IMPROVING SAFETY ON CONSTRUCTION SITES USING BIM-BASED DYNAMIC VIRTUAL FENCES AND ULTRA-WIDEBAND TECHNOLOGY

Shayan Setayeshgar

A Thesis

in

The Department of

Building, Civil and Environmental Engineering

Presented in Partial Fulfillment of the Requirements

for the Degree of Master of Applied Science (Building Engineering) at

Concordia University

Montreal, Quebec, Canada

January 2014

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

By: Shayan Setayeshgar

Entitled: Improving Safety on Construction Sites Using BIM-Based Dynamic Virtual Fences and Ultra-Wideband Technology

and submitted in partial fulfillment of the requirement for the degree of

Master of Applied Science (Building Engineering)

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

Signed by the final examining committee:

Dr. O. Moselhi ______________________ Chair

Dr. G. Gopakumar ______________________ Examiner

Dr. Z. Zhu ______________________ Examiner

Dr. O. Moselhi ______________________ Examiner

Dr. Amin Hammad ______________________ Supervisor

Approved by ______________________

Chair of Department or Graduate Program Director

____________ ______________________

Dean of Faculty

ABSTRACT

IMPROVING SAFETY ON CONSTRUCTION SITES USING BIM-BASED DYNAMIC VIRTUAL FENCES AND ULTRA-WIDEBAND TECHNOLOGY

Shayan Setayeshgar

The identification of potential accidents on construction sites has been a major concern in the construction industry and it needs a proactive safety plan to reduce the risk of accidents. There are no efficient methods for checking if safety measures are taken properly on construction sites. Consequently, workers on site are not given enough awareness about dangerous areas. In addition, construction sites are dynamic and on-site situations are changing in terms of permanent and temporary structures and facilities. This information can be represented using Building Information Modeling (BIM). The present research aims to investigate a new method for the automatic generation of Dynamic Virtual Fences (DVFs) as part of a BIM-based prevention program for construction safety following the Safety Code of Quebec Provence in Canada. First, the Safety Code is reviewed to identify the information that has spatial aspects and can be represented in BIM. Then, a method is proposed for automatic identification of falling and collision risks to generate DVFs for them. In this method, workspaces are generated in BIM based on Work Breakdown Structure (WBS) deliverables, the project schedule, the dimensions of equipment, and the geometry of the building. One set of DVFs for collision prevention is generated based on the defined workspaces. Another set of DVFs is generated where physical barriers are needed for fall prevention. The generated DVFs are used coupled with Real-time Location System (RTLS) tracking of workers and physical fences to check safety requirements and to provide safety warnings.

ACNOWLEDGEMENT

My greatest appreciation goes to my supervisor, Dr. Amin Hammad for his intellectual and personal support, encouragement and patience. His advice and criticism was my most valuable asset during my studies. Overall, I feel very fortunate having the opportunity to know him and work with him.

I would like to acknowledge the contributions of Ms. Cheng Zhang, Mr. Farid Vahdatikhaki amd Mr. Hassaan Siddiqui for performing several lab and field tests, Mr. JunYu Jian for developing the code for importing and visualizing UWB data in Autodesk Revit, Mr. Ahmad Doriani and Mr. David Chadore for preparing the 3D model of the new Turcot interchange. Data collection and execution of case studies could not be done without the information provided by Concordia University Facilities Management Office and the Ministry of Transport of Quebec.

I would like to thank my entire supportive lab mates who made the lab a friendly environment for working together, specially my friends Mr. Ali Motamedi and Mr. Mohammad Soltani who have helped, supported and criticized me in my research.

Last but not least, I would like to thank my parents: Mitra Farmand and Mahmood Setayeshgar, for their endless support throughout my life.

DEDICATION

To my grandmother Parvin Vosooghi, my parents, Mahmood Setayeshgar and Mitra Farmand and my sister Shermin who made all of this possible, for their endless encouragement and support.

TABLE OF CONTENTS

List of Figures ix

List of Tables xi

List of Abbreviations xii

CHAPTER 1 INTRODUCTION 1

1.1 General 1

1.2 Research Objectives 2

1.3 Thesis Organization 2

CHAPTER 2 LITERATURE REVIEW 4

2.1 Introduction 4

2.2 Safety in Construction Industry 5

2.2.1 Research on Construction Safety 9

2.3 Building Information Modeling 11

2.3.1 Definition and Scope 11

2.3.2 Research on BIM for Safety 14

2.4 Tracking of Moving Objects 16

2.4.1 Tracking Construction Equipment 16

2.4.2 UWB Technology 18

2.5 Applications of BIM and UWB in Construction Safety 21

2.6 Summary 24

CHAPTER 3 PROPOSED APPROACH 25

3.1 Introduction 25

3.2 Concept of The Approach 25

3.3 Extracting Information with Spatial Aspects from Safety Code 28

3.4 Generating DVFs in BIM 31

3.4.1 Fall Prevention DVFs 32

3.4.2 Collision Prevention DVFs 35

3.4.3 Workspaces 40

3.5 Real-time Safety Management 43

3.6 Summary and Conclusions 44

CHAPTER 4 Implementation and CASE STUDIES 46

4.1 Introduction 46

4.2 Implementation 47

4.3 Case Study 1: Fall Prevention 49

4.4 Case Study 2: Collision Prevention 50

4.5 Case Study 3: Workspace Generation for Crane Operations 54

4.6 Case Study 4: Collision Prevention Lab Test 61

4.7 Summary And Conclusions 64

CHAPTER 5 CONCLUSIONS AND FUTURE WORK 67

5.1 Summary of Research 67

5.2 Research Conclusions 67

5.3 Limitations and Future Work 68

References 73

Appendix A – CSST Report on Safety 81

Appendix B - The code for automatic detection of falling hazards in Revit 83

Appendix C - List of Related Publications 90

LIST OF FIGURES

Figure 2-1 Number of fatal injuries to workers in construction by kinds of accident, 1996/97 - 2008/09 (Walters et al., 2009) 6

Figure 2-2 Fatal occupational injuries by major event, 2011 (National census of fatal occupational injuries in 2011, 2012).......... 7

Figure 2-3 Fatal falls to lower level by height of fall, 2011 (National census of fatal occupational injuries in 2011, 2012).......... 7

Figure 2-4 Quebec's cause of accident and occupational diseases in the building sector... 8

Figure 2-5 Lifecycle information view (NIBS, 2011) 13

Figure 2-6 Virtual safety barriers (Kiviniemi et al., 2011) 15

Figure 2-7 Signals sent to sensors are used to calculate the 3D position of a tag (Ubisense, 2013) 20

Figure 2-8 UWB settings (Zhang et al., 2012a).......... 21

Figure 2-9 Visualization of close calls (a.k.a. near misses) using simulated data (Cheng and Teizer, 2013). 23

Figure 3-1 Flowchart of the proposed method (Hammad et al., 2012).......... 26

Figure 3-2 Concept of sending warnings to workers on foot.......... 28

Figure 3-3 Edge examination for detection of hazardous areas.......... 33

Figure 3-4 Edges with fall hazard.......... 34

Figure 3-5 Flowchart of the automatic generation of DVFs in hazardous areas 35

Figure 3-6 Concept of micro WBS 37

Figure 3-7 Defining workspaces.......... 39

Figure 3-8 Different levels of workspaces.......... 42

Figure 4-1 Generating Virtual Fences for openings in slab 48

Figure 4-2 Physical guardrails and virtual fences in BIM 49

Figure 4-3 Workspace generated for the task of installing HVAC ducts (Hammad et al. 2012) 51

Figure 4-4 Subtasks and work packages 53

Figure 4-5 Workspace generated for the task of installing a highway span using a launching gantry.. 55

Figure 4-6 3D Models 57

Figure 4-7 Frustum cone workspace... 58

Figure 4-8 Naviswork's animator module.. 60

Figure 4-9 Flowchart of creating 4D animation including equipment movements 60

Figure 4-10 Workspaces generated for the task of removing a highway span 61

Figure 4-11 The setting of case study (Setayeshgar et al., 2013) 63

Figure 4-12 Raw and processed UWB data (Setayeshgar et al., 2013) 63

Figure 5-1 Proposed method for future work (Setayeshgar et al., 2013).......................... 71

Figure 5-2 The concept of the proposed method for future work.................................... 72

Figure A-1 Number of accidents by type of the project ………..……………………...82

Figure A-2 Number of accidents by the sector… ……………………………………….82

LIST OF TABLES

Table 3-1 Spatial information related to prevention program for safety (Hammad et al., 2012) 30

Table 4-1 The schedule of 7th floor of JMSB building 52

Table 4-2 Specifications of equipment 62

LIST OF ABBREVIATIONS

Abbreviation	Description
API	Application Programming Interface
A-GPS	Assisted GPS
AOA	Angle-of-Arrival
BIM	Building Information Model
BrIM	Bridge Information Modeling
CAD	Computer-Aided Design
CHASTE	Construction Hazard Assessment with Spatial and Temporal Exposure
CSA	Critical Space Analysis
CSV	Comma Separated Value
DoF	Degree of Freedom
DVF	Dynamic Virtual Fence
DWS	Daily Works Space
GIS	Geographic Information Systems
GPS	Global Positioning System
GUID	Globally Unique Identifier
IFC	Industry Foundation Classes
IR	Infrared
MEP	Mechanical, Electrical and Plumbing
NBIMS	National Building Information Model Standard
OBI	On-Board Instrumentation
PECASO	Patterns Execution and Critical Analysis of Site-space Organization
QSC	Quebec Safety Code
RAPIDS	Real-time Automated Project Information and Decision Systems
RC	Radio-Controlled
RF	Radio Frequency
RFID	Radio Frequency Identification
RSS	Received Signal Strength

RTLS	Real-time Location System
SS	Signal Strength
SWS	Self Workspace
TDOA	Time Difference of Arrival
TWS	Task Workspace
UWB	Ultra Wideband
VR	Virtual Reality
WBS	Work Breakdown Structure
WLAN	Wireless Local Area Network
WWS	Weekly Work Sspace

CHAPTER 1 INTRODUCTION

1.1 GENERAL

Keeping the construction site safe is a priority for all construction companies. Safe construction sites boost the morale of the workers, which increases productivity and improves work quality. It is important to identify risks on construction sites so as to eliminate them before accidents occur. According to the European Agency for Safety and Health at Work's statistics, the construction sector showed the highest incident rate for accidents with at least 3 days of sickness absence (around 6000 workers per 100,000) in 2005 (European Agency for Safety and Health at Work, 2006). Among incidents on construction sites, falls account for double the number of deaths caused by electrocution or being buried in trenches (ASP Construction, 2003). Therefore, it is a priority to place safety barriers and guard-rails around the hazard areas, excavations and trenches. Other than spaces that should be protected by physical fences, there are many spaces on site that should be identified for the safety of workers, for example, previous research has indicated that machinery-related incidents were the fourth leading cause of traumatic occupational fatalities in the construction industry between 1980 and 1992, resulting in 1,901 deaths (2.13 deaths per 100,000 workers) (NIOSH, 2007). The same research has indicated that the construction equipment most frequently associated with fatalities are cranes (17%), excavators (15%), tractors (15%), loaders (9%), and pavers (7%).

Although special safety rules are defined for the construction industry, there are no efficient methods for checking if safety measures are taken properly on construction sites. This research proposes automatic detection of major hazardous areas on construction sites, creating dynamic workspaces for different tasks, generating Dynamic Virtual Fences (DVFs) where needed, and monitoring the movement of the workers and equipment using Real Time Location System (RTLS) in order to trigger warnings when necessary. By detecting the hazardous areas, DVFs can be generated for them. DVFs can be used for either alerting workers when they are near hazardous areas by generating warnings or checking if safety measures are taken properly. Using the proposed method, collisions between different crews and/or equipment can be avoided.

1.2 RESEARCH OBJECTIVES

The objectives of the present research are the following: (1) to extract risk information with spatial aspects from a safety code and to represent some of this information using Building Information Modeling (BIM); (2) to investigate a method to identify falling risks and equipment workspaces automatically, and to generate DVF around them; and (3) to integrate the RTLS data with the BIM model to protect workers from reaching dangerous areas by generating warnings when they approach the DVFs. The ultimate goal is providing a method for the automatic generation of DVFs and workspaces as part of BIM-based prevention program for construction safety.

1.3 THESIS ORGANIZATION

This study will be presented as follows:

Chapter 2 Literature Review: This chapter reviews the major technologies and standards that are used in the research. The literature review covers different technologies related to the tracking of the moving objects and their applications’ in the construction industry.

BIM is covered briefly in this chapter, including data storage/exchange/sharing models, Industry Foundation Classes (IFC) and National Building Information Model Standard (NBIMS).

This chapter also reviews related safety research in the construction industry. Moreover, applications of BIM and RTLSs in construction safety are discussed.

Chapter 3 Proposed Approach: In this chapter the proposed approach for automatic generation of workspaces and DVFs is elaborated. This chapter includes the conceptual and interaction design of the system as well as the proposed integration method of Ultra-Wideband (UWB) tags and BIM.

Chapter 4 Case Studies: In this chapter, the proposed approach is demonstrated in four case studies. In the first case study, the approach is used to check if physical fences are located as defined in the safety code. In the second case study workspaces and DVFs are automatically generated for the task of installation of HVAC ducts in John Molson School of Business of Concordia University. The third case study is focused on the workspace generation for a bridge demolition task, using synchronized mobile cranes. And finally, the last case study is carried out in the laboratory to detect the collision between two different equipment using radio-controlled (RC) equipment.

Chapter 5 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

The literature review focuses on topics related to the present research in the areas of safety, BIM and tracking of moving objects in construction sites. The aim is to explore the trends in research and in the industry and to investigate the possibility of applying advanced technologies to automatically detect hazardous areas on construction sites in order to allow workers to have a better awareness of site information and to get support from an intelligent system.

Safety codes have been reviewed in order to distinguish different construction hazards. Quebec safety code (QSC) is used as a basis for the proposed method in the current research. Statistical data have been used to find the most hazardous risks in the construction industry. Related literature review stated that falling from height and being struck by a moving vehicle are amongst the most dangerous hazards in the construction industry (Walters et al., 2009). Therefore this research is mainly focused on the aforementioned hazards and more details are explained in Section 2.2.

BIM is another major topic briefly covered in Section 2.3. It is considered as a transformation of the traditional design process and a rich modeling technology, which provides both graphical and non-graphical data (Estman et al., 2011).

Tracking technologies are widely used in construction research mainly to monitor the movement of different equipment and to calculate their productivity (Teizer et al., 2009). This research proposes using the same technology for workers in order to improve safety onsite. However when it comes to safety, it is very important to have accurate and real-time data. Different tracking technologies including Radio Frequency Identification (RFID) and UWB are reviewed and compared in Section 2.4.

Section 2.5 is focused on the applications of BIM and RTLS in construction safety. Several approaches have been proposed to improve safety on construction sites but only a few of them were using real-time data. Therefore the need for a real-time safety system is identified.

2.2 SAFETY IN CONSTRUCTION INDUSTRY

Safety and productivity issues on construction sites are always amongst the major concerns of project managers. The large number of people working close to each other, many unpredictable activities and high impact of unplanned activities make the construction projects prone to high number of serious accidents (Fewings, 2005). Despite all the efforts to keep the construction sites safe, it remains amongst the most hazardous industries. In 2006, 9.5 fatalities reported per 100,000 construction workers in Europe (Eurostat, 2013). Also according to the Bureau of Labor Statistics (2012), the construction industry accounted for the second highest number of fatal work injuries of any industry sectors in 2011 in the United States after the transportation and warehousing. The construction industry experienced 721 total deaths, or 15.6% of all work-related fatalities in the United States (National census of fatal occupational injuries in 2011, 2012).

Falling from height; being struck by a moving vehicle, being struck by a moving/falling object; or becoming trapped by overturning/collapsing objects are considered as the main causes of accidents according the statistical data (Walters et al., 2009). Figure 2-1 shows fatalities by kind of accident in the United Kingdom for the interval of 1996 to 2009.

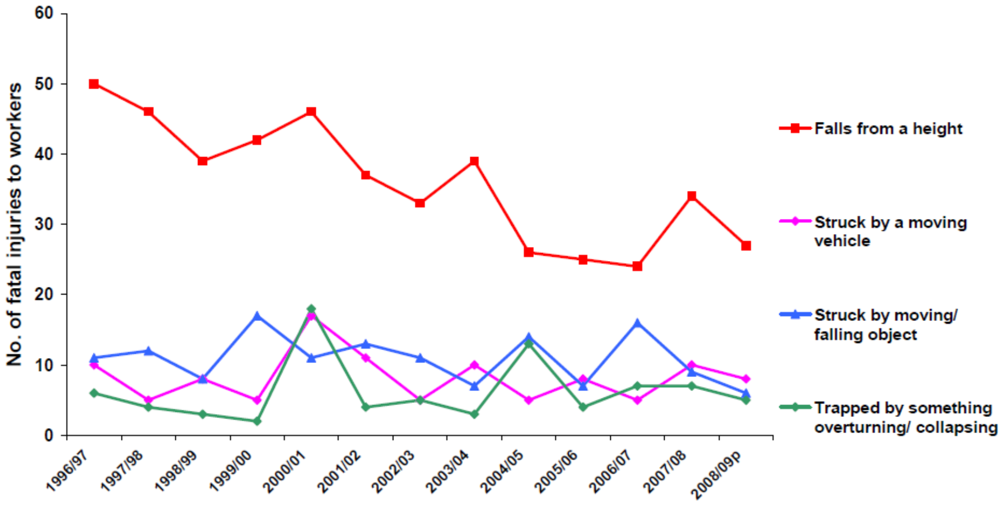


Figure 2-1 Number of fatal injuries to workers in construction by kinds of accident, 1996/97 - 2008/09 (Walters et al., 2009)

Other records show that in 2011, fatal falls, slips or trips resulted in the death of 666 workers in the United States, which is about 14% of all fatal work injuries. 541 of the aforementioned fatalities were because of falling to a lower level. Figure 2-2 shows the fatal occupational injuries by major event in 2011 in the United States (National census of fatal occupational injuries in 2011, 2012).

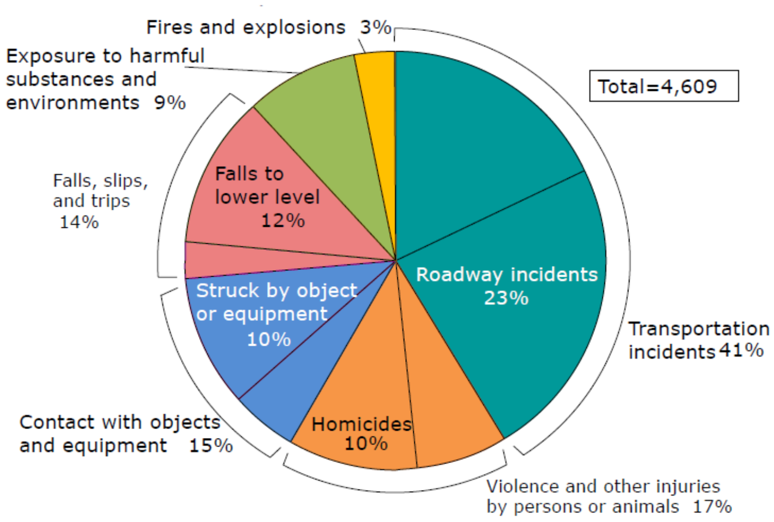


Figure 2-2 Fatal occupational injuries by major event, 2011 (National census of fatal occupational injuries in 2011, 2012)

Figure 2-3 categorizes the fatal falls to lower level by the height of fall. It shows that the number of falls of 10 feet or less is almost the same with the falls of over 30 feet (about 21%).

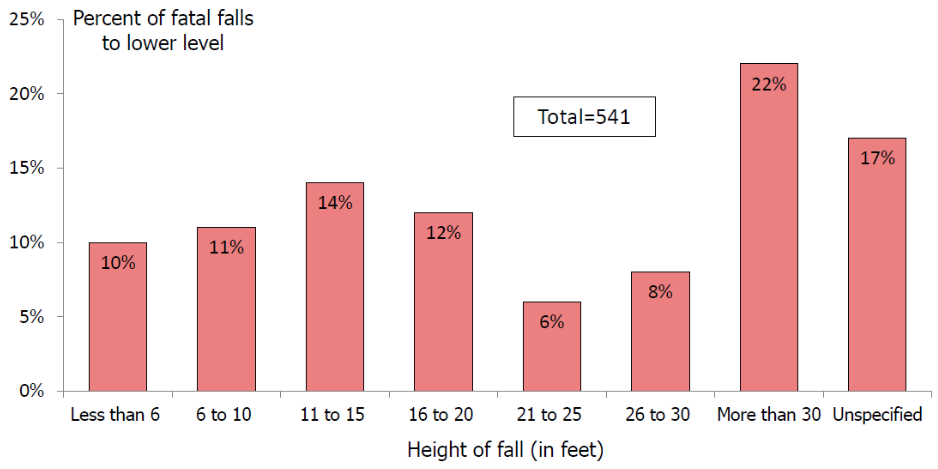


Figure 2-3 Fatal falls to lower level by height of fall, 2011 (National census of fatal occupational injuries in 2011, 2012)

Quebec Statistical information on the causes of accidents and occupational diseases in the building sector are extracted from the Quebec's commission on health and safety (CSST, 2013). As Figure 2-4 shows, from 2001 to 2010, 75% off the accidents and occupational diseases presented in the construction industry had happened in the specialty trade contractors section (CSST, 2013). More information about causes of accidents and occupational diseases in Quebec are presented in Appendix B.

