Worker **S**afety **I**n **C**onfined **S**paces **U**sing **E**merging **T**echnologies

By

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To my parents and my sisters,

Their love and support has always been a source of inspiration to me.

Certificate of Originality

I hereby declare that the Research Thesis titled "***Worker safety In Confined Spaces Using Emerging Technologies***" is my own work and to the best of my knowledge. It contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST or any other education institute, except where due acknowledgment, is made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST or elsewhere, is explicitly acknowledged in the thesis.

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Muhammad Arslan

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List of Abbreviations

AEC	Architecture, Engineering and Construction
API	Application Programming Interface
BIM	Building Information Modeling
CAD	Computer Aided Design
CIB	Capacity and Institution Building
CoSMoS	Confined Spaces Monitoring System
CSV	Comma Separated Values
GUI	Graphical User Interface
H&S	Health and Safety
HSE	Health and Safety Executive
IB	Intelligent Building
ICT	Information and Communication Technology
MEP	Mechanical, Electrical and Plumbing
NIBS	National Institute of Building Sciences
OSHA	Occupational Safety and Health Administration
RFID	Radio Frequency Identification
RTM	Real Time Monitoring
SDK	Software Development Kit
WSN	Wireless Sensor Networks

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Abstract

Acquisition of sensor data from the field is essential not only for ensuring reliable building operations but can also help in dynamic management of various tasks which are associated with H&S. An important aspect of H&S management in a building or a construction site is to monitor and control the potential risks associated with worker safety. Within the construction industry, accident statistics indicate that there are fatalities as well as serious injuries in confined spaces due to exposure to hazardous environment. A review of international safety regulations suggest that lack of oxygen and temperature extremes contribute to make these work environment hazardous in confined places.

Building Information Modeling (BIM) offers a new epitome to provide comprehensive solutions for H&S and evacuation planning in confined spaces. It has the potential to provide improved visualization for effective monitoring of confined spaces on construction sites. Researchers around the globe have presented hybrid solutions for integrating different sensing technologies with BIM such as Radio Frequency Identification (RFID) tags, Ultra High Frequency (UHF) Readers and Sensors. A review and critical evaluation of literature on integrated solutions of BIM with various sensing technologies is performed in order to present a hybrid solution based on BIM and Wireless Sensors Networks (WSNs) along with a notification system for confined spaces. The application, entitled *CoSMoS*, deals with acquisition and presentation of data received from wireless sensors placed at confined spaces in a building or a construction site. The proposed solution will help safety managers to monitor confined spaces through real-time sensor data to avoid time sensitive emergency situations in confined spaces.

Chapter 1: Introduction

Safety records in the construction industry continue to be one of the poorest [1]. Research shows that major causes of accidents are related to the unique nature of the industry, human behavior, difficult site conditions, and poor safety management, which result in unsafe work methods, equipment and procedures [2]. Emphasis needs to be placed on the utilization of comprehensive safety programs and deployment of modern information and communication technologies to improve safety performance of the industry [3-5]. Consequently, in the developed countries the construction environment has incorporated safety as an integral part in the regulatory framework where areas of safety concerns and accident categories are monitored and recorded [6, 7].

One such area of safety concern, on construction as well as other jobsites, is workers operating in confined spaces. A confined space has been defined by Occupational Safety and Health Administration (OSHA) as "any space that has limited means for entry or exit and that is primarily not designed for continuous worker occupancy will be treated as a confined space" [8]. Tanks, boilers, storage bins, silos and poor ventilated rooms are some of the examples of confined spaces [9]. In 1993, OSHA issued safety regulation for confined spaces (29 CFR 1910.146) and a code of conduct which was intended to avoid thousands of injuries and fatalities each year [10]. However, working in confined spaces remains a problem even in presence of these regulations. According to the U.S. Bureau of Labor Statistics, out of 4,609 workers killed on jobsites due to illness and fatalities 9% of injuries were due to the exposure to hazardous environment and 3% of injuries were caused by fire and explosions [11, 12].

Table 1: Acceptable Limits of Oxygen in Confined Space

H&S Regulators	Upper limit (%)	Lower limit (%)	References
Safe Work AU	23.5	19.5	[15]
OSHA	22	19.5	[16]
HSE	20.8	16	[13]

Table 2: Acceptable Limits of Temperature in Confined Space

H&S Regulators	Upper limit ($°C$)	Lower limit ($°C$)	References
OSHA	32	-	[16]
HSE	30	13	[13]

Deficiency of oxygen and increase in temperature in confined spaces are the main causes of instant death and other fatalities faced by construction workers [12]. All occupational health and safety regulators such as Health and Safety Executive (HSE) [13], OSHA [7], Safe Work Australia (AU) [14] etc. have provided code of practices to reduce H&S hazards in confined spaces and have suggested minimum and maximum oxygen and temperature levels to be monitored and maintained (see Table 1 and Table 2 for acceptable upper and lower limits of oxygen and temperature in confined spaces in US, UK and AU). Safe Work AU suggests that in confined spaces oxygen content should be continuously monitored both during and prior to starting work. If oxygen content in air drops by 19.5% by volume or increases from 23.5 % by volume then entry in confined spaces should be avoided [15]. While OSHA made 22 % by volume as upper limit of oxygen content [16]. OSHA suggests that increase in oxygen level beyond the upper limit in a confined space may be hazardous since any ignition source may cause fire. Consequently, there is a need of an effective ‘real-time’ monitoring of oxygen and temperature levels in a confined space environment in order to improve worker safety.

BIM and WSN based integrated solution is proposed with the objective of monitoring the environment of confined spaces, where the physical condition and safety of operators is at high risk. Visualization of confined spaces is achieved using BIM based Autodesk Revit Architecture software whereas, WSN consists of a number of sensors to monitor real-time temperature and oxygen values. In addition, the proposed system sends alerts and notifications to building supervisors and H&S manager to take necessary actions if wireless sensor data goes across the defined thresholds.

Statement of the Problem

The literature of the past and present contains comprehensive studies on the integration of Radio Frequency Identification (RFID) technology with Building Information Modeling (BIM) but RFID is limited in its functionalities and does not provide cost effective solutions.

The purpose of this research study is to investigate the challenges and will explore the possibility of integrating wireless sensor technology with BIM and making an application for reducing the risks involved in working in confined spaces of a building or a construction site.

Background of the Study

“Working in a confined space is more hazardous than working in other workspaces” [10]

And

“With BIM and sensor technology, H&S management can be improved” [17]

The above first quotation highlights the importance of research need to be done for the purpose of reducing the hazards involved in working in confined spaces. Second above quotation gives a vision of improving the safety of workers in a building or in construction site with the help of BIM and sensor based emerging technologies, which will be used for the purpose of monitoring the confined spaces and will help to reduce hazards.

Significance of the study

"During the retro of 2005-2009, approximately 100 fatalities occurred each year in confined spaces and about 61% of these fatalities happened during construction, repairing or cleaning activities according to US Department of Labor Statistics"[11].

Atmospheric hazards are the most common type of confined space emergencies and oxygen deficiency is one of the important kinds of atmospheric hazards [11]. A large number of fatalities have been observed during the construction and maintenance phases of a building lifecycle, which not only shows a lack in H&S management technologies but also demands a reliable means to monitor the building or construction site during the worker activity to avoid exposures. The reliable and effective monitoring of a building will not only help the building/site supervisors and H&S managers to ensure the safety culture in work but also contribute in reducing the cost of fatalities occur due to environmental hazards.

Research Questions

The research questions include:

a) How to monitor confined spaces in a building/construction site for air monitoring?

b) How to integrate and display the acquired environmental sensor data on Building Information Modeling (BIM) software for H&S management?

Thesis Structure

The thesis is divided into five chapters. Below Figure 1 illustrates the schematic layout of the thesis, and the subsequent text describes the content of each chapter.

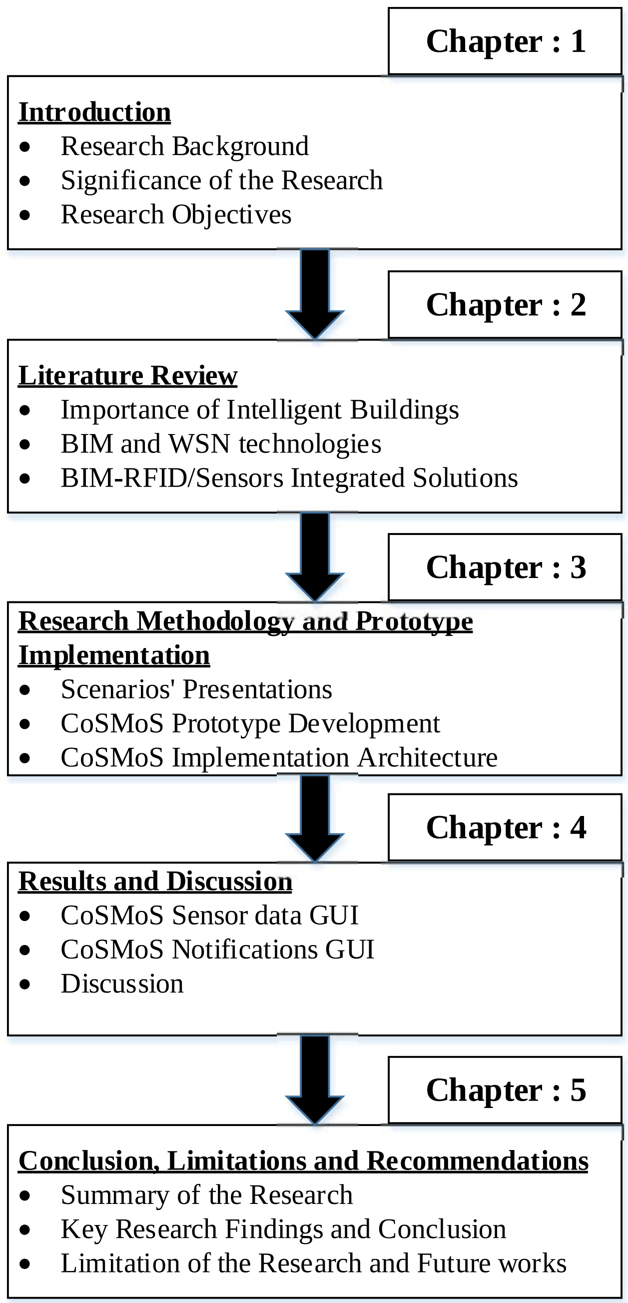

Figure 1: Thesis Structure

Chapter Summary

Having provided the contextual to the research and have justified the need for it, this chapter also identified the key research questions to be addressed and its impact and importance to the construction industry for H&S management. It has also been highlighted that atmospheric hazards make confined environments in any building or construction sites hazardous and cause fatalities and deaths of workers. Brief summary of the background of the research area has also provided.

