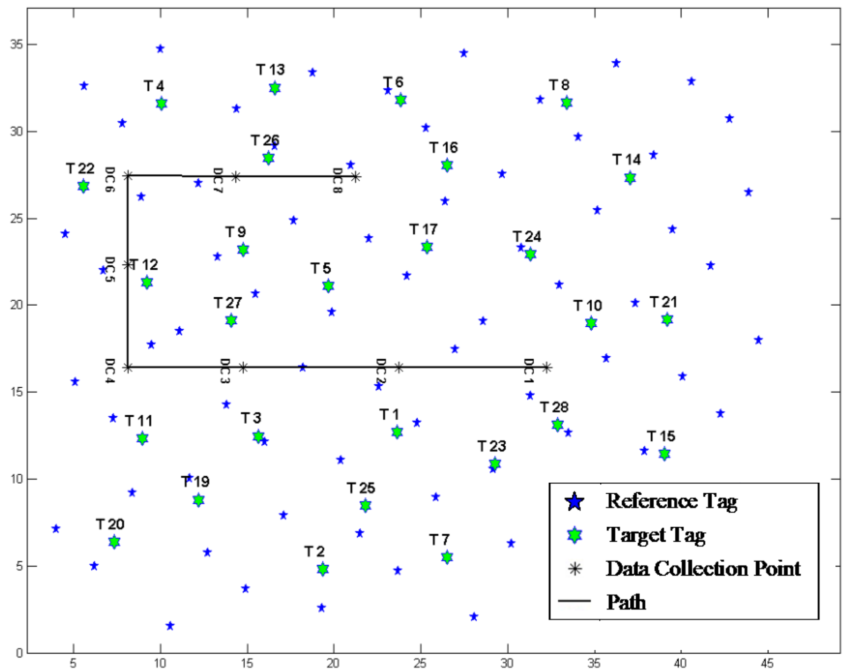
In addition to locating fixed assets, location data on fixed tags can help users finding their approximate locations in the building. Additionally, before the user locates fixed or movable assets, he/she needs to know his/her own location to be able to find the path to the target asset. There are two scenarios for estimating the user location from surrounding fixed tags: (1) ***Scanning a visible tag***: the user scans a visible tag on an asset that is located in a close proximity and read the *current location* data of the tag. The location data are read from the tag and the location is shown on the floor plan; and (2***) Scanning the area***: The user scans the area and reads the location data of surrounding tags to be used for one of the described RFID reader localization techniques referenced in Subsection 2.3.5.2.

4.8 DEVELOPMENT OF A SIMULATION ENVIRONMENT

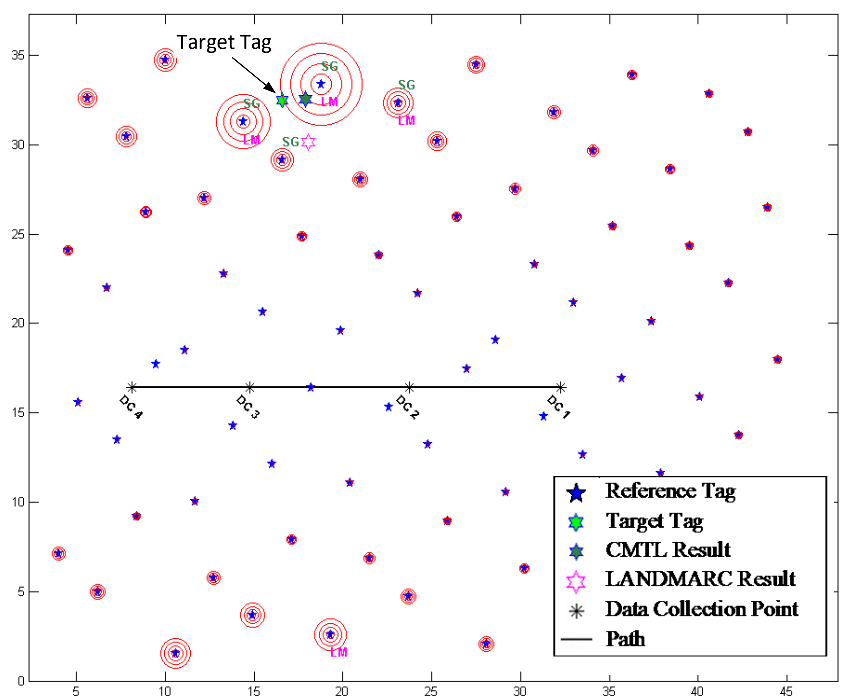
A simulation environment is developed in Matlab (MathWorks, 2012) in order to evaluate the proposed methods for various distributions of reference and target tags, data collection points, RSSI behaviours, and the number of readings in each data collection point. Furthermore, new mathematical and procedural techniques (e.g., data filtering, pattern matching techniques, clustering and localization modules) are developed and tested. The simulation platform provides a flexible environment to define and place multiple reference and target tags. The simulation can help evaluating the impact of a large number of parameters, such as the number, distribution and RF behavior of tags. It also provides the convenience of performing a large number of tests with less time and cost compared to field tests because it does not require the set up and data collection time needed in the field tests. Moreover in order to perform comparative studies, some factors, such as the effect of material and noise should be kept constant. Due to the fact that field tests exhibit changing parameters, the simulation environment can be used for such tests. The Matlab code used in the simulation environment is also used to process real data in the field tests.

The simulator comprises different modules, such as: (1) Parameters definition; (2) RSSI generator; (3) Pattern similarity assessment; (4) Clustering; (5) Localization; (6) Data comparison and sensitivity analysis; and (7) Field test data processing. The generation of RSSI values in the simulation uses Monte Carlo approach based on our field test results explained in Subsection 4.9.1. The signal similarity between target and reference tags are calculated for a set of data collection points that are specified in the simulation input. The clustering module finds the best group of reference tags based on signal pattern similarity score and geometric proximity of reference tags in each selected cluster as explained in Subsection 4.6.5. However, the simulation environment does not consider the effect of obstacles on the propagated radio signals. Hence, the current version of the simulator simulates an obstacle-free environment where the behavior of the RFID signals follow the results of our field test in a similar environment. Consequently, the simulator does not provide the validation for the proposed method of localizing moveable tags in cluttered indoor environments. In order to validate the method in such environments, field tests are performed (Subsection 4.9.4.2).

Figure 4-11(a) shows a snapshot of a sample simulation input data with 75 randomly distributed reference and 25 target tags. The small and large stars show the location of reference tags and target tags, respectively. The path that the user with a handheld reader took to localize the target tags is shown by a line. Stars on the path show the data collection points. As shown in the figure, there are eight data collection steps. Figure 4-11(b) shows the results of one case where target tag 13 is localized with four data collection points. The dark large star is the estimated location of the target based on the clustering method and the white star represents the position of the target calculated by the LANDMARC method. The diameters of the circles around reference tags are inversely proportional to the β values. Hence, the bigger the diameter of the circle, the closer the associated reference tag is to the target tag. As shown in the figure, the simulation tool is able to identify the closest reference tags to the target and to estimate its location. More details about the simulation results are given in Subsection 4.9.2.



(a) Defining reference and target tags and data collection points



(b) Simulation results for sample target tag (T13)

Figure 4-11 Sample simulation input data and results

4.9 TESTING AND VALIDATION

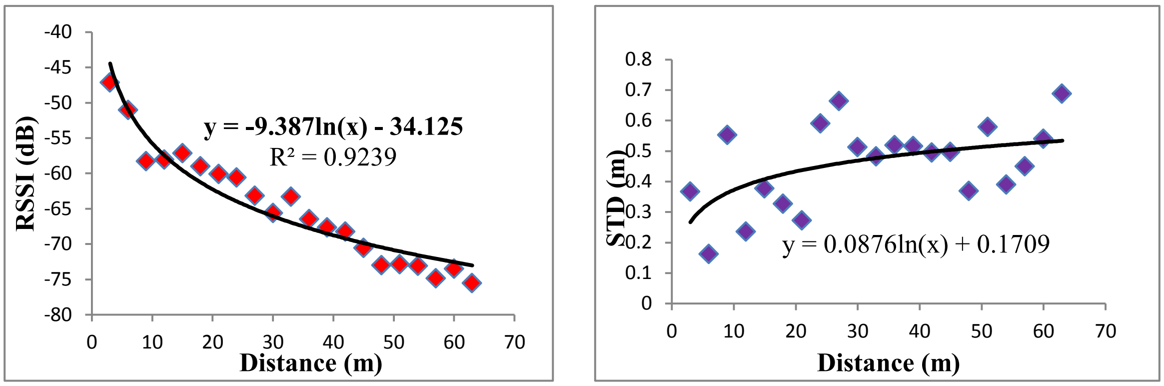
4.9.1 TESTING RFID CHARACTERISTICS

In order to realize the proposed method for locating moveable assets (i.e., CMTL), the characteristics of an available RFID system are analyzed. Active RFID tags from Identec Solutions (Identec, 2013) with relatively long nominal range (100 m), operating frequency of 915 MHz, and 32 KB of storage are used together with a handheld reader (Tables C-2 and C-5 in Appendix C). Available tag's antenna are omnidirectional (1/4-wave monopole with 2/3 vertical element and 1/3 horizontal element).

In order to perform the tests, an application is developed to log received signals by the RFID reader and to store them in data tables. The frequency of reading and the power of the antenna are customizable. Several tests were conducted to test the readability range and the effect of various environment factors on the RFID tags. The first test was performed at Concordia Stinger Dome (120 m x 70 m) to examine the readability range and signal attenuation of tags in an obstacle-free environment. An RFID tag was placed on a tripod and RSSI values were collected at various distances from the tag. Figure 4-12(a) shows the decrease of RSSI values by increasing the distance. It is also observed that the gain is higher in front on the same long axis of the tag. Figure 4-12(b) shows that the standard deviations of RSSI values slightly increase as the distance between the tag and the reader (l) increases. Equation 4-10 shows the relationship between the distance and RSSI value based on our field test. Equation 4-11 formulates the relationship between the standard deviation of the RSSI values and the distance where RSSI measured in decibels milliwatt (dBm) and l in meters.

RSSI = -9.387 ln(l) - 34.125 Equation 4-10

σ_{RSSI} *= 0.0876 ln(l) + 0.1709* Equation 4-11



(a) Average values (b) Standard deviations

Figure 4-12 RSSI vs. distance relationship

4.9.2 LOCALIZATION ACCURACY COMPARISON USING SIMULATION

In order to compare the applicability of our proposed CMTL method, a comparative study has been performed using our simulation environment. The accuracies of localization using CMTL and LANDMARC methods are compared by developing both approaches in the simulation environment. For static clustering (with fixed number of tags), a list of all combinations of groups with *o* members can be formed. Clusters of three and four reference tags and equal weights of one (Equation 4-8) are used in the simulation environment.

As explained earlier, Figure 4-11(a) shows a simulation scenario with 75 randomly distributed reference tags and 25 target tags. Three different scenarios for three data collection paths were considered which are a straight path (I-shape) (first four points), an L-shape path (first six points) and a U-shape path (all eight points). For each run of the simulation, a target tag is placed randomly on the map. The simulation is repeated to localize the 25 target tags using the above-mentioned data collection paths for the cluster sizes of three and four reference tags. Moreover, the simulation is repeated for four different densities of randomly distributed reference tags (45, 60, 75, and 90 reference tags).

Table 4-1 shows the localization error using cluster sizes of three and four tags. The table shows that localization with the cluster size of four tags provides mostly better localization accuracy. Hence, cluster size of four tags is used for positioning in the subsequent comparative studies. As shown in Figure 4-13, the accuracy of the CMTL method greatly increased when the shape of data collection path diverges from the straight line. This is related to the fact that taking an L-shape or U-shape paths reduces the probability of selecting a wrong target cluster resulting from the symmetry of the distribution of reference tags with respect to the data collection path.

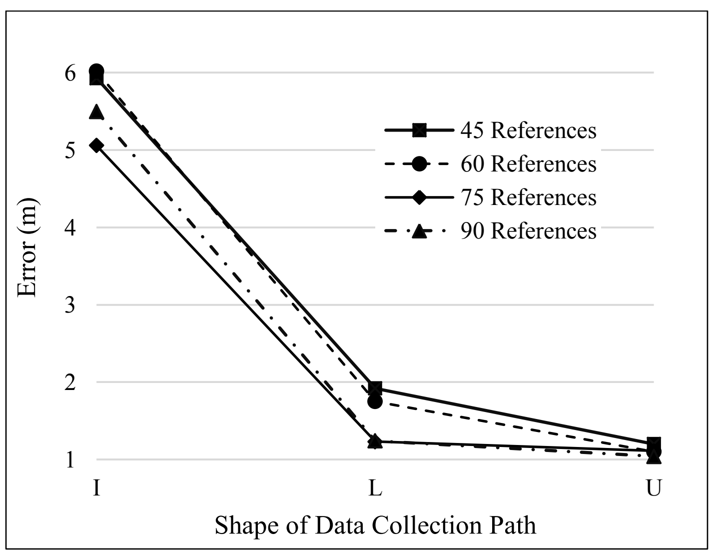


Figure 4-13 Shape of data collection path vs. CMTL error

Table 4-1 Accuracy comparison between three-tag and four-tag CMTL localization for different data collection paths and reference tag densities

Number of Reference Tags		45			60			75			90		
Data Collection Path Shape		I	L	U	I	L	U	I	L	U	I	L	U
Cluster Size	3 Tags Error (m)	7.3	3.03	1.44	8.31	1.89	1.17	6.23	1.6	1.28	5.06	1.74	1.13
	4 Tags Error (m)	5.93	1.92	1.2	6.02	1.75	1.1	5.06	1.23	1.11	5.5	1.24	1.04
Improvement (%)		**19**	**37**	**17**	**28**	**7**	**6**	**19**	**23**	**13**	**-9**	**29**	**7**

Table 4-2 illustrate the average localization error of the 25 five randomly placed target tags using four reference tags for positioning, for different data collection paths and reference tag densities based on CMTL and LANDMARC methods. The last row presents the improvement percentage that CMTL provides over the LANDMRC method.

Table 4-2 Accuracy comparison between CMTL and LANDMARC for different data collection paths and reference tag densities

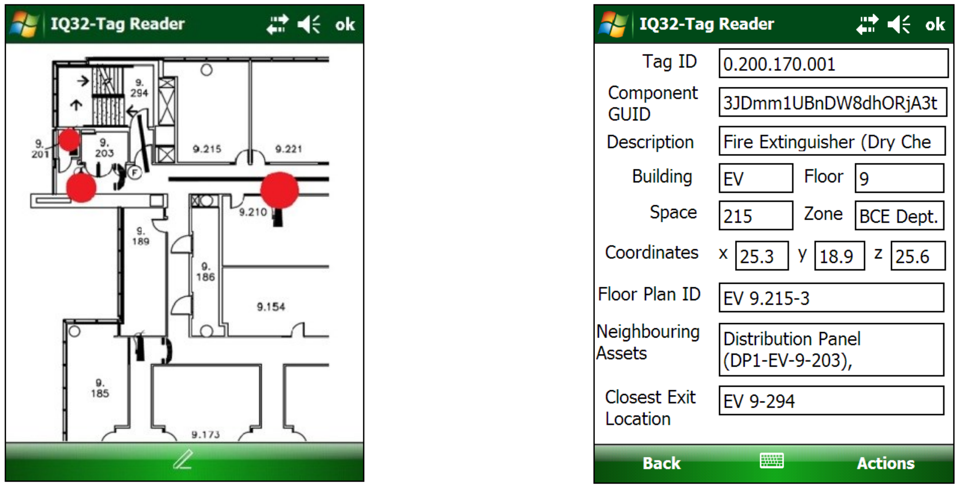
Number of Reference Tags	45			60			75			90		
Data Collection Path Shape	I	L	U	I	L	U	I	L	U	I	L	U
LANDMARC Error (m)	7.26	2.77	1.26	7.23	2.31	1.14	7.71	1.62	1.15	7.01	1.69	1.07
CMTL Error (m)	5.93	1.92	1.2	6.02	1.75	1.1	5.06	1.23	1.11	5.5	1.24	1.04
Improvement (%)	**18**	**31**	**5**	**17**	**24**	**4**	**34**	**24**	**4**	**22**	**27**	**2**

In the I-shape data collection scenario, the results show improvements of 18%, 17%, 34% and 22% for the densities of 45, 60, 75, and 90 reference tags per area, respectively. In the L-shape path for data collection scenario, the results show improvements of 31%, 24%, 24% and 27% for the densities of 45, 60, 75, and 90 reference tags per area, respectively. In the U-shape path for data collection scenario, the results show an improvement of 5%, 4%, 4% and 2% for the densities of 45, 60, 75, and 90 reference tags per area, respectively. The improvement for the cases of U-shape path is small due to the fact that the four closest tags selected in CMTL and LANDMARC methods are mostly identical.

4.9.3 CASE STUDY FOR FIXED ASSETS LOCALIZATION

RFID tags are attached to fire extinguisher cabinets that are inspected frequently and are highly spread in the building. The memory of the RFID tags contains information about the extinguishers as well as location specific data. The information is saved in XML format where XML-tags are partially taken from the definitions in IfcXML (Nisbet, 2005) to facilitate the mapping of BIM data with the data on tags.