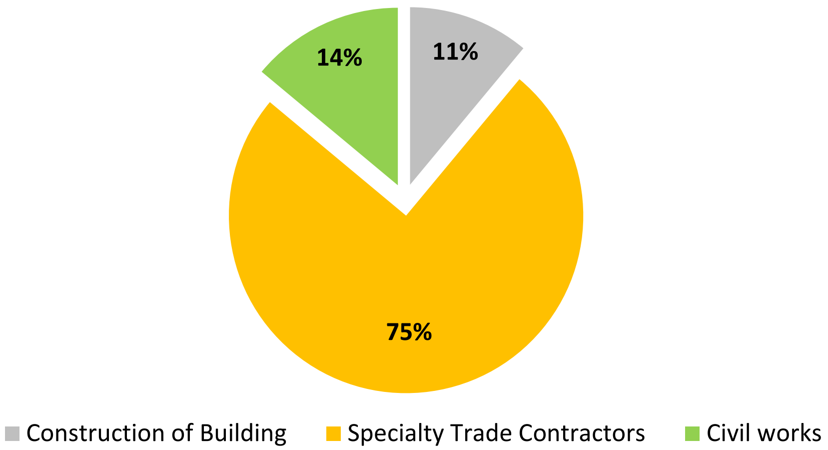


Figure 2-4 Quebec's cause of accident and occupational diseases in the building sector

Out of the construction workers that suffer from fatal injuries, more are involved in falls than any other single cause (Huang et al., 2003). Falls account for double the number of deaths caused by electrocution or being buried in trenches (ASP Construction, 2003). Using guardrails, safety nets, harnesses, etc., is an effective way to prevent the workers from being at risk of falling and it is a priority to place safety barriers and guard-rails around the hazard areas, excavations and trenches. Regulations have been made to specify the location, dimensions and other important issues of fencing on a construction site. For example, holes in the ground should have a secure lid and railing around the perimeter. In QSC of the Construction Industry (2012), sections 2.9.1, 3.15.5 and 5.2.3(a) are assigned to the required fencing for construction sites. As stated in QSC, the installation of guard-rails is necessary around any excavation with a minimum vertical distance of 1.2 meters (3.93 ft.), where a worker uses any vehicle such as wheelbarrow. Furthermore, the edges of any excavation or trench with depth of more than 3 m (9.84 ft.) have to be protected by barriers and barricades with at least 0.9 m (2.95 ft.) high.

2.2.1 RESEARCH ON CONSTRUCTION SAFETY

Other than the spaces that should be protected by physical fences, there are many spaces on site that should be identified for the safety of workers, e.g., the workspaces of construction equipment. Physical fences are not mandatory in these spaces; however, workers should be notified that those areas are dangerous and they should keep a safety distance from those areas.

Workspaces represent the space used for construction activities (Guo, 2002). These spaces are reserved for the crew and their equipment, moving paths, material storage areas, etc. (Akinci et al., 2002). Workspace analysis aims to create different types of workspaces for crew, equipment, and other required spaces in the work site, to detect conflicts between these workspaces, and then to resolve these conflicts. Heesom et al. (2003) have developed a dynamic Virtual Reality (VR) system for visualizing construction space usage focusing on workspaces required within proximity of the components being installed, such as workspaces for crews, equipment, and hazardous and protected areas.

Researchers proposed some approaches for safety evaluation based on simulation and workspaces. Dawood et al. (2006) have introduced a Critical Space Analysis (CSA) methodology and a software tool named PECASO (Patterns Execution and Critical Analysis of Site-space Organization) that was developed to encapsulate the CSA methodology and to assist site managers in the assignment and identification of workspace conflicts. Different scenarios with distinct execution patterns and sequences of tasks can be simulated using this method in order to investigate the effect of changes in patterns and sequences which will result in the minimization of workspace congestions. A 3D model and a schedule were linked to visualize conflicts between different workspaces in each scenario. Tansisevi et al. (2007) have proposed automatic generation of workspaces for mobile cranes to support conflict detection. They generated an equipment workspace based on the collection of small workspaces generated for each piece of the equipment and materials attached to it. Doriani et al. (2013) have integrated the 4D modeling and simulation techniques in the planning and scheduling phases to create a probabilistic 4D model in order to identify any potential conflicts between the construction and demolition operations.

To calculate the probability of potential victims exposed to a set of loss-of-control (hazardous) scenarios, a method has been proposed by Sacks et al. (2009) as part of the synthesis and development of the Construction Hazard Assessment with Spatial and Temporal Exposure (CHASTE) method. A formula has been proposed to calculate the safety risk level that is predicted for a crew exposed to a loss-of-control event caused by another crew using different parameters such as exposure in time and space, number of workers in each crew, the local managerial context, physical environment, etc. Nevertheless the accuracy of this method depends on the accuracy of the risk forecasts.

The foible of the above-mentioned methods is that they do not support real time warnings and they only show the probability of having conflicts if a certain sequence of tasks is executed following a predefined pattern, which is not guaranteed to happen. Simulation can be used to detect possible conflicts and safety issues during the project execution, although the results are not reliable enough to be considered for real-time safety management and for generating warnings. In the execution phase of construction projects, RTLS can be used to track the actual locations of workers and construction equipment in order to give safety warnings.

2.3 BUILDING INFORMATION MODELING

Due to the nature of the construction industry, each construction project has a huge amount of data which are necessary for the successful execution of the project. Data include the 2D or 3D model of the project, structural information, schedule, etc. These data come from different sources and may change as the project goes on.

BIM has been developed to provide effective management, sharing and exchange of building information through its entire lifecycle in order to tackle the problems related to the interoperability and information integration (Isikdag et al., 2008).

2.3.1 DEFINITION AND SCOPE

BIM is a new approach to design, construction, and facilities management in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in a digital format. It provides both graphical and non-graphical data such as drawings, specifications, and schedule. BIM helps to create and use coordinated, consistent, and computable information about a building project (Estman et al., 2011). Virtual 3D models can be built to represent a realistic scene of the construction site. Using BIM is changing the approach to designing and constructing buildings in the construction industry.

Furthermore, unlike traditional Computer Aided Design (CAD) systems, BIM-based CAD systems are object oriented. In earlier CAD systems, building components were represented by geometrical entities such as lines, rectangles, etc. whereas in BIM-based CAD systems, components of drawings are building elements. Additionally, in a building data model, spaces are substantial parts of the building data model which can define the relationships between different building elements such as walls, ceilings, and floors, while defining these relationships was difficult in earlier 2D and 3D CAD systems (Khemlani, 2004).

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

Moreover, time information can be added to 3D BIM models to generate 4D models which contain the schedule. The relationship of space and time can be accurately described in a systematic way in 4D modeling. In addition, the parametric nature of this information helps in design decision making, production of high-quality construction documents, prediction of building performance, cost estimating, and construction planning. Besides, providing a 3D simulation of the building, its components and their relationships, BIM can be used to predict possible collisions and to calculate material quantities (Estman et al., 2011). It can also be used in renovation or demolition work (Becerik-Gerber et al., 2012). The lifecycle management of facilities components using RFID and BIM is studied by Motamedi and Hammad (2009).

Figure 2-5 shows the usability of BIM during the whole lifecycle of a facility from the design phase to the demolition. Using BIM, information will be transferred from one phase to the next one resulting in improved data quality and integrity and avoiding unnecessary reworks of information management (NIBS, 2011).

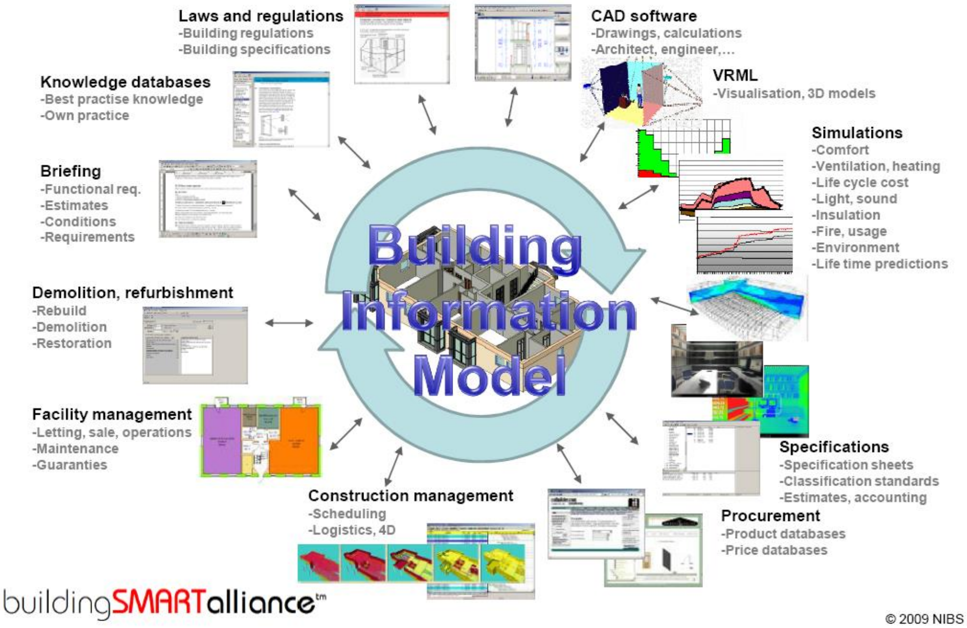


Figure 2-5 Lifecycle information view (NIBS, 2011)

BIM is an intelligent, object-oriented, data-rich and parametric digital representation of facilities. Different information and views can be extracted based on the users’ needs.

Analyzing the extracted data, different aspects of the process of delivering the facility can be improved (The Contractors' Guide to BIM, 2006).

The scope of BIM has been described by NBIMS (2007) within the following relationships:

"(1) As a product or intelligent digital representation of data related to a capital facility,

(2) As a collaborative process which covers business drivers, automated process capabilities, and open information standards use for information sustainability and constancy,

(3) 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." (NBIMS, 2007).

2.3.2 RESEARCH ON BIM FOR SAFETY

Using BIM as a tool, several approaches have been proposed in research. Analysis can be carried out for solving conflicts on site based on the spatio-temporal information provided by BIM (Zhang et al., 2011). Considering the context of the project, different types of models can be used in addition to BIM, such as Bridge Information Modeling (BrIM) which can be used for bridges (Chen et al., 2006). Other research has been aiming to improve efficiency, to reduce cost, and to improve safety on construction sites using BIM. Information of the structure under construction can be captured based on the project progress monitoring, which can be retrieved from BIM. Based on this spatio-temporal information, analysis can be carried out for solving conflicts and improving safety and efficiency on site. For example, BIM was used as a 4D safety planning and management tool by Kiviniemi et al. (2011). Virtual safety barriers are modeled and manually generated for edges and openings with falling hazard. Figure 2-6 shows the virtual safety barriers. This research has indicated that BIM technology presents a new way to solve site safety problems. 4D BIM can be a central technology for planning activities related to construction site safety. By displaying the information in the office to the site staff, general understanding of the risks onsite can be improved (Kiviniemi et al., 2011). However, in addition to the manual generation of the virtual safety barriers in this research, the barriers are static and for visualization purpose only. There is no real-time control for safety by using the aforementioned virtual barriers.

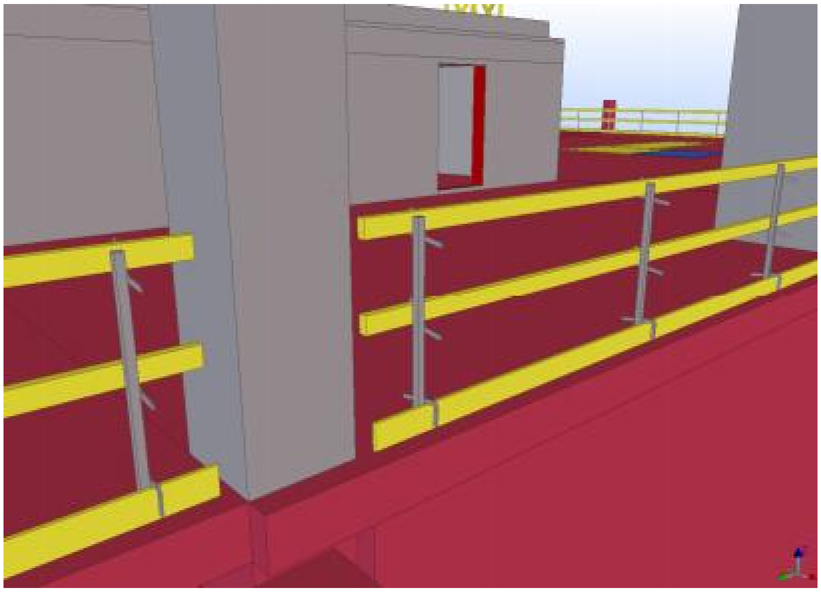


Figure 2-6 Virtual safety barriers (Kiviniemi et al., 2011)

2.4 TRACKING OF MOVING OBJECTS

RTLS have been applied in different areas, such as in logistics and manufacturing. Moreover, construction industry has a great interest in systems which provide the location of project resources such as workforce, equipment and materials (Cheng et al., 2013). RTLSs usually consist of two main parts, tags which are attached to objects and sensors which are usually fixed at known locations. Signals emitted by the tags are detected by the sensors and the system will calculate the location of each tag according to the spotted signal.

In order to mitigate safety risks in construction sites, the location data of all moving objects including equipment and workers should be updated continuously. Subsection 2.4.1 reviews research related to tracking of moving objects. Subsections 2.4.2 introduce UWB technology and its applications in construction.

2.4.1 TRACKING CONSTRUCTION EQUIPMENT

During the past years, the need for indoor localization has been rapidly expanding in many fields (Lachapelle, 2004), including the construction industry. Improvements in real-time localization engendered significant potentials especially for the construction industry (Anumba et al., 2006). Researchers were investigating the benefits of using localization technologies for different sections of the industry. For example, variety of research and commercial studies have been focused on measuring the performance of automated progress monitoring, including the monitoring of workforce (Teizer et al., 2009). Technologies used for tracking objects in the aforementioned researches range from RFID based tracking (Ergen et al., 2007 and Song et al., 2006), Global positioning systems (GPS), barcodes, laser scanning (Cheok et al., 2000 and Navon et al., 2003), or hybrid systems of two or more technologies (Teizer et al., 2009). 3D laser scanners, 3D range cameras, total stations, GPS, RFID, and other types of sensors and technologies are being evaluated for automated collection and processing of data for applications in construction projects by the Real-time Automated Project Information and Decision Systems (RAPIDS) lab at Georgia Institute of Technology (Teizer et al., 2005; Teizer et al., 2006; Teizer and Castro-Lacouture, 2007). However, most of this research is still at the initial testing stage.

Amongst different tracking technologies, GPS is widely used in earthmoving, mining, surveying and infrastructure projects. For example, Shehata et al. (2013) conducted a research to evaluate the effects of adopting advanced machine guidance technology and GPS on performance, time, unit cost and productivity of road projects. The results showed 30% improvement in utilizing the equipment, using automated machine guidance and GPS. GPS is used by Alshibani and Moselhi (2007) to forecast the performance of earthmoving equipment (Alshibani and Moselhi, 2007). Navon et al. (2003) proposed a real-time tracking and control system using GPS and on-board instrumentation (OBI) to monitor the activity of major construction equipment, such as tower cranes, concrete pumps, etc. GPS is also used for safety purposes. For example, vehicles and workers have been tracked using GPS and sensors in order to reduce accident rates on construction sites (Riaz et al., 2006).

Due to the limitations and high price of the accurate GPS receivers, other tracking technologies such as infrared (IR), optical, ultrasound, UWB and RFID have been applied in several research projects. For instance, RFID is used by Razavi et al. (2011) to increase the productivity by improving the material tracking process in construction sites.

The accuracy and coverage offered by different location technologies such as passive RFID, electromagnetic, laser, ultrasound, IR proximity, conventional Radio Frequency (RF) timing, UWB, Wireless Local Area Network (WLAN), Received Signal Strength (RSS), and assisted GPS (A-GPS) are compered by Ward et al. (2009) in order to identify the ideal technology.

2.4.2 UWB TECHNOLOGY

UWB is a wireless technology which is capable of transmitting large amounts of digital data over a wide spectrum of frequency bands at very low power (less than 0.5 milliwatts). The system was first developed as a military tool to see through trees and beneath ground surfaces but recently, it has been focused on consumer electronics and communications. According to Ghavami et al. (2004), the ideal targets for UWB systems are: "*low power, low cost, high data rates, precise positioning capability and extremely low interference*" (Ghavami et al., 2004).

One of the key characteristics of the UWB system is its signals. Compared to conventional signals, in the same data rate, UWB signals have greater potential to penetrate obstacles that tend to reflect signals such as walls and doors (Miller, 2003). However, due to the limitations set by the Federal Communication Commission of the USA on the coverage zone for pulse UWB systems, the UWB coverage area cannot exceed 100 meters (Bunin and Valikov, 2006). In good condition, where metallic objects are not in the vicinity of the UWB system and direct line-of-sight from tags to sensors is available, the accuracy of the UWB system can be up to 15 cm (Muthukrishnan and Hazas, 2009).

In order to locate a node in a wireless system, location information of radio signals traveling between the target node and a number of reference nodes should be collected. Depending on the applicable positioning technique, one of the following methods can be selected to determine the location of a node: (1) Angle of Arrival (AOA): this method measures the angles between a given node and a number of reference nods; (2) Signal Strength (SS): this method measures the energy of the received signal; and (3) Time Difference of Arrival (TDOA): which measures the travel time of the received signal (Gezici et al., 2005).

A UWB RTLS consists of sensors and tags which work as a single operation unit. In order to locate tags, cells should be defined. Each cell consists of two or more sensors (depending on the selected positioning technique) and it is assigned some tags. Each cell has a schedule which determines when should an assigned tag emit UWB signals to be located by the cell. There is no limit on the number of cells which can be defined and several cells can be defined for the same project. Sensors are synchronized and connected to the timing source through timing cables. When a tag emits a signal, the UWB Channel will be used to transmit the radio signal to one or more sensors in the cell (Zhang, 2010).

As shown in the Figure 2-7, the slave sensor(s) receive and decode the UWB signal and send the angle of arrival as well as the timing information back to the master sensor through an Ethernet connection. The master sensor accumulates all sensed data and computes the location based on trilateration. The angle of arrival of the signal sent by the tag is measured at several stationary receivers when using the AOA method. Each measurement forms a radial line from the receiver to the tag (Zhang, 2010).

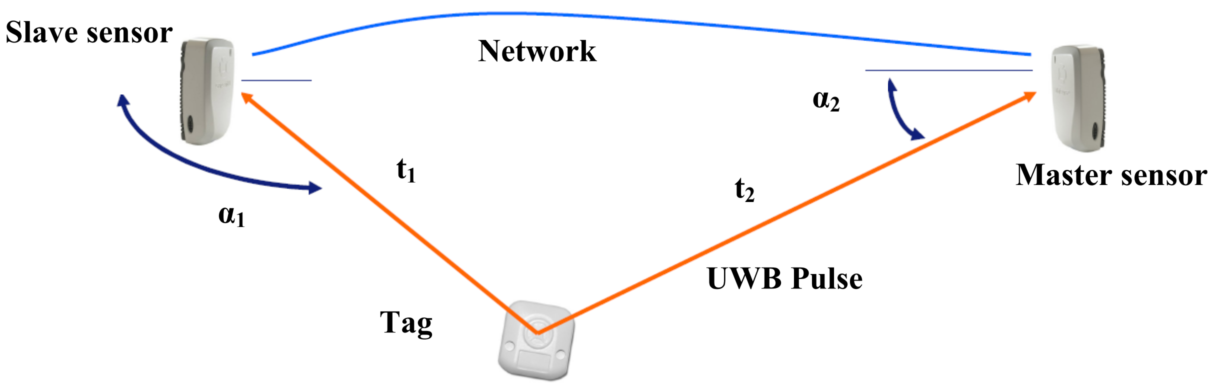
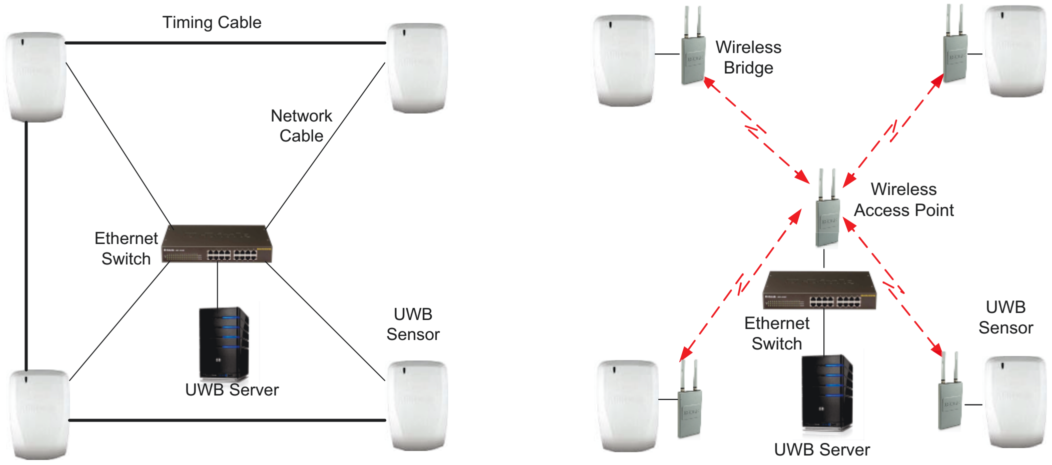


Figure 2-7 Signals sent to sensors are used to calculate the 3D position of a tag (Ubisense, 2013)

In 2D positioning, tags are defined at the intersection of two directional lines of bearing. This method neither requires synchronization of the receivers nor an accurate timing reference; instead, receivers require regular calibration in order to compensate for temperature variations and mismatches (Ghavami et al., 2004). While in 3D, at least four receivers are required due to the need for synchronization of the receivers' clocks (Ghavami et al., 2004). Usability of the UWB technology can be evaluated using the commercial products such as Ubisense (2013) and Zebra (2013).