Chapter 2: Literature Review

Introduction

Due to the need of incorporating H&S systems in buildings, a significant amount of attention has been given to the construction of the Intelligent Buildings (IB) in recent years [18, 19]. This chapter provides an insight into the basic concept of IB and understanding of BIM and WSN. Moreover, this chapter provides the summary of the integrated solutions based on BIM and RFID/Sensors technology, which are taken from the past literature.

Importance of Intelligent Buildings

Capacity and Institution Building (CIB) Working Group W98 on Intelligent and Responsive Buildings defined Intelligent Building (IB) as " *a dynamic and responsive architecture that provides every occupant with productive, cost effective and environmentally approved conditions through a continuous interaction among its four basic elements: Places (fabric; structure; facilities): Processes (automation, control; systems): People (services; users) and Management (maintenance; performance) and the interrelation between them*" [20]. Automatic control, learning abilities and occupancy trends incorporation are the main features of any IB [21]. Every system in the IB is interconnected with various environmental monitoring sensors such as air flow, activity sensing and control to provide user comfort with energy efficiency [22]. Monitoring of environmental parameters such as oxygen and temperature are important factors to ensure H&S of building occupants. However, such monitoring can be useful in construction phase as well. BIM is a powerful platform to manage complex building information which can be used to visualize building virtually during a complete building lifecycle.

Building Information Modeling

Building Information Modeling (BIM) has gained widespread attention in the Architectural, Engineering and Construction (AEC) industry [23-25]. Using BIM approach (see Figure 2), virtual models of buildings are constructed with all minor and major details prior to its physical construction [16, 17]. US National Institute of Building Sciences (NIBS) defines BIM as "*a digital representation of physical and functional characteristics of a facility*" [26-28].

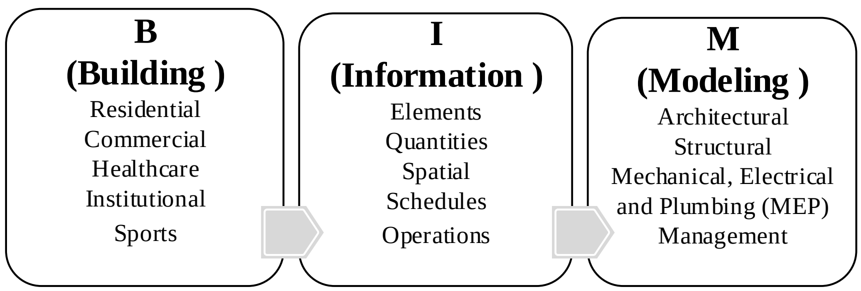

Figure 2: A Visual Representation of BIM Concept

NIBS declare BIM as a shared knowledge resource from conception to demolition of a facility, "… *forming a reliable basis for decisions during its life cycle. A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in BIM to support and reflect the roles of various stakeholders*" [28]. There are many software based on BIM technology, some of them are:

- Autodesk Revit (Architecture, Structures, MEP)
- Autodesk NavisWorks JetStream
- Bentley (Architecture, Structural Modeler, Mechanical designer)
- Graphisoft ArchiCAD
- Gehry Technologies Digital Project
- Tekla Structures

Some main characteristics of BIM have been discussed in Table 3 below.

Table 3 : BIM Characteristics

Characteristics of BIM	Description	References
Object Oriented	BIM is object-oriented in nature.	[29]
Interoperability	Exchanges and maintains the information through the entire lifecycle of buildings.	[29, 30, 31]
Vendor Neutral and Data Exchange	Building data can be exported into external database which can be used by several other applications.	[29, 30, 31]
Semantics	Functional information about the building elements is maintained in internal database of BIM in order to incorporate semantics.	[29]
View Generations	Different 3D snapshots can be easily generated and visualized.	[29, 30, 31]
Data Rich	Incorporates all the "physical" and "functional characteristics" of all building elements.	[29]

The main difference between BIM and conventional 3D CAD is the independent 3D view such as that of plans, sections and elevations [32]. In the conventional 3D CAD, editing any one of the views requires other views to be updated manually, but in case of BIM all 3D views are automatically updated and maintained [32]. In addition, drawings in the conventional CAD are the collection of lines, arcs and circles whereas, in BIM, all drawing objects are defined in terms of building elements such as wall, doors and columns. The information which corresponds to the properties to these building elements is maintained in internal database by a BIM software. Some of features of 3D CAD and BIM are compared in Table 4 [33-35]. This work will focus on visualization and facility management aspects of BIM.

Table 4 : Differences between 3D CAD and BIM

Features	**3D CAD**	**BIM**
Coordination between views	×	✓
Parametric solution	×	✓
Visibility management of objects	✓	✓
Auto zoom control	×	✓
Internal relational database	×	✓
Realistic visualization and rendering	×	✓
Cost estimation	×	✓
Energy simulations	×	✓
Lighting analysis	×	✓

Wireless Sensor Networks

Sensors are used to measure any physical quantity in the environment and play a vital role in situational awareness applications [36]. A sensor network is a collection of sensors which are scattered in the environment; these sensor nodes may gather data for temperature, sound, vibrations, humidity etc., process it and then transmit to a sensor network base station [38]. The sensor nodes can be connected to each other by wires or wirelessly [37]. Reliability, sensitivity, cost and size are some of the parameters in which sensors nodes can be classified [37].

Wireless Sensor Network (WSN) is an established paradigm that uses sensor nodes (i.e. motes) which communicate with each other wirelessly to collect and disseminate information to other motes or to publish it on the web [37]. WSNs provide sensing, processing and computing capabilities at low cost and eliminate the need of human involvement in sensor data collection [38, 39]. Sensor nodes have on-board processing power, on-board memory, wireless connectivity and a battery power source. Due to the portability of these motes, WSNs have gathered much attention as compared to wired networks. In the past and recent literature, there is a growing interest in establishing the WSNs to monitor building for temperature, energy consumption, indoor air quality and earthquake damage [41-45]. As mentioned earlier, the buildings which capture and sense such information are referred to as IBs. The building information provided through WSN can provide many opportunities to facilitate emergency situations during a building lifecycle.

Figure 3: TelosB Mote

TelosB is a commercially available mote by Crossbow Technology Inc. and it enables the creation of WSN to monitor environmental attributes such as temperature, humidity and light [40]. In this research work, IEEE 802.15.4 compliant TelosB motes (see Figure 3) based sensor network is established to monitor confined space environment and aim to avoid critical environmental situations by alerting safety manager timely. TelosB mote is one of the most popular sensor node design which is compatible with TinyOS operating system developed by UC Berkeley. TinyOS is a small, open source operating system which supports self-configuring sensor networks [46].

BIM and RFID Integrated Solutions

A BIM software, a BIM database, RFID tag information and software application are the main components of any BIM and RFID integrated system [46]. This integration is only possible by Application Programming Interfaces (API) offered by BIM as well as by RFID systems. A summary of BIM-RFID integrated solutions are listed in Table 5.

Taylor, et al. in 2009 discussed the importance of BIM-RFID integration by discouraging the manual material management process using flagging technique [47]. Hajian, et al. in 2009 suggested the BIM-RFID integration for project information management to increase the productivity rates of AEC industry [48]. Motamedi, et al. in 2009 showed the importance of distributed databases by using BIM-RFID technique for managers who don`t have access to centralized databases in real time [49]. Meadati, et al. in 2010 presented BIM-RFID integration to increase the information retrieval efficiency during the operation and management phases of a building [50]. Components installed in a building have RFID tag on it, which helps facility manager to locate it on BIM software. After getting the exact location it`s operating manuals and specifications can easily be accessed at the time of hazardous situations in buildings. Sattineni, et al. in 2010 demonstrated RFID-BIM integration for tracking assets and workers in a building [51]. It aimed to increase safety and productivity of workers on job sites and visualization is achieved using Autodesk Revit Architecture BIM based software.

Cheng, et al. in 2011 applied BIM-RFID integrated approach to planning, manufacturing, construction, maintenance and recycling phases of project management [52]. Tracking of building components is achieved and a Microsoft Access based database is maintained. Construction managers can view stored information about available resources during the entire life cycle of a building and actual quantities of components can easily be determined. This stored information can help in making calculations about the loss occurred by fire hazards in worksites. Costin, et al. in 2012 used BIM-RFID integrated solution for tracking the location of RFID tagged building components by providing a management system interface to a facility manager [53]. Motamedi, et al. in 2012 provided localization methods to locate fixed as well as movable assets inside a building using RFID and BIM integration [54]. The main advantage of this integrated technique based on localization method is it`s adaptability to environment. If positions of assets are changed with time, information will automatically be updated in a database and reference points are set accordingly for locating movable assets in a building. This integrated solution can also help to track the workers in building in hazardous situations. Hence, the solutions are primarily focusing on tracking and progress monitoring.