In the first scenario, location data are used to help the FM personnel find extinguishers. The FM personnel use the handheld reader to scan the environment and the software shows detected tags on the floor plan. Detected assets are shown on the floor plan with dots of different colors that specify the type of the asset (Figure 4-14(a)). The FM personnel can select the desired tag from the floor plan and retrieve detailed information (Figure 4-14(b)). In the second scenario, RFID data are used to help users detect their location. A facility user (e.g., a student) scans the environment and the software shows the floor plan of the building with dots representing detected tags. The size of dots is proportional to RSSI value for each detected tag. The user is able to find his/her location visually from the floor plan. Moreover, the user is able to read data stored on the tag for which he has access permission to get more information about the environment (e.g., department's name, emergency exits). RFID tags used in this case study are equipped with Light-Emitting Diodes (LED) that help the user to visually locate the closest tag.



(a) Tag location

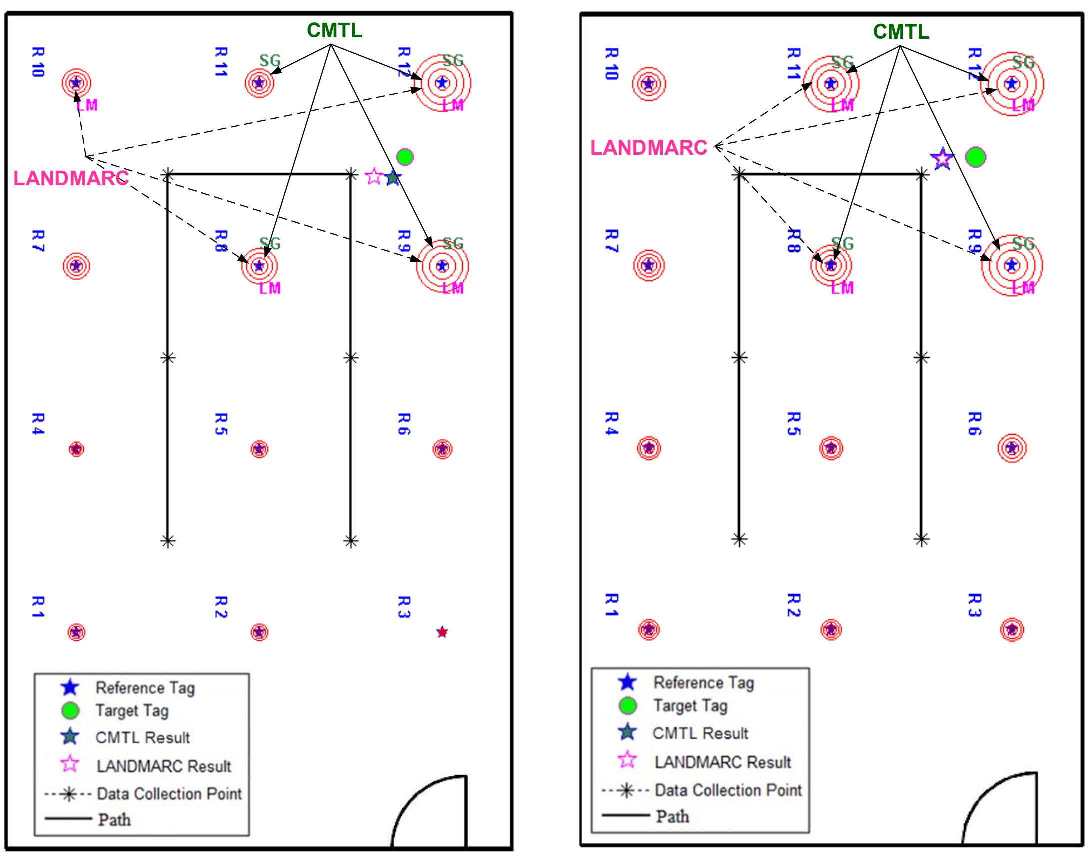
(b) Tag data

Figure 4-14 Fixed asset localization software

4.9.4 CASE STUDIES FOR MOVEABLE ASSETS LOCALIZATION

4.9.4.1 Obstacle-Free Environment (with Line-of-Sight)

This case study is performed to test the applicability of CMTL for tracking moveable assets in a multi-tag indoor environment. The test was conducted in an obstacle-free environment where all tags were placed inside one room. The tags were placed on the ground in a grid of 5 m ×7.5 m. A target tag was placed randomly in the room with the distance of 70 cm from the closest reference tags (R_9 and R_{12}) and data were collected using a handheld reader at six data collection steps forming a U-shaped path for 30 seconds at each data collection step. The calculated β values for all reference tags are presented in Table 4-2. Figure 4-15(b) shows the same setup in the simulation environment. The RSSI values were generated using our signal propagation model (Equations 4-10 and 4-11) and are compared with the actual measured data. In Figure 4-15, the diameters of the circles around reference tags are inversely proportional to their β values. The results show that R_{12} has the least β value in both field test and simulation environment. As can be seen in Table 4-2, the simulated β values are systematically less than those of the test values. This can be explained by the fact that the space used in the test is much smaller than the one used in the test explained in Subsection 4.9.1. Table 4-3 shows the comparison between the two localization techniques for this case study. The results of the field test show that localization based on four reference tags using CMTL is more accurate than the results of the LANDMARC method. The improvement in accuracy is due to the fact that the LANDMARC's four-nearest reference tags (shown in Figure 4-15(a)) are different from the ones of the best selected cluster.



(a) Test results (b) Simulated results

Figure 4-15 Obstacle-free test

Table 4-3 β value for field test and one instance of the simulation (obstacle-free environment)

	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}	R_{12}
Field Test	13.5	13.2	33.1	15.4	13.7	12.2	8.7	6.2	4.3	8.1	8.3	4.1
Simulation	11.1	11.3	10.5	10.2	10.3	8.6	8.2	6.1	4.1	7.6	4.4	3.8

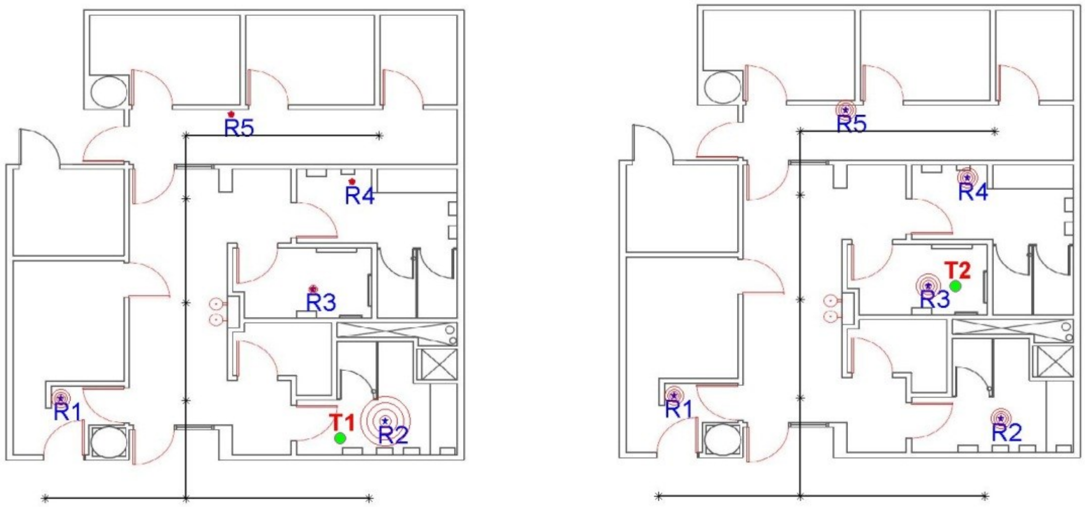
Table 4-4 Comparison between field test and simulated results for 3 and 4 tags

	Field test results				**Simulated results**			
Method	CMTL		LANDMARC		CMTL		LANDMARC	
Number of Tags	3 Tags	4 Tags	3 Tags	4 Tags	3 Tags	4 Tags	3 Tags	4 Tags
Error (m)	0.43	0.34	0.43	0.51	0.28	0.45	0.28	0.45

4.9.4.2 Environment with Obstacles (without Line-of-Sight)

Preliminary Test

In this test, five reference tags and two target tags were placed in different adjacent rooms of the building. Figure 4-16 shows the setup for the test. The user with an RFID handheld reader collected data in eight data collection steps. The data are collected for 30 seconds at each data collection step. The target tags were placed with the distance of approximately 1.5 meter from the closest reference tag in the same room. Table 4-5 shows the calculated β values of the two target tags for each of the reference tags. The results show that the proposed approach is capable of detecting the closest tag in a cluttered environment where the signal strength cannot be converted to distance using signal propagation formulas.



(a) Target tag 1 (b) Target tag 2

Figure 4-16 Preliminary test setup

Table 4-5 β values for preliminary test (environment with obstacle)

	Target 1	Target 2
R1	15.13	15.14
R2	**5.60**	14.22
R3	30.05	**11.72**
R4	47.32	13.92
R5	49.68	14.06

Field test

The field test is performed using 20 long range active RFID tags placed inside four different rooms on the 9th floor of the EV building of Concordia University. The area for the test is approximately 35m × 25m. The test is done in a cluttered and noisy environment where tags were attached to various assets in the rooms. The placement layout of the tags is shown in Figure 4-17 where four rooms were selected with five tags in each room. The active tags used in this case study were from a newer generation of RFID tags compared to the previous tests described in Subsections 4.9.1, 4.9.4.1, and the preliminary test. These tags have longer nominal read range (250 m) and more stable

RSSI values (Table C-1 in Appendix C). The data is collected at six different data collection points in the corridors using a handheld device. About 100 readings for each tag are collected at each data collection point and the data are then filtered and processed for localization.

The analysis for the accuracy of localization is performed for all tags. In this test, each tag is selected as a target tag and is localized using data recorded from the rest of the tags. The comparative analysis is performed to evaluate the results of localization using the LANDMARC method (selecting four tags with highest similarity score) and CMTL method. As shown in Table 4-6, the average error for the localization is 1.59 m vs. 2.8 m for the LANDMARC method. Table 4-6 also shows the localization error of four center tags (1, 9, 14, and 16 in Figure 4-17) that are surrounded by four tags in each room. The result shows that in the settings where target tags are surrounded by reference tags, the accuracy for localization is radically increased. The improvement in the results compared to LANDMARC is related to the fact that in most of cases, CMTL chooses spatially close tags for localization. However, LANDMARC may select tags from other rooms due to their signal pattern similarity with target because of random noise or symmetry. Figure 4-17 shows an example of a target tag localization using CMTL and LANDMARC. The figure shows that the CMTL method chooses tags inside the same room as the target for localization.

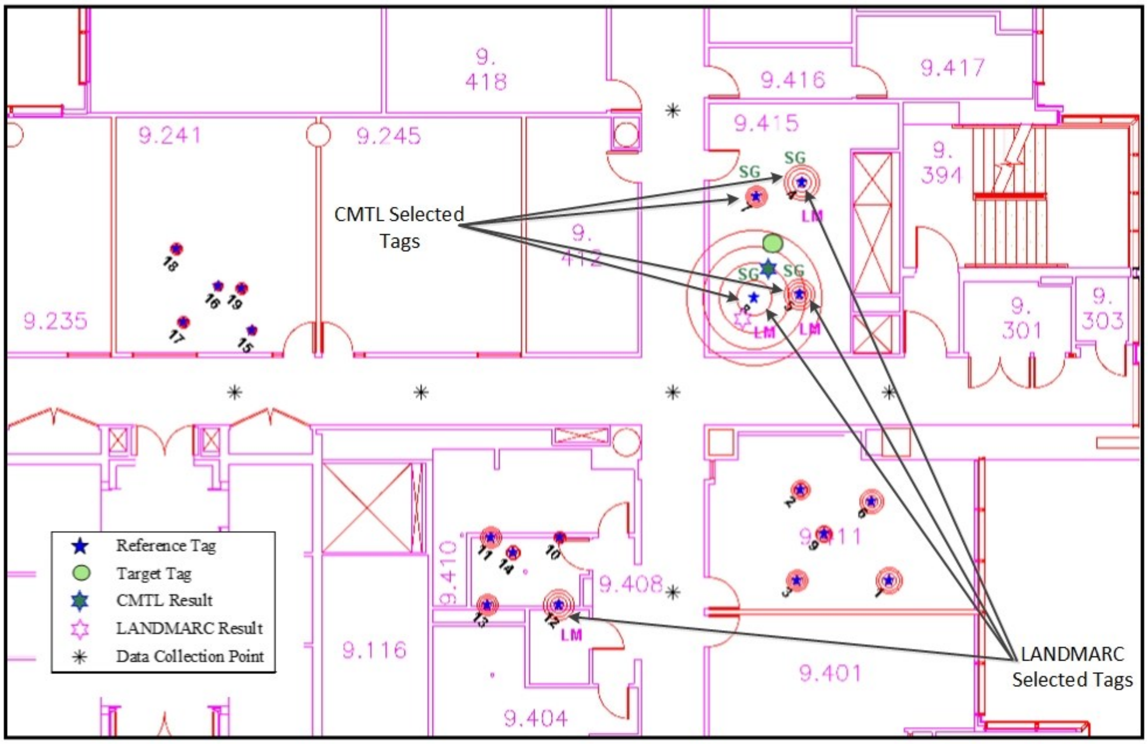


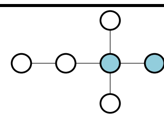
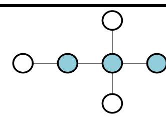
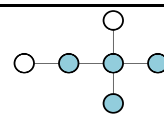
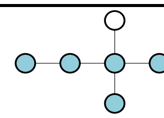
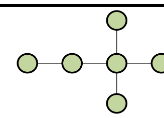
Figure 4-17 Field test in cluttered and noisy environment

Table 4-6 Accuracy comparison of CMTL and LANDMARC methods (environment with obstacles)

	Average error	
	All tags (m)	**Center tags (m)**
LANDMARC	2.87	1.55
CMTL	1.59	0.77
Improvement (%)	**44**	**50**

The effect of increasing the number of data collection points on the accuracy of localization is presented in Table 4-7. In each column, the error is calculated based on the data gathered in the set of data collection points shown in the first row. The number of data collection points is increased from two to six and the incremental improvement in the accuracy compared with the previous column is calculated. The results show that by increasing the number of data collection points, the accuracy of both methods improves. However, the improvement rate decreases by adding more data collection points.

Table 4-7 Effect of increasing the number of data collection points

Selected data collection points						
LAND-MARC	Average error (m)	8.38	5.61	3.91	2.96	2.87
	Incremental improvement (%)	**N/A**	**33**	**30**	**24**	**3**
CMTL	Average error (m)	9.31	4.65	3.07	2.12	1.59
	Incremental improvement (%)	**N/A**	**50**	**34**	**31**	**25**

4.10 SUMMARY AND CONCLUSIONS

The research presented in this chapter investigated methods to localize *fixed* and *movable* RFID-equipped assets in a building using handheld RFID readers. For *fixed assets* localization, it is proposed to use the location data saved on their RFID tags' memories and locate them on the floor plan. Additionally, *location tags* are introduced as a cost-effective way to store location information for several assets in the area. The RFID tags attached to *fixed assets* act as *reference tags* for locating *movable assets*. The proposed method for locating movable assets (i.e., CMTL) is neighbourhood-based methods that uses handheld computers and does not require a fixed RTLS infrastructure for localization. It utilizes available RFID tags in the building and it can adapt to the changes in the environment.

The conclusions of this chapter are: (1) The proposed method provides the user with the location of fixed assets on the floor plan, using the location data saved on their RFID tags' memories. In addition, location tags are introduced as an efficient method to store location information for several assets in the area; (2) The proposed method for locating movable assets (i.e., CMTL) is based on neighborhood methods. However, CMTL uses a handheld reader instead of a fixed number of fixed readers in similar LANDMARC-based methods. Using a handheld reader provides the flexibility to choose the number of data collection points and paths; (3) The CMTL introduced major improvements in the accuracy in case of symmetrical settings of reference tags with respect to the data collection path or the cases in which some reference tags randomly show high similarity with the target tag; and (4) The results of the case studies showed that CMTL is able to estimate the location of the target asset with higher accuracy compared to the LANDMARC method. Additionally, the case studies showed that although increasing the number of data collection points improved the accuracy, the major improvement happens when the shape of the data collection path diverges from a straight line.