In order for an UWB RTLS system to work, two types of wired connectivity are required between its components: (1) the connectivity between sensors via timing cables to exchange timing information, and (2) Ethernet connectivity to the central switch for network connectivity between sensors and the server. To achieve the highest accuracy, both types of cabling are required and two localization methods should be used (Figure 2-8 (a)) (Zhang et al., 2012).

Providing cables between sensors in a construction site is troublesome and in some cases is not feasible. To solve this issue, the AOA technique can be used. In AOA setting, only network connectivity is required to provide communication between sensors and the server. Using this technique, timing cables can be removed and the network cables that connect the sensors to the central switch can be replaced with wireless bridges and an access point. The wireless hardware replaces cables and makes the system completely wire-free (Figure 2-8 (b)). The distance between UWB sensors in a regular cell is considerably shorter than the effective range of standard wireless bridges. Hence, the wireless connectivity is assumed to be reliable (Zhang et al., 2012a).



(a) Wired setting (AOA and TDOA)

(b) wireless setting (AOA only)

Figure 2-8 UWB settings (Zhang et al., 2012a)

2.5 APPLICATIONS OF BIM AND UWB IN CONSTRUCTION SAFETY

Construction sites are dynamic and on-site situations are changing in terms of permanent and temporary structures. Therefore, information of the construction site should be updated based on the project progress monitoring, and the prevention measures for safety should be used to give more awareness to workers. Much research has been done to develop new tools for hazard prevention and safe project delivery using digital technologies such as online databases, VR, Geographic Information Systems (GIS), and BIM, sensing/warning technologies, etc. (Zhou et al., 2012).

Research also has been done aiming to improve workers' safety in real time. Giretti et al. (2009) have proposed a safety management system that gives an alarm when a worker is approaching a static, known dangerous area using RTLS. Fullerton et al. (2009) have proposed a proactive safety system, which works in real time to alert personnel of the dangers arising, and for reactive safety, which collects data to be analyzed in order to determine the best practices and to suggest process improvements. Carbonari et al. (2009) have proposed a safety management system for tracking workers' trajectories to prevent accidents. Hammad et al. (2011) have proposed an approach to visualize data from different sources including a BIM model, video monitoring, and an UWB RTLS. The benefits of the data fusion from different sources can be expected to improve quality, productivity and safety of the project. Cheng and Teizer (2013) stated that the information related to safety and field operation activities can be automatically monitored and visualized in real-time. They collected live field data from dynamic construction resources, filtered the data to reduce errors, processed it and finally streamed valuable safety information to a real-time virtual model of the construction site. One of the benefits of the real-time visualization is that it can be used by workers, equipment operators, or decision makers anywhere on a construction project or from a remote location to increase situational awareness. Figure 2-9 shows the visualization of close calls using simulated data.

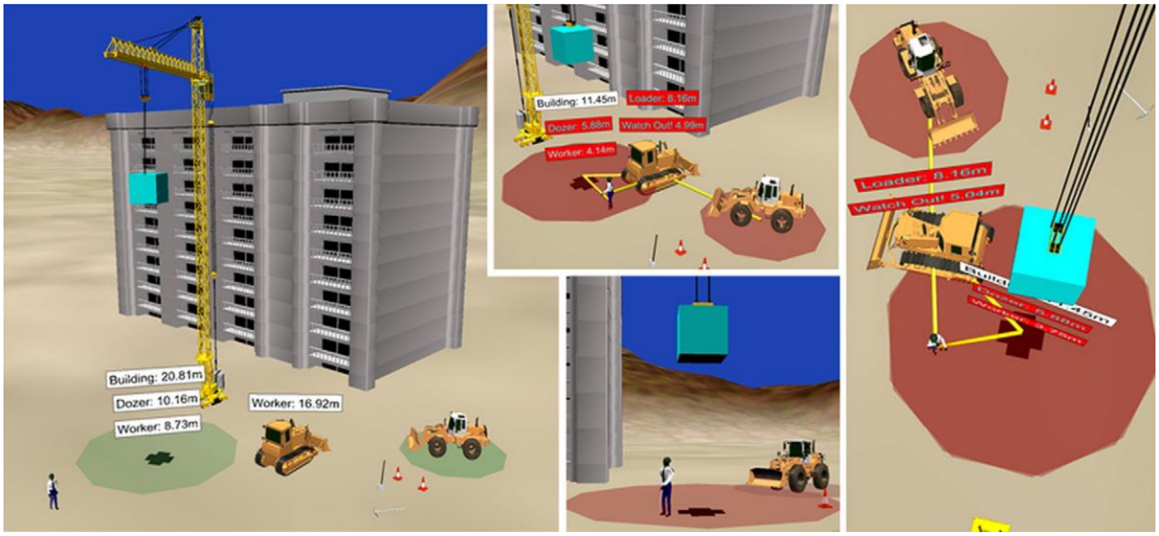


Figure 2-9 Visualization of close calls (a.k.a. near misses) using simulated data (Cheng and Teizer, 2013).

Zhou et al. (2013) proposed a safety management system using visualization techniques. Before the construction begins the schedule and design information of construction components are used to automatically detect potential unsafe activities and conditions and also to provide instructions for correction. During the construction process, the actual site monitoring data are continuously compared to the 4D model to visualize the safety status of the related components. In addition, commercial products are available for improving on-site safety, such as Personnel Shield (Safety shield systems, 2012), which protects the workforce by restricting machine/vehicle activity when in proximity of personnel. However, the combination of prevention system for safety using BIM and real-time safety management has not been discussed in previous research.

Improving crane safety taking advantages of UWB system has been proposed by (Fontana, 2007). Teizer et al. (2007) have studied the usability of a UWB tag attached to a crane hook to track the position of the hook. Giretti et al. (2009) have indicated that UWB behavior is rather constant during most parts of the construction progress. They have noted that, in an open area, tests confirm an accuracy of about 30 cm. They have also discussed a safety management system that gives an alarm when a worker is approaching a static, known dangerous area. In the research of Zhang and Hammad (2012) and Zhang et al. (2012b), tags are attached to cranes and the geometry of the crane boom is calculated in near real time. Collision detection is applied for the movement of two cranes working near each other, and real-time re-planning is applied to avoid collisions. However, the accuracy of the RTLS system and the moving velocity of equipment require safety buffers around each piece of equipment when applying collision detection. Therefore, it is simpler and more efficient to identify workspaces for each piece of equipment carrying out each construction task and to keep the workers away from these workspaces using virtual fences to assure their safety on site.

2.6 SUMMARY

In this chapter, several technologies, standards and applications related to tracking of moving objects, safety and BIM were reviewed. The literature showed that different tracking technologies have been widely used for construction equipment. They have been mainly used to calculate productivity and avoid collisions between different equipment. However, movement tracking has not been used for workers and indoor construction scenarios due to the limitation of the available technologies. BIM and RTLS can work together as complimentary technologies. This idea is central to the proposed approach and is introduced in this research as a new opportunity for real-time safety management where RTLS data are integrated with BIM and provide information which can be used for real-time safety management during the construction process.

CHAPTER 3 PROPOSED APPROACH

3.1 INTRODUCTION

The present chapter introduces the methodology used in this research. Section 3.2 explains the concept of the proposed methodology. Section 3.3 introduces the information with spatial aspects which are extracted from the safety code of Québec. In Section 3.4 different types of DVFs and the requirements for applying them are introduced and followed by a brief explanation of different types of workspaces. The potential benefits of a real-time safety management system are discussed in Section 3.5.

3.2 CONCEPT OF THE APPROACH

As shown in Figure 3-1, the safety code is used to extract information which has spatial aspect; this information is used along with the BIM model, schedule, Work Breakdown Structure (WBS) deliverables and the dimensions of the equipment, in order to identify falling risks and workspaces on the construction site. The processes used to identify falling risks and workspaces are discussed in Section 3.4. In the next step, DVFs are generated in the BIM model for the identified hazards and workspaces. Real-time locations of the workers, equipment and physical fences are visualized in the model and used to detect potential hazardous scenarios as well as to trigger warnings. It should be noted that the BIM model is based on as-planned information and it is assumed that the as-built model is the same. The BIM model can be updated using as-built information, which is beyond the scope of the present research.

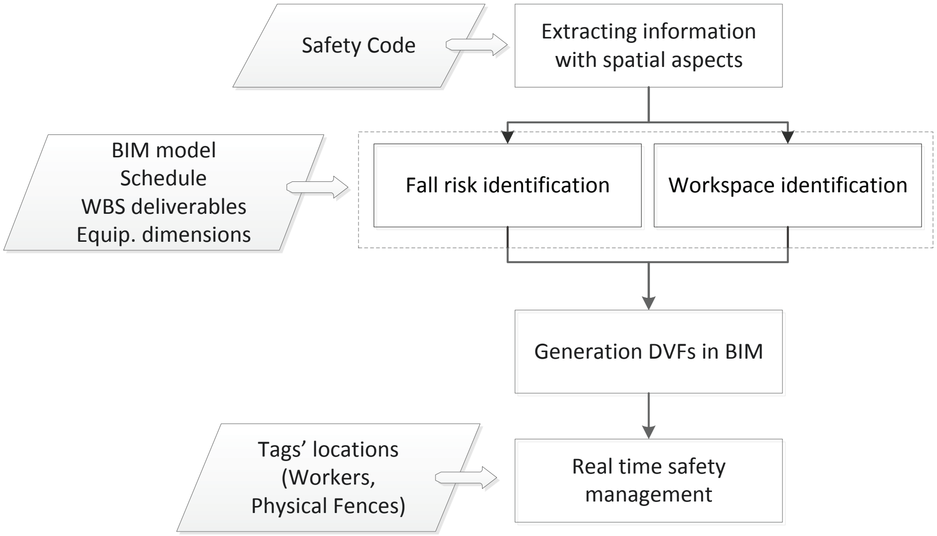


Figure 3-1 Flowchart of the proposed method (Hammad et al., 2012)

Focusing on falling and collision hazards, the regulations of physical fences are categorized into groups to define the required dimensions to protect specific areas on the construction site (more details are given in Section 3.3). According to QSC (ASP Construction, 2003), there are two types of physical fences that should be installed in construction sites; guard-rails for preventing from falling and barricades for limiting access into dangerous places. Another concern is protecting workers from collisions with moving equipment. In order to cover guard-rails and barricades, two types of DVFs are elaborated. The first type is generated where it is necessary to install physical fences according to the safety code and the second type is generated for workspaces to limit the access of workers to dangerous areas.

For the first type of DVFs, the linkage between the physical fences and their virtual representations is built using their locations to check if the physical fences are installed at the proper locations with the proper dimensions. Tags are attached to the physical fences and the locations of these tags are compared with the location of the corresponding virtual fences that were created according to the regulations. The safety manager and/or the superintendent are able to see a graphical representation of the construction environment, including the locations of the virtual fences, using a smart device (e.g. an iPad).

For the second type of DVFs, a method is proposed to automatically identify risks and workspaces, using a 4D BIM model, the project schedule and the WBS deliverables. The WBS is used to create the hierarchy of the tasks and subtasks of the construction project. Each WBS deliverable is associated with a reference object, which can be a building component including Mechanical, Electrical and Plumbing (MEP) components, or temporary structures. Resources such as construction equipment for specific tasks/subtasks are also identified within the WBS. The virtual fences are generated at the four sides of the defined workspaces. The height of the virtual fences will match the maximum reaching height of the equipment to cover its workspace.

In addition, tags are attached to workers on foot. Locations of workers are updated in real-time. Buffers are created for the workers using a virtual cylinder around each worker in the environment model. Once a buffer intersects with a virtual fence, an alarm is sent to the worker involved and the nearby workers (if any) through a portable device (e.g., a smart phone). Figure 3-2 shows the concept of sending warnings to workers on foot. Sensors are installed on site to detect the location of the tags. DVFs are created based on the workspace defined for the scissor lift working on the installation of ducts, and an opening in the slab. When a worker approaches the virtual fence, he/she will receive a warning alert. When the task of the scissor lift is finished or the opening is covered, the DVFs associated with these tasks are removed from the model.

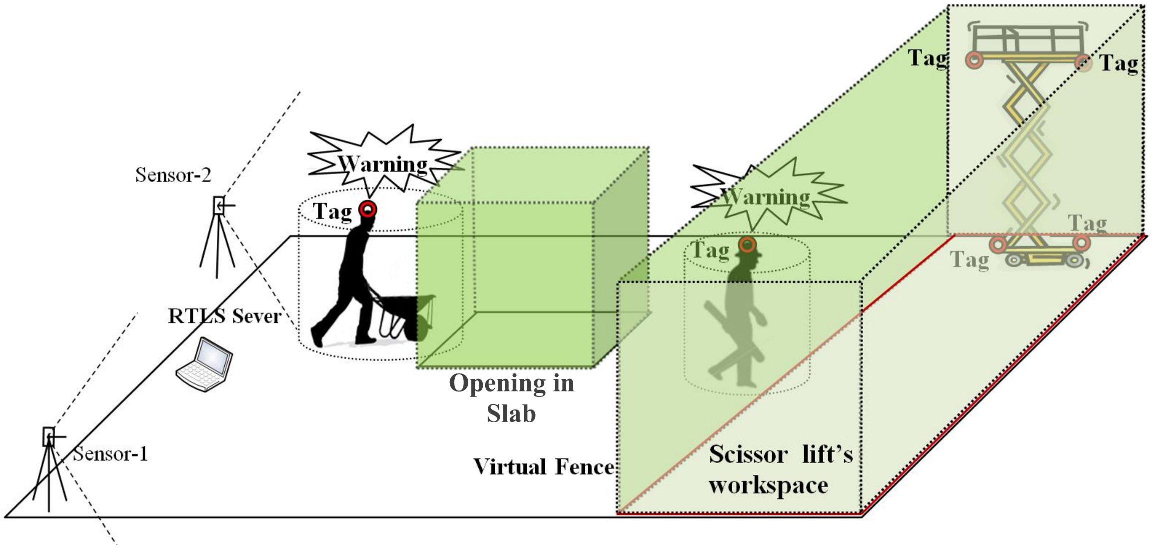


Figure 3-2 Concept of sending warnings to workers on foot

3.3 EXTRACTING INFORMATION WITH SPATIAL ASPECTS FROM SAFETY CODE

In the present research, the QSC for the Construction Industry (ASP construction, 2003) is reviewed and information that has spatial aspects is extracted either indicating problems or providing solutions, as shown in Table 3-1 (Hammad et al., 2012).

***SCAFFOLDING*:** BIM can be used to virtually show the places where scaffolding is needed, to identify the edge of the scaffolding and to check if the guardrails are installed (Table 3-1 (e) and (f)).

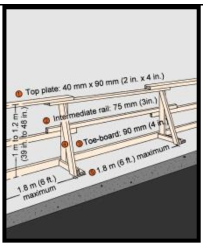
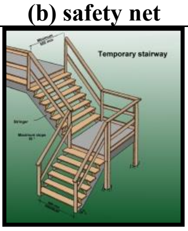
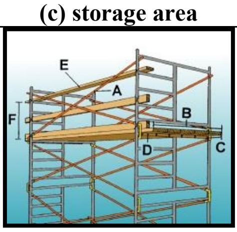
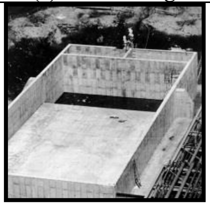
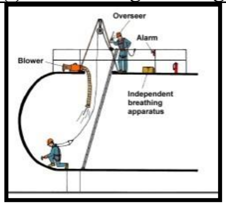
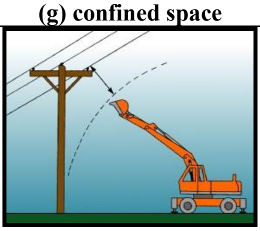
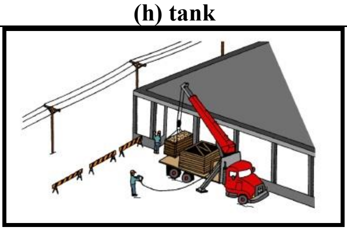
***PROTECTION AGAINST FALLING*:** Locations and dimensions of the physical safety barriers that should be installed to prevent falling can be modeled and visualized in the BIM model, for example, a guardrail installed around an opening on the floor and a safety net (Table 3-1 (a) and (b)).

HOUSEKEEPING AND MEANS OF ACCESS: The areas for stacking materials or disposal of waste materials should be fenced or identified to prevent injuries caused by falling objects or materials (Table 3-1 (c)). Places can be identified where the rods for concrete formwork and other protruding parts may have not been cut. Furthermore, BIM can be used to plan the means of access for both permanent and temporary usage, in case of accident. These means of access will make it possible to evacuate workers quickly and will make it easier for first aid to reach (Table 3-1 (d)).

***CONFINED SPACES*:** A confined space is not designed or meant to be occupied by persons, but may on occasion be occupied for doing certain work; can be accessed only by means of a narrow opening; can present health or safety risks for whoever enters because of its design, construction or position, its air quality or inadequate natural or mechanical ventilation, or the materials or substances it contains (Table 3-1 (g) and (h)). BIM can be used to identify those confined spaces to give workers adequate information as to the risks connected with their work in a confined space and to provide them with the appropriate training, assistance or supervision to allow them to safely perform the work assigned to them.

***ELECTRICITY*:** Locations of power lines and safety work zones can be identified in BIM (Table 3-1 (i) and (j)). For example, the minimum approach distance for a power line of 25,000 volts is 3 meters.

Table 3-1 Spatial information related to prevention program for safety (Hammad et al., 2012)

Protection against Falling	 (a) guardrail	 (b) safety net
House Keeping and Means of Access	 (c) storage area	 (d) temporary access
Scaffolding	 (e) scaffolding	 (f) scaffolding shoring
Confined Space	 (g) confined space	 (h) tank
Electricity	 (i) overhead power lines	 (j) near power lines
Heavy Machinery and Self-Propelled Vehicles	 (k) reserved workspace	 (l) close to heavy machinery
Trenches and Excavations	 (m) barriers	 (n) fence or wall

HEAVY MACHINERY AND SELF-PROPELLED VEHICLES: Workspaces for the equipment can be identified and virtual fences can be generated to protect workers (Table 3-1 (k) and (l)).

TRENCHES AND EXCAVATIONS: Barriers or barricades at least 0.9 m high shall be set up around the edge of any trench or excavation whose depth is more than 3 m (Table 3-1 (m)). Any sidewalk and any other public way used by pedestrians and skirting a construction site shall be separated by a fence or a wall of at least 1.8 m if the sidewalk or public way is less than 2 m away and there is any danger to pedestrians (Table 3-1 (n)).

3.4 GENERATING DVFS IN BIM

As mentioned earlier, after the information with spatial aspects is extracted from the safety code, two types of safety risks are identified where virtual fences can be generated automatically in the 4D BIM model. The first type is generated where physical guardrails should be installed (e.g., Table 3-1 (a), (c) and (m)). UWB tags are attached to physical fences monitored in real time. Mapping the physical fences with their corresponding virtual fences is applied to check if they are installed at the proper locations with the proper dimensions. If any physical fence is missing, the corresponding virtual fence in the model is highlighted and a reminder is sent to the manager to install that fence. The second type is generated for the workspaces that are reserved and from which workers should keep a safe distance (e.g., Table 3-1 (k) and (l)). A method is proposed for automatic workspace identification using a 4D BIM model, WBS deliverables, and associated equipment. UWB tags are attached to workers, and the locations of the workers are monitored in real time to send them alerts when they approach dangerous areas. In addition, the operator of the construction equipment also gets a signal indicating that there is a worker nearby and the operator should slow down the machine or stop the operation.

Based on the locations where physical barriers should be installed and the workspaces of each equipment, two types of DVFs are generated to protect the workers from safety risks as explained in the following sub-sections. DVFs are defined as temporary objects in the BIM model. The duration of these DVFs is equal to the corresponding tasks' durations. Those DVFs are removed after the task is completed.

3.4.1 FALL PREVENTION DVFS

Falling is the major risk on site as mentioned in Chapter 1; therefore, fall prevention is taken as one of the main purposes for automatic risk identification. Falling happens at unprotected external boundary edges of the slabs (where usually there are external walls) or unprotected openings within the slabs (such as elevators shaft, stairs, etc.). There are three major locations where physical guardrails are mandatory: floor edges and elevators and stairs' openings.

To establish a prevention program, the first task is to identify potential hazards of construction projects to prepare for safety measures. The proposed method uses a 4D BIM model in order to automatically detect areas with potential risk of falling and the duration of the risk. BIM is used as a visual reference and a database for construction components such as slabs, walls, etc. By determining different construction components and their locations, slabs and related heights from a reference plane can be determined, as well as the edges of the slabs. Slabs' edges are used to find spots with potential risk of falling. Falling happens at an edge where there is a difference between levels of planes located on the two sides of the edge and this is used as the main concept of the automatic detection of areas with potential hazard of falling. Figure 3-3 shows the relationships at the edges between different adjacent slabs. Figure 3-4 shows the height relationships at the edges with fall hazards.