BIM and Sensors Integrated Solutions

Alahmadi, et al. in 2011 integrated BIM with Real Time Monitoring (RTM) system to monitor energy consumption in a building [55].

RTM consists of numerous sensors which are placed at different locations in a building for collecting energy usage data. By this integration, facility manager would able to monitor and control the unnecessary energy consumption in different locations in a building and a wireless communication between different energy consuming devices and BIM enables remotely shut down different devices in emergency situations in a building.

Table 5 : BIM and RFID Integrated Solutions

Primary Purpose	***Tracked Components and State***	***Location***	***Findings***	***Reference***
Material Management using RFID/GPS-BIM Approach	*Building material components (Stationary)*	*Power Plant Expansion project-Outdoor*	*Achieved easy and fast material tracking process in construction phase.*	*[47]*
Progress monitoring and lifecycle management	*HVAC components, Fire safety equipment* *(Movable and Stationary)*	*Construction building – Indoor and Outdoor*	*Achieved visualization of the status of a facility in Construction and Maintenance phases of a building under construction.*	*[49]*
Real-time monitoring of RFID tags in BIM Model	*Objects and People (Movable)*	*Building-Indoor*	*Imported RFID data in BIM model and displayed.*	*[51]*
Automated management of life cycle information of buildings	*Building components i.e. facilities, pipes etc. (Stationary)*	*Building-Outdoor*	*Generated 4-D virtual reality model, examined construction interfaces and conflicts in design phase and monitored construction installation works in real-time.*	*[52]*
Automated Identification	*Building component i.e. Projectors (Stationary)*	*Building-Indoor*	*Accessed* Operations *and Management (O&M) information of building components.*	*[50]*
Fixed Assets localization	*Fire extinguisher cabinets (Stationary)*	*Building-Indoor*	*Located RFID tagged building components without RTLS Services.*	*[56]*
Movable Assets localization	*RFID tags* *(Movable)*	*Building-Indoor*	*Located movable RFID tags without RTLS Services.*	*[54]*
Tracking of valuable assets in real-time	*HVAC, Light switch, Valve etc. (Stationary)*	*Building-Indoor*	*Maintained Database of valuable assets by tracking using passive RFID tags*	*[53]*

Woo, et al. in 2011 also presented BIM-Sensor based integrated solution with XML parsing engine for monitoring electricity consumption in a building [57]. Lee, et al. in 2012 integrated BIM with sensors to develop a Tower Crane Navigation (TCN) system which provides three dimensional information of lifted object by crane and surroundings using different sensors [58]. It will not only make easier for crane operator to work efficiently and will also increase safety at construction sites. Attar, et al. in 2012 proposed the concept of sensor enabled cubicles for visualizing the building performance in terms of its physical attributes of environment [59]. Analog outputs from different sensors has been digitized using interface board and sent to embedded computer. Web based database is maintained by collection of data received by embedded computer on a wireless channel. Front end software has been designed to use sensor data from a web database for visualization purposes. The proposed framework does not encounter user centric approach of visualization because every user which can be building occupant, facility manager or owner has its own requirements for deploying sensor network, which need to be explored.

Cahill, et al. in 2012 and Ozturk, at al. in 2012 also highlighted the importance of sensor networks deployment in buildings for the purpose of decreasing the operational and maintenance costs of buildings [60, 61]. Incorporating sensors in buildings for facility management operations like monitoring energy performance will be a next step towards intelligent buildings. The summary of above discussed BIM-Sensors based integrated solutions are mentioned in Table 6.

Table 6 : BIM and Sensors Integrated Solutions

Purpose	***Type of Sensors Used***	***Location***	***Findings***	***Reference***
Building Energy Management	*Temperature, Humidity, Light sensors*	*Building-Indoor*	*Proposed a wireless sensor network design tool to support building energy management.*	*[62]*
Building Energy Monitoring	*Electricity consumption sensors*	*Building-Indoor*	*Highlighted importance of BIM-based Baseline Building Model for monitoring building environments.*	*[57]*
Real Time Building Energy Monitoring	*Voltage, Current, Power sensors*	*Building-Indoor*	*Proposed solution to reduce energy usage in a building.*	*[55]*
Crane Navigation System for blind lifts	*Laser, Load sensors*	*Building-Outdoor*	*Displayed location of a lifted object by crane in the context of a building and the surroundings using an imported BIM model where data is collected through sensors and a video camera.*	*[58]*
Visualization of Building Performance	*Temperature, Humidity, Light, motion, CO_2, Current sensors*	*Building – Indoor*	*Achieved Real-time visualization of building performance data.*	*[59]*
Optimization of Building Operations	*Temperature, Humidity, Light, CO_2 , Presence Detection sensors*	*Building – Indoor*	*Monitored sensor data and identified relevant IFC objects that could support sensor data*	*[60]*
Post Occupancy Evaluation (POE) in Residential Buildings	*Temperature, Humidity, energy consumption sensors*	*Building – Indoor*	*Monitored real-time building related energy performance*	*[61]*

Continues…

…Continued

Purpose	***Type of Sensors Used***	***Location***	***Findings***	***Reference***
BIM based generation of multi-model views	*Temperature and Humidity sensors*	*Building – Indoor*	*Examined the control of the air conditioning system via sensors for the case of rooms with smart IT devices.*	*[62]*
Use of BMS to monitor a building's operation and energy performance.	*Temperature, CO2 and Humidity*	*Building – Indoor*	*Proposed an improvement for the controlling and monitoring of building services based on the Building Management System (BMS) and (BIM).*	*[63]*
WSN for building energy management application	*Temperature, Humidity Light sensors, Motion and Occupation sensors*	*Building – Indoor*	*Presented design and development of a Zigbee based WSN for building monitoring and explored its usage as an input tool the development of BIM models.*	*[64]*
Integration of BIM with sensors to improve the mobility and practicality of BIM models.	*Inclinometers and GPS sensors*	*Building – Indoor/outdoor*	*Proposed a framework for real-time interactive BIM models as a real-time interactive visualization tool.*	*[65]*
Establishment of fire control management system in BIM environment	*Fire sensors*	*Building – Indoor*	*Proposed an approach to determine the authenticity of fire alarms to prevent disturbances due to false alarms.*	*[66]*
To identify, archive and manage building performance data and information.	*Temperature and Flow sensors*	*Building – Indoor*	*Proposed a system for visualizing of performance information through desktop and handheld interfaces and long term sensor data storage.*	*[67]*

Chapter Summary

The chapter has examined that practice of various sensing technologies to introduce intelligence in buildings for improved productivity and also provided an outlook that how the integration of technologies can contribute to H&S management in buildings and remote monitoring. It is concluded after detailed review of past integrated solutions based on BIM and RFID/Sensors that the application of BIM-WSN integrated approach should not only be explored for H&S management on construction sites for worker safety but also for improved visualizations of confined spaces.

Chapter 3: Research Methodology and Prototype Implementation

Introduction to Research Method

The literature review was initially performed to systematically gather information about emerging BIM infrastructure and wireless sensor technologies and their integration (briefly discussed previously in Table 5 & 6). Applications of similar technologies in other industries were also reviewed and a conceptual model for technology application was developed from this review. It was later shaped into a scenario through an iterative process by carrying out a series of semi-structured interviews and a survey with industry experts. This combination, of analysis and expert input and the literature review, was used to develop and refine realistic user scenario; in which the capabilities of BIM and wireless sensor technologies were mapped to the information needs of the construction workforce responsible for health and safety. This was followed by a prototype development as a proof of concept. The next step for the research will be detailed evaluation of this prototype by the international construction industry experts to find out more about the effectiveness, utility and barriers of proposed prototype from the construction industry perspective. This understanding will lead to drawing up user needs, gathering system requirements and eventually system design and its evaluation.

This research work proposes a prototype system entitled '*CoSMoS*' (Confined Space Monitoring System) exploring the integration of wireless sensors and BIM to address the H&S concerns of workers in under construction buildings. In an attempt to reduce environmental hazards in confined spaces, *CoSMoS* focuses on:

- Monitoring the oxygen and temperature sensor values using data collection from sensors placed in two different locations (confined space areas) in a building.

- Displaying updated sensor data in Revit Architecture Graphical User Interface (GUI).
- Enabling sound based alerts and notifications to Building/Site Supervisors and H&S manager to take necessary actions if sensor data crosses threshold limits.

Scenario Presentation

This section describes the scenario for *CoSMoS* from the user perspective. There are two roles that are taken into account, these roles are: Site/Building Supervisor and Health and Safety (H&S) Manager. The sequence listed below describes the order of occurrence for *CoSMoS* interactions and also corresponds to the numbers listed in Figure 4.

1. Site supervisor logs into Revit Architecture (BIM based software) using a work station or a handheld device. From the Revit User Interface (UI), *CoSMoS* application is invoked using External Tools of the software (see Figure 4). A self-updating Graphical User Interface (GUI) is displayed with latest sensor data of TelosB wireless sensors embedded in confined spaces located on first floor and basement for this scenario. Real-time data on temperature and oxygen is monitored through this GUI.
2. *CoSMoS* application is programmed to store all the temperature/oxygen sensor data in SQL Server database with timestamps and their associated confined spaces unique Identifications (IDs). Site Supervisor requests the GUI to generate a report to retrieve previously stored sensor data from the database by specifying date and time (see Figure 4).
3. Once the *CoSMoS* GUI is invoked by the Site Supervisor and if sensor data crosses over defined temperature and oxygen level thresholds, the system highlights the confined space in a virtual model constructed in Revit Architecture software. In case of consistent or abrupt increase/decrease of the sensor data system generates sound and flash light based alarms outside the physical confined space.