CHAPTER 5 INCORPORATING INFORMATION OF RFID TAGS ATTACHED TO BUILDING COMPONENTS TO THE BIM

5.1 INTRODUCTION

As explained in Subsection 2.4, BIM is emerging as a method of creating, sharing, exchanging and managing the building information throughout the lifecycle between all stakeholders. RFID, on the other hand, has emerged as an automatic data collection and information storage technology, and has been used in different applications in the AEC/FM industry. In our previous research (Subsection 2.5), RFID is proposed to be used to store lifecycle and context aware information taken from a BIM during the lifecycle as a distributed database. Furthermore, RFID tags can be considered as components of the constructed facility. Consequently, there is a need for a standard and formal definition of RFID technology components in BIM. The research goal is to propose adding the definitions for RFID technology to the BIM standard and to map the data to be stored on RFID memory to associated entries in a BIM database. A requirements' gathering is performed to add new entities, data types, and properties to the BIM (Subsection 5.3.1). Furthermore, the research identifies relationships between RFID tags and building assets (explained in Subsection 5.3.2). It provides the opportunity to interrelate BIM data and RFID data using predefined relationships. Eventually, the data related to objects that are required to be saved on RFID tags can be automatically selected using defined relationships in a BIM. To explore the technical feasibility of the proposed approach, a case study has been implemented and tested using available BIM software applications that is explained in Subsection 5.4.

The objectives of this chapter are: (1) to perform requirements' gathering in order to define RFID system components, their properties, and their relationships with other building elements; (2) to integrate the definitions and property sets into the IFC standard by either mapping them into existing IFC definitions or defining new entities; and (3) to demonstrate the technical feasibility of the proposed approach using a case study by employing available IFC-compatible software packages.

5.2 THE NEED FOR INCLUDING RFID DEFINITIONS IN BIM

As explained in Subsection 2.2, RFID tags are extensively used for supply chain management and are attached to various assets and building components. Moreover, several industrial and research projects suggested attaching RFID to assets for lifecycle management and various process improvements especially during the construction and operation phase of the building. It is also proposed to include the tags in the design of the objects as an integrated subcomponent (explained in Subsection 2.2.3). Consequently, the tag would accompany the asset throughout the lifecycle to host its information. Knowing that RFID tags and readers will be extensively available in buildings, they can be considered as components of the buildings. Thus, there will be a need for standard and formal definitions of RFID systems in a BIM. In the rest of the thesis the terms IFC database and BIM database are used interchangeably.

Available RFID tags in a facility can be used to store data related to assets. Based on our framework explained in Subsection 2.5, these data are dynamic and taken from a standard BIM file/database. Figure 5-1 shows how data chunks from the BIM database are copied into the memories of different RFID tags. For example the memory of a tag can contain the maintenance information of the asset, such as the condition or the last inspection date.

Moreover, the tags memory can contain data related to several assets or spaces. For example, the tag can contain the location coordinates of various assets in a room (i.e., the *location tags* as explained in Subsection 4.5.1), or it can have the list of occupants in the room. In order to relate the assets' data stored in a BIM to their associated tags' memory, the relationship between the assets and their associated tags should be identified and modeled. Having these relationship defined in a BIM, the process of selecting data to be stored on tag's memory can be facilitated. Two scenarios that describe the process flow to use the IFC database to update/synchronize RFID data are presented in the following Subsections.

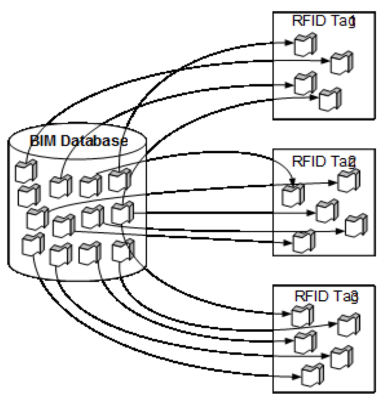


Figure 5-1 Conceptual BIM-tag data relationship (Motamedi and Hammad, 2009a)

5.2.1 SAMPLE SCENARIO: UPDATING ASSET'S INSPECTION RESULTS ON ITS RFID TAG

As explained in Subsection 2.5.3, RFID tags can be used to store information related to the maintenance of the assets they are attached to. Having the information available on the tags will provide technicians with the condition and inspection status of the asset while they are performing maintenance activities. In order to update these data on the tag, an updated IFC database is used. Having RFID tags definition in the BIM model together with their relationship to other assets will facilitate the process of automatically composing the data file to be saved on tags. Figure 5-2 shows the process flowchart to construct the inspection data to be saved on a tag attached to a certain asset: (1) The user scans the tag and the software reads its ID; (2) The software queries the ID in the IFC database; (3) Using available relationships in the IFC database, the software identifies the related asset(s); (4) The software reads the inspection status of each related asset from the IFC database; (5) The software builds a file containing the result of the queries; and (6) The file is merged into the data on the tag.

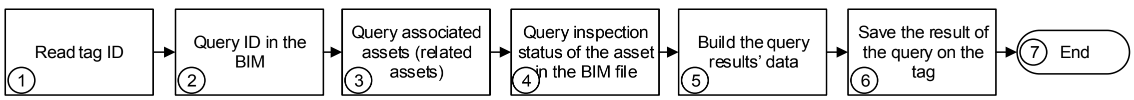


Figure 5-2 Process flowchart to update inspection data

5.2.2 SAMPLE SCENARIO: UPDATING THE LOCATION COORDINATES OF ASSETS ON A LOCATION TAG

An RFID *location tag* is a tag that its memory contains information related to several assets in an area (explained in Subsection 4.5.1). The list of coordinates for related assets should be stored and updated on the tag. Consequently, when the user is looking for an asset, the location tag's data can be read and the location of the target asset can be queried and shown on the floor plan for localization purpose. Figure 5-3 shows the flowchart of the process to update the assets' coordinates on the location tag's memory: (1) The tag is scanned and the ID is read by the software; (2) The software queries the ID in the IFC database; (3,4) the software reads the properties of the scanned tag from the IFC database and verifies if the detected tag is a *location tag*; (5) Using available relationships in the IFC database, the software identifies the related assets; (6) The software reads the location coordinates of each related asset from the IFC database; (7) The software builds the data file containing the queried data; and (8) The data file is merged into the data on the tag.

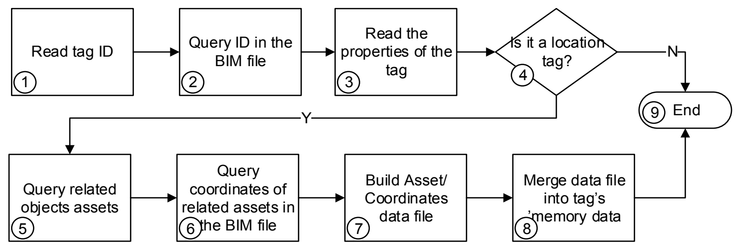


Figure 5-3 Flowchart of the process to update assets' coordinates on a location tag

These sample scenarios show how adding the definitions of RFID tags together with their relationships with other objects in the BIM will facilitate the process of data management and synchronization. They also demonstrate the process steps to use the IFC database for updating the data of tags.

5.3 PROPOSED EXTENSION FOR IFC

Definitions and data structure of the latest version of available IFC standard (i.e., IFC 2x4) are used as the basis for our proposed extension module. The aim is to define the minimum number of new definitions of objects and relationships. This will avoid the unnecessary expansion of the model by reusing available relationships and property sets.

5.3.1 REQUIREMENTS GATHERING FOR RFID SYSTEM DEFINITIONS

In order to add definitions of RFID system components (i.e., tags, readers and antennas) to the IFC model, a detailed requirements gathering is performed. These include following steps: (1) Identifying RFID technology components (explained in Subsection 5.3.1.1); (2) Identifying properties for each RFID component type including:

Physical properties and *specifications,* such as electrical, radio, enclosure rating and shape; *Operation properties,* such as installation date and the write-cycle count; and *Data management properties,* such as encryption type and markup language (explained in Subsection 5.3.1.2); and (3) Identifying the relationships with other elements (explained in Subsection 5.3.2).

Various resources are used for the design phase including the RFID manufacturer's data sheets and specifications , scenario/case studies in which RFID technology is utilized for lifecycle management of facilities (e.g., Motamedi and Hammad, 2009a; Ergen and Guven, 2009). In order to identify relationships between RFID components and assets/building components, our proposed framework (Explained in Subsection 2.5) in which RFID tags are assigned or attached to building components is used.

5.3.1.1 RFID system elements

As Explained in Subsection 2.2.2, RFID hardware can be grouped in three major categories; (1) RFID tag (transponder); (2) RFID reader (Transceiver); and (3) antenna. Each of these entities and their associated attributes should be defined. An antenna is defined in IFC as an enumeration of *IfcCommunicationsApplianceType.* Hence, this definition can be used to model the antenna attached to readers and tags.

The RFID components are defined under the *IFC Electrical Domain* schema which forms a part of the *Domain Layer* of the IFC model (IFC, 2013). A new type (i.e., *RFIDSystemType*) is proposed to be defined in IFC with four enumerations: (1) Passive tag; (2) Active tag; (3) Passive reader; and (4) Active reader. Figure 5-4 shows the hierarchy of entities for the new defined object. Other possible types, such as *Semi-Active*

RFID that inherits properties of both active and passive tags, can be identified using a combination of properties related to each of the above major types.

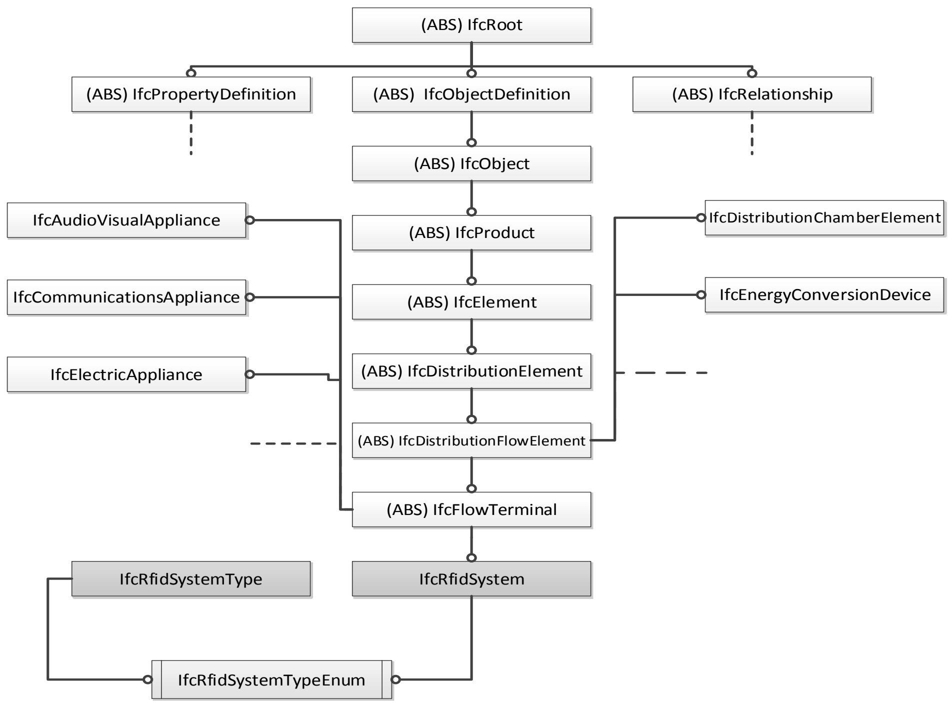


Figure 5-4 IFC hierarchy for RFID system

5.3.1.2 RFID system properties definition

As explained in Subsection 5.3.1, various resources are used to identify the required property sets of RFID systems' components. For example, data sheets provided by RFID tags manufacturers were used to identify the required set of electrical and radio property types to be included. A survey of available RFID systems is conducted to identify various shapes and casing materials for RFID tags. Moreover, properties related to the operation of RFID components during the lifecycle are added, such as: installation date, current battery level and the incremental write-cycle count. These data are used to identify the state of RFID usage at any given time. These data can be used to plan for replacement or maintenance of the tags that are reaching the end of their lifecycle. Due to the fact that

RFID tags' memory is used to store data, some properties related to the data should be captured. For example, various standard IDentifiers (IDs) that are assigned, the type of cipher that is used to encrypt the data (Motamedi et al., 2011), and the markup language are required to be defined. It is also suggested to add a local copy of the memory content of the tags in the BIM database. Having a local copy of the last updated content of the memory can be used to check for data integrity and synchronization.

The properties of RFID systems are defined according to *property set assignment concept* of the IFC (IFC, 2013). Available property sets are used, such as *Electrical Device Common*, *Condition*, *Environmental Impact Indicators*, *Manufacturer* (Type and Occurrence), *Service Life,* and *Warranty*. IFC standard (IFC, 2013) can be referred for details on abovementioned sets. Table 5-1 shows the existing property sets in the IFC that are reused as shared property sets for the RFID system.

Table 5-1 Shared property sets for RFID system

Name of Pset	Description
Pset_ElectricalDeviceCommon	A collection of properties that are commonly used by electrical device types
Pset_Condition	Determines the state or condition of an element at a particular point in time
Pset_EnvironmentalImpactIndicators	Environmental impact indicators are related to a given "functional unit" (ISO 14040 concept)
Pset_ManufacturerOccurrence	Defines properties of individual instances of manufactured products given by the manufacturer
Pset_ManufacturerTypeInformation	Defines characteristics of types (ranges) of manufactured products given by the manufacturer
Pset_PackingInstructions	Packing instructions are specific instructions relating to the packing that is required for an artifact in the event of a move (or transport)
Pset_ServiceLife	Captures the period of time that an artifact will last
Pset_Warranty	An assurance given by the seller or provider of an artifact

IFCMaterialUse definition is used to define the material used for the tag and its casing. Identifying the material for casing of the tag has special importance since the radio communication capability of a tag is highly influenced by the type of its casing when attached to metallic objects. Separate property sets are defined to include type-specific information. For example, the battery life can be only a property of active tags. Table 5-2 shows the recommended property items for all RFID system entities. The property items can be grouped into three categories: (1) *General specifications* including, radio, electrical, physical, safety and memory properties; (2) *Operation properties* including the data about the usage of RFID, and (3) *Data management* properties including the IDs and the memory encoding and markup language. These property items are placed in five property sets (PSet) that are: RFID Common PSet (for properties that are shared between all types), Active tag Pset, Passive Tag Pset, Active reader Pset, and Passive reader Pset.

Table 5-2 Proposed property sets

Category	Property item	Description	Example	Active Tag	Passive Tag	Reader
General Specifications	Standard compliance	Communication, memory, ID type, and data type standards	ISO18000	✓	✓	✓
	Range	Operating readability range of tag or reader	300 m	✓	✓	✓
	Frequency	Communication frequency range for the tag	915 MHz	✓	✓	✓
	Operating temperature	Temperature range at which the device operates	-30 C-45 C	✓	✓	✓
	Enclosure rating	IP and NEMA Ratings	IP65	✓	✓	✓
	Shock	Environmental testing standard	DIN/IEC68-227	✓	✓	✓
	Vibration	Environmental testing standard	DIN/IEC68-2-6	✓	✓	✓
	Antenna type	Type of internal or attached antenna to the tag	1/4 *wave monopole*	✓	✓	✓
	Total memory size	Total size of tags memory	32 KB	✓	✓	
	Transmit power	Maximum transmission power	0.5 mW	✓	✓	✓
	Data transmission rate	Data communication rate	128 Kbps	✓	✓	✓
	Shape type	(1) *Label*, (2) *Ticket*, (3) *Card*, (4) *Glass bead*, (5) *Integrated*, (6) *Wristband*, (7) *Button*	Label	✓	✓	
	Battery type	Battery type standard	LR AA	✓		
	Max. write-cycle	Number of cycles that the tag can be written on	100,000	✓	✓	
	Encoding	Content encoding standard	ASCII	✓	✓	
	Storage type	Read-write, read-only and WORM (write once, read many)	WORM		✓	
	Reader type	*Mobile, Fixed*	Mobile			✓
	Number of antennas	Total number of supported or attached antennas	4	✓	✓	✓
	Antenna connector	The standard for the RF antenna connector	RP-TNC			✓
	Reader buffer	Number of tags that can be read	400			✓
Operation Properties	Installation date	Date when the unit is installed	01/01/2012	✓	✓	✓
	Battery level	Percentage of available battery	40%	✓		
	Write-cycle-count	Number of the write-cycles	1280	✓	✓	
Data Management	EPC number	Universal identifier as defined in the EPCglobal tag data standard	urn:epc:id:sgtin:0134000.213254.343	✓	✓	
	TID	32-bit transponder identification number	2E8E0D4C	✓	✓	
	Encryption	Method and possibly keys for encryption of the data	AES	✓	✓	
	Markup language	Data presentation standard/ markup language	XML	✓	✓	
	Memory content	Reference for the existing content on the tag's memory	ID	✓	✓	

5.3.1.3 Location of the RFID tags and readers

The locations of the RFID system entities are modeled using available methods in IFC for representing the location, orientation and placement of items as follows:

Absolute or relative placements: The RFID entity placement can be identified in various methods such as: (1) *Absolute*: by an axis placement, relative to the world coordinate system; (2) *Relative*: by an axis placement, relative to the object placement of another product (for example, the element to which the tag is attached to); (3) *By grid reference*: by the virtual intersection and reference direction given by two axes of a grid. In IFC, this placement can be represented using *IfcObjectPlacement* and its subtypes *IfcLocalPlacement* and *IfcGridPlacement. IfcLocalPlacement* defines the relative placement in relation to the placement of another product or the absolute placement within the geometric representation context of the project. Details related to this placement method can be found in the documentations of the IFC standard (IFC, 2013).