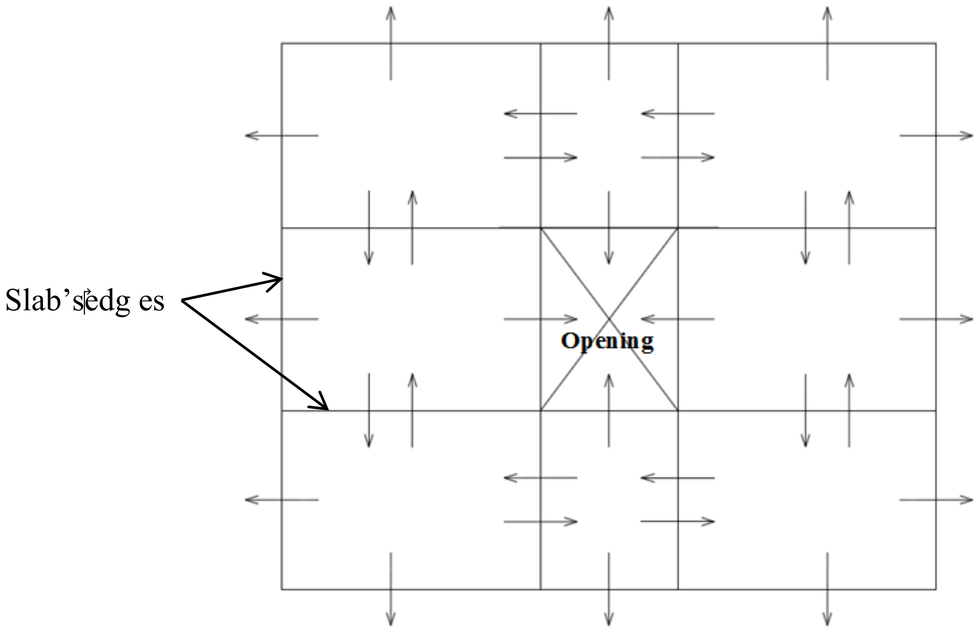
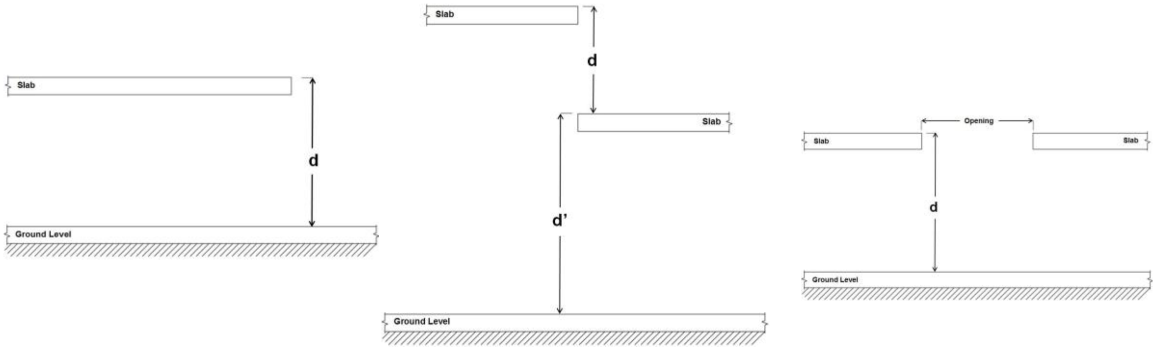


Figure 3-3 Edge examination for detection of hazardous areas

Figure 3-5 shows the flowchart for the automatic detection of areas with fall hazards and the generation of DVFs for these areas. A 4D model is used as a reference to determine slabs and their edges. Upon the detection of an edge *E* of a slab *S*, the system checks if there is a barrier at this edge or another slab *S’* at the same or lower levels (Figure 3-3). If another slab is detected, the vertical distance *d* between the two slabs (*S* and *S’*) is calculated. The edge is considered as hazardous if: (1) *d* is more than the specified value in the safety code (e.g. 3 m according to QSC), (Figure 3-4 (b)), or (2) no slab is detected on the other side of *E* (Figures 3-4 (a) and (c)).



(a) No slab on the other side (b) Different levels of slabs (c) Slab with an opening

Figure 3-4 Edges with fall hazard

After defining hazardous edges, DVFs are generated along these edges to prevent workers from falling. The heights of the DVFs are determined by the height required for the guardrails, which should be 1 to 1.2 m above the surface on which the worker is working according to QSC, s. 3.8.3.-1 (ASP Construction, 2003). Given that fences are temporary structures, they should be removed when the hazard of falling no longer exists. Therefore, a task for fencing is added to the project schedule so that it can be visualized in the 4D model as a temporary structure. Information about walls and other physical barriers at a specific edge is required in order to determine the appropriate time for removing the fences. The lifespan of fall hazard of an edge is from the finishing date of the slab to the finishing date of the hazard-eliminating barrier (wall, stair or installation of elevator(s)).

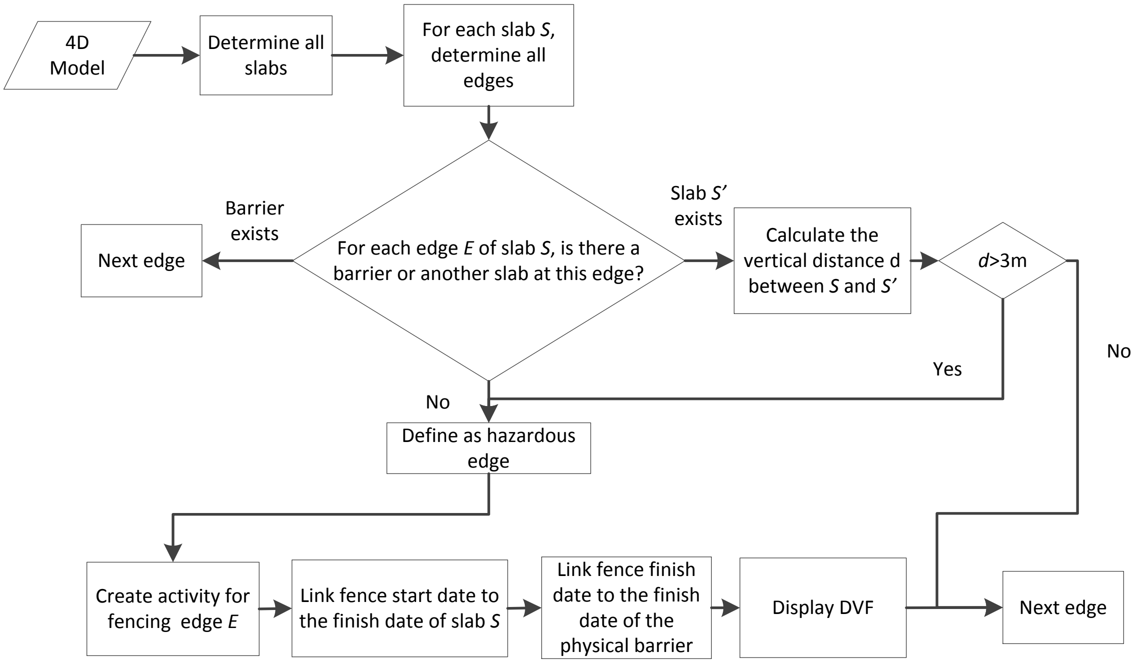


Figure 3-5 Flowchart of the automatic generation of DVFs in hazardous areas

3.4.2 COLLISION PREVENTION DVFS

The 3D model, the schedule and the WBS are used to automatically generate workspaces. Workspaces are defined as bounding boxes and represent spaces reserved to perform a specific task or a group of tasks. Information about the components (i.e. location, size and elevation) are retrieved from the 3D model. For example, the length, height from the floor, and the location of a duct are retrieved from the 3D BIM model.

The schedule provides information such as start date, finish date and the precedence of the tasks. The schedule data can be linked with a 3D model in order to generate a 4D model. There are different ways to link the schedule with the 3D model, for example Autodesk Navisworks reads the schedule data from a Microsoft Project or Primavera file and links the field name of each schedule task in the scheduling software with its respective field of the object in Navisworks. A BIM model consists of many components; each has its own attributes. The present research defines attributes representing the schedule data for the components in the 3D model for which safety workspaces have to be created by breaking down the schedule to a micro level.

The WBS divides a complex project into simpler and manageable tasks. The project type and the management style determine the level of breakdown. However, there are a few rules for determining the smallest task. For example, the rule "8-80" implies that the smallest task should not be smaller than 8 hours of work and also no tasks should be larger than 80 hours of work (Alez, 2012). WBSs can be provided as a list or a diagram. According to Taylor (2009) each completed WBS task should contain the following four items: (1) The scope of the work, including any "deliverables"; (2) The start and finish dates for the scope of the work; (3) The budget for the scope of the work; and (4) The resources allocated to the scope of the work. On the other hand, the nature of the construction sites also limits the level of the break down. Breaking down the schedule to the level of components requires defining very small tasks in the schedule which is time consuming. For example, as shown in Figure 3-6, the task of installing HVAC ducts involves other subtasks such as measuring, marking, attaching studs, assembling ducts on the ground, lifting the assembled ducts and attaching ducts to the studs. Also the scheduled order of the components in a work package to be performed may change on site due to factors such as the availability of the workers and/or the materials, limitations of the site layout, etc. Therefore the start date, finish date and the duration of a work package are assigned to all its related activities. For example, referring to Figure 3-6, the start date, finish date and the duration of the work package 1.1.1, will be assigned to all of its sub activities which are measuring, marking, attaching studs, assembling ducts, lifting ducts and attaching ducts.

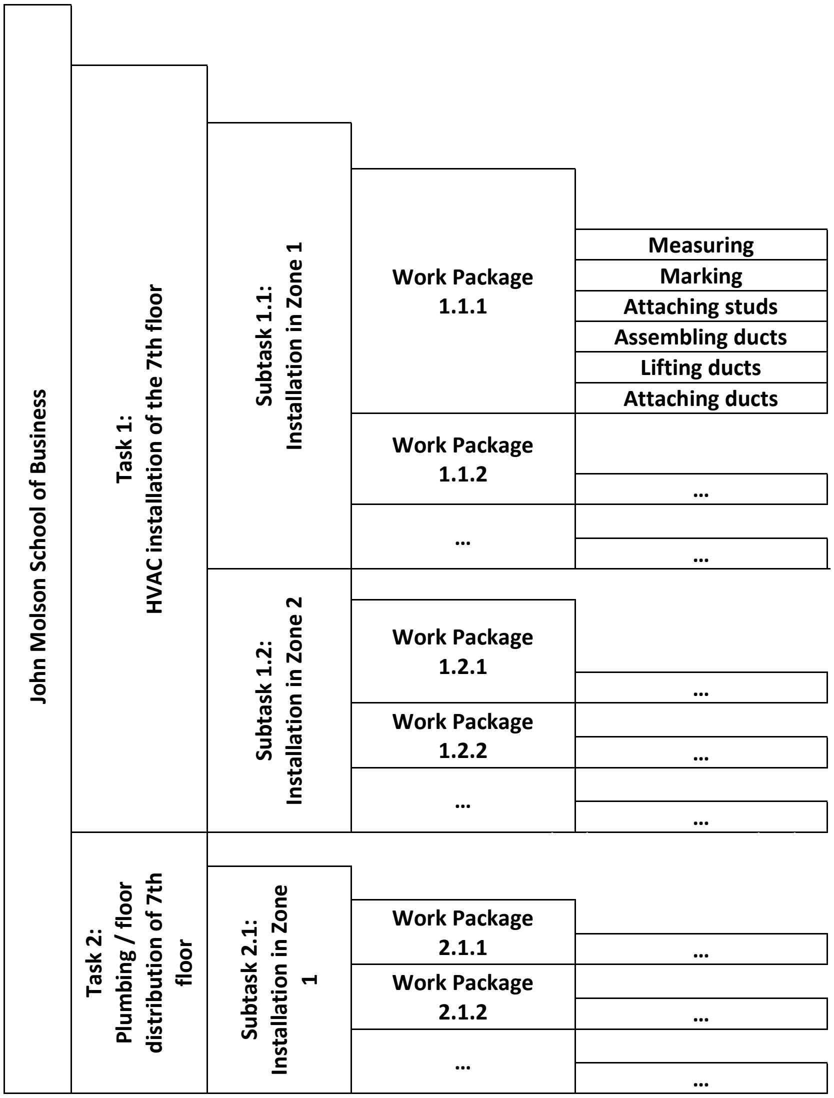


Figure 3-6 Concept of micro WBS

Having the WBS along with the schedule, the start date, finish date and the duration for the subtasks, work packages and components can be extracted and linked with the respective object/component in the model.

As shown in Figure 3-7, Tasks are broken down into subtasks; the duration of subtasks are assigned considering the start date, finish date and the duration of the main task.

Subtasks are broken down into work packages and their start dates and finish dates will be assigned in the same way. The process of breaking down the schedule continues until the required level of detail is reached. In the next step, a list of all components is extracted from the BIM model containing a Globally Unique Identifier (GUID) generated for each component. The GUID is used to link the schedule data with the components of the BIM model. After the schedule data is linked with the BIM model, components which are planned to be finished within a specific period are selected. The dimensions of the selected components are automatically extracted from the model. However, In order to create a proper workspace for each task, not only the dimensions of the components, but also the dimensions of the necessary equipment should be considered. The height of the workspace is equal to the maximum reaching height of the equipment, which is equal to the height of the room in the case of an indoor construction task. A buffer is also added to workspaces for safety purposes. Having the dimensions of components, equipment and the safety buffer, workspaces are generated and the start date and finish date of the corresponding tasks are assigned to them. DVFs are generated for the four sides of the defined workspaces, lasting for the duration of the corresponding tasks.

The workspaces proposed in this research are the spaces required within the proximity of the components being installed, defined as micro-level spaces, and the spaces required to be left clear for the movement of people, materials, and debris, defined as paths according to Akinci et al. (2002).

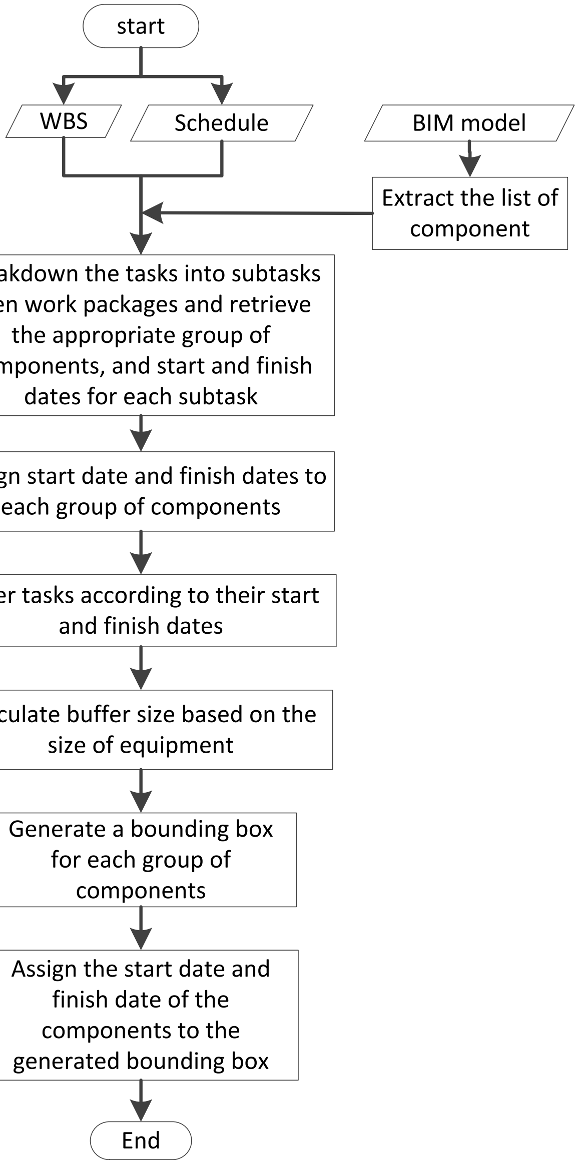


Figure 3-7 Defining workspaces

As mentioned earlier, for each construction task, a reference object is identified first. For example, for installing HVAC ducts in a room, the sections of ducts are identified as reference objects. The length, height from the floor, and the location of a section is retrieved from the BIM. The installation is further divided into subtasks, such as fixing the studs to the ceiling for hanging the ducts. In this case, a scissor lift may be used to help the worker reach the ceiling. Thus, the workspace of the equipment should be defined for that specific duration. A buffer is added around these dimensions to create a box-shaped workspace for the subtask. Similar rules are defined to create workspaces for hazardous and protected areas. For example, an opening in the floor should be surrounded by a protected space by adding a buffer to the dimensions of the opening.

3.4.3 WORKSPACES

It is critical to detect when to send warnings to equipment operators and workers. In order to make the proposed method more flexible, i.e. to accommodate different scales of time and space, different levels of workspaces can be defined.

(1) Self Workspace (SWS): SWSs are reserved for each worker and equipment. Having the location of the tags attached to a worker or an equipment a workspace can be generated for the worker or equipment (Figure 3-8 (a)).

SWSs are updated continuously and in near real time; in other words, a safety zone (SWS) is generated for each tagged object upon the entrance to the area covered by sensors and it exists as long as the sensors can detect the tag(s).

Defining SWSs helps improve safety in cases when a worker or equipment is out of the predefined Task Workspace or when they are moving toward or away from it. For example, when a loader is moving from the parking area to the excavation area, if it passes by a worker closely a warning is triggered to notify the worker and the driver of the arising hazard.

(2) Task Workspace (TWS): TWS are workspaces defined based on information from WBS, schedule and 3D model of objects related to a task (e.g. installing HVAC ducts).

TWSs contain one or more SWSs and they are updated on an hourly basis. The location of the TWSs is defined based on information coming from the 3D model (e.g. BIM). As an example for the task of installing HVAC ducts of the 3rd floor, the location of the ducts which are supposed to be installed on a specific day is derived from the 3D model (Figure 3-8 (b)). All the necessary requirements for performing a task can be extracted from the WBS, such as type and size of the needed equipment. Knowing the type, size and the location of the task, and the size of the required equipment, a workspace can be defined for each task. The size of the TWS is the minimum area inside which workers and equipment can move safely. In addition, the duration of the task is extracted from the schedule and linked with the workspace defined for that specific task. Therefore by the end of the task its workspace will disappear.

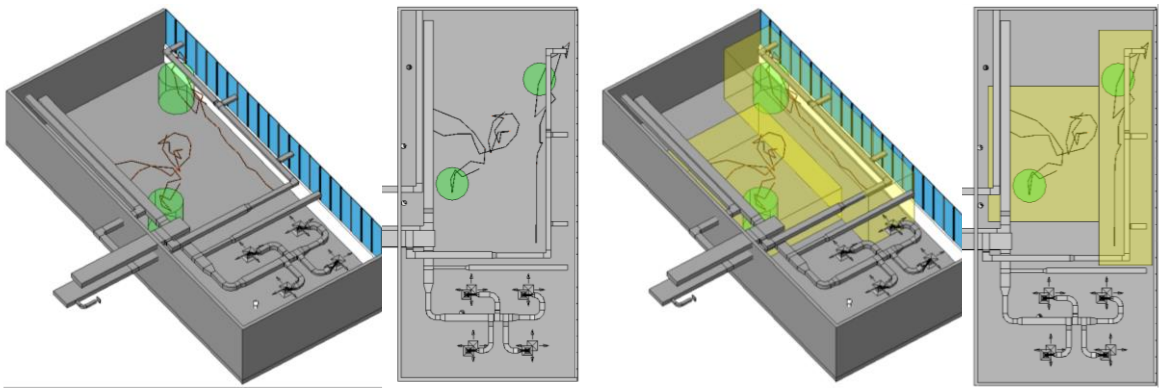
The system makes sure that there is no hazardous area inside the TWSs (e.g. an opening). In cases where a hazardous area exists, the system automatically generates a virtual fence around it in order to prevent potential accidents.

(3) Daily Workspace (DWS): DWSs contain tasks which are supposed to be executed on the same day. Hence, each DWS covers one or more TWS and is updated on daily basis. All the TWSs which are located near each other and are executed on the same day are covered by a DWS. Depending on the site layout, construction sites with sporadic tasks may have more than one DWS.

The schedule provides the tasks which are planned on the same day. On the other hand, the project's 3D model provides the locations of those tasks (as mentioned for TWSs), and accordingly, DWSs are generated for the project.

(4) Weekly Workspace (WWS): WWSs are updated every week. They cover tasks which are planned to be performed within a week. Like DWSs, for WWS, the schedule and the 3D model provide the necessary information.

Figure 3-8 shows the four different levels of workspaces. SWSs are represented in green, TWSs in yellow, DWSs in Blue and WWSs are represented in red.



(a) Self Workspaces (represented in green)

(b) Task Workspaces (represented in yellow)

Figure 3-8 Different levels of workspaces

BENEFITS OF DEFINING DIFFERENT LEVELS OF WORKSPACES

Some of the advantages of defining different levels of workspaces are:

1. Useful information for emergency management: data such as the total number of workers and equipment working in each workspace can be generated based on real time data. Providing the safety manager with the locations of workers helps in managing emergency situations (e.g. when there is a fire on site), and may result in a faster site evacuation and decrement in the number of fatalities.

2. Flexible method for warning generation: warnings are generated using different layers of workspaces. As an example, in the case a crew of workers finishes their task sooner than what is expected, the worker can leave the predefine TWS and move to the next TWS within the DWS if it is available.

3. Easier schedule update: Defining different levels of workspaces eases the process of updating the schedule. As mentioned above, SWSs are updated in near real time and TWSs are updated on hourly basis. This makes it possible to monitor the work progress each hour. When the system automatically updates the TWSs each hour, it will also check if the SWSs are located inside their assigned TWSs or not. In the case where the SWSs are out of the TWS, it means that crews are either ahead or behind the schedule.

3.5 REAL-TIME SAFETY MANAGEMENT

On the construction site, an RTLS is installed to monitor and update the locations of workers and objects on site. Tags are attached to physical barriers and workers to collect location data in real time. The fall prevention DVFs are linked with the physical barriers to check if the physical barriers are installed properly at the right location and with right dimensions for the right duration. The collision prevention DVFs are linked with the locations of workers on site. Warnings are given to the workers if they come too close to the danger areas.