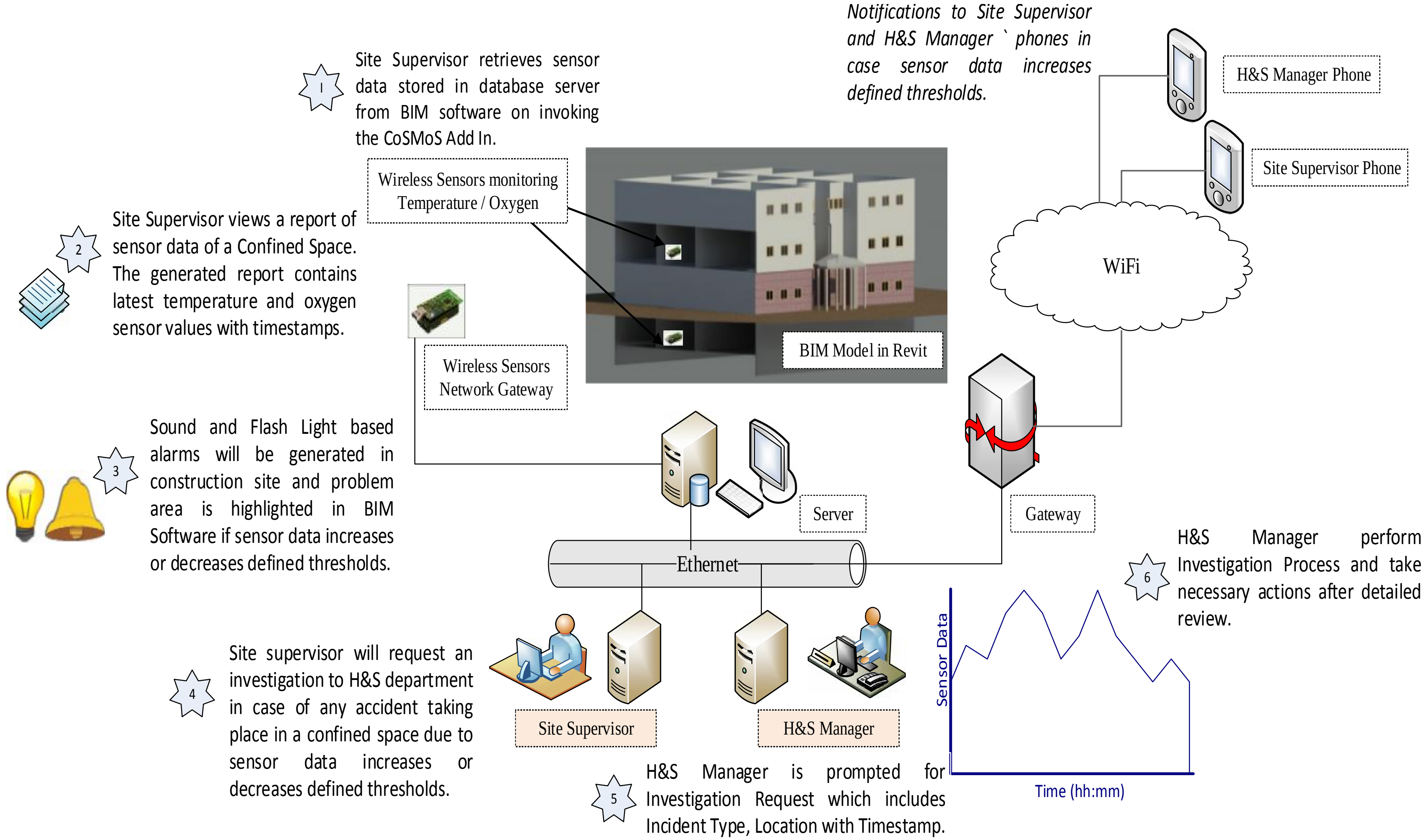

Figure 4: *CoSMoS* Conceptual Scenario Presentation

4. These notifications will help the Site Supervisors take timely action on hazardous situation in the confined space. In case of any accident occurring in the confined space, the supervisor can generate an investigation request to the H&S department using the *CoSMoS* GUI.
5. A history of investigation requests is maintained at the Accident Investigation Information System, primarily used by the H&S department. Depending on the type of incident, the H&S Manager can use the *CoSMoS* data for investigation purpose as well.

The scenario was used to develop a prototype system for a proof of concept.

CoSMoS Prototype Development

Choice of Development Environment

The *CoSMoS* prototype use wireless sensors comprises of Crossbow`s TelosB motes and Autodesk Revit Architecture due to reasons as mentioned below.

Table 7 : Choice of Software and Hardware

Crossbow`s TelosB motes	**Revit Architecture 2013 software**
Availability and low cost	High quality visual presentations and rendering of BIM models
Open Source	Connectivity with external databases
IEEE 802.15.4 compliant wireless sensor module	
Programmability features for customizing according to desired needs	

Prototype Implementation Architecture

One TelosB sensing motes and one TelosB gateway mote has been used to make a WSN in two poor ventilated rooms in a building (see Figure 5). Sensor data has been stored in a human understandable format in database tables so that it can easily be interpreted by users. *CoSMoS* uses a self-updating GUI which has been designed as a Revit Add In (an external application), which is

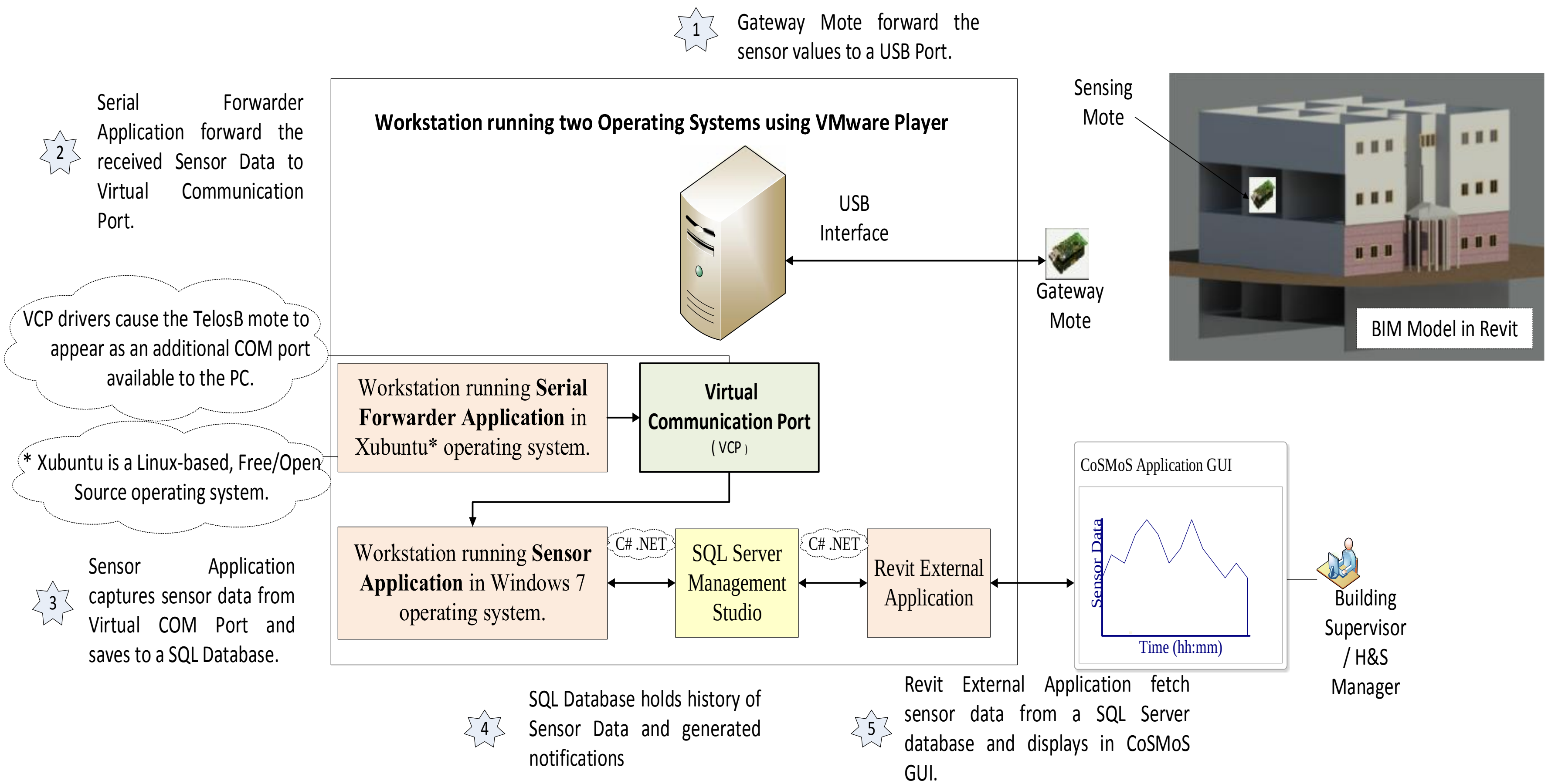

Figure 5: *CoSMoS* Implementation Architecture

programmed to fetch sensor data from a database.

Visual Studio .Net is used as application development platform, using which an application is created to read the wireless sensor placed in confined spaces with their Room Identification (ID). Application is programmed to read USB port and to provide connectivity to wireless sensor gateway. After reading the sensors data, values of temperature are stored with timestamps in an SQL Server database. Database is updated with latest values of sensor data after every 15 minutes; this time interval of saving a sensor data in a database can be increased or decreased by a user as required. Revit External Application with a GUI is also designed using C# language. A GUI is composed of a list which consists of all the rooms' information which is tagged by a user as confined spaces. Two data grid views are added to show the sensor data of temperature and history of generated notifications from their database tables. In the designed prototype, temperature data is real time and collected from TelosB motes however, oxygen data have not been monitored in real time due to non-availability of oxygen monitoring sensors. A file of Comma Separated Values (CSV) of oxygen data is created, stored in a database and linked to a data grid view in a *CoSMoS* GUI to show the connectivity of Revit with external database.