Containment: The RFID system entity is located in a space that is part of a building and a floor. The location of the tag can be identified based on the containment relationship to know the spatial level that the tag is located in. *IfcRelContainedInSpatialStructure*, is used to assign elements to a certain level of the spatial project structure. Predefined spatial structure elements in IFC to which RFID tags can be assigned are: (1) Site; (2) Building; (3) Storey; and (4) Space.

Figure 5-5 shows how an RFID tag (instance of *IfcProduct*) can have containment relationship with certain building story or space. It shows that in addition to containment relationship, the tag has its absolute or relative placement definitions using *IfcLocalPlacement*.

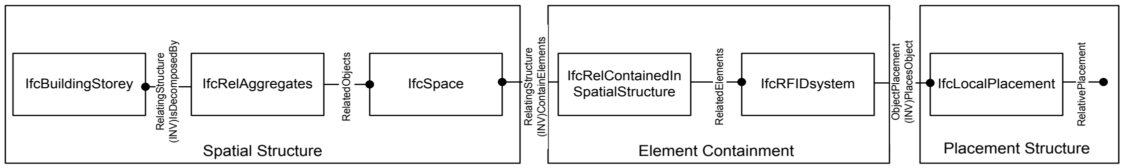


Figure 5-5 IFC containment relationships (adapted from IFC, 2013)

5.3.2 RELATIONSHIPS WITH OTHER OBJECTS

The RFID tag/reader is either attached to an asset/building element or is part of it (as a subcomponent). These relationships are physical attachment or decomposition type. Figure 5-6 shows how an RFID tag or reader has one-to-one physical relationship with an element that it is attached to. Although each tag/reader is attached to only one element, several RFID tags/readers can be physically attached to one element.

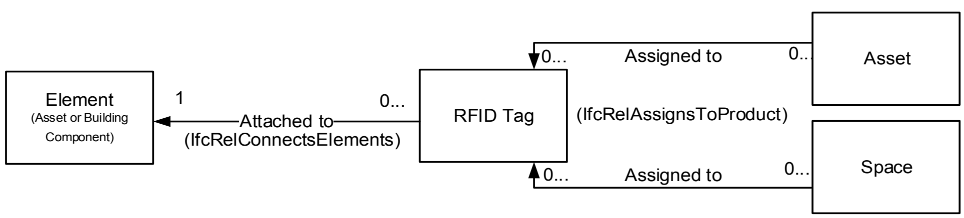


Figure 5-6 RFID tag attachment and assignment relationships

The *decomposition* relationship between an RFID tag and the associated element (e.g., asset or building component) can be defined using existing IFC relationship definitions. For example, the reader can be an internal part of a communication device, such as a handheld computer or cell phone. In this case, a decomposition relationship can be used to identify such setting. Entities, such as *IfcRelDecomposes* and its subtype *IfcRelAggregates* are used to realize this relationship between tags and their associated elements. As shown in Figure 5-7, these relationships are used when the tag is an internal part of an asset.

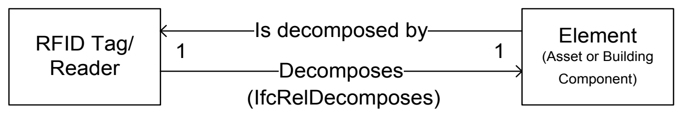


Figure 5-7 Decomposition relationship

In order to describe the physical connectivity between an RFID tag/reader and an asset or building component, *IfcRelConnectsElements* together with *IfcConnectionGeometry* are used. *IfcConnectionGeometry* is added to describe the geometric constraints of the physical connection of two objects. The physical connection information is given by specifying exactly where at the relating and related element the connection occurs. Additionally, IFC provides the eccentricity subtypes, to describe the connection when there is a distance between the tag and the element. IFC provides the following connection geometry/topology types: (1) Point/vertex point; (2) Curve/edge curve; and (3) Surface/face surface.

Furthermore, one or many elements or spaces can be logically assigned to a tag in order to keep data related to them on its memory. The following are different alternatives for object-to-tag assignments: (1) A single asset is assigned to a tag (*asset tag*): The tag contains data about one asset. In this scenario, the tag is attached to the same asset; (2) A group of assets is assigned to a tag (*group asset tag*): More than one asset is assigned to the tag (for example, the fire extinguisher, fire hose and the first aid box are assigned to a tag); (3) Several spaces and/or assets are assigned to a tag (*location tag*): The tag contains data about the space (e.g., coordinates, room number and occupants) and data about selected assets in that space; (4) A space is assigned to a tag (*area tag*): The tag contains data about the space (e.g., floor plan, occupants); and (5) A group of spaces is assigned to a tag (*zone tag*): The tag contains data about a group of spaces (e.g., contains department name). Figure 5-6 conceptually shows the relationship of an RFID tag and associated and attached assets and spaces. All of the above-mentioned logical relationships between tags and elements can be described in IFC by using *IfcRelAssignsToProduct* entity.

RFID systems connections and ports

Ports are defined for different types of RFID System entities, such as tags and readers in order to model the connectivity to/between antennas as well as the connection to the power source. *IfcRelConnectsPortToElement* and *IfcRelConnectsPorts* are used in order to realize these connections. Table 5-3 shows defined ports for different RFIDsystem types. The table presents the name of the port, its flow direction, its flow type, and a short description. Figure 5-8 shows the sample port connectivity diagram between an RFID active reader and an active tag. In this connectivity diagram, the active reader is equipped with an external antenna which is connected to the reader via a cable.

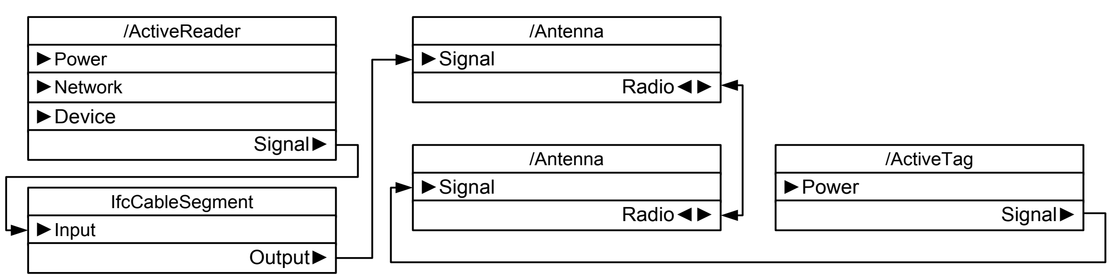


Figure 5-8 RFIDSystem connectivity and ports

Table 5-3 Definitions and properties of ports

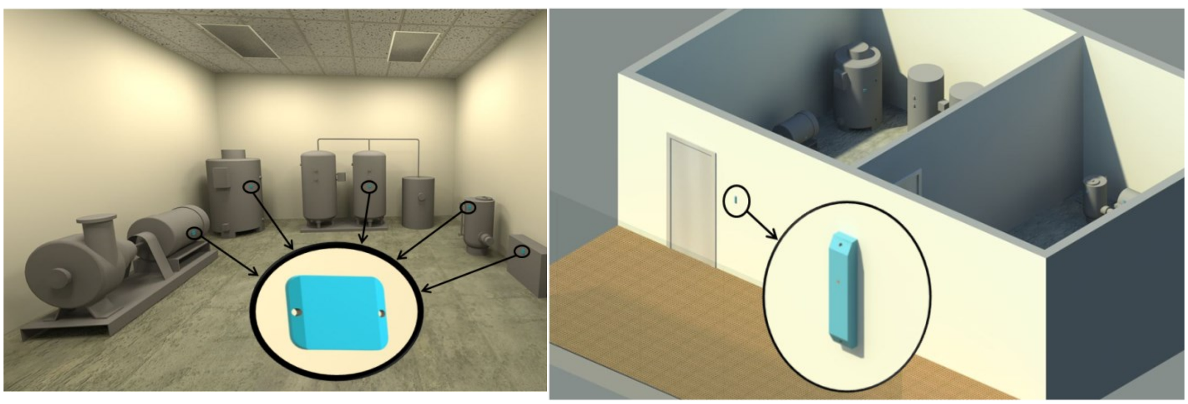
Element Type	Port Name	Flow Direction	Type	Description
Antenna	Radio	SinkSource	Signal	Electromagnetic waves.
	Signal	SinkSource	Signal	The modulated analog signal in a circuit
Active Reader	Power	Sink	Electrical	Receives electrical power.
	Network	Sink	Data	A network link to a routed device.
	Device	Sink	Signal	A device connection such as USB or serial
	Signal	Source	Signal	The modulated analog signal in a circuit
Active Tag	Power	Sink	Electrical	Receives electrical power.
	Signal	Source	Signal	The modulated analog signal in a circuit
Passive Tag	Signal	Source	Signal	The modulated analog signal in a circuit
Passive Reader	Power	Sink	Electrical	Receives electrical power.
	Network	Sink	Data	A network link to a routed device.
	Device	Sink	Signal	A device connection such as USB or serial
	Signal	Source	Signal	The modulated analog signal in a circuit

5.4 CASE STUDY

5.4.1 MODELING RFID TAGS IN BIM APPLICATION

A sample mechanical room has been modeled in Autodesk Revit Architecture 2012 (Revit, 2012) to show the feasibility of the proposed method. RFID active and passive tags are modeled in Revit environment under the electrical equipment category. The model is then exported to the IFC format and extra codes are added to the EXPRESS file in order to define new properties and relationships for tags and assets based on IFC 2x4 standards. The modified IFC model is then viewed by standard IFC viewer (Nemetschek IfcViewer, 2012) to verify the consistency of the model.

In the case study, passive asset tags are attached to each asset and a long range active location tag is attached to the wall near the entrance of the mechanical room to provide the maximum readability from the corridor. Figure 5-9 shows the modeled passive and active tags that are attached to mechanical assets (e.g., pump, boiler) and the wall, respectively. The active tag contains various data types related to the room and selected assets that are located in the room. Table 5-4 shows the types of data that are saved on passive and active tags. As shown in Table 5-4, passive asset tags contain only the ID of the tag and the last inspection date of the asset that the tag is attached to, due to the limited memory size of passive tags. The active location tag's memory contains data related to other assets and spaces in addition to its own ID. For example, it stores the location coordinates of assets in the room. Consequently, the user that is reading the memory of the tag from a distance would be able to identify the locations of assets as well as their room number. The location tag's memory also contains the information related to the authorized users who have access to the room and the hazardous materials that are stored in the room. These data can be used for procedures related to access security, safety and emergency management.



(a) Passive tag (b) Active tag

Figure 5-9 Modeled RFID tag attached to the wall

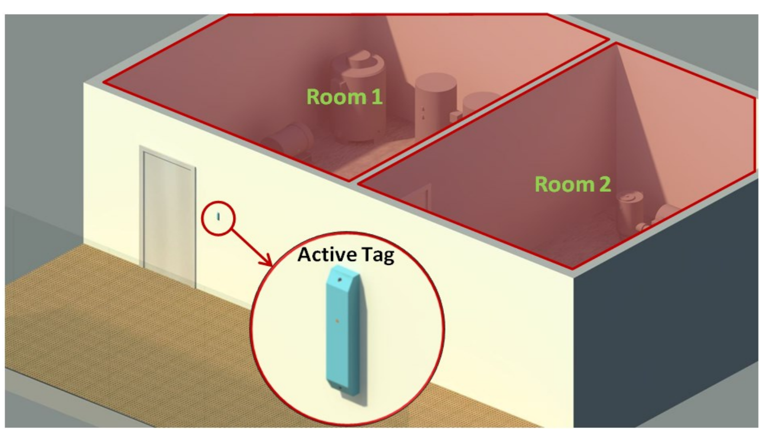


Figure 5-10 Assignment of an active location tag to rooms

Four main relationship types are defined for the active *location tag*: (1) *Physical relationship (attachment)*: which is the relationship between the tag and the object it is attached to (i.e., wall); (2) *Spatial containment*: the relationship between the tag and the space that contains the tag (i.e. corridor); (3) *Assignment to spaces*: which is the logical relationship of the tag and spaces assigned to it (e.g., rooms assigned to the *location tag*). Figure 5-10, Figure 5-11, and Figure 5-12 show the areas of room 1 and 2 which are assigned to the active tag; and (4) *Assignment to assets*: it is a logical relationship to show the relation between specific assets and the tag. It is neither physical, nor spatial. In our case study, four assets are assigned to the active *location tag* (Figure 5-12). Similarly, three main relationships are defined for the passive *asset tag*: (1) *Physical relationship (attachment)*; (2) *Spatial containment*; and (3) *Assignment to assets.*

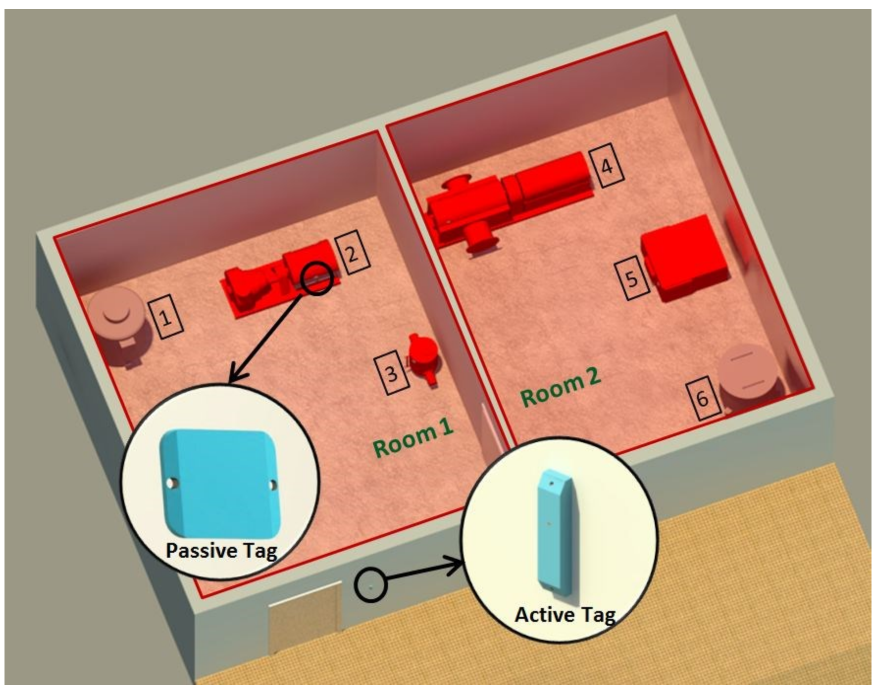


Figure 5-11 Assignment of selected assets to a tag

Table 5-4 Data saved on the tags

Tag type	Data	Example
Asset passive tag	ID	urn:epc:id:sgtin:0134000.213254.343
	Related Asset's Last Inspection Date	12/12/12
Location active tag	ID	123
	Related Spaces Name	Room_1
	Related Space IDs	123
	Related Spaces Authorized Users	John Smith
	Related Spaces Hazardous Materials	None
	Related Assets Name	M_Pump
	Related Assets ID	321
	Related Assets Coordinates	X,Y

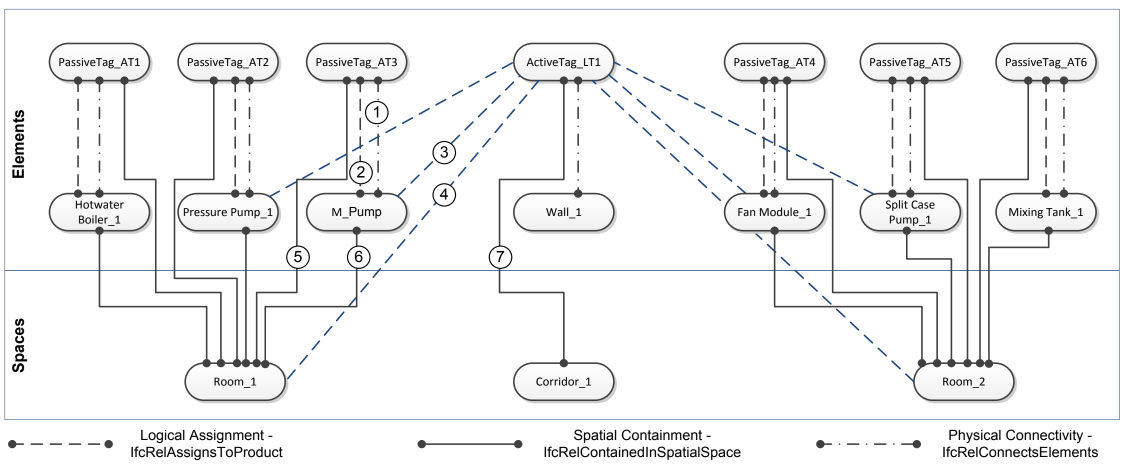


Figure 5-12 Case study entities and relationships

5.4.2 ADDING RELATIONSHIPS USING EXPRESS LANGUAGE

After creating the model objects in the Revit application, various relationships should be defined. The current version of the tool supports only the spatial containment relationship (i.e., *IfcRelContainedInSpatialStructure)* from required types of relationships. Hence, the model is exported to IFC format and other relationships are manually added using standard EXPRESS format (IFC, 2013). Figure 5-12 shows the relationships between various elements including the spaces and assets and their attached tags. As shown in the figure, four mechanical assets and two rooms are assigned to the *location tag* (i.e., ActiveTag_LT1). This *location tag* is attached to Wall_1 and contains the data types presented in Table 5-4. The figure also identifies various types of relationships to be added to the IFC database in order to realize the required relationship definitions for the case study.