The outputs of the system can be in one of the following forms: (1) warnings, (2) graphical reports, and (3) written reports. Warnings are generated when there is a potential collision between workers and/or equipment with virtual fences which can be either because a worker is approaching a reserved workspace of equipment or approaching an area with falling hazards. Graphical output will highlight the areas with falling risks. As mentioned in Section 3.3.1 the proposed system is able to automatically detect falling hazards and highlight them on the 3D BIM model. A written report gives information about the location, duration, start date, finish date and type of DVFs.

In order to use real-time data for safety purposes, two important parameters should be considered, the accuracy of the data and the update rate. Since warnings are generated and the simulation is updated based on the location information, it is important to have accurate data. The more accurate the data are, the more reliable the results will be. Safety can be improved by giving the workers more awareness of the environment.

3.6 SUMMARY AND CONCLUSIONS

The present chapter has presented an overview of the proposed methodology and defined several requirements for the use of this methodology in construction to improve workers' safety. Information with spatial aspects has been extracted from the QSC for the construction. This information can be used along with the BIM to detect hazardous areas on construction sites.

Two different types of DVFs have been proposed for fall and collision preventions. Falling hazards are detected automatically and fall prevention DVFs are generated for hazardous edges in the BIM. For collision prevention, four different levels of workspaces are proposed for each task/group of tasks with respect to the components involved in those tasks and their schedules. The collision prevention DVFs are generated based on the edges of the defined workspaces in order to avoid collisions between different crews and/or workers and equipment.

Furthermore, the proposed method uses RTLS to capture and update real-time data (e.g. location) of workers and objects on site. The data provided by an RTLS along with a BIM can be used for real-time safety management. For example, the proper installation of physical fences can be checked in real time on the BIM. It can be concluded that having the real-time data linked with BIM can improve safety on construction sites.

CHAPTER 4 IMPLEMENTATION AND CASE STUDIES

4.1 INTRODUCTION

Four case studies are implemented to validate the proposed approach. In the first case study, edges with falling hazard are detected automatically and the proper installation of the physical fences are checked for the hazardous edges using the UWB system.

The second case study focuses on a building project. A semi 4D model of the target area is created based on 2D drawings using Autodesk Revit Architecture (2012) and MEP (2012). The term "*semi 4D model*" is used because Autodesk Revit is not able to visualize a 4D model, new attributes are defined for all of the components of the model and the time related information are imported from the schedule. So, the model contains the schedule data but it cannot be visualized. After the schedule data are imported to the 3D model, workspaces are generated for the task of installation HVAC ducts as an example of indoor construction tasks. An UWB RTLS is used to collect location data of physical guardrails, workers and equipment and the semi 4D model is used to visualize these locations.

In order to demonstrate the feasibility of the proposed method for different projects, the third case study focuses on an outdoor construction project. Two different tasks of a highway interchange have been selected for this case study. The task of installing new spans for the new interchange using a launching gantry and the task of demolition of the existing interchange using synchronized mobile cranes. The 4D models for the new and existing interchange are developed in Autodesk Navisworks (2012) based on the existing

3D model of the interchange and workspaces are generated for the launching gantry and synchronized mobile cranes.

The fourth case study is concentrated on the UWB system. A sample scenario is planned and the UWB system is utilized to track RC construction equipment in the lab environment.

4.2 IMPLEMENTATION

Autodesk Revit Architecture 2012 is selected to develop the case studies since it is one of the most widely used BIM software in the market (Lucy, 2011) and it is capable of representing different building components such as slabs, walls, ducts, etc. However it has some disadvantages as well. Revit 2012 is not able to detect openings and edges of slabs. So, Revit Application Programming Interface (API) is used to develop an add-in in C# environment, which can automatically detect openings and edges of slabs. The developed code is based on a similar code is developed to determine the plane that a given curve resides in and to return its normal vector (Tammik, 2011). This code is modified to generate DVFs and can be found in Appendix B.

The developed add-in is linked with Autodesk Revit using a text file called Manifest. The Manifest file has to be created in the specific folder where Revit Architecture is installed. It contains the path of the developed code on the computer and a unique ID generated by C# which is used to link the developed code with Revit. After the link is established, the developed add-in is available on Revit and it can be used after the project is modeled.

Figure 4-1 shows the result of the developed add-in. The circular opening in the slab is detected automatically and a virtual fence is created around it.

Ubisense UWB system (Ubisense real-time location systems, 2012) is utilized to locate the physical barriers/barricades, the workers, and the equipment. Location data of the tags attached to the workers and equipment are collected and processed by the RTLS server. Integrating data from the UWB system into the 3D model provides the real time location of workers and the scissor lift. Autodesk Revit and Ubisense APIs have been used by Jian (2011) to develop a code to import and visualize the RTLS data in the Revit environment. However, this code is not able to import the data captured by the UWB system in real time. In order to visualize the traces of movement of an UWB tag in Revit, the location data captured by the UWB system have to be exported from the Ubisense software as Comma Separated Value (CSV) format. The CSV file is then imported to the developed code and visualized in Autodesk Revit.

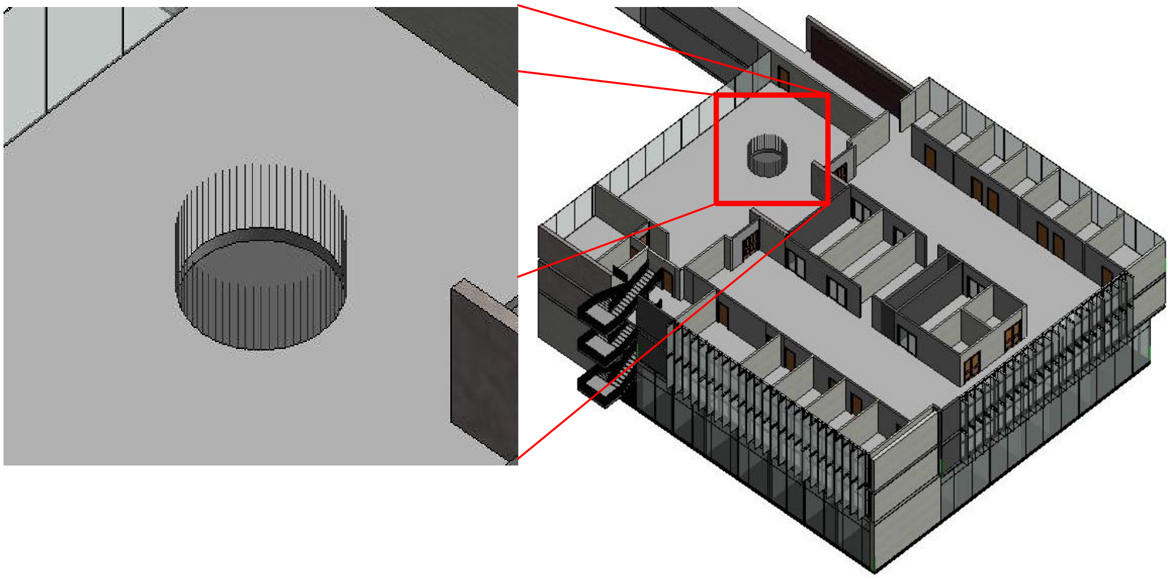
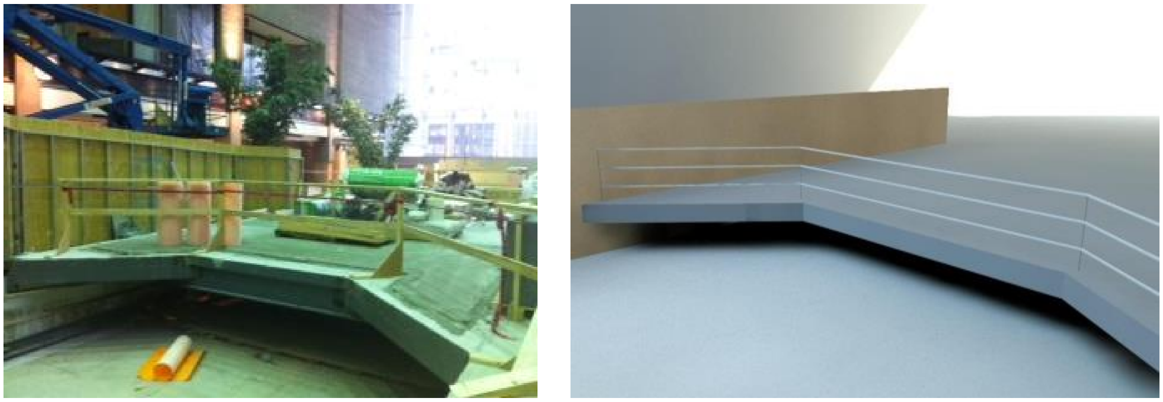


Figure 4-1 Generating Virtual Fences for openings in slab

4.3 CASE STUDY 1: FALL PREVENTION

The first case study is about automatic searching of fall risks. The developed add-in is used to identify the edges of the slabs and openings in the BIM model and to generate DVFs around those areas. The duration for each fence is manually assigned according to the schedule of the tasks. Figures 4-2 (a) and (b) show the physical guardrails installed around the edge of the floor and the DVFs generated in the BIM model, respectively. The height of the DVFs follows the required height of the guardrail, which is 1.2 meter according to the QSC. Tags are attached at the top and along the length of the guardrail. The location data of these tags are collected to compare with the DVFs' locations. If there is any mismatching, the virtual fence in the BIM is highlighted to show that a correction measure needs to be taken for the guardrail. Although the hazardous edges are detected and DVFs are generated automatically in this case study, the code for comparing DVFs and physical fences is part of our future work.



(a) Picture of the site

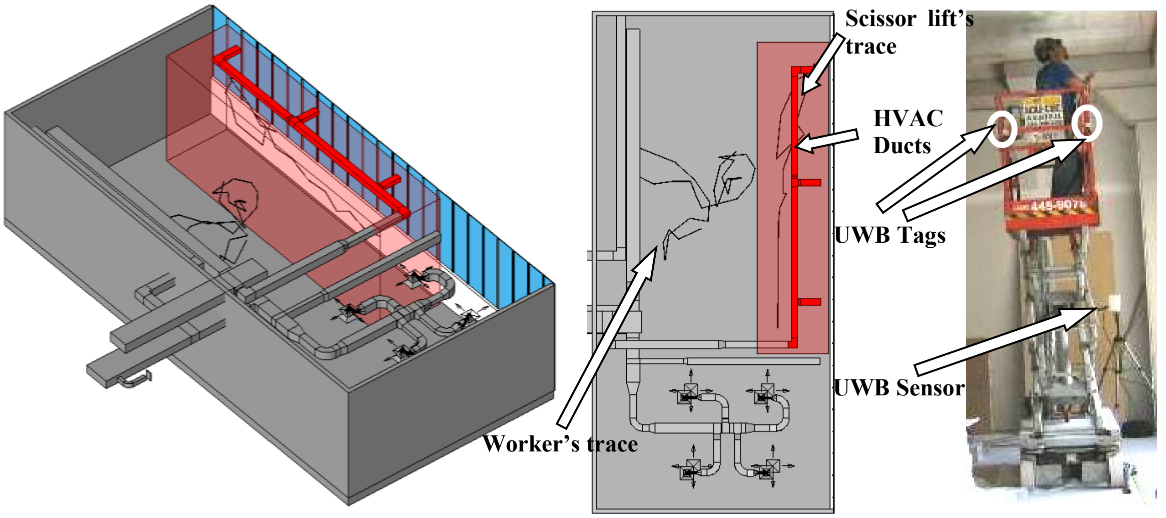
(b) BIM model of the site

Figure 4-2 Physical guardrails and virtual fences in BIM

4.4 CASE STUDY 2: COLLISION PREVENTION

The following case study aims to evaluate workspace identification and generation of the collision prevention DVFs for the task of installing HVAC ducts. A part of the 7th floor of the JMSB Building of Concordia University has been developed in Autodesk Revit Architecture 2012. The WBS is used alongside the schedule in order to obtain the appropriate start dates, finish dates and the durations of subtasks and work packages. The UWB data, which contains the time labeled locations of the workers and equipment, are taken form a case study which was done by Rodriguez (2010).

In the current practice, there are many situations in which workers and equipment are working in the same area. Based on safety regulations, physical barriers/barricades are not mandatory in these situations. The case study was carried out related to the installation of HVAC duct where several workers and equipment were working in the same area. Figure 4-3 shows the HVAC ducts that will be installed in a room and the workspace generated for the installation of a portion of ducts in this room in 2D and 3D. Four UWB tags were assigned to the sides of the scissor lift to monitor the pose of the lift. However, to make the model less crowded, the traces of the tags assigned to the scissor lift are not visualized. A tag was assigned to each worker on his safety helmet. Sensors are installed at the locations providing the best coverage of the area.



(a) 3D View (b) Plan View (c) Scissor Lift

Figure 4-3 Workspace generated for the task of installing HVAC ducts (Hammad et al. 2012)

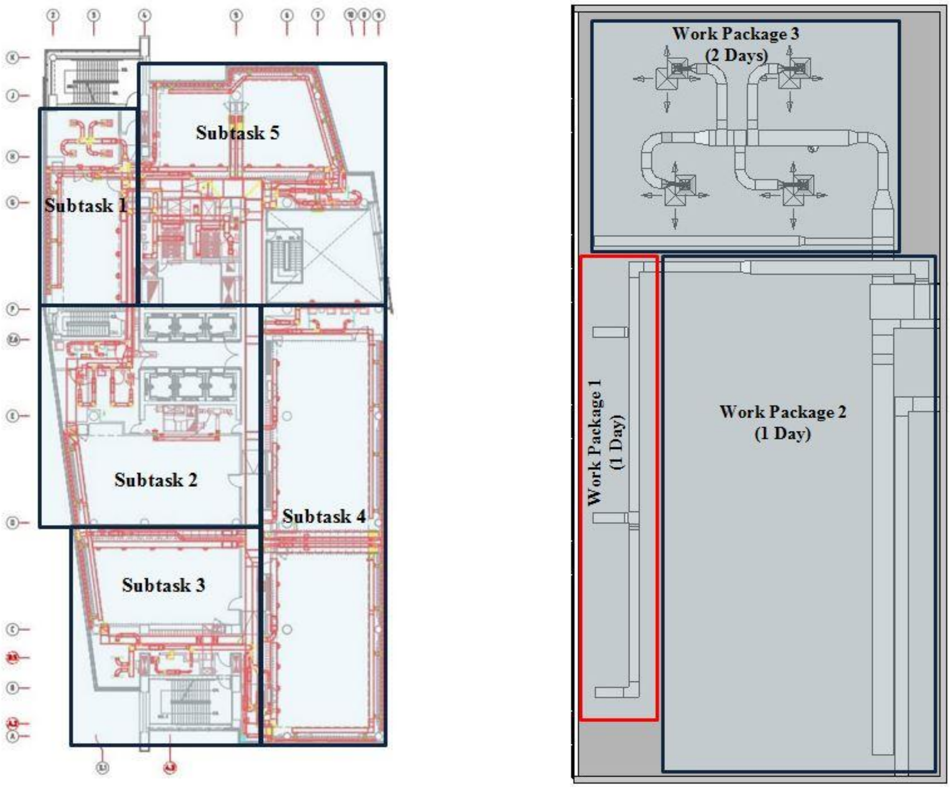
The 4D model has a sufficient level of detail and is used to provide a spatio-temporal reference as well as to visualize different phases of the work, e.g., to show the ducts that have been already installed and those that will be installed later. The 4D model was also used to show the locations of the virtual fences and workers. Figure 4-3 (a) shows the plan view of the 7th floor of the JMSB Building with the ventilation ducts to be installed shown in red. According to the schedule, the ducts of this floor should be installed in 25 days (Table 4-1). WBS is used to divide the plan and the schedule into several small pieces in order to obtain the required durations for each part (Figure 4-4). The process of dividing the schedule and the plan into smaller pieces continues until the duration for the installation of each component is reached.

Table 4-1 The schedule of 7th floor of JMSB building

Name of the Task	Duration	Start	Finish
Level 7	**206 d**	**Tue 2/5/08**	**Fri 12/12/08**
Ventilation / main horizontal ducts & distribution	**25 d**	Fri 4/4/08	Thu 5/8/08

For the simplification of the analysis, this case study only focuses on the task of installation of the HVAC ducts within the Subtask 1 and total duration of 3 days out of 25 days is assigned for the aforementioned Subtask. Subtask 1 consists of three work packages. Work package 1 consists of 12 components which should be installed during one working day. Work package 2 consists of 15 components that should be installed in one day, and work package 3 consists of 50 components, most of which are small, and they should be installed in the period of 2 days.

Since Aurodesk Revit does not support 4D, start date and finish date are defined as new attributes for all of the components in the model. The recently defined schedule attributes and the predefined attributes (e.g., the ID of the component) are exported to an Excel file using the WhiteFeet tool for Revit (Guttman, 2011). The required duration, start date and finish date of each object which is derived from braking down the schedule into small tasks is updated in the Excel file. At this point the Excel sheet contains information related to the ducts of work package 1 (i.e. Identification (ID), TypeName, StartDate, EndDate and the Duration).



(a) Subtasks of the 7th Floor of JMSB Building (b) Work packages of the Subtask 1

Figure 4-4 Subtasks and work packages

The schedule data is assigned to objects and the Excel sheet is imported to Revit through the WhiteFeet tool. Changes made to the Excel sheet are automatically updated in the model.

Autodesk Revit's filtering provides the possibility to change the appearance of object(s) having a specific amount assigned for their particular attribute(s). Using this feature all the ducts which are supposed to be installed on 04/04/2008 are selected and their color is changed to red. Figures 4-3 (a) and (b) show the 3D model of the Subtask 1 modeled in Revit. The red colored ducts are going to be installed according to the schedule; the rest will be installed later. After the ducts are specified based on their StartDate value, workspaces are generated for them using the b.i.m.m ToolBox (b.i.m.m, 2011). The workspaces are represented as bounding boxes. The ducts which are physically attached to each other and have the same StartDate and Duration value share the same workspace, and the size of the workspaces are adjusted automatically to contain all of the selected ducts installed on the same day. Other objects can have their own workspaces (i.e. painting a wall). The b.i.m.m ToolBox provides the option of automatically adding margins for the bounding boxes or they can be adjusted manually within Revit. In this case study, the bounding boxes for ducts are adjusted manually to cover the full height of the floor as shown in Figure 4-3 (a). A virtual fence is generated on the edges of the defined workspace to protect workers for the time period of the task.

Traces of the workers are presented in the 3D model of the area providing a spatial reference as shown in Figure 4-3. Once a worker is close to the virtual fence, an overlap is found; which means there is a high probability of danger for the worker. In this case the worker is alerted by an audio or a vibration alert on his/her mobile phone or other portable devices. Simultaneously, the operator of the scissor lift will get an alert showing that there is a worker nearby and he/she should slow down the machine or stop the operation. The worker's trace in Figure 4-3 (b) shows the movement of the worker without entering the fenced area.

4.5 CASE STUDY 3: WORKSPACE GENERATION FOR CRANE OPERATIONS

The following case study focuses on the workspace generation for some of the equipment involved in the construction and demolition of a bridge project. The Turcot interchange in Montreal, Canada is selected for this case study. Two types of crane are considered in order to demonstrate the feasibility of the proposed approach, a launching gantry crane for the construction of the bridge, and synchronized mobile cranes for the demolition of the bridge.

For the construction of the bridge, the 3D model of the new Turcot interchange in Montreal, Canada was developed in Bentley Leap Bridge Enterprise V8i by our research group. This 3D model was developed base on the original 2D drawings and the data provided by the Ministry of Transport of Quebec. The 3D model is exported to Autodesk Navisworks and linked with the schedule in order to generate the 4D model of the project. Additionally, a launching gantry is modeled and a workspace is generated for it in Autodesk Revit using the same method introduced in Case Study 2. The gantry and the workspace are then exported to Navisworks and merged with the 4D model of the Turcot. Figure 4-5 shows the workspace generated for the launching gantry.