Chapter Summary

In an attempt to reduce the fatalities and deaths in the confined spaces, this chapter has reported upon the development of the prototype system, entitled *CoSMoS*, which includes the incorporation of BIM and WSN technology. *CoSMoS* focuses on monitoring the oxygen and temperature sensor values using data collection from sensors, recording them in a database, displaying updated sensor data in Revit Architecture Graphical User Interface (GUI) and enabling sound based alerts and notifications to building supervisor and H&S manager.

Chapter 4: Results and Discussion

Introduction

The *CoSMoS* prototype uses BIM and wireless sensor technologies and this integration is presumed to lead to a far reaching technology platform, where information needs of Building Supervisors and H&S Managers in a building or on a construction site regarding sensor data associated with confined spaces are addressed. This chapter discusses displaying the sensor data and history of generated notifications in the *CoSMoS*. Finally, system operation of the *CoSMoS* application (using screens of the system) are presented.

CoSMoS Operation and Discussion

For a *CoSMoS* operation, a GUI is designed using C# language which is composed of a list which consists of all the rooms' information which is tagged by a user as confined spaces. *CoSMoS* main GUI is divided into two sections. First section displays the list of the rooms with their associated Room IDs and their floor number, which are tagged by the Building Supervisors as confined spaces. In the second section, two data grid views are added to show the latest sensor data value of temperature and last generated notification. Sensor reading is displayed on main *CoSMoS* GUI with its Sensor ID, Timestamp and its Status. After reviewing the regulation given by OSHA and HSE regarding the acceptable limits of temperature values in confined spaces as mentioned in Chapter: 1, the value of Status is set according as shown in Table 8. Figure 6 shows the *CoSMoS* main GUI invoked from Revit Architecture. Once it's invoked by user, it will start updating itself with latest values of temperature sensor data and last generated notification.

Table 8 : Value of Status of Sensor Data

Status	Upper limit (℃)	Lower limit (℃)	Color Representation
Normal	30	13	
Critical	35	31	
Very Critical	50	36	

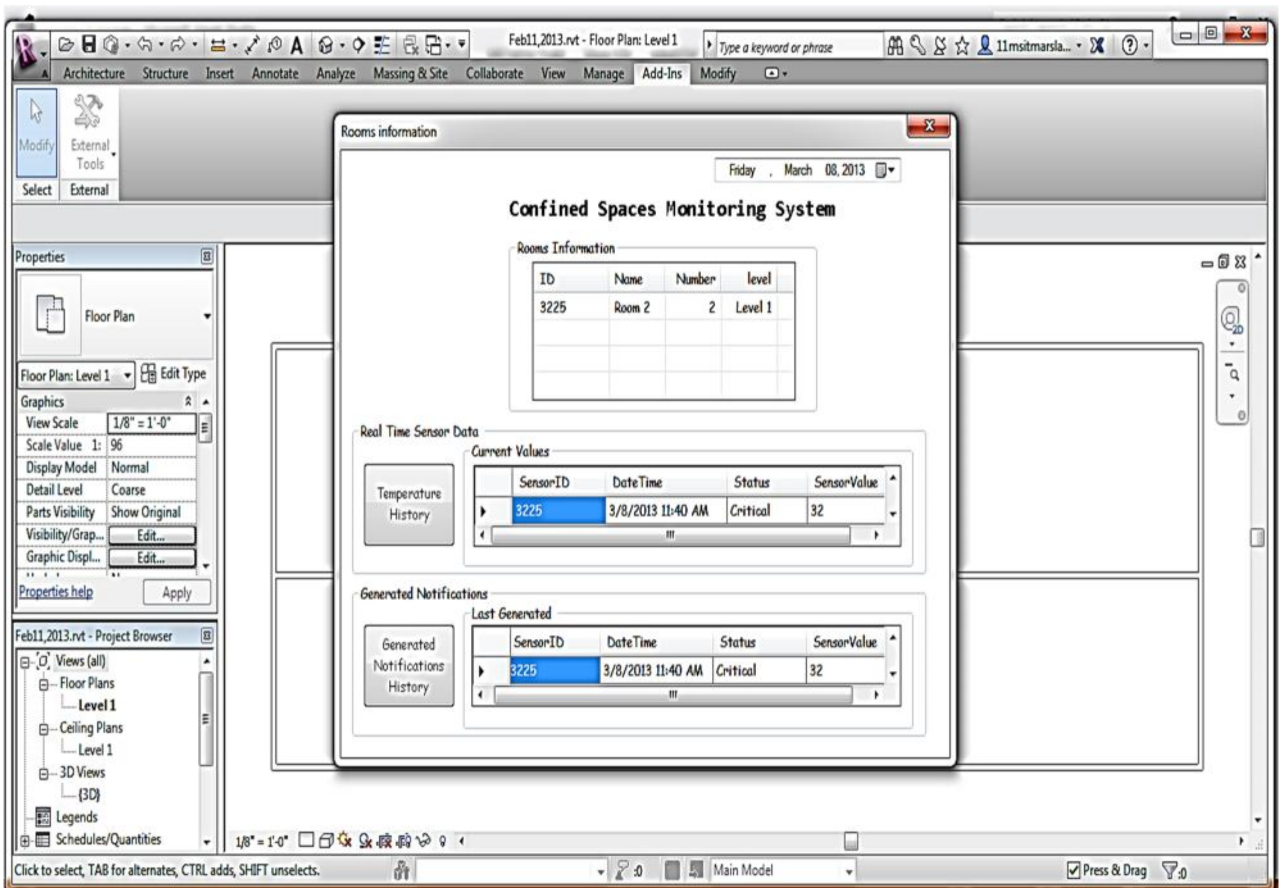

Figure 6: *CoSMoS* Application Invoked from External Tools in Revit

Temperature sensor data history GUI can be displayed by clicking the button “Temperature History” from the main *CoSMoS* GUI as shown in Figure 7. User need to click on “Update” button so that GUI start updating itself with the latest values collected from wireless sensing motes. Three different colors are used to show the value of “Status” of the sensor data.

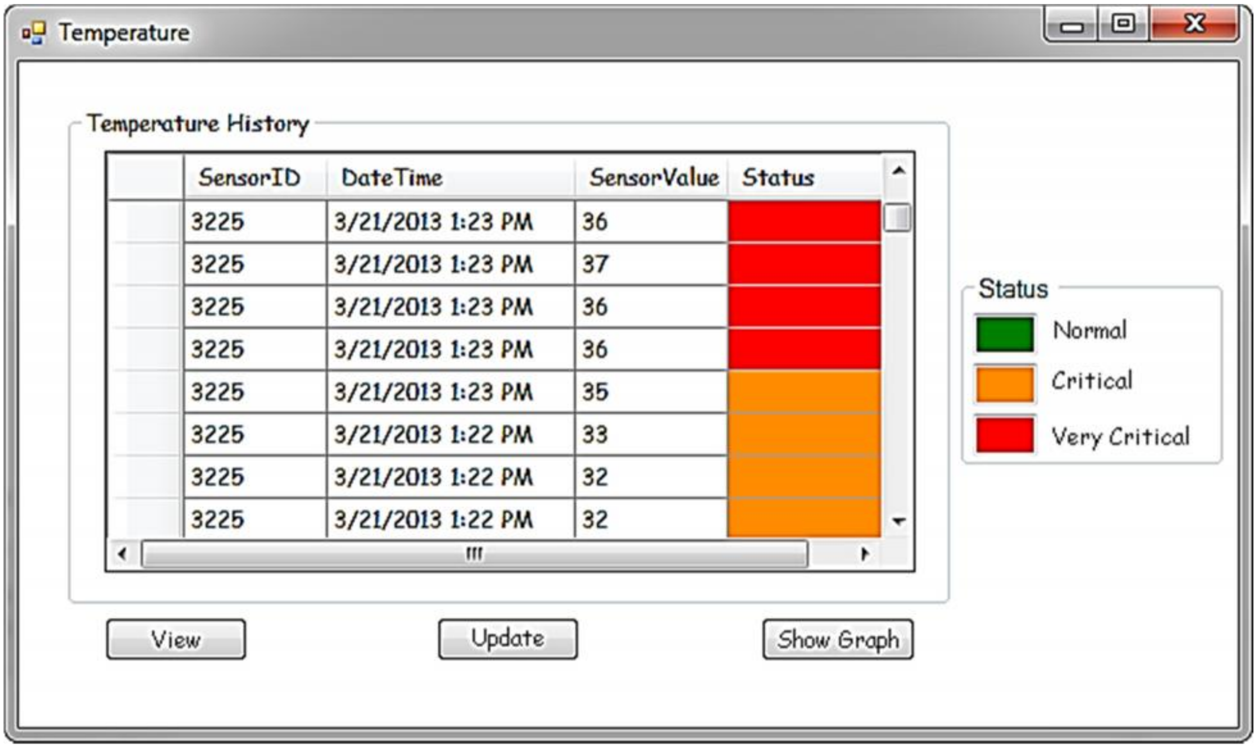

Figure 7 : Temperature Sensor Data history invoked from *CoSMoS* GUI

Graph of sensor data stored in a database can be generated by clicking the “Show Graph” button from the sensor history GUI as shown in Figure 8. In case, the value of temperature sensor values increases defined thresholds, a notification will be recorded in a database. This notification occurs from the sensor application and it also generate a sound and make the notification icon visible in Task Bar of Windows. The history of generated notifications can be invoked from the main *CoSMoS* GUI by clicking the “Generated Notifications History” button as shown in Figure 9.