Table 5-5 shows parts of the modified IFC file that describe the following: (1) The *definitions* of some elements (i.e., the active *location tag* (LT1), pump (M_Pump), the passive *asset tag* attached to the pump (AT3), the room (Room_1), and the corridor (Corridor_1); (2) The *coordinates* of LT1, AT3, and M_Pump; (3) Various *relationships* including: *physical relationship* between passive tag and pump, *logical relationships* between passive tag and pump, *logical relationships* between active tag and all assigned assets and spaces, *containment relationship* between corridor and all the assets in it, and *containment relationship* between room_1 and all the assets in it; and (4) Sample *property set definitions* and their values for sample passive tag (AT3) and sample asset (M_Pump). The numbers shown in Figure 5-12 correspond to the noted numbers in the comment column of Table 5-5. For example, the assignment of several assets and spaces (including M_Pump and Room_1) to the *location tag* is realized with line #38599 in the EXPRESS code.

As explained in Subsection 5.1, the recorded data and relationships in the IFC database are used to automatically construct the data file to be saved on the tag's memory. The data types to be saved on tags memory are selected based on the process requirements. Two scenarios explained in Subsections 5.2.1 and 5.2.2 can be realized in our case study. For the first scenario (to update the asset's inspection results on its RFID tags), data presented in Table 5-5 can be used. The table contains the definitions of passive tag (AT3) (#34846) and the pump (M_Pump) (#14928), the assignment relationship between the pump and its tag (#38598), condition history of the pump including inspection date and the inspection results (#38600, #38601), and EPC ID of the tag (#38602).

Table 5-5 also includes the sample data to realize the second scenario (to update the location coordinates of assets on a location tag). It includes the definitions of the active location tag (LT1) (#31635), the definitions of sample asset (M_Pump) (#14928) and the room (Room_1) (#74), the coordinates of the pump (#14925), and the assignment of the pump to the *location tag* (#38599). The application that is used to update the tags should have a procedure to lookup the needed entries in the IFC database and create a new file to be merged into the memory of scanned RFID tag.

Table 5-5 Part of EXPRESS code for the model

EXPRESS Code	Comment
/* Definitions */	
#14928=IFCBUILDINGELEMENTPROXY('*GUID*',#33,'M_Pump ',$,'38 LPS - 358 kPa Head',#14927,#14921,'127731',.ELEMENT.);	Definition of "M_Pump"
#31635=IFCBUILDINGELEMENTPROXY(*GUID*',#33,'ActiveTag_LT1',$,'RFID Active Tag',#31634,#31628,'154693',.ELEMENT.);	Definition of "Active Tag_LT1"
#34846=IFCBUILDINGELEMENTPROXY('*GUID*',#33,'Passive Tag_AT3',$,'RFID Passive Tag',#34845,#34839,'170619',.ELEMENT.);	Definition of "Passive Tag_AT3"
#74=IFCSPACE('*GUID*',#33,'1','',$,#61,#73,'Room_1',.ELEMENT.,.INTERNAL.,$);	Definition of "Room_1"
#242=IFCSPACE('*GUID*',#33,'0','',$,#231,#241,'Corridor_1',.ELEMENT.,.INTERNAL.,$);	Definition of "Corridor_1"
/* Coordinates */	
#34843=IFCCARTESIANPOINT((-5659.35|,2299.71|7,431.87|));	Coordinates of PassiTag_AT3
#31632=IFCCARTESIANPOINT((-667.21|,1239.61|,1408.45|));	Coordinates of ActiveTag_LT1
#14925=IFCCARTESIANPOINT((-6193.54|,1111.19|,11.15|));	Coordinates of M_Pump
/* Physical Relationships */	
#38597=IFCRELCONNECTSELEMENTS('*GUID*',#33,$,$,$,#14928,#34846)	Attachment of Passive tag (AT3) to the M_Pump: Relationship (1)
/* Logical Relationships */	
#38598=IFCRELASSIGNSTOPRODUCT('*GUID*',#33,$,$,#14928,$,#34846)	Assigning pump to the passive tag: Relationship (2)
#38599=IFCRELASSIGNSTOPRODUCT('*GUID*',#33,$,$,(#2216,#14928,#23239,#26872,#27053,#30856,#162,#74),$,#31635)	Assigning assets and spaces to the active tag: Relationships(3), (4)
/* Spatial containment Relationships */	
#38442=IFCRELCONTAINEDINSPATIALSTRUCTURE('*GUID*',#33,$,$,(#2216,#4539,#4603,#4635,#4667,#14928,#23239,#34846,#35551,#38367),#74);	Containment relationship for assets inside "Room_1" including: Relationships (5), (6)
#38444=IFCRELCONTAINEDINSPATIALSTRUCTURE('*GUID*',#33,$,$,(#31635,#34063,#34119,#34151),#242);	Containment relationship for assets inside "Corridor_1" including: Relationship (7)
/* Properties Values */	
#38600=IFCPROPERTYSINGLEVALUE('AssessmentDate',$,IFCDATE('2012-12-12'),$);	Inspection date
#38601=IFCPROPERTYSINGLEVALUE('AssessmentCondition',$,IFCLABEL('Good-8/10'),$);	Inspection results (condition)
#38602=IFCPROPERTYSINGLEVALUE('EPCNumber',$,IFCIDENTIFIER('urn:epc:id:sgtin:0134000.213254.343'),$);	EPC number
/* Property Sets Definitions */	
#38606=IFCPROPERTYSET('*GUID*',#33,'Pset_Condition',$,(#38600,#38601));	Condition property set
#38607=IFCPROPERTYSET('*GUID*',#33,'Pset_RFIDSystemPassiveTag',$,(#38602,#38603,#38604));	Passive RFID property set
/* Relating Property sets to elements */	
#38608=IFCRELDEFINESBYPROPERTIES('*GUID*',#33,$,$,(#14928),#38606); #38609=IFCRELDEFINESBYPROPERTIES('*GUID*',#33,$,$,(#34846),#38607);	Relating "condition property set to M_Pump and RFID property sets to Passive tag (AT3)

5.5 SUMMARY AND CONCLUSIONS

The research presented in this chapter elaborated on the needs, motivations and benefits of including standard definitions of RFID systems in the BIM. A model based on requirements' gathering is developed in order to identify and define the entities, property sets, ports, and relationships for RFID system components. For the case study, various IFC-compatible tools were utilized to test the proposed extension of IFC.

The results of tests showed that the current tools have several limitations for extending the definitions of the IFC. The exported IFC file of a model that is created in a certain tool lacks several details of the same model when opened by standard IFC viewers. Additionally, the exported IFC file has compatibility issues when opened by other BIM tools. Although the tested tools claim to be fully compatible with certain versions of IFC implementation, they were unable to utilize existing properties and relationship types available in that IFC version. This shows that the current state of practice has major limitations for adding new objects, relationships and properties as well as utilizing existing classes of IFC. Hence, in the case study a combined approach is used by utilizing IFC tools as well as manually adding EXPRESS code and finally visualizing the model using standard viewers.

The conclusions of this chapter are as follows: (1) The proposed BIM extension provided definitions for new entities, relationships, and property sets for the IFC; (2) Using definitions of RFID tags together with their spatial and logical relationships to other assets, the subset of BIM data that is required to be copied on RFID tags can be easily selected; (3) The proposed extension took full advantage of reusing available entities, relationships, and property sets in IFC. Only the necessary and unavailable entities are proposed to be added; (4) The case study showed that, although current BIM tools have major limitations in extending the definitions and utilizing existing IFC entities, the scenarios for interrelating BIM and RFID data can be done by manually editing the EXPRESS code.

CHAPTER 6 KNOWLEDGE-ASSISTED BIM-BASED VISUAL ANALYTICS FOR FAILURE ROOT-CAUSE DETECTION IN FACILITIES MANAGEMENT

6.1 INTRODUCTION

Facilities managers need to identify failure causes-effect patterns in order to prepare corrective and preventive maintenance plans. This task is difficult because of the complex interaction and interdependencies between different building components. Asset management systems focus mainly on the data management aspects (i.e. asset inventory, work orders and recourse management) and lack the functionalities necessary to analyze the collected data in order to identify failure patterns and causes. Standardization based on BIM provides new opportunities to improve the efficiency of FM operations by sharing and exchanging building information between different applications throughout the lifecycle of the facilities. BIM can also be used as the main repository of information related to the facility throughout its lifecycle. The research presented in this chapter proposes a knowledge-assisted BIM-based visual analytics approach for failure root-cause detection in FM where CMMS inspection and maintenance data can be integrated with a BIM and used for interactive visualization exploiting the heuristic problem solving ability of field experts.

The main objective of this chapter is to investigate the potentials of knowledge-assisted BIM-based VA for failure root-cause detection scenario. In this research, the BIM is considered to be the primary data source for information related to building lifecycle.

BIM data is linked to data stored in FM software applications (e.g., CAFM, EAM, and CMMS).

6.2 PROPOSED APPROACH FOR FM VISUAL ANALYTICS

The current research aims to provide a framework for generating knowledge-assisted, BIM-based, and customized visualizations in order to assist problem solving using the cognitive and perceptual reasoning of FM technicians. The proposed framework results in an FM Visual Analytics System (FMVAS) to provide visualization aids.

6.2.1 CURRENT PRACTICE VS. FMVAS

In the current practice of using CMMS, a technician inputs data, such as inspection and maintenance information to the CMMS database. He/she can retrieve the information related to work orders. Facilities managers are also provided with customized reports regarding maintenance issues. Reports are mainly in the format of text-based documents, table, and charts. Figure 6-1(a) shows the current practice of using CMMS to obtain reports related to FM activities. In the proposed approach, CMMS and FMVAS use a BIM database to store data, so both facilities managers and technicians can have FM data visualization by making customized visualization queries. Figure 6-1(b) demonstrates the proposed approach using FMVAS to visualize FM data. The details related to FMVAS are provided in following sections.

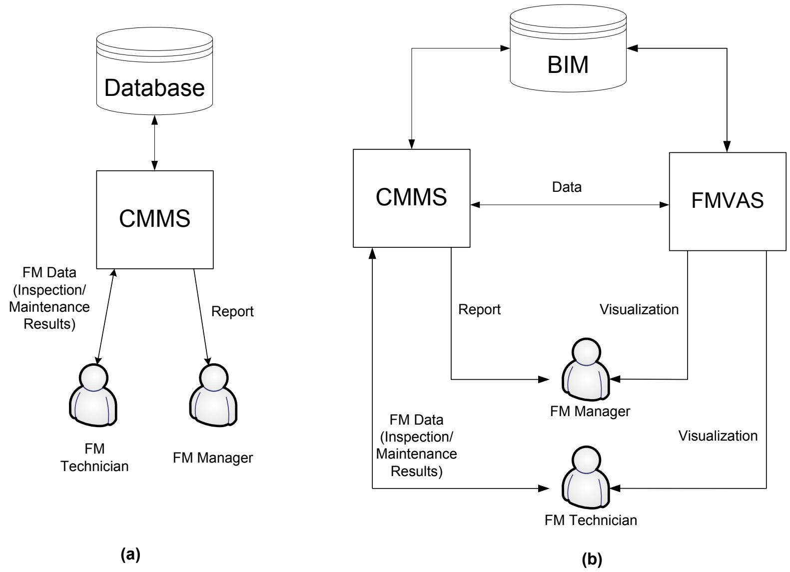


Figure 6-1 (a) Current practice of using CMMS reports, (b) Proposed method to provide visualization for FM stakeholders

6.2.2 FMVAS ARCHITECTURE

FMVAS provides customized visualization through the interaction with the user for analyzing building knowledge and data. The initial input is the failure mode scenario. FMVAS engine uses the knowledge/data layer to provide the user with the related possible causes and options for visualization based on the identified failure. Finally, FMVAS uses a BIM-based visualization tool (e.g., Revit) to generate customized views for visual analytics based on queries.

As shown in Figure 6-2, FMVAS consists of three main layers. The bottom layer contains various FM data resources that are integrated through predefined database relationships. Moreover, FM knowledge, such as fault trees, are stored using IF-THEN rules that formalize the stored knowledge. The engine consists of procedures that drive the interactions with the user through the user interface to collect inputs, and a query builder module that extracts data from the lower layer according to user inputs. The engine launches the visualization tool (e.g., Revit) and provides it with visualization queries. The visualization queries are the result of an interactive process that, in each step, takes user inputs and provides him/her with the related information visualized on top of the BIM 3D model.

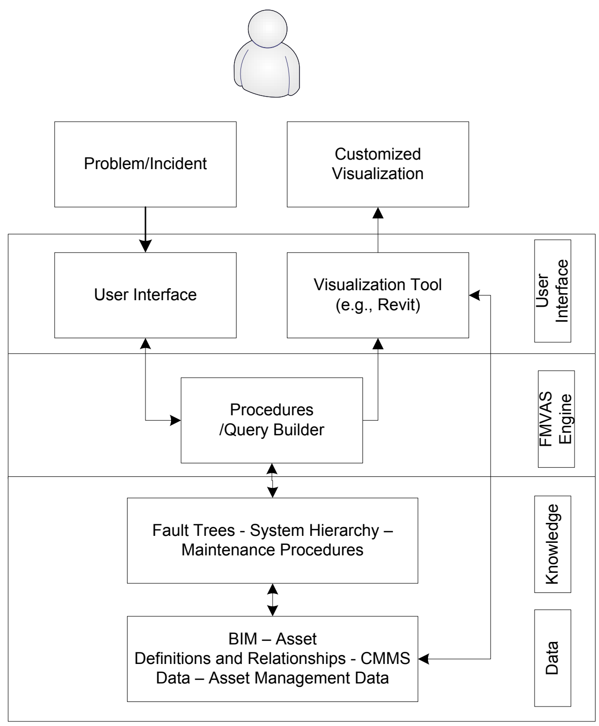
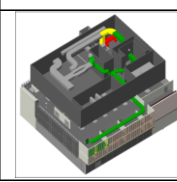


Figure 6-2 FMVAS architecture

6.2.3 VISUAL ANALYTICS SCENARIO PROCESS FLOW

In order to clarify the process flow of FMVAS, an application scenario for failure's root-cause detection using VA is elaborated as shown in Table 6-1. In the first step, the user inputs the failure mode, which is related to an asset, a system or a location in the building. The resources available for identifying the problems/incidents in the building are corrective work orders, service tickets or inspection and condition assessment results (for example, a *too hot* work order for *room#123*). In the second step, the FMVAS engine queries the possible causes for the problem based on the stored knowledge, such as fault trees and cause-effect diagrams. For example, in the case of the *too hot* problem, the related values are extracted from the knowledge base and the possible causes are shown to the user. In the next step, the FMVAS engine builds queries to populate generic asset types that may have caused the problem with specific instances related to the defined incident using BIM relationships. The user then chooses the criteria for the visualization and the assets to be visualized. For example, the user chooses to check all related assets that have bad condition or the assets that have not been inspected for the past two years. Finally, FMVAS provides the user with the customized visualization specific to the defined failure mode.

Table 6-1 Process flow for root-cause detection visual analytics

Process	Identify Problem/ Effect/Incident/Failure Mode (Symptoms) →	Identify Related Systems/Spaces/ Components/Causes →	Identify Related Elements for Visualization →	Define Visualization Query Attributes →	Visualize
Resources	● CMMS corrective work orders ● Inspection results ● Service tickets	● Fault tree analysis ● Cause-effect diagrams	● BIM relationships	● BIM (based on assets properties, history, condition) ● CMMS	● BIM visualization tool
Example	● Too hot ● Room#123	● HVAC system ● Openings ● Heat generated from assets in the room	● HVAC system#2 ● Openings in room#123 ● Assets in room#123	● Condition=bad ● Status=inactive ● Last inspection > 2012	

6.3 STEPS TO REALIZE FMVAS

In order to realize FMVAS, a series of activities should be performed: (1) *Data integration*: various sources of data related to the lifecycle of the facilities should be integrated; (2) *Knowledge capture*: Expert knowledge, systems relationships, and O&M procedures should be formally captured; (3) *FMVAS engine developement*: An application should be developed to use the captured data and knowledge with the user inputs to provide the visualizations. Moreover, application scenarios in the form of preprogrammed use cases can be used to help the user define the required visual queries; and (4) *Visualization:* The visualizations based on the user's requirements and a set of properties are generated to be used for heuristic problem solving. The details about these steps are provided in the following Subsections.