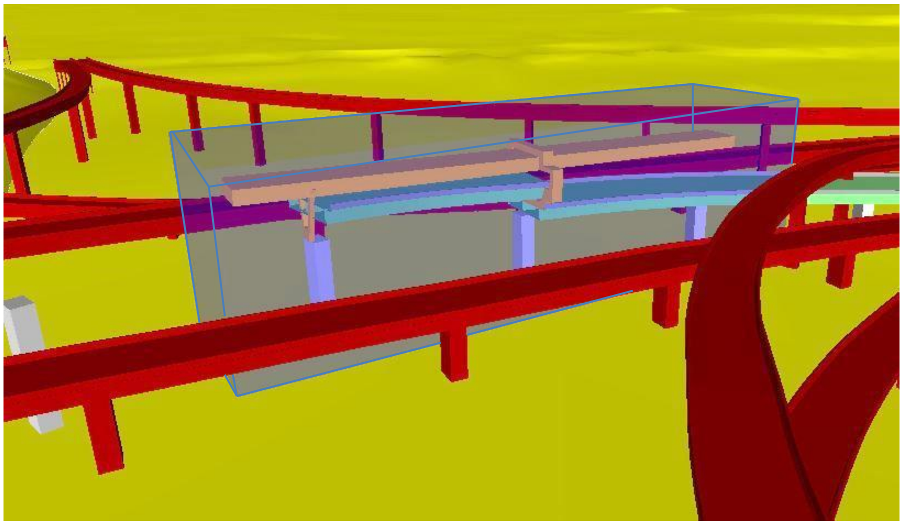
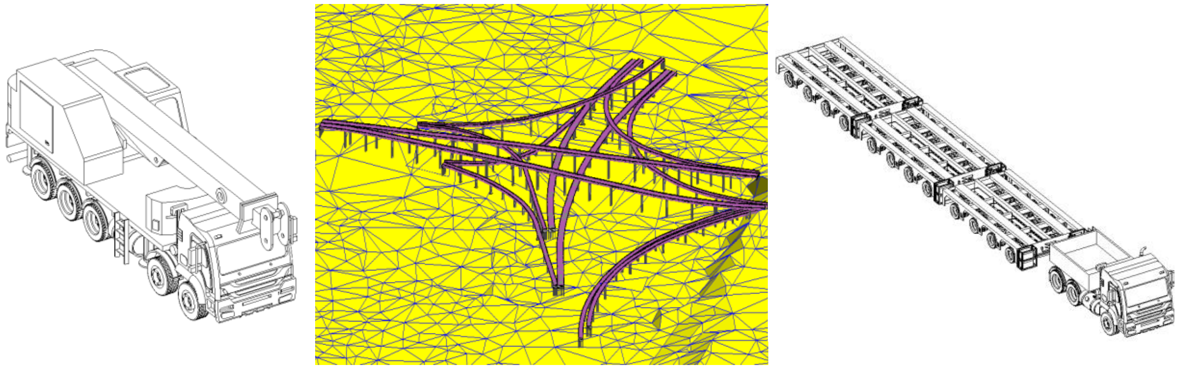


Figure 4-5 Workspace generated for the task of installing a highway span using a launching gantry

For the demolition of the bridge, the 3D model of the existing Turcot interchange is imported to Autodesk Revit. Detailed 3D models of two heavy duty truck mounted cranes and a heavy truck puller with a trailer assembly are used to visualize the process of removing a span. Figure 4-6 shows the 3D models used in this case study.

The model for the cranes, truck puller and the trailer were downloaded from the GrabCAD website (3D CAD Library, 2013) and imported to Autodesk Revit along with the 3D model of the Turcot interchange. The Turcot model is considered as the main model and equipment are scaled and positioned accordingly. In the next step, workspaces are defined for equipment and the span which is going to be dismantled. The workspace for the span is generated using the same method introduced in Case Study 2. Defining the workspaces of equipment is based on the location of the object in the BIM/BrIM model and the characteristics of the movement of the equipment. In Case Study 2, the scissor lift's workspace was a simple box surrounding the ducts to be installed. In this case study it is more difficult to define the workspaces of cranes due to their complex movements. In order for a crane to perform the task of loading/unloading an object, a range of movements is required, which results in a significant change in the size of the workspace. Due to these changes in the dimensions of the crane (e.g. boom extension/rotation), the movement of the equipment (e.g. movement of the truck or the crane's boom swing), and limitation of the b.i.m.m ToolBox which is used in the previous case study to generate bounding box for HVAC ducts, workspaces are generated manually in this case study.

One of the limitations of Autodesk Naviswork is that it does not allow the creation of new objects in the model; as a result, workspaces are generated in Revit and then the whole model (Turcot, equipment and workspaces) are exported to Navisworks for the 4D visualizations.



(a) Heavy duty truck mounted crane

(b) Existing Turcot interchange

(c) Heavy truck puller with axles assembly

Figure 4-6 3D Models

Two different workspaces are defined for the cranes; the first one is a rectangular workspace for when the boom is completely retracted and located on top of the truck (i.e. when the crane is moving on site or between sites) and the second one is a frustum cone workspace for when the crane is positioned to move the target object. In order to switch between these two types of workspaces, UWB tags can be attached to the crane's outriggers and by the extension of outriggers, the rectangular workspaces will be switched to the frustum cone workspace.

Since workspaces are defined for safety purposes, the extreme case is considered which is when the boom has its maximum length. The idea is that if the maximum length of the boom in different poses is covered in the workspace, all other possible poses will be covered accordingly. This result in a frustum cone shape workspace which has greater diameter at the bottom, and the diameter is decreasing by height. In order to generate the appropriate workspace for each crane, four main parameters are required which are: (1) Maximum allowable length of the boom (L_{max}), (2) Maximum height of the boom when extended (H_{max}), (3) Minimum angle of the boom to the ground (θ_{min}) and (4) Maximum angle of the boom to the ground (θ_{max}).

The maximum length of the crane's boom is associated with the weight it is going to move and the angle of the boom to the ground and can be derived from the crane's load chart. H_{max}, θ_{min} and θ_{max} can also be found in the crane's specifications. Figure 4-7 explains the frustum cone shape of the workspace. It should be mentioned that due to the clearance required between the equipment and surroundings, a safety buffer (δ) is added to both the H_{max} and the horizontal length of the L_{max} to have a greater workspace. R_{bottom} and R_{top} are calculated using the following equation.

$$R_{bottom} = (\cos\theta_{min} \times L_{max}) + \delta \qquad (4\text{-}1)$$

$$R_{top} = (\cos\theta_{\mathrm{max}} \times L_{max}) + \delta \qquad (4\text{-}2)$$

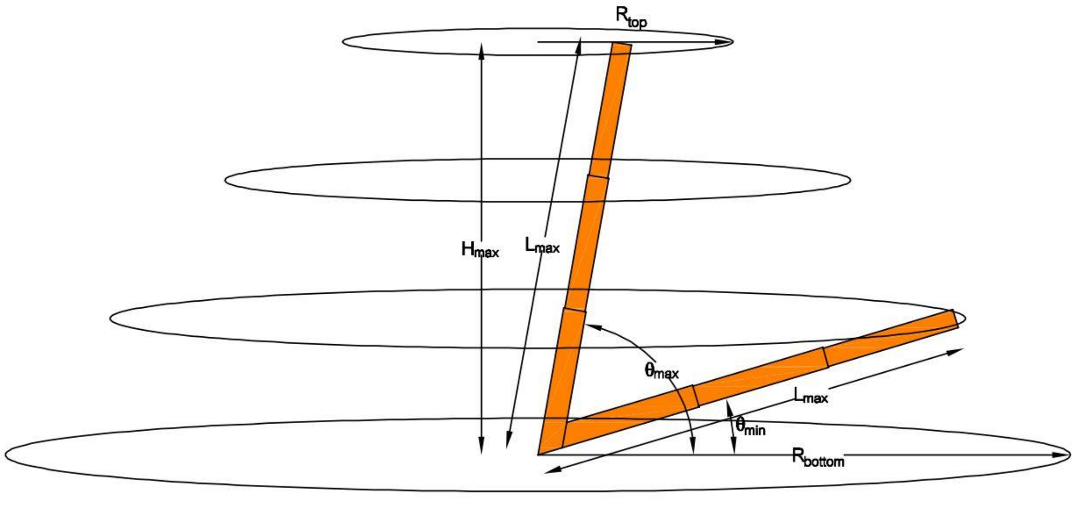
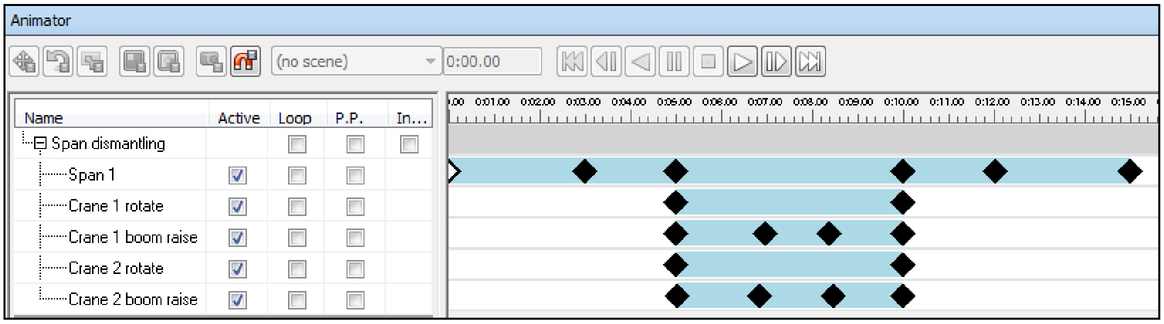


Figure 4-7 Frustum cone workspace

In addition to the crane's workspaces, another workspace is manually defined in this case study to cover the area beneath the span while it is being moved. This workspace contains the workspaces of the cranes', the span and the truck puller.

After the workspaces are defined, the whole model is exported to Navisworks to get linked with the schedule. Since the schedule is prepared only for the components of the bridge and not the equipment, the movement of the equipment are animated in Navisworks and linked with the related task in the schedule.

In order to create the detailed movement of the cranes, the movement of individual parts are animated separately and grouped as a scene. Animations are made using key frames. Key frames define the start point and the end point of the animation. On the right side of Figure 4-8, in the timeline view, key frames are displayed as black diamonds. The duration of each can be edited by dragging the key frame to the desired location in the timeline. On the left side of Figure 4-8, in the scene view, five different animations are created for the movement of Span 1, rotation and boom raise of cranes 1 and 2. These animations are all grouped under the span dismantling scene which is linked with the task of the demolition of Span 1 in the scheduler. Figure 4-9 shows the flowchart used in this case study to create the 4D model and the animations as explained.



Name	Active	Loop	P.P.	In...
Span dismantling		☐	☐	☐
Span 1	☑	☐	☐	
Crane 1 rotate	☑	☐	☐	
Crane 1 boom raise	☑	☐	☐	
Crane 2 rotate	☑	☐	☐	
Crane 2 boom raise	☑	☐	☐	

Figure 4-8 Naviswork's animator module

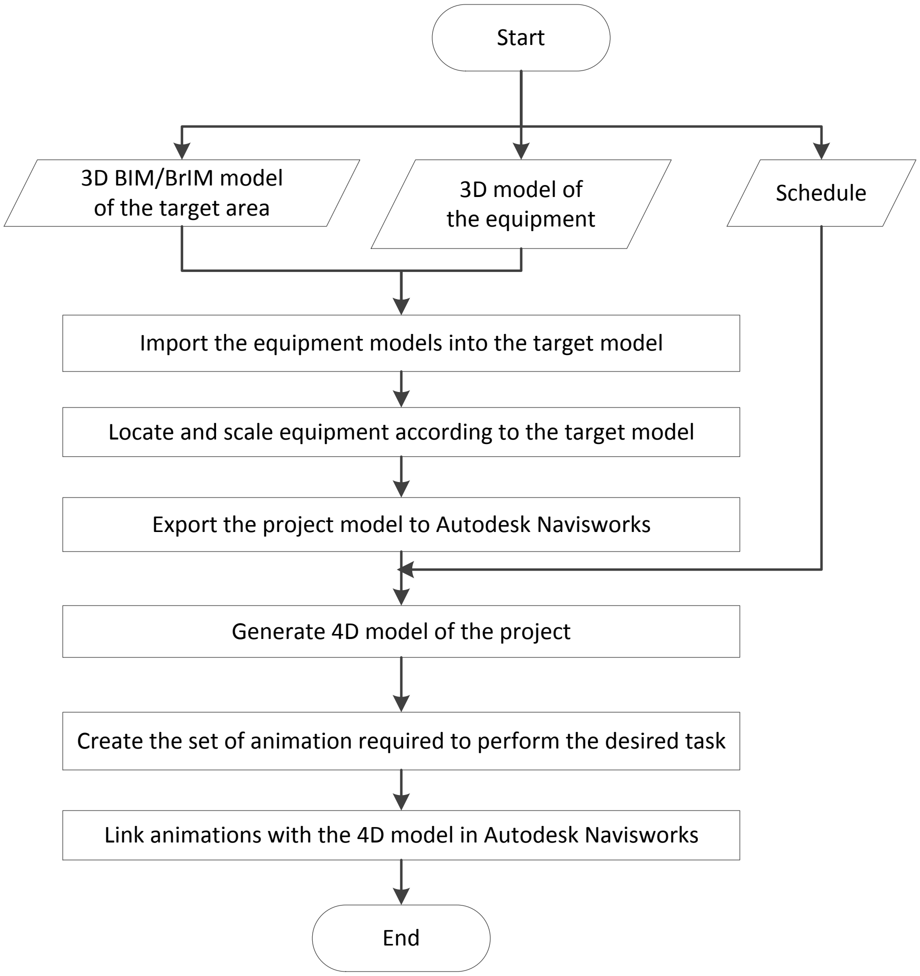
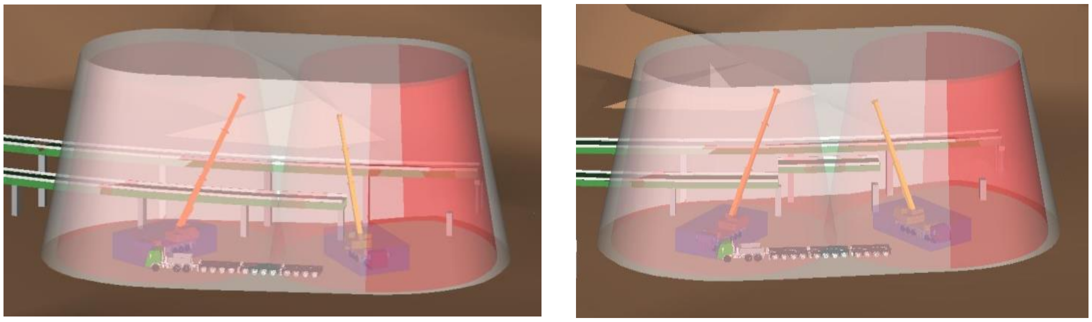


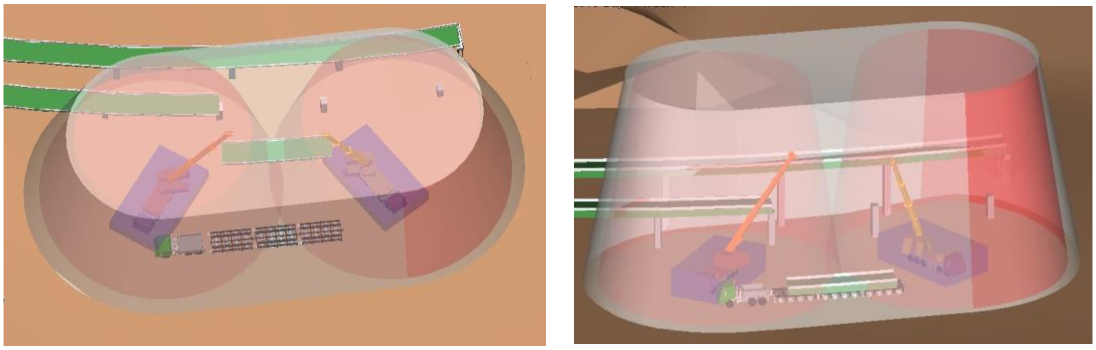
Figure 4-9 Flowchart of creating 4D animation including equipment movements

Figure 4-10 shows the different poses of the cranes and workspaces generated for them in Autodesk Navisworks.



(a) Locating the boom (rigging)

(b) Raising the span



(c) Moving the span on top of the trailer

(d) Lowering the span

Figure 4-10 Workspaces generated for the task of removing a highway span

4.6 Case Study 4: Collision Prevention Lab Test

The third case study is carried out in the laboratory. Two RC models of a truck and an excavator (Hobby Engine, 2013) are used. The truck has two motors that allow the movement of the body (drive forward/backward, turn right/left) and the bed of the truck (up/down). The excavator has five motors that allow the movement of the body (drive forward/backward, turn right/left) and the boom and stick (turn up/down). Both models can be controlled using a remote control that allows the movement of one Degree of

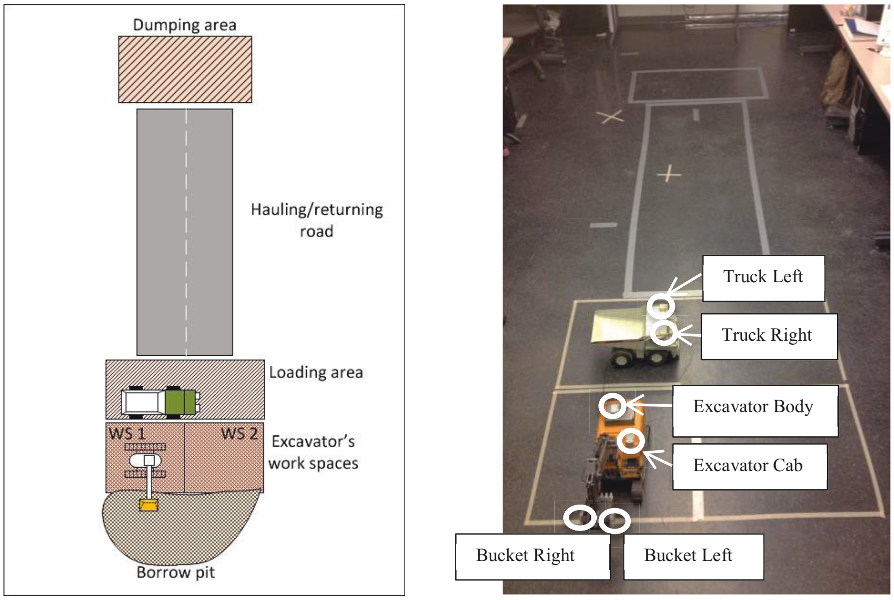
Freedom (DoF) at a time. An excavator has three joints which provide DoFs for the movement of the boom, the stick and the bucket. However, the model used for the case study has only two DoFs for the rotations of the boom and the stick. More details related to the equipment are given in Table 4-2.

Table 4-2 Specifications of equipment

Specification Equipment	Dimensions	Moving Forward Speed	DoFs	Range (°)	Angular speed
Truck	445 × 220 × 330 mm	0.58 m/s	Bed rotation	[0, +40]	10 °/s
Excavator	743 × 222 × 490 mm	0.23 m/s	Body swing	[-180, +180]	8 °/s
			Boom rotation	[+40, +80]	10 °/s
			Stick rotation	[-70, -30]	10 °/s

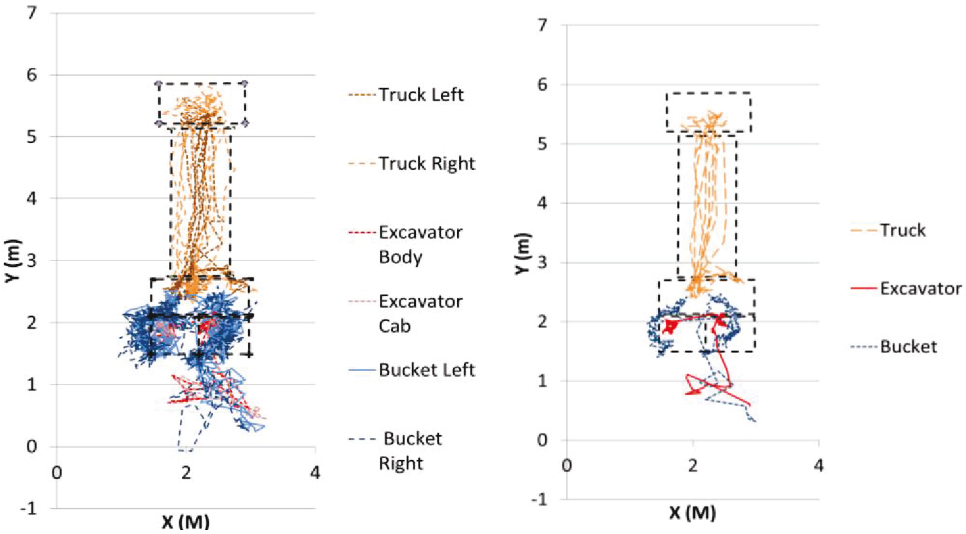
Ubisense UWB system (Ubisense real-time location systems, 2013) was utilized to locate the model equipment. Four UWB tags were attached to the excavator and two were attached to the truck to monitor their movement. Sensors are installed at the locations providing the best coverage of the monitored test area. The nominal update rate of the tags was set to 10 Hz while analyzing the results of the test showed an actual update rate of about 8 Hz.

Figure 4-11 shows the setting of the case study which contains four main parts, namely, the excavation area, loading area, hauling/retuning area and the dumping area. The truck is loaded in the loading area by the excavator; it moves to the dumping area and dumps its load. Traces of movement for different tags are shown in different colors in Figure 4-12. The raw data gathered from the site require a multi-step processing before it can be used for data analysis.



(a) 2D model of the case study (b) A picture of the actual case study

Figure 4-11 The setting of case study (Setayeshgar et al., 2013)



(a) Raw data (b) Processed data

Figure 4-12 Raw and processed UWB data (Setayeshgar et al., 2013)

The processing is required to compensate for the missing or erroneous data. The data processing includes two main parts: (1) averaging the tags' locations over a period of time, i.e. 1 second; and (2) averaging the locations of the two tags attached to the equipment in order to calculate the location of the equipment. Figures 4-12 (a) and (b) show how the data processing helps increase the accuracy of the data. These steps are the minimum requirements for the identification of the location data and further processing is required if the poses of the machines are to be identified too. This simple data-processing can be further improved through the consideration of additional constraints, e.g. velocity constraints (Zhang et al., 2010).

The traces of movement in Figure 4-12 show that the excavator left the defined workspace and entered an unexpected area. In this case a warning should be triggered immediately when the excavator approached the virtual fence at the edge of the workspace (WS2 in Figure 4-11 (a)) to notify the driver of a potential danger. The project manager also should receive a warning since the excavator was not supposed to leave the workspace according to the schedule.

4.7 SUMMARY AND CONCLUSIONS

The implementation was focused on the advantages and disadvantages of the software used to prepare 3D and 4D models of the target projects. Automatic detection of openings and edges of slabs using the add-in developed for Autodesk Revit 2012 and the process of linking this add-in with Autodesk Revit have been briefly explained.