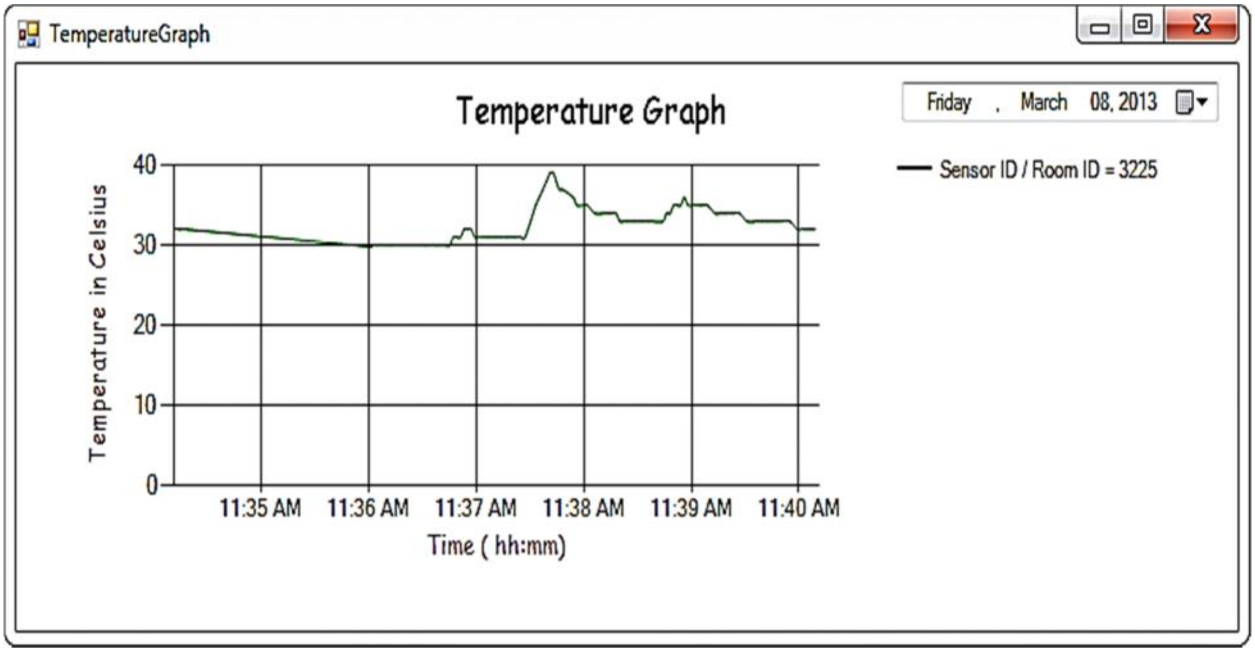

Figure 8 : Temperature Sensor Data Graph invoked from *CoSMoS* GUI

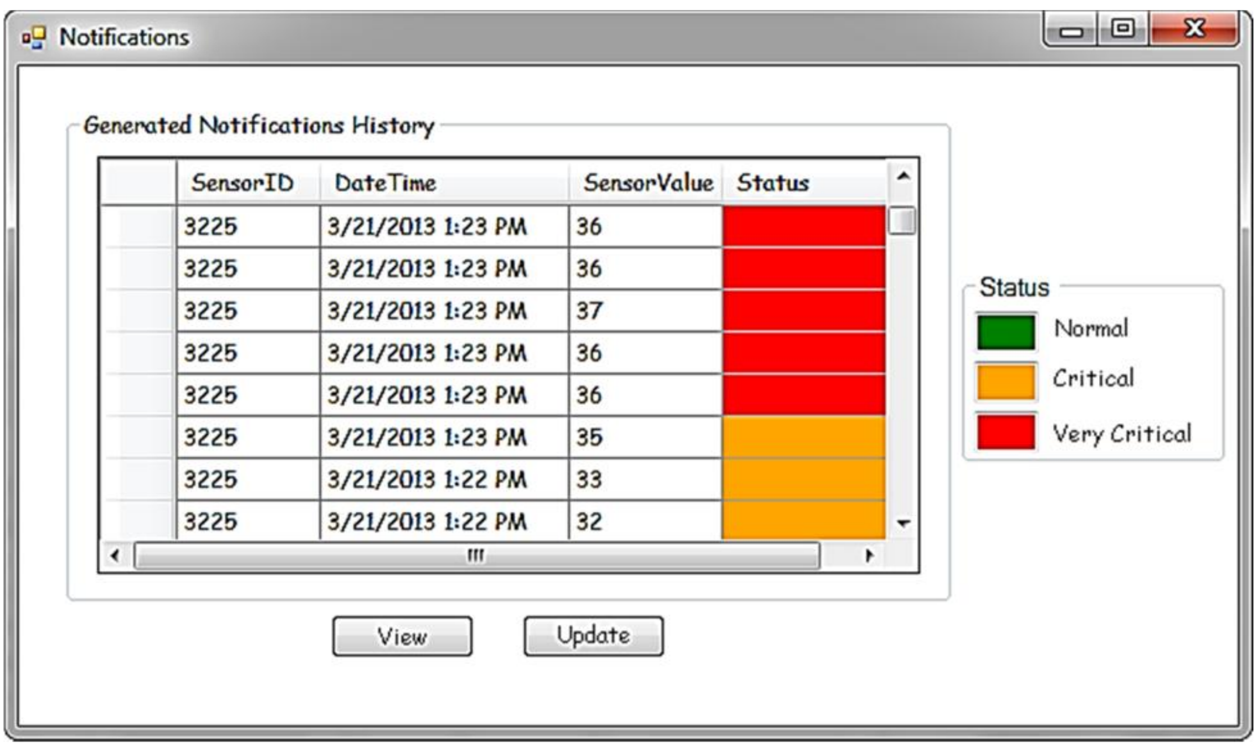

Figure 9 : Generated Notifications history invoked from *CoSMoS* GUI

Test results

Overall, the system functionalities were successfully tested in the university and the wireless sensing motes had worked effectively. One wireless temperature sensing TelosB mote is placed in a room and other TelosB mote is configured as a wireless gateway, which captures the sensor readings and forward it to the communication port of the laptop. The longer transmission range (20 m) of TelosB motes will also make it attractive particularly when the system is deployed on a construction site.

Prototype Evaluation – Industry Feedback

The construction industry contributors were the employees of the contractors (20) and consultants (3). There was a difference in opinion with regard to how plausible the *CoSMoS* scenario was (Table 10) and the barriers to the *CoSMoS* scenario being realized were also suggested (Table 9). However, the industry representatives have also suggested some additions to the *CoSMoS* scenario, which they feel that would be useful to them in future from their perspective (Table 11).

Table 9: Barriers in the implementation to the *CoSMoS*

Barrier	Example Feedback
Lack of knowledge regarding BIM	" … special trainings should be conducted to deliver knowledge to people and industry about its pros. "
Resistance to adopt new technology	"Industry is using traditional methods to ensure H&S in work and will be reluctant to accept *CoSMoS*".
Not suitable for Rugged environment	"*CoSMoS* is too delicate for construction site`s harsh working conditions."
Cost to deploy *CoSMoS* is too high.	"Cost is too high for a building like it has rare oxygen level or poisonous gases problems."
Lack of basic communication infrastructure	"…developing countries like Pakistan usually don't have Wi-Fi technology on construction sites." and "Lack of other helpful technology required to deploy *CoSMoS* on construction sites".

Casual attitude towards safety culture	"… in developing countries, lack of awareness or poor attitudes towards safety and unwillingness to spend or to invest in safety measures are major barriers in adoption to safety systems like *CoSMoS*".

Table 10: Industry Representatives` reactions to the *CoSMoS*

Plausible	Neutral	Implausible
"Interesting solution but need to be adaptive – e.g. if temperature or oxygen values of confined spaces are not varying much then interval of collecting readings should be increase to reduce battery power consumption." "You could make it more cost effective to make affordable to small and medium size construction companies, who do not have adequate funds for H&S practices on sites". "Fairly close to what we would like to be in our company but special training and time would be required to use and deploy such systems". "… by connecting it to alert and actions tools and procedures, it can be improved to avoid hazardous situations".	"…it's not too futuristic solution but this prototype system is limited to your assumed scenarios and I do believe that it will introduce some proactivity and protection on construction sites to avoid hazards if such system are used in real time scenarios". "…it is a powerful tool especially with BIM but awareness of BIM in our industry is not so much".	"I think if you make sensors by yourself then this technology can be affordable to construction industries of developing countries". "In construction types, like tunnels, where monitoring the oxygen level is a major issue, it will be difficult to have a Wi-Fi network coverage over there".

Table 11: Suggested additions to the *CoSMoS*

Integration with other systems/procedures	**Use of low cost sensors which are less susceptible to damage**	**Further processes to be addressed**
"It should be integrated with Google Maps to provide position and paths to nearest hospitals or first aid at construction site". "It can be improved by incorporating Geographic Information System (GIS) technology in *CoSMoS*, instead of using Wi-Fi technology."	"Wireless sensors which provide greater accuracy and life span should be used for rugged environment of construction sites".	"*CoSMoS* should also suggest actions, which should be taken on the occurrence of the hazardous situations in buildings". "*CoSMoS* should take into account the Intelligent / Green building concepts". "*CoSMoS* can be improved by adding various other type of environmental monitoring sensors and making GUI more user friendly".

Chapter Summary

In an attempt to record sensor data of confined spaces to reduce accidents in buildings and construction sites, this chapter reported upon the test results of *CoSMoS* prototype system. The prototype system includes activities such as communication with TelosB motes, monitoring of the sensor data of confined spaces, generate sound based and Task Bar notifications to Building Supervisors and H&S Managers. To implement these activities, the prototype system has employed BIM and TelosB based WSN technology and this technology platform is believed to lead to a proactive solution for H&S management of worker safety in the confined spaces.

