ITcon
www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

REAL-TIME ENVIRONMENTAL MONITORING, VISUALIZATION AND NOTIFICATION SYSTEM FOR CONSTRUCTION H&S MANAGEMENT

SUBMITTED: September 2013
REVISED: May 2014
ACCEPTED: May 2014
PUBLISHED: June 2014 at http:/itcon.org/2014/4
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SUMMARY: *Construction workers who are exposed to hot and humid environments are at high risk of heat stress. Excessive exposure to such environments can result in occupational illnesses and injuries. Acquisition of sensor data from such environments is essential to ensure improved Health and Safety (H&S) of workers. Building Information Modeling (BIM) offers a new epitome to provide comprehensive solutions for H&S and evacuation planning in buildings. 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 Network (WSN) along with a notification system for real-time environmental monitoring of buildings. The application, entitled "Real-Time Environmental Monitoring, Visualization and Notification System", is expected to provide a new horizon for effective visualization, reliable data capturing and catering to time sensitive emergency situations for construction H&S management. The paper will also outline scope of future research in this domain.*

KEYWORDS: *Building Information Modeling (BIM), Health and Safety Management, RFID, Sensors, Technology*

REFERENCE: *Muhammad Arslan, Zainab Riaz, Adnan Khalid Kiani, Salman Azhar (2014). Real-time environmental monitoring, visualization and notification system for construction H&S management. Journal of Information Technology in Construction (ITcon), Vol. 19, pg. 72-91, http://www.itcon.org/2014/4*

1. INTRODUCTION

Environmental stress is an important issue in the construction industry which can seriously affect health of workers (Yi and Chan, 2013). Severe environmental stress at work sites, not only deteriorates worker productivity and efficiency but also threatens their survival (Wolkoff, 2013; Jones, *et al.*, 2013; Rowlinson, *et al.*, 2014). According to results from the Census of Fatal Occupational Injuries (CFOI) conducted by the U.S. Bureau of Labor Statistics (BLS), a total of 4,384 fatal work injuries were recorded in the US in 2012 out of which 10% fatalities were due to exposure to hazardous environment, fire and explosions.

Regardless of numerous efforts by safety professionals and government agencies to enforce workplace health and safety regulations such accidents continue to occur (as shown in Figure 1). Exposure to high temperature at construction sites may cause illness such as heat strokes, exhaustion, cramps, rashes etc. and death in case of prolonged exposure to such environments (Grubenhoff, *et al.*, 2007; Chan, *et al.*, 2012). In contrast, prolonged exposure to cold temperature can lead to hypothermia, frostbite and trench foot (Grooms and Straley, 2013). Therefore, work environments should be carefully monitored to ensure the thermal comfort level for both workers' well-being and productivity.

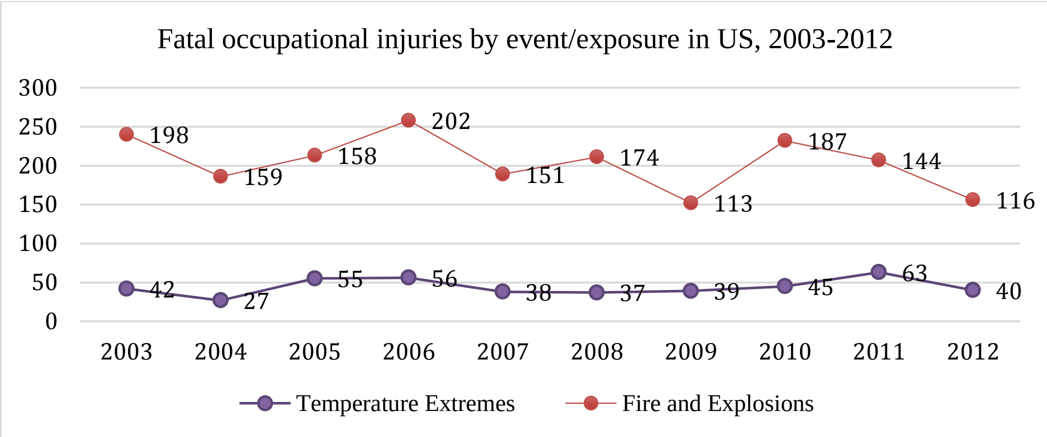

FIG. 1: Fatal Occupational Injuries by Event/Exposure in US, 2003-2012 (BLS, 2013)