6.3.1 DATA INTEGRATION

In our proposed method, various sources of facilities' data should be integrated including BIM, CMMS, COBIE, CAS, and CAFM data. As explained in Subsection 2.4.5, COBIE data is stored in the spreadsheet format. The BIM data can also be stored in various database formats that are explained in Subsection 2.4.2. The data integration is done by defining relationships among the databases. BIM is mandated to accommodate all sources of data related to building lifecycle. However, the current standard of BIM (i.e., IFC2x4) is not complete and does not include all the required properties and relationships related to the O&M phase. Examples of such properties are: operational statuses (e.g., decommissioned, broken, inactive), downtime information, failure classes, and physical/operational conditions.

Table 6-2 shows various systems that are used in the operation phase of facilities and the data types that are commonly stored in their databases. The table shows that items, such as assets/location definitions can be used to link various data in these databases. Consequently, by identifying a unique ID of each asset and its location in all related O&M software applications, the databases for these applications can be easily linked.

Table 6-2 Various sources of building data

Properties	BIM	CMMS	COBIE	CAFM	CAS
Geometry	✓				
Assets definitions	✓	✓	✓	✓	✓
Assets properties	✓	✓		✓	
Building components definitions and properties	✓				✓
Assets conditions	✓	✓		✓	✓
Inspection results	✓	✓		✓	✓
Maintenance schedule		✓			✓
Assets hierarchy	✓	✓	✓	✓	✓
Distributions systems relationships	✓			✓	
Locations	✓	✓	✓	✓	✓
Asset's history	✓	✓		✓	✓
Meter readings/Sensor data	✓	✓		✓	✓

6.3.2 KNOWLEDGE CAPTURE

In addition to lifecycle data, building knowledge is captured by FM experts and system designers using different methods (e.g., fault trees) as explained in Subsection 2.6. In this Subsection, available IFC resources that can be used to capture various O&M-related knowledge are investigated.

6.3.2.1 Logical and Spatial Relationships Definition

Defining relationships among building elements is one of the basic steps to capture building knowledge. Two types of relationships between components and spaces are used: (1) *Logical relationships*: The logically related components are not necessarily physically connected. For example, the connection between a light switch and a light fixture can be considered as a logical relationship because the cable connecting the switch to the light is not usually added to the model (Liebich, 2009); and (2) *Spatial relationships*: A spatial relationship defines the relationship between components and/or spaces in which they are physically related (e.g., containment, connection, and adjacency relationships).

Various types of logical and spatial relationships are defined and the categorization of these relationships is done based on the literature and interviews with FM personnel. The Relationship between two related entities (E^i and E^j) is defined 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 and the instance of the relationship (e.g., a part of HVAC#1 system belongs to the electrical engineering 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 6-3, $R_l^{S^a,S^b}$ 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 that is located at a different floor from S^a but S^a provides S^b with heating/cooling. $R_l^{C^1,C^4}$ 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 ($R_s^{C^1,S^a}$).

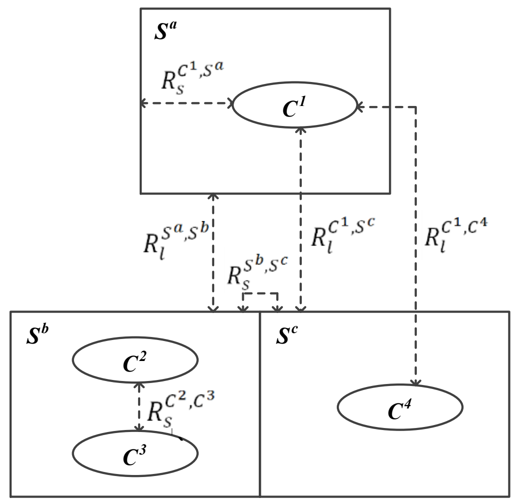


Figure 6-3 Examples of spatial and logical relationships between components and spaces

Realizing spatial and logical relationships in IFC

The *IfcRelConnectsElements* resource provides the generalization of a one-to-one logical connection between elements. In order to capture one-to-many relationships, *IfcRelAssignstoProduct* can be used. Moreover, the spatial containment relationship between a component and a space is defined in IFC by *IfcRelContainedInSpatialStructure*. The physical connectivity can be identified in IFC using tags, such as *IfcRelConnectsPorts*.

Various groups can be defined in IFC using the *IfcGroup* resource. Systems are examples of the logical grouping of assets. Elements are grouped under a system based on their roles regardless of their position in a building. *IfcRelServicesBuildings* defines relationships between building service systems (e.g., HVAC) and the site, the building, and its stories, spaces, and spatial zones.

The main resources related to grouping in the current version of IFC (2x4) are: (1) Building service systems (heating, cooling, waste water systems) represented by instances of *IfcDistributionSystem*; (2) Building systems (fenestration, shading) represented by instances of *IfcBuildingSystem*; (3) Zones as collection of logically grouped spaces represented by instances of *IfcZone; and (4)* Idealized structural analysis systems represented by instances of *IfcStructuralAnalysisModel*.

6.3.2.2 Knowledge Capture Using Fault Trees

Table 6-3 shows the list of the high level causes for heating/cooling service tickets in a certain space of a building. A part of the related fault tree is developed for the first four main causes for cooling problems as shown in Figure 6-4. The top event in this tree is the *too-hot* issue that is broken down to intermediate events, such as *HVAC failure* and *openings failure*. The intermediate events are further broken down to component level failures (such as *air supply fan failure*) and basic events (e.g., *blown fuse*). The triangles connected to intermediate events link the fault tree to other fault trees that are developed for the associated components' failure.

Table 6-3 Possible causes of heating/cooling problems in a space

1	HVAC malfunctioning (Boiler malfunctioning, ducts and supply diffuser deficiency)
2	Temperature sensor or thermostat malfunctioning (Akcamete et al., 2011)
3	Openings isolation problem
4	Window/door not closed properly (Ahluwalia, 2008)
5	Adjacent spaces heat transfer
6	Generation of excessive heat by equipment in the room

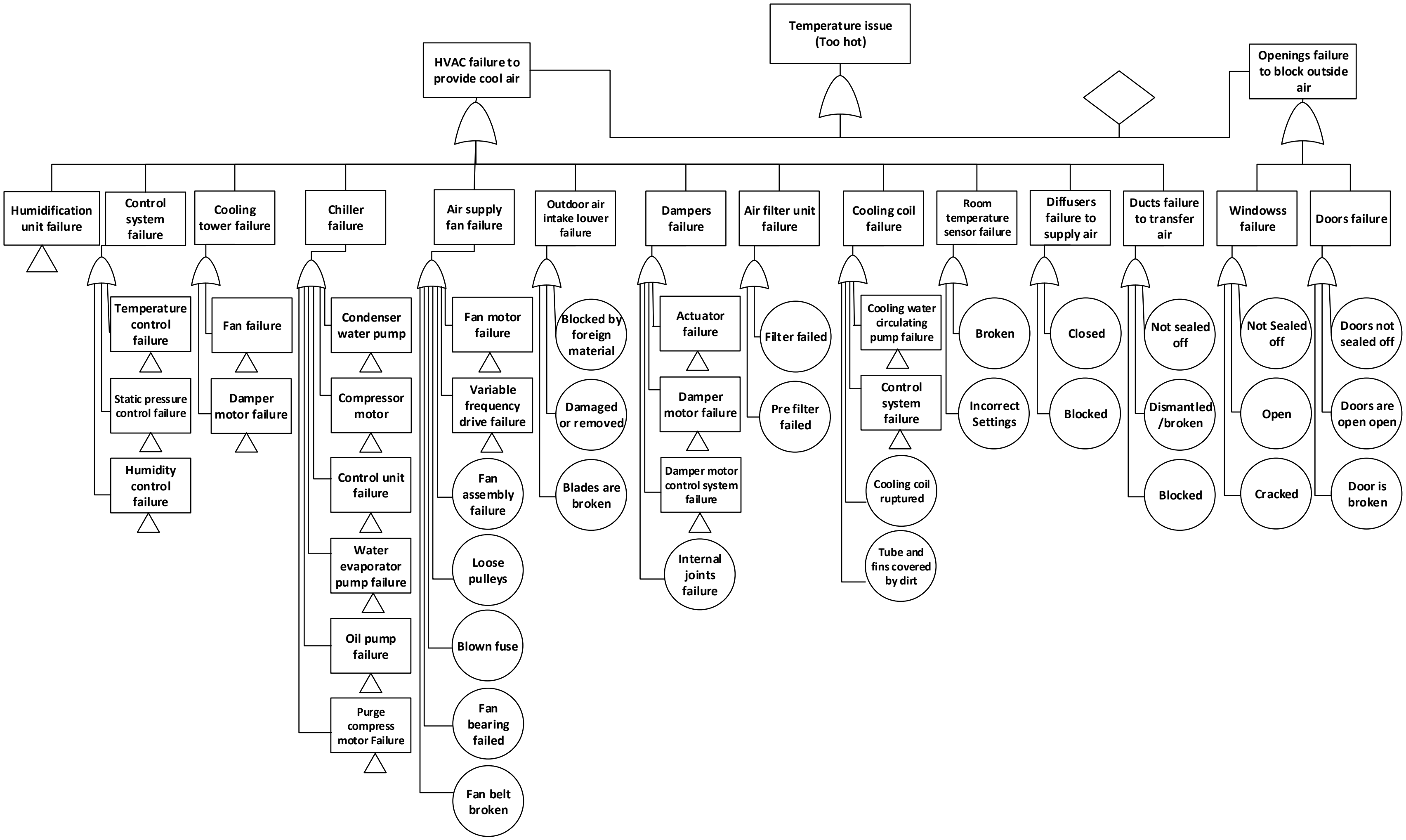


Figure 6-4 Fault tree for high temperature incident in rooms

Realizing fault trees and lifecycle knowledge in IFC

Classifications and hierarchies can be captured in IFC. *IfcClassification* is used for the arrangement of objects into a class or category according to a common purpose or their common characteristics. Hence, taxonomic schemes, arranged in a hierarchical structure can be captured using IFC definitions. These resources can be used to record system hierarchies and fault trees in an IFC database.

O&M processes can be captured in IFC using *IfcProcess* entity. An *IfcProcess* is an activity or event that is ordered in time and has sequence relationships with other processes. Products and resources can be assigned to an IFC process. Moreover, individual O&M tasks (*IfcTask*) or events (*IfcEvent*) can be defined in IFC. Using these resources, various processes related to the O&M can be recorded in IFC (e.g., shut down, lock-out/tag-out, and safety and maintenance procedures).

In order to capture historical data, IFC resources such as *IfcPerformanceHistory* can be used to document the actual performance of an occurrence instance over time. The captured data include machine-measured data from building automation systems and human-specified data, such as tasks and resources usage. The data can represent actual conditions, predictions, or simulation results. The real-time data tracked by performance history takes the form of property sets where all properties are based on time series (e.g., *Pset_UtilityConsumptionPHistory* (Consumption of utility resources), *Pset_BoilerPHistory*, and *Pset_ActuatorPHistory*).

6.3.3 FMVAS ENGINE

The FMVAS engine consists of procedures and a query builder that interacts with the user interface to collect user inputs and provide customized visualization in response to the queries. Figure 6-5 shows the process for the FMVAS engine for failure cause detection: (1, 2) The engine collects the failure mode and the location/asset ID of the incident from the user; (3) The engine applies IF-THEN rules that represent the knowledge imbedded in different fault trees or other knowledge sources; (4) The selected rules will be instantiated by applying adequate queries that link objects and attributes in the rules with the data from the CMMS and BIM databases. This step populates the fault tree with related asset/location IDs using BIM relationships through the constructed database queries; (5) The engine collects the user criteria for visualization. For example, the criterion for color coding of assets in the visualization can be based on recorded *condition* values of related assets in a BIM. The FMVAS engine queries the condition values from a BIM and correlates it with color codes. Other criteria can be the status of assets, inspection dates, and meter/sensor readings; and (6) The engine provides the visualization tool with the data deeded for the visualization.

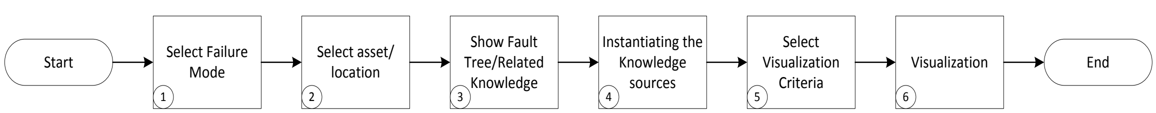


Figure 6-5 FMVAS engine process

6.3.4 VISUALIZATION IN 3D OR 4D

The visualization of the results of queries is done in 3D or 4D. The following analyses can be done by the user:

(a) Spatial analysis investigates the distribution of the events in the space using status and color coding, to infer the spatial patterns for certain problems. The visualization criteria can be related to: (a) the condition of the asset; (b) inspection dates (e.g., assets that have not been inspected in the past three months); (c) corrective work orders' status (e.g., assets that have at least one work order in progress assigned to them); (d) frequency of corrective work orders (e.g., assets that have more than three corrective work orders in the past year); (e) operational status data; and (f) failure probability

(b) Spatiotemporal analysis uses the history of changes in the properties of assets/components and spaces to help the expert inferring the changing patterns and the cause-effect relationships between different spaces/components over time using 4D modeling. For example, visualizing the changes in 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.

6.4 **CASE STUDY**

The case study has been realized using the data of the Genomics Research Center of Concordia University as an example. In this case study, VA is used to help technicians identify the possible causes of *too hot* incidents in the building. The 3D BIM model of the building was created based on its 2D drawings using Revit Architecture and Revit MEP (Autodesk, 2013). Moreover, new attributes about the conditions of the mechanical assets and their visualization codes were added to the model for the purpose of VA. FMInteract (FMSystems, 2013) is used as the CMMS software.

Figure 6-6 shows the modules of the prototype system. The asset inventory database in FMInteract is automatically imported from Revit and the selected CMMS attributes of a selected set of assets are synchronized with the corresponding BIM values in Revit. An IFC file is exported from Revit and the logical and spatial relationships between the components and spaces that are not generated automatically by Revit are defined manually in this file to demonstrate the possibility of using BIM to represent these relationships.

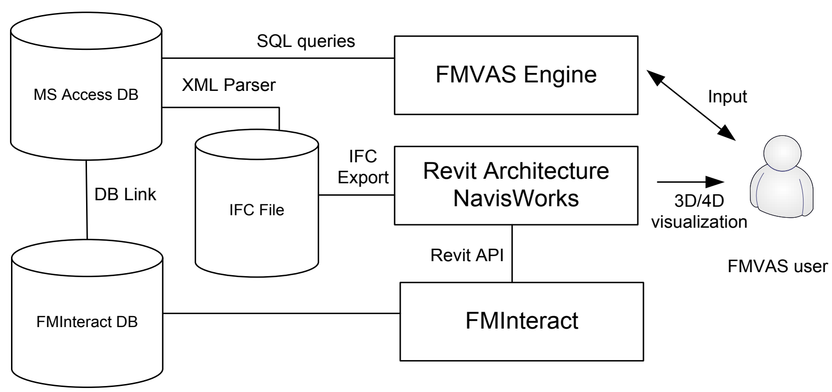


Figure 6-6 Prototype system modules

A Microsoft Access database is created as an intermediate database that is used by FMVAS engine for executing the queries. This database combines the data from the FMInteract database (e.g., work orders' data) and the data from the IFC file. The Globally Unique Identifiers (GUIDs) of entities are used as the IDs in all databases. Figure 6-7 shows the relational database developed in Microsoft Access (Microsoft, 2012). Queries are defined based on the following tables:

(1) *ELEMENT* table: contains all assets of a building and their attributes, such as the location, the system that they belong to, and their condition and status.

(2) *ELEMENT_CLASS* table: contains all types of assets (e.g., cooling coil, exhast fan).

(3) *SPACE* table: contains all the spaces and some of their attributes, such as the HVAC and electrical systms that are servicing them and their type.

(4) *SPACE_TYPE* table*:* contains types of spaces (e.g., office, mechanical room, lab).

(5) *SYS* table: contains all the distribution systems of a building and their attributes, such as the type, capcity, status, condition, and installation date. For example, a building can have different HVAC distribution systems.

(6) *SYS_TYPE* table: contains all the distribution system types used in a building, such as HVAC, plumbing, electrical, and sewage.

(7) *SPACE_SYS* table: contains the spaces and the distribution systems that are servicing those spaces. This table represents relationships between insctances of *IfcSystem* and *IfcSpace*. The entries in the table represent *IfcRelServicesBuildings* relationships that are added to the IFC file.

(8) *WO* table: contains the work orders related to assets or spaces with data related to the work order such as; work order type (corrective, inspection, and preventive), date, and status.

(9) *INCIDENT* table: contains a list of various incident classes with attributes, such as the element/location class that is assosiated with the incident and the severety of the incident.

(10) *VIS_CODE* table: contains codes that describe the visualization parameters. The visualization codes are used for the definition of filters in Revit to provide specific color/pattern for the elements.