Chapter 5: Research Conclusions, Limitations and Recommendations

Introduction

Findings emanating from the Health and Safety Executive (HSE) and OSHA statistics have led to an acknowledgement that accidents and fatalities in confined spaces have remained relatively high year in past years. This is in spite of many initiatives in form of code of conduct and regulations for working in confined spaces are taken by HSE and OSHA to improve H&S in working in confined environments in buildings and on construction sites. To work towards minimizing the causes of atmospheric hazards in confined spaces, H&S Managers and Building Supervisors on site must be equipped with fully integrated sensor based systems that allow them to manage the risk more efficiently and safety. A prototype system, entitled, *CoSMoS* was developed in the research undertaken and made capable to inform the H&S Managers and Building Supervisors using sound based alarms to avoid sensitive situations in the confined spaces.

This chapter also presents a summary of the research conducted and demonstrates how the aim and objectives were achieved using prototyping. Furthermore, a synopsis of main conclusions is presented. In addition, the main limitations of the research are presented together with recommendations for future study.

Summary of Research

The objective of this research was to investigate the H&S hazards which are associated with working in the confined spaces and to develop emerging BIM and WSN based application for the workers safety. This aim was developed to provide answers to the following research questions:

1. What are the safety concerns associated with working in confined spaces in buildings or on a construction site?
2. How to achieve the information rich visualizations of confined spaces for H&S management?
3. How to integrate BIM with wireless sensor technology for monitoring the confined spaces in real time for Building Supervisors and H&S Managers?

Subsequently, the following specific objectives were identified to achieve the aim:

1. To review the existing integrated solutions based on BIM and sensor technology to develop an understanding of integration approaches for a purpose to make an effective monitoring tool for H&S management.
2. To develop the implementation scenarios for monitoring the confined spaces for worker safety with respect to Building supervisors and H&S Managers.
3. To design and develop a prototype application that demonstrates the use of BIM and WSN for H&S management of workers in confined spaces.

Key Research Findings and Conclusion

The following conclusions can be drawn from this research:

1. The demand and investment for the H&S management in buildings and construction sites has increased dramatically in the past few years in UK and USA, whereas as enforcement of H&S practices and code of conduct need to be implemented in Pakistan.
2. As recorded by Department of Labor statistics US, around 100 fatalities occur each year in confined spaces and most the deaths are caused by the atmospheric hazards. Within the construction industry, accident statistics indicate that there are fatalities as well as serious

injuries in confined spaces due to exposure to hazardous environment. A review of international safety regulations suggest that lack of oxygen and temperature extremes contribute to make these work environment hazardous in confined places. For monitoring the confined spaces for sensor data in real time, *CoSMoS* prototype system has been developed. The proposed system aims to monitor temperature sensor data in real time, whereas, oxygen sensor data has been displayed from its comma separated file. Sound alarms and taskbar notifications will be generated for Building Supervisors and H&S Managers on abrupt changes of wireless sensors data. Proposed *CoSMoS* system will facilitate intelligent monitoring of confined spaces through real-time sensor data and will help reduce H&S hazards typically encountered by workers operating in such working environments.

Limitations of this Research

The research undertaken has certain limitations and these are briefly outlined below:

- The *CoSMoS* prototype functionalities were limited to the perspective of the Building Supervisors of any building or construction project. Therefore, the viewpoints of the H&S Managers need to be considered in future work.
- The *CoSMoS* prototype development was essentially a proof-of-concept application thus the oxygen sensor data has not been monitored in real time in the *CoSMoS* system.
- The *CoSMoS* prototype system is limited to construction phase of any building. The proposed application need to be explored for other aspects of BIM such as facility management phase of buildings in future study.

Recommendations and Future Works

It is important for the H&S management in an organization to recognize the work environments which are confined spaces according to standards given by OSHA and HSE to realize the potential atmospheric hazards associated with these work environments. Those organizations who lack in such comprehension and recognition, reinforcement efforts, trainings and education of H&S standards are needed.

Once a confined spaces identification process is completed, any nature of work activity associated with working in these confined environments should follow the guidelines recommended by HSE in its document, "Safe work in confined spaces: Confined Spaces Regulations 1997 published in 2009". These recommendation contains the code of conduct for carrying work activities in the industry sectors safely by minimizing health hazards in confined environments.

CoSMoS prototype system can be further extended according to the points as mentioned below:

1. Database of sensor data residing in buildings or construction sites data server can also be taken to the cloud so that sensor data can easily retrieved by concerned authorities from any location. It will eliminate the need of deploying costly data servers which consumes lot of power resources on a construction sites. It will make BIM-Sensor data accessible from any place and at any time and will help to conduct monitoring confined spaces with great efficiency.
2. The incorporation of activity and other gas monitoring sensors will add more value to a designed system to reduce deaths and injuries occur in confined spaces. Keeping the

temperature and oxygen sensors in sleep mode and as soon as activity is detected by activity sensors, the temperature and oxygen sensors will wake up and start monitoring the confined spaces.

3. Graphical User Interface (GUI) of the *CoSMoS* prototype system need to be simplified for Building Supervisors because of their perceived low technical literacy which will improve the user acceptance of the *CoSMoS* system in the local construction industry.
4. There is also a need to expand the scope of implementation of *CoSMoS* prototype system for H&S Managers of any building. Android based mobile application should be developed for H&S Managers to remotely monitor the confined spaces sensor data on their mobile devices.

It is important for construction industry to make users aware of *CoSMoS* system and to realize them the benefits of the proposed application, which will result in a need to make investments in user trainings to use technology to avoid hazardous situations at worksites.

Closing Remarks

The research has highlighted the importance of monitoring the confined spaces for their associated sensor data as working in these environments is one of the leading causes of atmospheric hazards in buildings and on construction sites. In order to address the hazards associated with working in confined spaces, a *CoSMoS* system has been recommended to promote a proactive H&S management system. The developed system investigated the integration of Building Information Modeling (BIM) approach with wireless sensor technology, which has led to the development the primary technology platform, where the information requirements of H&S management could be addressed. In addition, addition of more wireless sensors and catering the rugged construction environment could result in reduced fatalities and deaths occur in Confined Spaces.

References

[1] X. Huang and J. Hinze, "Owner's role in construction safety," *J. of Construction Eng. and Manage*., vol. 132, no.2, pp. 164-173, 2006.

[2] T.S. Abdelhamid, and J.G. Everett, "Identifying root causes of construction accidents," *J. of Construction Eng. and Manage*., vol.126, no.1, pp. 52-60, 2000.

[3] E. Koehn et al., "Safety in developing countries: professional and bureaucratic problems," *J. of Construction Eng. and Manage*., 121 no.3, pp. 261-265, 1995.

[4] S. Bowden et al., "Mobile ICT support for construction process improvement," *Automation in Construction*. vol. 15, no.6, pp. 664-676, 2006.

[5] A. Oloufa et al., "Situational awareness of construction equipment using GPS, wireless and web technologies," *Automation in Construction.* vol. 12, no.6, pp. 737– 748, 2003.

[6] European Commission. (2013). *Health and safety at work* [Online]. Available: http://ec.europa.eu/social/main.jsp?catId=148

[7] United States Department of Labor. (2013). *Occupational Safety and Health Administration* [Online]. Available: http://www.osha.gov/

[8] United States Department of Labor. (2013). *Occupational Safety and Health Standards*[Online].Available:http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=standards&p_id=9797

[9] WorkSafe BC (2013). *Safety at work* [Online]. Available: http://www2.worksafebc.com/topics/confinedspaces/WhatIsConfinedSpaces.asp

[10] United States Department of Labor. (2013). *OSHA-Regulations (Standards-29CFR)*[Online].Available:http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=standards&p_id=9797

[11] Bureau of Labor Statistics U.S. Department of Labor (2013). *National census of fatal occupational injuries in 2011* [Online]. Available: http://www.bls.gov/news.release/pdf/cfoi.pdf

[12] IACS (2007). *Confined space safe practice (rev.2)* [Online]. Available: http://www.iacs.org.uk/document/public/Publications/Guidelines_and_recommendations/PDF/REC_72_pdf212.pdf

[13] Health and Safety Executive. (2013). [Online]. Available: http://www.hse.gov.uk/temperature/faq.htm

[14] Safework Australia (2013). [Online]. Available: http://www.safeworkaustralia.gov.au/sites/SWA

[15] Safework AU. (2011, Dec.). *Confined spaces - code of practice* [Online]. Available:http://www.safeworkaustralia.gov.au/sites/SWA/about/Publications/Documents/634/Confined_Spaces.pdf

[16] OSHA. (2011, June). *OSHA Factsheet* [Online]. Available: http://www.osha.gov/Publications/confinedspacesafety-commercialfishingves sels-factsheet.pdf

[17] Lijun, Shen, and David, K.H. Chua. Application of Building Information Modeling (BIM) and Information Technology (IT) for Project Collaboration, EPPM, Singapore, 20-21 Sep 2011.

[18] S. Sharples et al., "A Multi-agent architecture for intelligent building sensing and control," *Int. Sensor Review J.*, pp.1-8, May 1999.

[19] H. Hagras et al., "A hierarchical fuzzy–genetic multiagent architecture for intelligent buildings online learning, adaptation and control," *Inform. Sci. (Elsevier)*, vol. 150, pp. 33-57, March 2003.

[20] T. Derek, and J. C. Croome, "What do we mean by intelligent buildings?," *Automation in construction*, vol. 6, no. 5, pp.395-400, 1997.

[21] J.F. Martins et al., "Smart homes and smart buildings," in *13th Biennial Baltic Electronics Conf.* (BEC), Oct. 2012. pp. 27-38. doi: 10.1109/BEC.2012.6376808

[22] Chen et al., "A review of smart living space development in a cloud computing network environment," *Computer-Aided Design and Applications*, vol. 6, no. 4, pp. 513-527, 2009. doi: 10.3722/cadaps.2009.513-527

[23] B. Succar, "Building information modelling framework: A research and delivery foundation for industry stakeholders," *Automation in Construction*, vol. 18, no. 3, pp. 357-375, 2009.