Four case studies showed the applicability of the proposed approach. In the first case study the proper installation of the physical fences are checked according to the QSC. It is concluded that the BIM can be used for visualizing construction safety measures and safety related information can be checked in BIM at different stages of a construction project.

In the second case study, new attributes are defined for all of the components of the 3D model and the schedule data are imported and linked with the 3D model in Autodesk Revit. Workspaces and DVFs are generated for the task of installing HVAC ducts and the traces of movements of workers and equipment are imported to the model. RTLSs can be used to monitor workers on site in order to give them safety warnings when necessary based on their relative locations with respect to workspaces and danger zones specified in the model in order to improve their safety awareness. It is concluded that RTLS systems can be used along with BIM model to improve safety on construction sites.

The third case study was focused on an outdoor construction and demolition project. The 4D models of the existing and the new Turcot interchange were developed and the workspaces are manually generated for two types of cranes: (1) a launching gantry which is used to install the new bridge spans; and (2) two mobile cranes which are used to remove the existing spans. This case study shows the applicability of the proposed method for different stages and types of construction projects. However, Autodesk Navisworks is designed to create 4D models but it is not suitable to develop animations of the equipment's movement. Unlike animation and gaming software, such as Unity and Softimage, different movements should be animated separately because joints cannot be defined in Navisworks while generating a 4D model is easier in Navisworks comparing with animation and gaming software. In addition, simulation and path planning can be used in animation and gaming software to detect the pose of the crane performing different tasks. The results can be used for automatic generation of the cranes' workspaces which can be part of the future work.

The fourth case study was carried out in the lab environment. A sample scenario was developed to demonstrate the feasibility of the UWB system. UWB tags were attached to two RC machines and tracked by the UWB system. The raw data gathered from the UWB system were processed to increase the accuracy of the data. The processed data illustrated that the excavator left its defined workspace. This case study indicated that the UWB system can be used as an RTLS to monitor the movement of a project's assets and resources.

CHAPTER 5 CONCLUSIONS AND FUTURE WORK

5.1 SUMMARY OF RESEARCH

Building Information Modeling can be used for visualizing construction safety measures. Safety related information can be modeled in BIM at each stage of a construction project, while RTLSs can be used to monitor workers on site and to give them safety warnings when necessary based on their relative locations with respect to danger zones specified in the model in order to improve their safety awareness. This research proposed a comprehensive approach for the automatic detection of falling hazards as well as generating the workspaces required for different construction tasks. It elaborated on the needs, motivations and benefits of the integration of the RTLS data with a BIM model as a visual reference to improve safety on sites. QSC is reviewed and data with spatial aspects are extracted and a method is developed to automatically detect falling from height hazard as one of the most fatal risks on construction sites. Moreover, this research proposed automatic generation of workspaces using the BIM and data provided by the project's schedule and the WBS. Furthermore, real-time data are linked with the 3D model and DVFs are generated to prevent accidents from happening.

5.2 RESEARCH CONCLUSIONS

The conclusions of this research are as follows: (1) A method has been proposed to automatically define areas with potential risk of falling using the 4D model of the building (2) fall prevention DVFs are generated for edges with falling hazard, where physical fences are mandatory; (3) collision prevention DVFs are generated on all edges of the defined workspaces; (4) workspaces and DVFs are dynamic and they are updated according to the project's schedule; and (5) the system notifies only the workers who are exposed to a danger and/or near the dangerous area.

Additionally, in order to achieve the goal of this research the BIM model of the Genomics building and part of the JMSB buildings of Concordia University were developed in Autodesk Revit. Furthermore, an add-in is developed for Autodesk Revit in C# environment to automatically detect slabs' edges and openings within the slabs.

5.3 LIMITATIONS AND FUTURE WORK

Autodesk Navisworks is designed to generate 4D models based the 3D model and the schedule. However, it also provides the ability to create animations within the 4D model but there are limitations on creating animations which are: (1) The laws of physics are not defined for Autodesk Navisworks, therefore it is not suitable to create detailed animations; (2) Autodesk Navisworks does not support hinges (joints), consequently animating hinged arms (e.g. excavator's boom) is troublesome and takes a lot of time; (3) The creation of new objects (e.g. workspaces) is not supported in Navisworks, hence objects have to be imported from a modeling software like Autodesk Revit; and (4) The format Navisworks uses to save the developed 4D model and the animations is not supported by modeling software such as Revit, therefore the 4D model can only be edited in Navisworks environment with its limited editing tools. However the 4D model and animations can be exported as video and/or image files.

More investigation and more complex case studies should be applied to further investigate the benefits of using BIM for improving safety on site. Furthermore, other safety hazards with spatial characteristics presented in Table 3-1 can be used to investigate BIM-based prevention program for construction safety.

Future work will consider the details of the probabilistic risk evaluation and the mechanism for generating and updating the workspaces based on the project data and real-time location updates. In this research it is assumed that the schedule will be followed as it is without any modifications. However, this may not happen and real-time data may be different from the schedule data. In order to overcome this limitation, the following method is proposed as future work.

Figure 5-1 shows the details of the proposed methodology for future work. It has two main phases, the planning phase and the execution phase.

Different sequences can be used to define the order in which tasks can be executed. As an example for the task of pouring concrete of foundations, it can start form the eastern sector of the foundation toward the western sector or it can start from northern sector towards the southern sector.

(1) Define workspaces: In the planning phase, workspaces are defined using data from the WBS, the schedule and the 3D model.

(2) Run simulation: The simulation will generate the duration information to be linked to the 3D model.

(3) Probabilistic 4D: Appending the defined workspaces to the results of the simulation, the probability of having collisions between different crews can be calculated which results in a probabilistic 4D model (Doriani et al., 2013).

(4) Extract information with spatial aspects from the safety code: For example, the QSC for the Construction Industry (ASP Construction, 2003) has been reviewed and information that has spatial aspects has been extracted and used for either indicating problems or providing solutions (Hammadet al., 2012).

(5) Evaluate Safety risk: Safety rules and regulations are used alongside the probabilistic 4D model in order to detect workspaces with safety hazards and to assign the severity level of that hazard.

(6) Generate DVFs: As a result of the previous step, areas having hazards are detected and DVFs are generated in order to prevent hazard.

(7) Capture Near real-time data: In the execution phase, near real-time data are used along with the data form the planning phase. UWB tags are attached to physical fences monitored in real time and to workers and equipment.

(8) Check workspaces: The locations of the workers and equipment are monitored in real time to prevent approaching dangerous areas and to ensure that they are working in the workspace assigned and predicted based on the schedule. In cases where workers are late or ahead of the schedule and they are not in the expected area, the real-time data are used to calibrate the simulation in order to have a real-time simulation.

(9) Check real fences: Mapping the physical fences with their corresponding virtual fences can be applied to check if they are installed at the proper locations with the proper dimensions. If any physical fence is missing, the corresponding virtual fence in the model is highlighted and a reminder is sent to the manager.

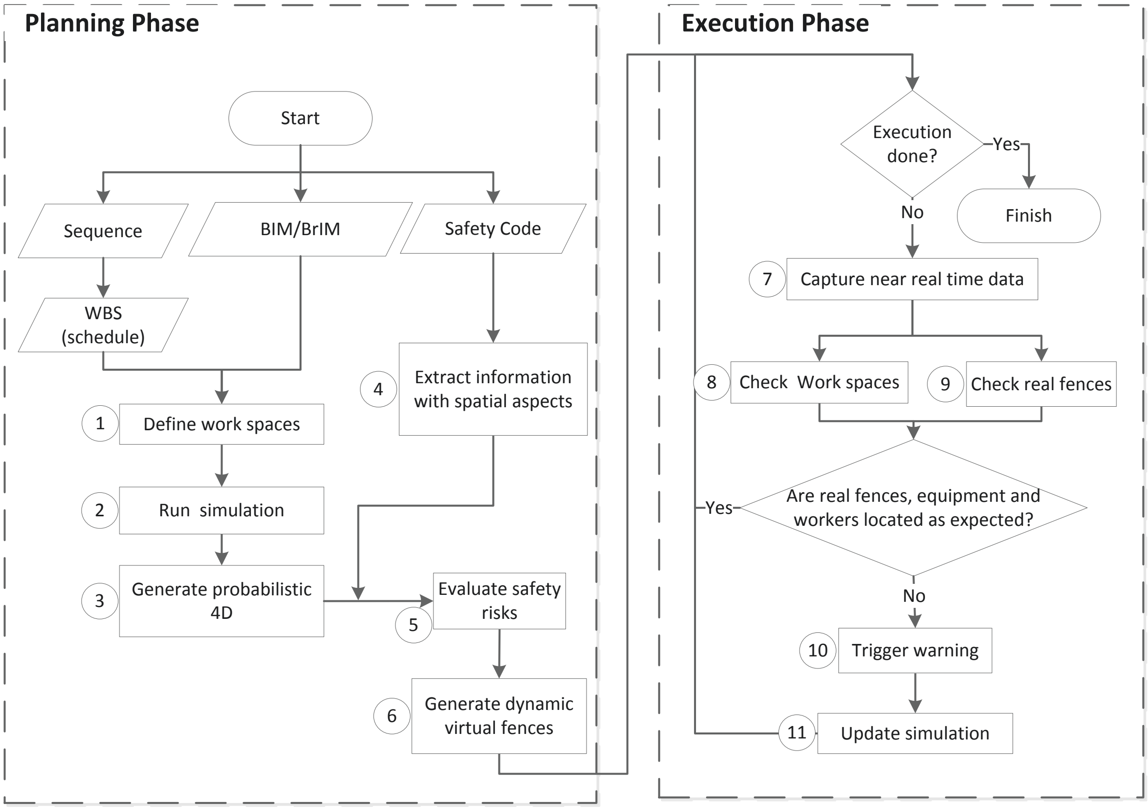
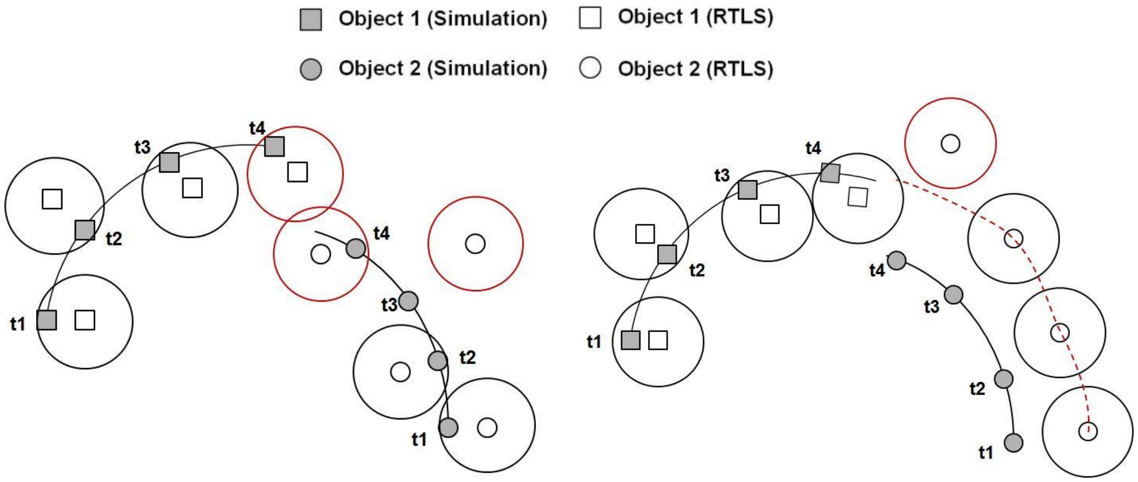


Figure 5-1 Proposed method for future work (Setayeshgar et al., 2013)

Figure 5-2 shows the concept of the proposed method when the tracking update rate of the RTLS is high enough to identify the locations of objects at any point of time. In this case, these locations can be used instead of the workspaces. The idea is to measure the distance between the expected and real-time locations of an object in real time (Figure 5-2 (a)). A buffer can be defined for this purpose. Since objects are being monitored in near real time (i.e., with a few seconds of delay), the inaccuracy of the measurement and delays can be compensated by increasing the size of the buffer. If the distance is equal or less than the defined buffer, it can be assumed that the predefined pattern is acceptable and the object is just diverging from it. However, if the distance becomes more than the buffer, it probably means that something unexpected has happened and a warning should be triggered (e.g., the object 2 at time t3 in Figure 5-2 (a)). In addition, in order to avoid clashes on the construction sites, regardless of the expected location, a warning will be triggered whenever there is a clash between two buffers (e.g., the collision between object 1 and object 2 at time t4 in Figure 5-2 (a)).

As shown in Figure 5-2 (b), in some cases an object does not follow a predefined pattern (path) all the way throughout the process, so a new pattern should be identified in real-time based on the captured real-time data. The initial pattern will be ignored and the new pattern is considered as the new expected pattern of the object. If the object diverges from the new pattern more than the buffer, a warning will be triggered.



(a) Diverging from the pattern

(b) Defining new pattern

Figure 5-2 The concept of the proposed method for future work

REFERENCES

3D CAD Library. (2013, November). Retrieved November 2013, from GrabCAD: <https://grabcad.com/>.

Akinci, B., Fischer, M., Kunz, J., and Levitt, R. (2002). Representing Work Spaces Generically in Construction Method Models. Construction Engineering and Management, ASCE, 128(4), pp. 296-305.

Alez, G. (2012). Work Breakdown Structure: Introduction, Design Principles, Terminal Elements, And More. Webster's Digital Services

Alshibani, M., and Moselhi, O. (2007). Tracking and forecasting performance of earthmoving operation using GPS. *Proceedings of Construction Management and Economics 25 th Anniversary Conference.* Reading, UK.

Anumba, C., and Aziz, Z. (2006). Case Studies of Context-Aware Services Delivery in AEC/FM. *13th EG-ICE Workshop on Intelligent Computing in Engineering and Architecture*, Ascona, Switzerland, pp. 23-31

ASP Construction. (2003). *Safety code for the construction industry.* ASP Construction. Quebec.

b.i.m.m. (2011). Building Information Model Management. Retrieved April, 2013, from: <http://www.bimm.eu/english>.

Becerik-Gerber, B., Jazizadeh, F., Li, N., and Calis, G. (2012). Application areas and data requirements for BIM-enabled facilities management. *Construction Engineering and Management, ASCE, 138*(3), pp. 431-442.

Bunin, S. G., and Valikov, D. P. (2006). Widening UWB system coverage zone by repeaters-regenerators. *Proceedings of the Ultrawideband and Ultrashort Impulse Signals*. Sevastopol, Ukraine. pp. 251-252.

Carbonari, A., Naticchia, B., Giretti, A., and Grassi, M. D. (2009). A proactive system for real-time safety management in construction sites. *26th International Symposium on Automation and Robotics in Construction (ISARC)*, Austin, Texas, U.S. pp. 47-54.

Chen, S. S., Li, J.-W., and Tangirala, V.-K. (2006). *Accelerating the design and delivery of bridges with 3D bridge information modeling: Pilot study of 3D-centric* *modeling processes for integrated design and construction of highway bridges.* Washington D.C.: NCHRP-IDEA Program Final Report.

Cheng, T., and Teizer, J. (2013). Real-time resource location data collection and visualization technology for construction safety and activity monitoring applications. *Journal of Automation in Construction, 34*, pp. 3-15.

Cheok, G. S., Lipman, R. R., Witzgall, C., Bernal, J., and Stone, W. C. (2000). Field demonstration of laser scanning for excavation measurement. *Proceedings International Symposium of Automation and Robotics in Construction*, pp. 683-688.

CSST (2013). Commission de la santé et de la sécurité du travail. Retrieved August, 2013, from <http://www.csst.qc.ca/Pages/index.aspx>.

Dawood, N., and Mallasi, Z. (2006). Construction workspace planning: Assignment and analysis utilizing 4D visualization technologies. *Computer-Aided Civil and Infrastructure Engineering, 21*(7), pp. 498-513.

Doriani, A., Mawlana, M., and Hammad, A. (2013). Simulation-based deterministic and probabilistic 4D modeling for planning and scheduling of elevated urban highway reconstruction projects. *Transportation Research Board (TRB).* Washington D.C.

Ergen, E., Akinci, B., and Sacks, R. (2007). Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS. *Journal of Automation in Construction, 16*(3), pp. 345-367.

Estman, C., Teicholz, P., Sacks, R., and Liston, K. (2011). *BIM Handbook: a guide to building information modeling for owners, managers, designers, engineers, and contractors.* John Wiley and Sons.

European Agency for Safety and Health at Work. (2006). Retrieved from: <https://osha.europa.eu/en/faq/accident-prevention/which-industry-sectors-are-most-dangerous>.

Eurostat. (2013). Retrieved Auguest, 2013, from The Statistical Office Of The European Communities: <http://epp.eurostat.ec.europa.eu/>.

Fewings, P. (2005). *Construction Project Management.* Taylor and Francis.

Fontana, R. J. (2007). Ultra wideband technology – obstacles and opportunities. *Plenary Talk, European Microwave Conference.* Munich, Gemany.

Fullerton, C. E., Allread, B. S., and Teizer, J. (2009). Pro-sctive-real-time personnel warning system. *Proceedings of the Construction Research Congress*. Seattle, Washington, U.S. pp. 31-40.

Gezici, S., Tian, Z., Biannakis, G. B., Kobayashi, H., Molisch, A. F., Poor, H. V., and Sahinoglu, Z. (2005). Localization via ultra-wideband radios: a look at positioning aspects for future sensor networks. *Signal Processing Magazine*, *IEEE*, 22(4), pp. 70-84.

Ghavami, M., Michael, L., and Kohno, R. (2004). *Ultra wideband signals and systems in communication engineering.* John Wiley and Sons.

Giretti, A., Carbonari, A., Naticchia, B., and Grassi, M. D. (2009). Design and first development of an automated real-time safety management system for construction sites. *Journal of Civil Engineering and Management, 15*(4), pp. 325-336.

Guo, S. J. (2002). Identification and resolution of work space conflicts in building construction. *Construction Engineering and Management, ASCE, 128*(4), pp. 287-295.

Guttman, M. (2011). WhiteFeet Tools for Revit. *WhiteFeet*. Retrieved April, 2013, from: <http://whitefeet.com/Tools/index.php>.

Hammad, A., Asen, Y., and Zhang, C. (2011). Visualising construction processes using sugmented reality: Fusing BIM, video monitoring and location information. *the 11th International Conference on Construction Applications of Virtual Reality.* Weimar, Germany.

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

Heesom, D., Mahdjoubi, L., and Proverbs, D. (2003). A dynamic VR system for visualizing construction space usage. *Construction Research Congress*.

Huang, X., and Hinze, J. (2003). Analysis of construction worker fall accidents. *Construction Engineering and Management, 129*(3), pp. 262–271.

Isikdag, U., Underwood, J., and Aouad, G. (2008). An investigation into the applicability of building information models in geospatial environment in support of site selection and fire response management. *Advanced Engineering Informatics*, *22*(4), pp. 504-519.

Jian, J. (2011). *Development of a Web Service for Visualizing the Data of Ultra Wideband Real-Time Location System.* Master Thesis, Concordia University. Montreal, Canada.

Khemlani, L. (2004). The IFC building model: A look under the hood. Retrieved February, 2013, from AECbytes: <http://www.aecbytes.com/feature/2004/IFCmodel.html>.

Kiviniemi, M., Sulankivi, K., Kähkönen, K., Mäkelä, T., and Merivirta, M. L. (2011). *BIM-based safety Management and Communication for Building Construction.* Retrieved March, 2013, from <http://www.vtt.fi/inf/pdf/tiedotteet/2011/T2597.pdf>.

Lachapelle, G. (2004). GNSS indoor location technologies. *Journal of Global Positioning Systems*, 3, pp. 2-11.

Lucy, J. (2011). Welcome to the world of BIM. *Electrical Wholesaling*. Retrieved September, 2013, from: <http://ewweb.com/e-biz/welcome-world-bim>.

Miller, L. E. (2003). Why UWB? A review of ultrawideband technology. *National Institute of Standards and Technology (NIST)*. Gaithersburg, Maryland.

Mitchell, J., and Schevers, H. (2005). Building information modelling for FM using IFC. *CRC for Construction Innovation.* Retrieved March, 2013, from <http://eprints.qut.edu.au/27188/1/27188.pdf>.

Motamedi, A., and Hammad, A. (2009). Lifecycle management of facilities components using radio frequency identification and building information model. *Information Technology in Construction, 14,* pp. 238-262.

Muthukrishnan, K., and Hazas, M. (2009). Position Estimation from UWB pseudorange and angle-of-arrival: A comparison of non-linear regression and kalman filtering. *Proceedings of the 4th International Symposium on Location and Context Awareness*. Tokyo, Japan. pp. 222-239.

NBIMS (2007). National Building Information Modeling Standard. *National Institute of Building Sciences.* Retrieved March, 2013, from <http://www.wbdg.org/pdfs/NBIMSv1_p1.pdf>.

National census of fatal occupational injuries in 2011. (2012). *Bureau of labor statistics, U.S department of Labour*. Retrieved March 08, 2013, from <http://www.bls.gov/news.release/pdf/cfoi.pdf>.

Navon, R., and Goldschmidt, E. (2003). Monitoring labor inputs: automated-data-collection model and enabling technologies. *Journal of Automation in Construction, 12*(2), pp. 185-199.

Navon, R., Goldschmidt, E., and Shpatnisky, Y. (2003). A concept proving prototype of automated earthmoving control. *Journal of Automation in Construction, 13*(2), pp. 225-239.

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

NIOSH (2010). The National Institute for Occupational Safety and Health, Goal 1: Reduce the major risks associated with traumatic injuries and fatalities in construction. Retrieved June, 2010, from <www.cdc.gov/niosh/nas/construction>.