The case study uses the sample fault tree explained in Figure 6-4 for some possible causes for high temperature in a room. The fault tree is expressed as a set of rules and generic queries that link the fault tree objects to building components. Figure 6-8 shows the flowchart for the prototype software application: (1) The user selects the failure type (e.g., *room too hot*) from *incident types* table; (2) The user selects the asset and/or the location related to the incident (e.g., room=EV1); (3, 4) The software shows the fault tree that is associated with the incident and populates it with the GUIDs of the related assets and/or locations; (5) The user selects the *visualization criteria.* For example, the user can choose to visualize all related assets in the fault tree that their condition is *bad* or their operational status is *inactive* due to corrective maintenance work; (6) The software changes the color/pattern of assets in the fault tree based on the user visualization criteria; (7) The user selects the elements to be included in the visualization; (8) The software changes the visualization codes for the selected assets and synchronize the table with the Revit model; and (9) The customized visualization is generated in Revit using predefined filters that associate the color/pattern of assets with their visualization codes.

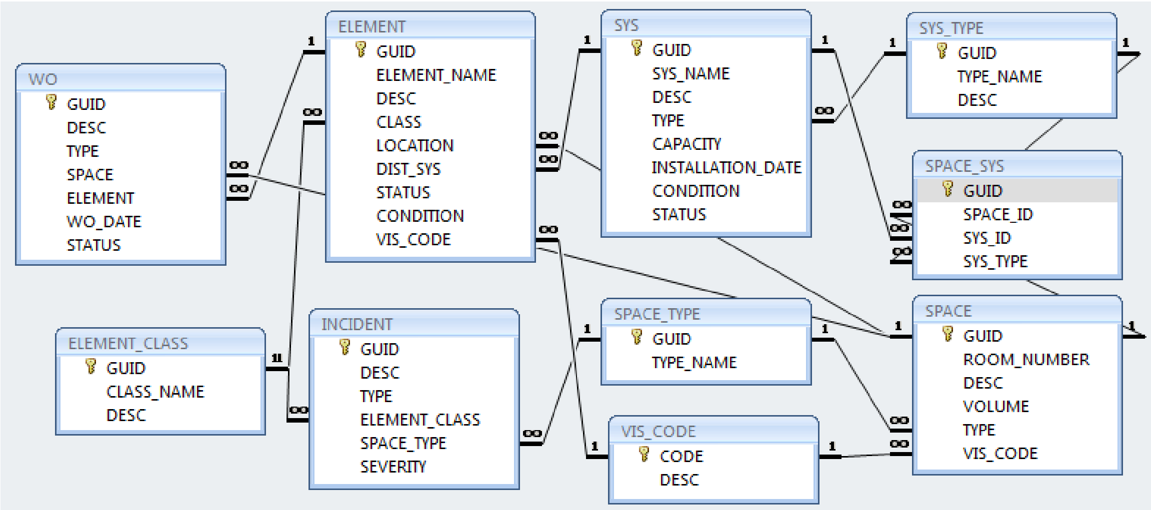


Figure 6-7 Relations between tables in the database

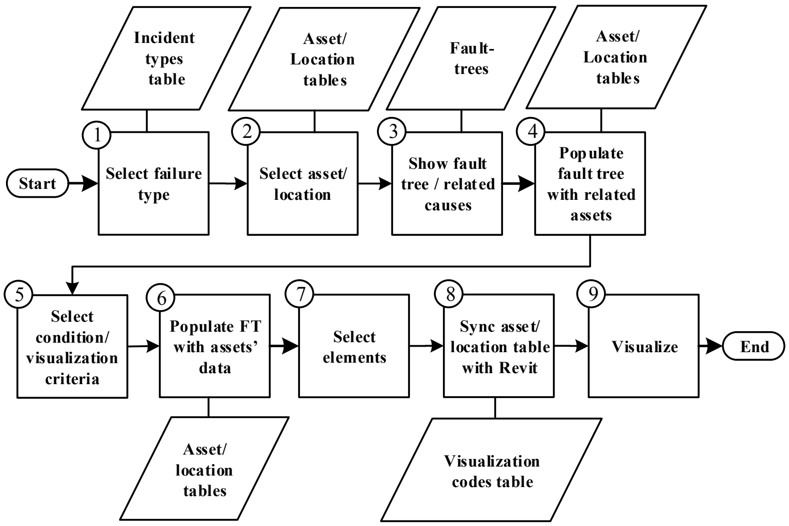


Figure 6-8 Flowchart of FMVAS prototype

Figure 6-9 shows an example SQL query that links a generic item in the fault tree (i.e., chiller failure) to the specific asset instance that is related to room# EV1. The query finds all assets that their class is "chiller" and that belong to the HVAC system that is servicing this room. This query also contains the visualization criteria that select the assets that their *status* is "inactive" or their *condition* is "bad". Figure 6-10(a) shows the visualization of the results of a similar query in 3D for VA. In this figure, the main potential causes of the high temperature problem of a space (the room at the corner of the lower floor) are identified based on the *condition* value. Figure 6-10(b) shows the chiller located in the mechanical room in red and some ducts connected to the chiller in yellow reflecting that the chiller and the ducts are in bad and fair conditions, respectively. Figure 6-10(c) shows the temperature sensor in red (bad condition) and two windows in yellow (fair condition). As the result of VA, it can be found that the chiller and the temperature sensor may be the source of the high temperature problem in the room. The components in fair condition should be investigated after those in bad condition as the possible cause of the problem.

```
SELECT
  ELEMENT.GUID FROM ELEMENT
WHERE
  ELEMENT.CLASS="Chiller"

AND
   ELEMENT.DIST_SYS=
(SELECT SYS.GUID FROM SYS INNER JOIN (SYS_TYPE INNER JOIN ([SPACE] INNER JOIN
SPACE_SYS ON SPACE.GUID = SPACE_SYS.SPACE_ID) ON SYS_TYPE.GUID = SPACE_SYS.SYS_TYPE)
ON SYS.GUID =SPACE_SYS.SYS_ID

WHERE ((SPACE.ROOM_NUMBER)="EV1") AND ((SYS_TYPE.TYPE_NAME)="HVAC"))

AND
((ELEMENT.STATUS)="INACTIVE" OR (ELEMENT.CONDITION)="BAD");
```

Figure 6-9 Sample SQL query

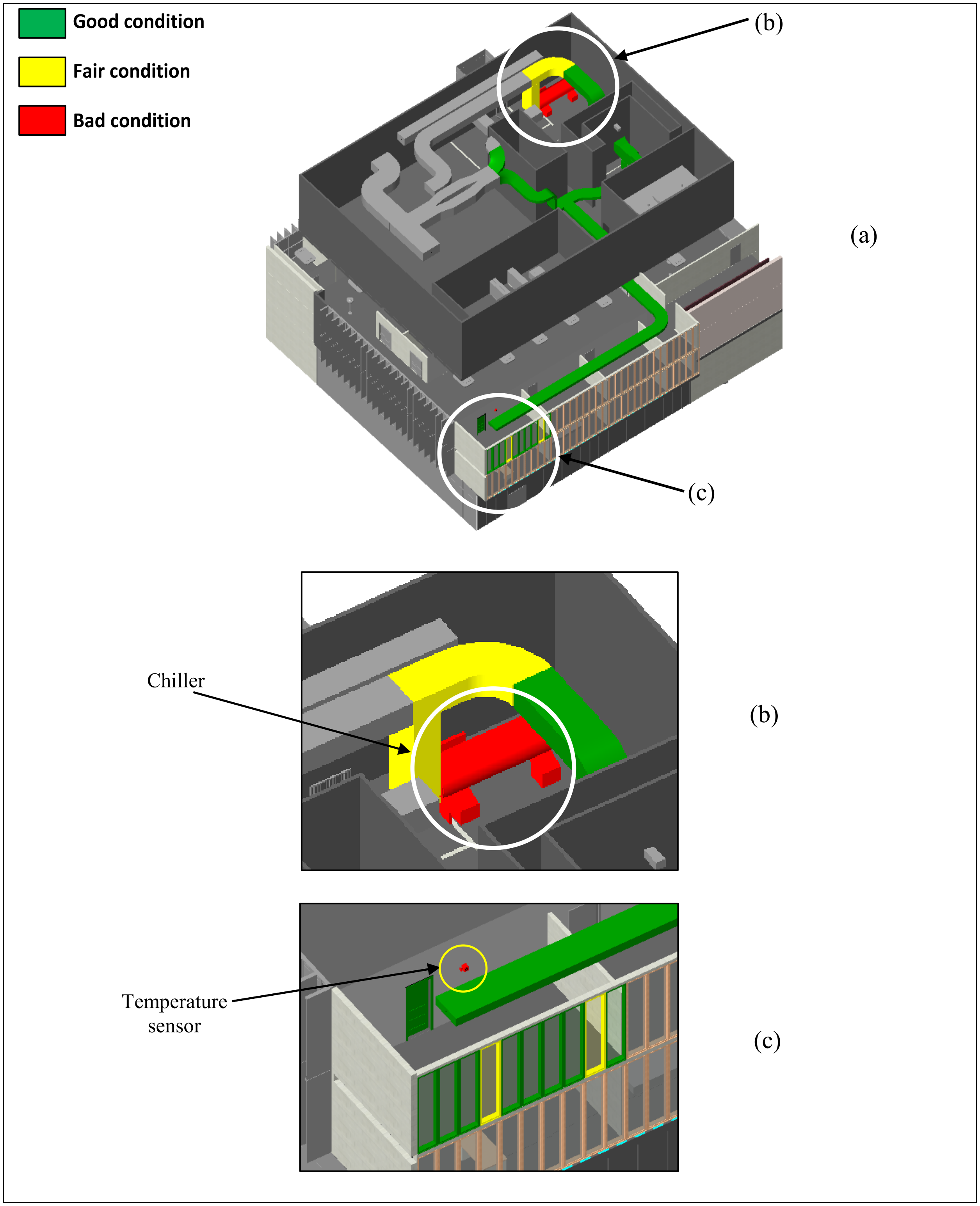


Figure 6-10 Visualization of the results of the query

6.5 SUMMARY AND CONCLUSIONS

The proposed FMVAS provides powerful tools for visualizing the possible causes of problems in a building by exploiting the spatial and logical relationships between components and spaces. It discussed the necessity of integrating various sources of lifecycle data and knowledge with BIM as a central database to provide customized visualizations. Moreover, the research presented in this chapter investigated the need to use various types of properties and relationships between components and spaces and their corresponding IFC definitions. A scenario for using FMVAS for problem root-cause detection was investigated. Finally, a case study was developed to demonstrate how FMVAS can be used to visually analyze the possible causes of temperature problems in a room based on the stored data and knowledge using database queries.

The conclusions of this chapter are: (1) In order to have a comprehensive database for FM, it is necessary to integrate data from various sources, such as CMMS with the BIM of the facility. Furthermore, building knowledge should be formally captured using several techniques such as fault tree analysis; (2) The proposed VA method provides powerful tools for visualizing the possible causes of problems in a building by exploiting the spatial and logical relationships between components and spaces. The spatial relationships can be readily captured in the IFC model and mapped into relationships in a database; while the logical relationships have to be added to the IFC model and the database; and (3) The case study demonstrated the feasibility of the proposed VA method using available CMMS and BIM tools.

CHAPTER 7 SUMMARY, CONCLUSIONS AND FUTURE WORK

7.1 INTRODUCTION

The research presented in this thesis aimed to improve processes related to the lifecycle of the facilities with the focus on the O&M phase. The problem related to inefficiencies of manual operations for finding assets is addressed in the first module of the research (RFID localization of assets). Limited research focused on providing localization of RFID-equipped assets using handheld devices. Our research has proposed an innovative approach to utilize a mass of RFID tags in the building for the localization of such assets. The problem related to the lack of standardization is addressed in the second module, which extended BIM to include RFID systems. The problem related to the complexity of processing large amount of assets' lifecycle data that are available in multiple sources for the purpose of failure root-cause analysis is addressed in the third module (VA for root-cause analysis). The use of BIM data together with other sources of building lifecycle knowledge for the purpose of visual analytics has not been fully explored. The present research investigated an approach to utilize visual analytics techniques for problem root-cause detection during the O&M phase of the lifecycle by integrating building lifecycle data and knowledge sources such as fault-trees.

In this chapter, the summary and conclusions of the three modules of the research, their contributions to the existing body of knowledge, and their limitations and future steps to improve the proposed approaches are discussed.

7.2 SUMMARY OF RESEARCH

The proposed framework for lifecycle location management using RFID (Subsection 3.2) provided details on the proposed approach to use RFID memory to store various location-related data to be used during the lifecycle of assets. The availability of RFID tags in the building provides localization opportunities in the O&M phase. Several examples of possible location-related data and their placement in the RFID tag memory are elaborated. The data recorded in the *current location* field of the memory are used for the localization of *fixed* and *movable* assets. Moreover, the data recorded in the *locations of other components* field of the memory are the key information of the *location tags* introduced in Chapter 4. The summary of each module of this research is presented as follows:

(1) The proposed approach for localization of RFID-equipped assets during the operation phase of facilities investigated several methods to localize various types of RFID-equipped assets in a building using handheld RFID readers. It discussed different scenarios to assist users (e.g., FM personnel or occupants) estimate their locations as well as the location of *fixed* and *movable* assets they are looking for. The main advantages of the proposed approach are that it can adapt to the changes in the environment, it utilizes available RFID tags in the building, and it does not require a fixed RTLS infrastructure for localization. In order to validate the approach several case studies are performed using a simulation environment and field tests.

(2) The proposed approach for incorporating information of RFID tags attached to building components to the BIM elaborated on the needs, motivations and benefits of including standard definitions of RFID systems in the BIM. A model based on requirements' gathering is developed

in order to identify the related attributes and relationships for RFID system components. Modularity and expandability of the model are taken into account to accommodate the possible future types and properties of RFID systems. Furthermore, new IFC entities, property sets and ports are defined for the RFID system. In the case study, various IFC-compatible tools were utilized to test the proposed extension of IFC.

(3) The proposed knowledge-assisted BIM-based visual analytics for failure root-cause detection in facilities management introduced the FMVAS approach. It discussed the necessity of integrating various sources of lifecycle data and knowledge with BIM as a central database. The integration of data can improve the correctness and completeness of the required data for FM. Moreover, the research investigated the need to use various types of properties and relationships between components and spaces and their corresponding IFC definitions. A scenario for using FMVAS for problem root-cause detection was investigated. The proposed framework uses building knowledge together with BIM visualization to allow the heuristic problem solving capabilities of FM technicians to find possible root-causes of failures in building systems. A case study was developed to demonstrate how FMVAS can be used to visually analyze the possible causes of temperature problems in a room based on the stored data and knowledge using database queries.

BIM has been a major interconnecting technology to all modules of the research. It is considered to be the main repository of information and its data can be used for location management, tracking of RFID tags in the building, and visual analytics for failure’s root-cause detection.

Moreover, all modules of the research aim to facilitate processes related to the O&M phase of the building.

7.3 RESEARCH CONTRIBUTIONS AND CONCLUSIONS

The specific research contributions to existing body of knowledge and conclusions are grouped in three modules as follows:

(1) Localization of RFID-equipped assets during the operation phase of facilities: The proposed approach for localizing *movable* RFID-equipped assets (CMTL) is a new neighborhood-based method that utilizes handheld devices for localization. This method improves LANDMARC method by employing clustering techniques in addition to the signal pattern similarity criterion for localization. The proposed approach is different from previous neighborhood-based methods by: (1) Using handheld devices instead of fixed infrastructure of RFID readers; (2) Using available tags that are randomly distributed in the building and are attached to *fixed* assets for localizing users, *fixed* and *movable* assets as opposed to fixed grid of *reference tags* that are employed only for the purpose of providing location references in similar methods; (3) Employing a multi-critera clustering technique to identify the *k* nearest neighboring tags for the purpose of positioning as opposed to selecting nearest neighbors based only on signal pattern similarity values; (4) Introducing a new procedure for estimating the accuracy of positioning; and (5) Introducing the *location tags* as cost effective solution for the localization of fixed assets that are not equipped with RFID tags or have short range passive tags.

The conclusions of this module are as follows: (1) The proposed method provides the user with the location of *fixed assets* on the floor plan, using the location data saved on their RFID tags' memories. In addition, location tags are introduced as an efficient method to store location information for several assets in the area; (2) The proposed method for locating movable assets (i.e., CMTL) is based on neighbourhood methods. However, CMTL uses a handheld reader instead of a number of fixed readers in similar LANDMARC-based methods. Using a handheld reader provides the flexibility to choose the number of data collection points and paths; (3) The CMTL introduced major improvements in the accuracy in case of symmetrical settings of reference tags with respect to the data collection path or the cases in which some reference tags randomly show high similarity with the target tag; and (4) The results of the case studies showed that CMTL is able to estimate the location of the target asset with higher accuracy compared to the LANDMARC method. Additionally, the case studies showed that although increasing the number of data collection points improved the accuracy, the major improvement happens when the shape of the data collection path diverges from a straight line.

(2) Incorporating information of RFID tags attached to building components to the BIM: The proposed extension to incorporate the definitions of RFID tags in the BIM includes the definitions of various entities, property sets, relationships and ports. To the best of our knowledge and based on our communications with NBIMS officials, such extension has not been proposed yet.