[24] Grilo et al., "Challenging electronic procurement in the AEC sector: A BIM-based integrated perspective," *Automation in Construction*, vol. 20, no. 2, pp. 107-114, 2011.

[25] T. Cerovsek, "A review and outlook for a 'Building Information Model' (BIM): A multi-standpoint framework for technological development," *Advanced engineering informatics - Elsevier*, vol. 25, no. 2, pp. 224-244, 2011.

[26] W. Kymmell, "Building Information Modeling: Planning and Managing Projects with 4D CAD and Simulations," McGraw-Hill Construction Series. McGraw-Hill Professional, 2008.

[27] S. Azhar, et al., "Building information modeling (BIM): now and beyond," *Australasian J. of Construction Econ. and Building*, vol.12, no.4, pp. 15-28, 2012.

[28] NIBS (2010). National Building Information Modeling Standard, [Online] Available: http://www.wbdg.org/pdfs/NBIMSv1_p1.pdf

[29] U. Isikdag et al., "Building information models: a review on storage and exchange mechanisms," in *24th W78 Conf. In Bringing ITC knowledge to work*, Maribor, vol. 26, pp. 135-143, 2007.

[30] A. Motamedi and A. Hammad, "Lifecycle management of facilities components using RFID and BIM", *J. of Inform. Technology in Construction*, pp. 238-262, June 2009.

[31] A. Motamedi and A. Hammad, "RFID-Assisted Lifecycle Management of Building Components Using BIM Data", in *Proc. of the 26th ISARC*, Austin TX, U.S.A , 2009, pp. 109-116.

[32] S. Azhar et al., "Building information modeling (BIM): A new paradigm for visual interactive modeling and simulation for construction projects," In *Proc., 1st Int. Conf. on Construction in Developing Countries*, pp. 435-446. 2008.

[33] D. Smith, "Building information modeling: a strategic implementation guide for architects, engineers, constructors, and real estate asset managers," Wiley, 2012.

[34] D. Conradi. (2009). BIM [Online]. Available: http://researchspace.csir.co.za/dspace/bitstream/10204/3364/1/Conradie_2009.pdf

[35] R. Gaidytė. (2010). *2D and 3D Modeling Comparison* [Online]. Available: http://brage.bibsys.no/hig/bitstream/URN:NBN:nobibsys_brage_12669/1/Gaidyte,R..pdf

[36] A. Sheth, et al., "Semantic sensor web," in *Proc. IEEE Internet Comput*., vol. 12, no. 4, pp. 78-83, 2008.

[37] S. Soloman, Sensors handbook. McGraw-Hill, Inc., 2009.

[38] D. Puccinelli, and M. Haenggi, "Wireless sensor networks: applications and challenges of ubiquitous sensing," *IEEE Circuits Syst. Mag.*, vol. 5, no. 3, pp. 19-31, 2005.

[39] D. Culler et al., "Guest editors' introduction: overview of sensor networks." *IEEE Computer*, vol. 37, no. 8, pp.41-49, 2004.

[40] Crossbow. (2013). TelosB [Online]. Available: http://www.willow.co.uk/TelosB_Datasheet.pdf

[41] U. Isikdag, "Sensor services for buildings: A framework and opportunities," in *Proc. GeoInformation for Disaster Management*, Antalya, Turkey, May 2011.

[42] Kwon et al., "Design of air pollution monitoring system using ZigBee networks for ubiquitous-city," in *Int. Conf. on Convergence IT, IEEE*, 2007, pp. 1024-1031.

[43] S.A. de la Campa et al.,"Distributed detection of events for evaluation of energy efficiency in buildings," *IEEE, 4th Int. Conf. on New Technologies, Mobility and Security (NTMS*), 2011, pp. 1-6.

[44] Tse et al., "A distributed sensor network for measurement of human thermal comfort feelings," *Sensors and Actuators A: Physical, Elsevier*, vol. 144, no. 2, pp. 394-402, June 2008.

[45] T. Torfs et al., "Low power wireless sensor network for building monitoring," *IEEE Sensors J*., vol. 13, no. 3, March 2013.

[46] P. Meadati, J. Irizarry, A.K. Akhnoukh, "BIM and RFID Integration: A pilot study", In: *Proceedings of the 2nd International Conference on Construction in Developing Countries*, Cario, Egypt, pp.570-578, August 2010.

[47] J.M. Taylor, S.A. Coady and J. Chesser, "RFID and BIM; Integrating the Lean Construction Process" In: *Proceedings of the 12th International Conference on Civil, Structural and Environmental Engineering Computing*, UK, pp.1-25, September, 2009.

[48] H. Hajian and B.B. Gerber, "A research outlook for real-time project information management by integrating advanced field data acquisition systems and Building Information Modeling", *Computing in Civil Engineering ASCE*, pp. 83-94, June, 2009.

[49] A. Motamedi, and A. Hammad, "Lifecycle management of facilities components using Radio Frequency Identification and Building Information Modeling", *Journal of Information Technology in Construction, ITCON*, Vol. 14, pp. 238-262, June, 2009.

[50] P. Meadati, J. Irizarry, A.K. Akhnoukh, "BIM and RFID Integration: A pilot study", In: *Proceedings of the 2nd International Conference on Construction in Developing Countries*, Cario, Egypt, pp.570-578, August, 2010.

[51] A. Sattineni, and S. Azhar, "Techniques for tracking RFID tags in a BIM model" In: *Proceedings of the 27th ISARC*, Bratislava, Slovakia, pp.346-354, June, 2010.

[52] M.Y. Cheng and N.Y. Chang, "Radio Frequency Identification (RFID) integrated with Building Information Model (BIM) for open-building life cycle information management", In: *Proceedings of the 28th ISARC*, Seoul, Korea, pp.485-490, 2011.

[53] A. Costin, N. Pradhananga, J. Teizer and E. Marks, "Real-time resource location tracking in Building Information Models (BIM)", In: *Proceedings of the 9th International Conference Springer*, Osaka, Japan, pp.41-48, September, 2012.

[54] Motamedi, A., Soltani, M.M. and Hammad, A. (2012), *Localization of RFID-Equipped Assets during the Operation Phase of Facilities*. Available at: http://www.slideshare.net/ferheenkhan5/localization-of-rfid-equipped-assets-during-the-operation-phase-of-facilities-bimrfid-2012 [Accessed: 27 January 2013].

[55] M. Alahmadi, W. Nader, A. Brumbaugh, Y. Cho, S. Ci, H. Sharif, J. Shi and J. Neal, "The "BIM's 4D +" Dimension: Real Time Energy Monitoring", In: *Proceedings of the GCC Conference and Exhibition IEEE*, Dubai, pp.589- 592, February, 2011.

[56] A. Motamedi and A. Hammad, "Location information management of RFID-equipped building components", In: *Proceedings of ISARC*, Seoul, Korea, pp.1026-1031, July, 2011.

[57] J.H. Woo, C. Diggelman, and B. Abushakra, "BIM-based energy monitoring with XML parsing engine" In: *Proceedings of the 28th ISARC*, Seoul Korea, pp.544-545, 2011.

[58] G. Lee, J. Cho, S. Ham, T. Lee, G. Lee, S.H. Yun and H.J. Yang, "A BIM and sensor-based tower crane navigation system for blind lifts", *Automation in Construction*, Vol.26, pp.1–10, October, 2012.

[59] R. Attar, E. Hailemariam, S. Breslav, A. Khan and G. Kurtenbach, "Sensor-enabled cubicles for occupant-centric capture of building performance data", In: *Proceedings of the ASHRAE Annual Conference*, October, 2011.

[60] B. Cahill, K. Menzel, and D. Flynn, "BIM as a centre piece for optimized building operation", *Taylor & Francis Group*, London, 2012.

[61] Z. Ozturk, Y. Arayici and Coates, "Post occupancy evaluation (POE) in residential buildings utilizing BIM and sensing devices: Salford energy house example", In: *Proceedings of the Retrofit*, Greater Manchester, January, 2012.

[62] A. Guinard, A. Mc Gibney and D. Pesch, "A Wireless sensor network design tool to support building energy management", In: *Proceedings of the 1st ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings, ACM*, NY, USA, pp. 25-30, 2009.

[62] Katranuschkov et al., "BIM-based generation of multi-model views," *In Proc. CIB W*, vol. 78, 2010, pp. 429-436

[63] L. Menzel. Building Management System to Support Building Renovation [Online], Available:http://zuse.ucc.ie/itobo/_publicMaterial/ITOBO_All_Publications/Yin_BuildingManagementSystemtoSupportBuildingRenovation.pdf

[64] O'Flynn, Brendan et al., "Development of miniaturized wireless sensor nodes suitable for building energy management and modelling," in *8th European Conf. on Product & Process Modelling*, Sep 2010.

[65] Ryoo et al., "Enhanced platform for BIM to improve reality", [Online], Available: http://www.iaarc.org/publications/fulltext/S04-2.pdf

[66] Shiau et al., "Establishment of fire control management system BIM environment," vol 5, pp. 67-72, 2012.

[67] M. Keller et al., "Integrating the specification, acquisition and processing of building performance information," *Tsinghua Science and Technology*, vol.13, no.1, pp.1-6, 2008.

Appendix

Publications

- Muhammad Arslan, Zainab Riaz, Adnan Khalid Kiani, Salman Azhar, Zeeshan Aziz, M. Bilal, “Integrated Solutions based on BIM and Sensing Technologies for Construction Health and Safety Management”, Proceedings of the International Postgraduate Research Conference (IPGRC) 2013, University of Salford, United Kingdom.

- Zainab Riaz, Muhammad Arslan, Adnan Khalid Kiani, Salman Azhar, "Integration of Wireless Sensors with BIM for Monitoring the Confined Spaces for Construction Health and Safety Management”, Proceedings of the Accepted in Portland International Conference on Management of Engineering and Technology 2013, Portland, Oregon United States.