Razavi, S. N., and Haas, C. T. (2011). Using reference RFID tags for calibrating the estimated locations of construction materials. *Journal of Automation in Construction, 20*(16), pp. 677-685.

Riaz, Z., Edwards, D. J., and Thorpe, A. (2006). SightSafety: A hybrid information and communication technology system for reducing vehicle/pedestrian collisions. *Journal of Automation in Construction, 15*(6), pp. 719 – 728.

Rodriguez, S. (2010). *Experimental study on location tracking of construction resources using UWB for better productivity and safety.* Master Thesis, Concordia University. Montreal, Canada.

Sacks, R., Rozenfeld, O., and Rosenfeld, Y. (2009). Spatial and temporal exposure to safety hazards in construction. *Construction Engineering and Management, ASCE, 135*(8), pp. 726-736.

Safety shield systems. (2012). *Personnel Shield*. Retrieved January, 2012, from: <www.utilityshield.co.uk/personnelshield.html>.

Setayeshgar, S., Hammad, A., Vahdatikhaki, F. and Zhang, C. (2013). Real-Time Safety Risk Analysis of Construction Projects Using BIM and RTLS, *International Symposium on Automation and Robotics in Construction (ISARC)*, Montreal, Canada.

Shehata, M. M., Khalek, H. A., and Hakam, M. A. (2013). Simulation analysis for productivity and unit cost by implementing GPS machine guidance in road construction operation in Egypt. *Proceedings of the 2012 International Conference on Sustainable Design, Engineering, and Construction*, *ASCE,* pp. 642-653.

Song, J., Haas, C. T., and Caldas, C. H. (2006). Tracking the location of materials on construction job sites. *Journal of Construction Engineering and Management, ASCE, 132*(9), pp. 911-918.

Tammik, J. (2011). Migrating the Building Coder Samples to Revit 2012. The Building Coder. Retrieved from: <http://thebuildingcoder.typepad.com/blog/2011/04/migrating-the-building-coder-samples-to-revit-2012.html>/

Tantisevi, K., Akinci, B. (2007). Automated generation of workspace requirements of mobile crane operations to support conflict detection. Journal of Automation in Construction, 16, pp. 262-276.

Taylor, M. D. (2009). *How to Develop Work Breakdown Structures.* Retrieved April, 2013, from <http://caldenergine.com/How%20to%20Develop%20Work%20Breakdown%20 Structures.pdf>.

Teizer, J., and Castro-Lacouture, D. (2007). Combined ultra-wideband positioning and range imaging sensing for productivity and safety monitoring in building construction. *Proceedings of the 2007 ASCE International Workshop on Computing in Civil Engineering, ASCE*, Pittsburgh, Pennsylvania, U.S., pp. 681-688.

Teizer, J., and Vela, P. A. (2009). Personnel tracking on construction sites using video cameras. *Advanced Engineering Informatics,* 23(4), pp. 452-462.

Teizer, J., Bosche, F., Caldas, C. H., and Haas, C. T. (2006). Real-time spatial detection and tracking of resources in a construction environment. *Proceedings of the Joint*

International Conference on Computing and Decision Making in Civil and Building Engineering, Montreal, Canada, pp. 494-502.

Teizer, J., Liapi, K. A., Caldas, C. H., and Haas, C. T. (2005). Experiments in real-time spatial data acquisition for obstacle detection. *Construction Research Congress.* San Diego, CA, U.S.

The Contractors' Guide to BIM. (2006). *The Associated General Contractors of America.* Retrieved March, 2013, from <http://tpm.com/wp-content/uploads/2013/02/AGC_Guide_to_BIM.pdf>.

Ubisense real-time location systems. (2013). Ubisense. Retrieved from Ubisense: <http://www.ubisense.net/en/>.

Walters, N., and Bolt, H. (2009). *Phase 1 Report: Underlying causes of construction fatal accidents – A comprehensive review of recent work to consolidate and summarise existing knowledge*. Retrieved March, 2013, from <http://www.hse.gov.uk/construction/resources/phase1.pdf>.

Ward, A. M., and Webster, P. M. (2009). Location device and system using UWB and non-UWB signals. *Patent No. US 7636062 B2.* U.S.

Zebra. (2013). Location solutions. Retrieved from: <http://www.zebra.com/us/en.html>.

Zhang, C. (2010). *Improving Crane Safety by Agent-Based Dynamic Motion Planning Using UWB Real-time Location System.* Ph.D. Thesis, Concordia University. Montreal, Canada.

Zhang, C., and Hammad, A. (2012). Multiagent approach for real-time collision Avoidance and path replanning for cranes. *Journal of Computing in Civil Engineering*, 26(6), pp. 782-794.

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

Zhang, C., Hammad, A., Soltani, M., Setayeshgar, S., and Motamedi, A. (2012a). Dynamic virtual fences for improving workers safety using BIM and RTLS. *14th International Conference on Computing in Civil and Building Engineering.* Moscow, Russia.

Zhang, C., Hammad, A., and Rodriguez, S. (2012b). Crane pose estimation using UWB real-time location system. *Journal of Computing in Civil Engineering, 26*(5), pp. 625-637.

Zhang, S., Teizer, J., Lee, J., Estman, C., and Venugopal, M. (2013). Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules. *Journal of Automation in Construction, 29* pp. 183-195.

Zhou, A., Ding, L. Y., and Chen, L. J. (2013). Application of 4D visualization technology for safety management in metro construction. *Journal of Automation in Construction, 34*, pp. 25-36.

Zhou, W., Whyte, J., and Sacks, R. (2012). Construction safety and digital design: A review. *Journal of Automation in Construction, 22*, pp. 102-111.

Appendix A – CSST Report on Safety

The following data are provided from the Quebec's Commission de la santé et de la securite du travail and represent the main risks of injury in different sectors of the construction industry between 2001 and 2010 (CSST, 2013).

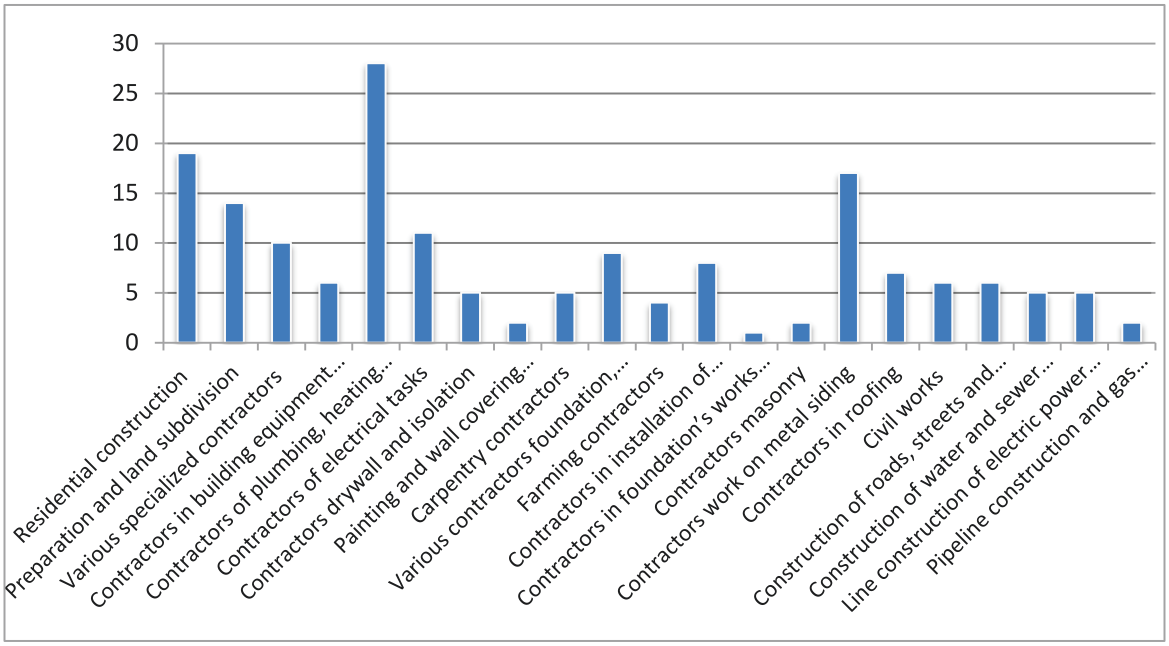


Figure A-1 Number of accidents by type of the project

Figure A-2 Number of accidents by the sector

Code	Category	Number of accident
Construction of Buildings	**Total:**	**19**
236220	Construction of buildings and structures in industrial buildings and commercial and institutional use	0
236110	Residential construction	19
Specialty Trade Contractors	**Total:**	**129**
238910	Preparation and land subdivision	14
238990	Various specialized contractors (except foundation, finish building, installation of technical equipment, …)	10
238291	Contractors of installation of lifts and escalators	0
238299	Contractors in building equipment (excluding lifts, escalators, electrical work, plumbing, …)	6
238220	Contractors of plumbing, heating and air conditioning	28
238210	Contractors of electrical tasks	11
238390	Contractors finishing building (except small carpentry, terrazzo flooring, painting, isolation, ...)	0
238310	Contractors drywall and isolation	5
238320	Painting and wall covering contractors	2
238350	Carpentry contractors	5
238340	Contractors tile and terrazzo	0
238330	Contractors work flooring	0
238190	Various contractors foundation, structure and building exterior (except roofing, masonry, carpentry, …)	9
238130	Farming contractors	4
238120	Contractors in installation of structural steel and precast concrete	8
238110	Contractors in foundation's works and poured concrete structure	1
238140	Contractors masonry	2
238170	Contractors work on metal siding	17
238160	Contractors in roofing	7
238150	Contractors work of glass and glazing	0
Civil works	**Total:**	**24**
237990	Civil works (Except land subdivision and construction of roads, streets, bridges and utility lines)	6
237310	Construction of roads, streets and bridges	6
237110	Construction of water and sewer line and related structures	5
237130	Line construction of electric power transmission and telecommunications and related structures	5
237120	Pipeline construction and gas pipelines and related structures	2
	Total Number of Accidents	**172**

APPENDIX B - THE CODE FOR AUTOMATIC DETECTION OF FALLING HAZARDS IN REVIT

The following code is developed based on a similar code found online at the BuildingCoder website (Tammik, 2011). The original code was developed by Jeremy Tammik and it has been developed to determine the plane that a given curve resides in and to return its normal vector. The following code is the modified version of the abovementioned code and it will automatically generate perpendicular lines at the edges and openings of slabs. These lines are assumed to represent virtual fences. All of the modification made to the original code are highlighted in yellow, enclosed in a box and explained in a comment.

```
namespace BuildingCoder
{
  class Creator
  {
    // these are
    // Autodesk.Revit.Creation
    // objects!
    Autodesk.Revit.Creation.Application _app;
    Autodesk.Revit.Creation.Document _doc;

    public Creator( Document doc )
    {
      _doc = doc.Create;
      _app = doc.Application.Create;
    }

    /// <summary>
    /// Determine the plane that a given curve resides in and return its normal
vector.
    /// Ask the curve for its start and end points and some curve in the middle.
    /// The latter can be obtained by asking the curve for its parameter range and
    /// evaluating it in the middle, or by tessellation. In case of tessellation,
    /// you could iterate through the tessellation points and use each one
together
    /// with the start and end points to try and determine a valid plane.
    /// Once one is found, you can add debug assertions to ensure that the other
    /// tessellation points (if there are any more) are in the same plane.
    /// In the case of the line, the tessellation only returns two points.
    /// I once heard that that is the only element that can do that, all
    /// non-linear curves return at least three. So you could use this property
```

```
  /// to determine that a line is a line (and add an assertion as well, if you
like).
  /// Update, later: please note that the Revit API provides an overload of the
  /// NewPlane method taking a CurveArray argument.
  /// </summary>
  XYZ GetCurveNormal( Curve curve )
  {
   IList<XYZ> pts = curve.Tessellate();
   int n = pts.Count;

   Debug.Assert( 1 < n,
    "expected at least two points "
    + "from curve tessellation" );

   XYZ p = pts[0];
   XYZ q = pts[n - 1];
   XYZ v = q - p;
```

```
   XYZ w, w1, w2, fence, normal = null;
   // *** Three additional parameters namely w1, w2 and fence
are defined to be used in the next steps.
```

```
   if( 2 == n )
   {
    Debug.Assert( curve is Line,
     "expected non-line element to have "
     + "more than two tessellation points" );

    // for non-vertical lines, use Z axis to
    // span the plane, otherwise Y axis:

    double dxy = Math.Abs( v.X ) + Math.Abs( v.Y );

    w = ( dxy > Util.TolPointOnPlane )
     ? XYZ.BasisZ
     : XYZ.BasisY;

    normal = v.CrossProduct( w ).Normalize();
   }
   else
   {
    int i = 0;
    while( ++i < n - 1 )
    {
     w = pts[i] - p;
     normal = v.CrossProduct( w );
     if( !normal.IsZeroLength() )
     {
      normal = normal.Normalize();
      break;
     }
    }

  #if DEBUG
    {
     XYZ normal2;
```

```
      while( ++i < n - 1 )
      {
        w = pts[i] - p;
        normal2 = v.CrossProduct( w );
        Debug.Assert( normal2.IsZeroLength()
          || Util.IsZero( normal2.AngleTo( normal ) ),
          "expected all points of curve to "
          + "lie in same plane" );
      }
    }
#endif // DEBUG

  }
  return normal;
}

/// <summary>
/// Miroslav Schonauer's model line creation method.
/// A utility function to create an arbitrary sketch
/// plane given the model line end points.
/// </summary>
/// <param name="app">Revit application</param>
/// <param name="p">Model line start point</param>
/// <param name="q">Model line end point</param>
/// <returns></returns>
public static ModelLine CreateModelLine(
  Document doc,
  XYZ p,
  XYZ q )
{
  if( p.DistanceTo( q ) < Util.MinLineLength ) return null;

  // Create sketch plane; for non-vertical lines,
  // use Z-axis to span the plane, otherwise Y-axis:

  XYZ v = q - p;

  double dxy = Math.Abs( v.X ) + Math.Abs( v.Y );

  XYZ w = ( dxy > Util.TolPointOnPlane )
    ? XYZ.BasisZ
    : XYZ.BasisY;

  XYZ norm = v.CrossProduct( w ).Normalize();

  Autodesk.Revit.Creation.Application creApp
    = doc.Application.Create;

  Plane plane = creApp.NewPlane( norm, p );

  Autodesk.Revit.Creation.Document creDoc
    = doc.Create;

  SketchPlane sketchPlane = creDoc.NewSketchPlane( plane );

  return creDoc.NewModelCurve(
    creApp.NewLine( p, q, true ),
```

```
    sketchPlane ) as ModelLine;
}

SketchPlane NewSketchPlanePassLine(
  Line line )
{
  XYZ p = line.get_EndPoint( 0 );
  XYZ q = line.get_EndPoint( 1 );
  XYZ norm;
  if( p.X == q.X )
  {
    norm = XYZ.BasisX;
  }
  else if( p.Y == q.Y )
  {
    norm = XYZ.BasisY;
  }
  else
  {
    norm = XYZ.BasisZ;
  }
  Plane plane = _app.NewPlane(
    norm, p );

  return _doc.NewSketchPlane( plane );
}

public void CreateModelLine( XYZ p, XYZ q )
{
  if( p.IsAlmostEqualTo( q ) )
  {
    throw new ArgumentException(
      "Expected two different points." );
  }
  Line line = _app.NewLine( p, q, true );
  if( null == line )
  {
    throw new Exception(
      "Geometry line creation failed." );
  }
  _doc.NewModelCurve( line,
    NewSketchPlanePassLine( line ) );
}

/// <summary>
/// Return a new sketch plane containing the given curve.
/// Update, later: please note that the Revit API provides
/// an overload of the NewPlane method taking a CurveArray
/// argument, which could presumably be used instead.
/// </summary>
SketchPlane NewSketchPlaneContainCurve(
  Curve curve )
{
  XYZ p = curve.get_EndPoint( 0 );
  XYZ normal = GetCurveNormal( curve );
  Plane plane = _app.NewPlane( normal, p );
```

```
    #if DEBUG
      if( !(curve is Line) )
      {
        CurveArray a = _app.NewCurveArray();
        a.Append( curve );
        Plane plane2 = _app.NewPlane( a );

        Debug.Assert( Util.IsParallel( plane2.Normal,
          plane.Normal ), "expected equal planes" );

        Debug.Assert( Util.IsZero( plane2.SignedDistanceTo(
          plane.Origin ) ), "expected equal planes" );
      }
    #endif // DEBUG

      return _doc.NewSketchPlane( plane );
    }

    public void CreateModelCurve( Curve curve )
    {
      _doc.NewModelCurve( curve,
        NewSketchPlaneContainCurve( curve ) );
    }

    public void DrawPolygons(
      List<List<XYZ>> loops )
    {
      XYZ p1 = XYZ.Zero;
      XYZ q = XYZ.Zero;

      XYZ fence = XYZ.Zero;
      // *** XYZ fence = XYZ.Zero in added to assign zero to the
X, Y and Z coordinate of the parameter fence.

      bool first;
      foreach( List<XYZ> loop in loops )
      {
        first = true;
        foreach( XYZ p in loop )
        {
          if( first )
          {
            p1 = p;
            first = false;
          }
          else
          {
            CreateModelLine( p, q );
          }
          q = p;
        }
        CreateModelLine( q, p1 );
      }
    }

    public void DrawFaceTriangleNormals( Face f )
```

```
{
  Mesh mesh = f.Triangulate();
  int n = mesh.NumTriangles;

  string s = "{0} face triangulation returns "
    + "mesh triangle{1} and normal vector{1}:";

  Debug.Print(
    s, n, Util.PluralSuffix( n ) );

  for( int i = 0; i < n; ++i )
  {
    MeshTriangle t = mesh.get_Triangle( i );

    XYZ p = ( t.get_Vertex( 0 )
      + t.get_Vertex( 1 )
      + t.get_Vertex( 2 ) ) / 3;
```

```
    XYZ v = t.get_Vertex(1);
      //- t.get_Vertex( 0 );

    XYZ w1 = t.get_Vertex(2);
      //- t.get_Vertex( 0 );

      XYZ w2 = t.get_Vertex(0);
     // - t.get_Vertex(1);

   // XYZ normal = v.CrossProduct(w1).Normalize() * 10;

  //  Debug.Print(
  //    "{0} {1} --> {2}", i,
  //    Util.PointString( p ),
  //    Util.PointString( normal ) );

      // *** The above comments were removed from the original code.
```

```
      if (v.X == w1.X & v.Y == w1.Y)
      {

          if (v.Z >= w1.Z)
          {
              XYZ fence = (v - w1) * 5;
              CreateModelLine(v, v + fence);
          }
          if (v.Z < w1.Z)
          {
              XYZ fence = (w1 - v) * 5;
              CreateModelLine(w1, w1 + fence);
          }
      }

      if (w1.X == w2.X & w1.Y == w2.Y)
      {

          if (w1.Z >= w2.Z)
```

```
              {
                  XYZ fence = (w1 - w2) * 5;
                  CreateModelLine(w1, w1 + fence);
              }
              if (w1.Z < w2.Z)
              {
                  XYZ fence = (w2 - w1) * 5;
                  CreateModelLine(w2, w2 + fence);
              }
          }

          if (v.X == w2.X & v.Y == w2.Y)
          {

              if (v.Z >= w2.Z)
              {
                  XYZ fence = (v - w2) * 5;
                  CreateModelLine(v, v + fence);
              }
              if (v.Z < w2.Z)
              {
                  XYZ fence = (w2 - v) * 5;
                  CreateModelLine(w2, w2 + fence);
              }

              // *** This part is added to compare the coordinates
of the v, w1, and w2 parameters in order to assign the proper
value for the fence parameter. For example this command “if (v.X
== w1.X & v.Y == w1.Y)” will check if the X and y value of
parameter v and w1 are equal.
          }

      }
    }
  }
}
```

APPENDIX C - LIST OF RELATED PUBLICATIONS

Articles in refereed conference proceedings:

1. Vahdatikhaki, F., Hammad, A., and **Setayeshgar. S. (2013)**. A Location-Aware Real-Time Simulation Framework for Improved Productivity and Safety of Earthmoving Projects Using Automated Machine Guidance, *Winter Simulation Conference (WSC)*, Washington D.C., USA.
2. **Setayeshgar, S**., Hammad, A., Vahdatikhaki, F. and Zhang, C. **(2013)**. Real-Time Safety Risk Analysis of Construction Projects Using BIM and RTLS, *International Symposium on Automation and Robotics in Construction (ISARC),* Montreal, Canada.
3. Vahdatikhaki, F., Hammad, A., and **Setayeshgar, S. (2013)**. Context-Aware Real-Time Simulation of Earthmoving Projects Using Automated Machine Guidance, *International Symposium on Automation and Robotics in Construction (ISARC),* Montreal, Canada.
4. Motamedi, A., **Setayeshgar, S.**, Soltani, M. M., and Hammad, A. **(2013)**. Extending BIM to Incorporate Information of RFID Tags Attached to Building Assets, *International Conference on Computing in Civil and Building Engineering,* Montreal, Canada.
5. Hammad, A., Zhang, C., **Setayeshgar, S,** and Asen, Y. **(2012)**. Automatic Generation of Dynamic Virtual Fences as Part of BIM-Based Prevention Program for Construction Safety, *Winter Simulation Conference (WSC),* Berlin, Germany.
6. Zhang, C., Hammad , A., Soltani, M. 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.
7. Mawlana, M., Hammad, A., Doriani A., and **Setayeshgar, S. (2012)**. Discrete Event Simulation and 4D Modeling for Elevated Highway Reconstruction Projects, *International Conference on Computing in Civil and Building Engineering,* Moscow, Russia.