The conclusions of this module are as follows: (1) The proposed BIM extension provided definitions for new entities, relationships, and property sets for the IFC; (2) Using definitions of RFID tags together with their spatial and logical relationships to other assets, the subset of BIM data that is required to be copied on RFID tags can be easily selected; (3) The proposed extension took full advantage of reusing available entities, relationships, and property sets in IFC. Only the necessary and unavailable entities are proposed to be added; (4) The case study showed that, although current BIM tools have major limitations in extending the definitions and utilizing existing IFC entities, the scenarios for interrelating BIM and RFID data can be done by manually editing the EXPRESS code.

(3) Knowledge-assisted BIM-based visual analytics for failure root-cause detection in facilities management: The proposed framework to employ visual analytics for failure root-cause detection in the O&M phase of the building is different from previous research by: (1) Proposing the use of various sources of integrated building lifecycle data (such as CMMS, and CAFM) together with the BIM as the main database; (2) Proposing the use of various sources of lifecycle knowledge (e.g., system hierarchies, fault/fault models), and investigating methods to include part of this knowledge in the BIM using the IFC standard; and (3) Investigating the logical and spatial relationships available between building components and spaces, and exploring available IFC entities to capture these relationships using IFC.

The conclusions of this module are: (1) In order to have a comprehensive database for FM, it is necessary to integrate data from various sources, such as CMMS with the BIM of the facility. Furthermore, building knowledge should be formally captured using several techniques, such as fault tree analysis; (2) The proposed VA method provides powerful tools for visualizing the possible causes of problems in a building by exploiting the spatial and logical relationships between components and spaces. The spatial relationships can be readily captured in the IFC model and mapped into relationships in a database; while the logical relationships have to be added to the IFC model and the database; and (3) The case study demonstrated the feasibility of the proposed VA method using available CMMS and BIM tools.

7.4 LIMITATIONS AND FUTURE WORK

The proposed method for localizing *movable* assets can be further improved by applying more advanced signal processing methods for removing noise from logged data. Moreover, other pattern matching techniques can be employed and compared. In order to form clusters, dynamic clustering methods can be employed. BIM data can also be used to enhance the selection of the target cluster by considering spatial constraints, building materials and hierarchical location information (e.g., room number). Other positioning techniques, in addition to the weighted averaging, can be developed, tested and compared. Additionally, methods to identify the convergence of the localization should be investigated in order to find the optimum number and location of data collection steps. Furthermore, more in-depth research to evaluate the effects of density and dispersion of reference tags on the accuracy of the system is required. Finally, the simulation environment can be further enhanced to include the effect of building materials on radio signals.

The future steps related to the BIM extension includes proposing the newly defined objects to the BSA to be added in upcoming versions of the IFC standard. Moreover, the same methodology can be used to add the definitions of other types of sensors to BIM.

The proposed method for FMVAS can be further developed by considering other scenarios for VA including spatiotemporal trend detection and events tree analysis (Table B-1). Moreover, new fault tree diagrams for other types of incidents can be developed and condition prediction models, in addition to the last recorded condition values, can be used in the analysis.

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APPENDICES

APPENDIX A - LIST OF RELATED PUBLICATIONS

Articles submitted/published in refereed journals:

1. **Motamedi, A.**, Hammad, A., and Asen, Y. **(2013)**. Knowledge-Assisted BIM-Based Visual Analytics for Failure Root-cause Detection in Facilities Management*, Journal of Automation in Construction.* (Submitted)
2. **Motamedi, A.**, Soltani, M., Setayeshgar, S., and Hammad, A. **(2013)**. Incorporating Information of RFID Tags Attached to Building Components to the BIM, *Journal of Automation in Construction.* (Submitted)
3. **Motamedi, A.**, Soltani, M. and Hammad, A. **(2013)**. Localization of RFID-Equipped Assets During the Operation Phase of Facilities, *Advanced Engineering Informatics* (Available Online).
4. **Motamedi, A.**, Saini, R., Hammad, A. and Zhu, B. **(2011)**. Role-based access to facilities lifecycle information on RFID tags. *Advanced Engineering Informatics*, Vol. 25, issue,3, pp. 559-568.
5. **Motamedi, A.**, Hammad, A. **(2009)**. Lifecycle Management of Facilities Components Using Radio Frequency Identification and Building Information Model, *Journal of Information Technology in Construction*, Vol. 14, *Special Issue on Next Generation Construction IT: Technology Foresight, Future Studies, Roadmapping, and Scenario Planning* , pp. 238-262.

Articles submitted/published in refereed conference proceedings:

6. Soltani, M., **Motamedi, A.**, and Hammad. A. **(2013)**. Enhancing Cluster-Based RFID Tag Localization Using ANN and Virtual Reference Nodes, *Fourth International Conference on Indoor Positioning and Indoor Navigation, IEEE*, Montbeliard-Belfort, France. (Submitted)
7. **Motamedi, A.**, Soltani, M. and Hammad, A. **(2013)**. Indoor Localization of RFID-Equipped Movable Using Mobile Reader Based on Reference Tags Clustering, *International Symposium on Automation and Robotics in Construction (ISARC),* Montreal, Canada.
8. **Motamedi, A.**, Setayeshgar, S., Soltani, M. and Hammad, A. **(2013)**. Extending BIM to Incorporate Information of RFID Tags Attached to Building Assets, *Canadian Society of Civil Engineering (CSCE) Annual Conference,* Montreal, Canada.
9. **Motamedi, A.**, Soltani, M. and Hammad, A. **(2012)**. Localization of RFID-Equipped Assets during the Operation Phase of the Building, *International Conference on Computing in Civil and Building Engineering,* Moscow, Russia.

10. Asen, Y., **Motamedi, A.**, Hammad, A. (**2012**). Bim-Based Integration and Visualization of Facilities Management Information**.** *International Conference on Computing in Civil and Building Engineering,* Moscow, Russia.

11. Zhang, C., Hammad , A., Soltani, M. Setayeshgar, S. and **Motamedi, A. (2012)**. Dynamic virtual fences for improving workers safety using BIM and RTLS, *International Conference on Computing in Civil and Building Engineering,* Moscow, Russia.

12. **Motamedi, A.** and Hammad, A. **(2011)**. Location Management of RFID-Equipped Building Components, *International Symposium on Automation and Robotics in Construction (ISARC)*, Seoul, Korea.

13. **Motamedi, A.**, Saini, R., Hammad, A. and Zhu, B. **(2010)**. Role-Based Access to Facilities Lifecycle Information on RFID Tags, *International Conference on Computing in Civil and Building Engineering*, Nottingham, UK, June 30-July2.

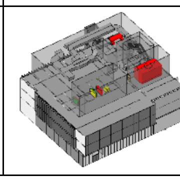
14. **Motamedi, A.** and Hammad, A. **(2009)**. RFID-Assisted Lifecycle Management of Building Components Using BIM Data, *26th International Symposium on Automation and Robotics in Construction (ISARC)*, Austin, Texas, June 24-27.

15. **Motamedi, A.** and Hammad, A. **(2009)**. Lifecycle Management of Facilities Components Using radio Frequency Identification and Building Information Model, *Fifth International Conference on Construction in the 21th century*, Turkey, 20-22 May.

16. Hammad, A. and **Motamedi, A. (2007)**. Framework for Lifecycle Status Tracking and Visualization of Constructed Facility Components, *Proceedings of the 7th International Conference on Construction Applications of Virtual Reality*, October 23-24, Penn State University, University Park, PA.

APPENDIX B – PROCESS FLOW FOR VISUALIZING CHAIN OF EVENTS

Table B-1 Process flow for risk assessment/ event tree analysis

Process	Identify Incident/ Possible Failure (Actions) →	Identify Related Systems/Spaces/ Components/ Procedures →	Identify related elements for visualization →	Define Visualization Query attributes →	Visualize
Resources	Incident management plan/ change management software	Field Expertise FMECA Cause Effect Charts Event Tree	BIM Relationships	BIM (based on assets properties, history, condition)	BIM visualization tool
Example	Electrical Panel # 1 failure	All electrical Components connected to the panel	Lighting in room 123 Heater in rooms 1,2,3 Pipes in room 2 (freeze)	Asset's criticality index>5 Asset type=HVAC	

APPENDIX C - TECHNICAL SPECIFICATIONS FOR RFID TAGS, READERS, AND HANDHELD DEVICE USED IN THE RESEARCH

Table C-1 Technical Specifications for RFID Tag: i-Q350 (Identec, 2012b)

Identec Solutions: i-Q350 RTLS		
Category	**Type**	**Specification**
Communication Broadcast 350	Operation Mode	Transmits Sensor ID and user data in pre-defined interval
	Read Range	up to 500m
	Compatibility	i-PORT M350, i-CARD CF 350 and i-PORT 4-350
	Operating Frequency	868 MHz (EU) or 920 MHz (NA)
	Transmit Power	<1mW
Communication Response 350	Operation Mode	Bi-directional communication (reading log, blink LED, write/read data)
	Read Range	up to 250m
	Compatibility	i-PORT M350 and i-CARD CF 350
	Operating Frequency	868 MHz (EU) or 920 MHz (NA)
	Transmit Power	<1mW
Data	Data Retention	> 10 years without power
	Write Cycles	100,000 writes
	Memory Size	10,000 Bytes user definable
	Identification Code	48 bit fixed ID
Configuration	Device	i-PORT M350 or i-CARD CF350
	Ping Rate	Configurable from 0.5 to 300 seconds insteps of 0.5 seconds
	Number of Bursts	Configurable from 0 to 15
	Broadcast	User Data Up to 50 Bytes
Electrical	Power Source	Lithium Battery (replaceable)
	Battery Monitoring	Yes
Environmental Conditions	Operating Temperature	–40 °C to +85 °C (–40 °F to +185 °F)
	Humidity	10% to 95% relative humidity @ 30°C
	Shock	Multiple drops to concrete from 1m (3ft), 3 times DIN IEC 68-2-27
	Vibrations	3G, 20 sine wave cycles, 5 to 150 Hz, DIN IEC 68-2-6 5G, noise 5 to 1.000 Hz, 30 minutes, DIN IEC 68-2-64
Standard/Certification	Europe	CE (EN 300 220-1, -3; EN 301 489-1,-3; EN 60950)
	North America	FCC Part 15 (US); Industry Canada
Physical	Dimensions	137 x 37.5 x 26.5 mm (5.4 x 1.48 x 1.04 in.)
	Enclosure	Plastic
	Weight	50g
	Enclosure Rating	IP65

Table C-2 Technical Specifications for RFID Tag: i-Q32 (Identec, 2007)

Identec Solutions: i-Q32		
Performance	Read rate	p to 100 tags/s (Identification Code only) Up to 35 tags/s @ 128 bit data reading
	Max. response time	< 150 ms (single tag)
	Multiple tag handling	Up to 2,000 tags in the read zone
Communication	Read/Write range to i-PORT 3	Up to 100 m (300 feet) @ free air
	Operating frequency	868 MHz (EC) or 915 MHz (NA) ISM Band
	Data rate (download to tag)	115.2 kbits/s
	Data rate (upload to reader)	115.2 kbits/s
	Maximum transmission power	0.75 mW ERP
	Standards / Certification	EN 300 220 (EC); FCC Part 15 (US); Industry Canada
Electrical	Power source	Lithium battery (not replaceable)
	Expected battery life	6 Years @ 600 times 128 bit readings/day
	Battery monitoring	Yes
Data	Data retention	10 years without power
	Write cycles	100,000 writes to a tag
	Memory size	32,431 bytes user definable (i-Q32)
	Identification code	48 bit fixed ID
Environmental	Operating temperature	–40°C to +85°C (–40ºF to +185ºF)
	Shock	50 G, 3 times DIN IEC 68-2-27 Multiple drops to concrete from 1 m (3 ft)
	Vibration	3 G, 20 sine wave cycles, 5 Hz to 150 Hz, DIN IEC 68-2-6 5 G, noise 5 Hz to 1000 Hz, 30 minutes DIN IEC 68-2-64
Physical	Dimensions	131 mm x 28 mm x 21 mm (5.2 in. x 1.1 in. x 0.85 in.)
	Enclosure	Plastic (ASA / Luran®S)
	Weight	50 g
	Enclosure rating	IP 65

Table C-3 Technical Specifications for RFID Reader: i-CARD CF 350 (Identec, 2012a)

Identec Solutions: i-CARD CF 350		
Communication Broadcast	Operation mode	Receiving sensors ID's and data
	Read range	Up to 500m (1600ft)*
	Compatibility	i-B350 and Q350 series of sensors
	Operating frequency	868 MHz (EU) or 920 MHz (NA)
Communication Response	Response mode	Bi-directional communication (reading log, blink LED, write/read data)
	Communication range	up to 250m (800ft)*
	Compatibility	i-Q350 series of sensors
	Operating frequency	868 MHz (EU) or 920 MHz (NA)
	Transmit power	< 1mW
Antennas	Broadcast/Response (350)	1 MMCX connector for external antenna at 868 (EU) or 920 MHz (NA)
Performance	Multiple sensor handling(Response)	Up to 500 sensors per read zone
Interfaces	Data interface master/host	CF Type 1
Electrical	Power source	Dual 3.3 V and 5 V
	Power consumption	< 250 mW (50mA)
Environmental Conditions	Operating temperature	-20°C to +60°C (-4°F to +140°F)
	Storage temperature	-40°C to +80°C (-40°F to +176°F)
Standard/Certification	Europe	CE (EN 300 220-1, -3; EN 300 328, EN 301 489-1, -3; EN 60950)
	North America	FCC Part 15 (US); Industry Canada
Physical	Dimensions	55 × 43 × 3.3/6 mm (2.2 × 1.7 × 0.13/0.24 in.)
	Enclosure material	ABS / Metal
	Weight	15 grams (0.52 ounces)

Table C-4 Technical Specifications for RFID Reader: i-CARD 3 (Identec, 2005)

Identec Solutions: i-CARD 3		
Compatibility	ILR i-Q tags and ILR i-D tags.	ILR i-Q tags and ILR i-D tags.
Performance	Read/write range (adjustable)	Up to 100 m (300 ft) with i-Q tag*
	Read/write range (adjustable)	Up to 6 m (20 ft) with i-D tag*
	Read rate – ID only	100 tags/s
	Read rate – 128 bit data	35 tags/s
	Multiple tag handling	Up to 2,000 tags in the read zone * The communication range depends on the antenna type, the antenna cable runs and the environmental conditions.
Communication	Frequency	868 MHz (EU) or 915 MHz (NA)
	Certification	EN 300 220 (EU); FCC part 15 (US); Industry Canada
	Data rate (up-/download)	115.2 kbits/s (i-Q Tag)
	Data rate (upload to tag)	38.4 kbits/s (i-D Tag)
	Data rate (download from tag)	115.2 kbits/s (i-D Tag)
	Number of antennas	1
	Output power	≤ 27 dBm, digitally adjustable
	Sensitivity	-85 dBm/high sens., -55 dBm/low sens., digitally adjustable
User Interfaces	Parallel interface	PCMCIA
	Option serial interface	RS-232, JTAG via PGM 15 connector
	Number of status indications	3 LEDs (Host TxRx, RF Tx, RF Rx)
Electrical	Input power	5 VDC ±5 %
	Power consumption	≤ 500 mW (100 mA @ 5V)
	Standards / Safety	CE and EN 300 220
Environmental	Operating temperature	-20 °C to +60 °C (-4 ºF to +140 ºF)
	Storage temperature	-40 °C to +80 °C (-40 ºF to +176 ºF)
	Humidity	90 % non-condensing
Physical	Dimensions	Standard Type II PC Card (86 × 54 × 5 mm) (3.38 in. × 2.12 in. × 0.19 in.)
	Enclosure	Metal
	Weight	32 grams (1.13 oz)

Table C-5 Technical Specifications for Handheld Device: WORKABOUT Pro 3 C (Psion, 2011)

Psion Teklogix: WORKABOUT Pro 3 C	
Platform	PXA270 624 MHz Processor
	1 GB Flash ROM, 256 MB RAM
Expansion Slots	One SD/MMC memory card slot
	End-cap USB interface supports GPS expansion module
	100-PIN expansion interface: supports PCMCIA (type II), GPRS/ EDGE and other third-party expansion modules developed using Psion Hardware Development Kit
	Flex cable interface supports scanner (serial) and imager (USB) modules
	One Type II CF card slot
Operating System	Microsoft Windows Mobile® 6.1 Classic, Professional
Physical Dimensions	8.78" x 2.95"/3.94" x 1.22"/1.65" (223 mm x 75/100 mm x 31/42 mm)
Approvals	Safety: CSA/UL60950-1, IEC 60950-1, EN60950-1; EMC: FCC Part 15 Class B, EN 55022, EN 55024, EN301 489
	Laser: IEC 60825-1, Class 2, FDA 21 CFR 1040.10., 1040.11 Class II
	Bluetooth: 1.2
	In-vehicle cradle: e Mark
Environmental	Withstands multiple drops from 6 ft (1.8 m) to concrete
	Rain/dust: IP65, IEC 60529
	Operating temperature: -4°F to 122°F (-20°C to +50°C)
	5%-95% RH non-condensing
	Storage temperature: -40°F to 140°F (-40°C to +60°C)
	ESD: +/- 8kVdc air discharge, +/-4kVdc contacts