The regulation on thermal comfort at work highlights that temperature and humidity are two major factors that contribute to a worker`s thermal comfort. All major occupational H&S regulators, such as Occupational Safety and Health Administration (OSHA) in US and Health and Safety Executive (HSE) in UK, have provided code of practices to reduce environmental hazards in buildings and have suggested minimum and maximum temperature and humidity levels to be monitored for maintaining thermal comfort of workers at worksites (see Table 1 for acceptable upper and lower limits of temperature and humidity in buildings in US and UK).

Table 1: Acceptable Limits of Temperature and Humidity at Work Environments (OSHA, 2011; HSE, 2013; HSE, 2011)

H&S Regulators	***Environmental parameters***	***Upper limit***	***Lower limit***
OSHA	*Temperature*	*24 ºC*	*20 ºC*
	Humidity	*60 %*	*30 %*
HSE	*Temperature*	*30 ºC*	*13 ºC*
	Humidity	*70 %*	*40 %*

In order to detect environmental hazards in buildings, there are various potential technologies that can be used for monitoring purpose. RFID tags and environmental monitoring sensors are some of these technologies that are considered suitable for such situations however, they also present certain limitations (Bohn and Teizer, 2009; Goodrum, *et al.,* 2006). The main focus of researchers in the last decade has been to track various objects and workers using RFID technology. However, this technology is limited in sensing capabilities and does not provide cost effective solutions when there is a need of two-way communication (Nikitin, *et al.,* 2006; Kaur, *et al.,* 2011). In order to achieve wireless communication and environmental monitoring, WSN is a promising technology which overcomes certain limitations of RFID technology and effectively monitors environmental parameters like temperature, light, humidity etc. (Lynch, 2004). Wireless sensing technology has been improved over time by reduced sensor cost, size and increased functionalities (Long, *et al.,* 2010). It can contribute significantly in the design of safety applications where WSN can be created by distributing sensor nodes in an environment that report to a wireless gateway. It can then be configured to send alerts for avoiding H&S hazard at work sites (Kainan, *et al.,* 2010).

Recently, there has been significant interest in improving construction site safety through real-time monitoring using Building Information Modeling (BIM) (Chi, *et al.,* 2012). BIM, virtual model of a building, is constructed with all the minor details prior to its physical construction. It allows H&S managers to visually assess construction site conditions and recognize safety hazards (Chi, *et al.,* 2012). There have been substantial attempts to integrate BIM with RFID technology and BIM with sensing technology to provide H&S solutions to construction industry and built environment. However, there is a need to develop a solution for environmental monitoring of buildings and construction sites as environmental accidents continue to plague these worksites (Sousa, *et al.,* 2014) (Riaz, *et al.,* in press). A review of BIM-RFID and BIM-Sensor based integrated solutions has been presented and an application of BIM-WSN is proposed to ensure thermal comfort in buildings. In order to monitor buildings "real-time environmental monitoring, visualization and notification system" is developed using BIM and Wireless Sensor Network (WSN). The main aim of this integration is to benefit from the rich User Interface (UI) of BIM based software and to supplement the BIM model with real-time temperature and humidity sensor values. The information is useful for H&S managers for real time environmental monitoring of buildings and aims to reduce H&S hazards inside buildings or construction sites.

2. Building Information Modeling (BIM)

BIM is one of the emerging developments in Architecture, Engineering and Construction (AEC) industries (Azhar, *et al.,* 2008). Associated General Contractors Guide (2006) defines BIM as, "a data-rich, object-oriented, intelligent and parametric digital representation of facilities" (Motamedi and Hammad, 2009). With BIM technology, a virtual model of a building is digitally constructed that can be very beneficial in planning, designing, preconstruction and post construction processes (Azhar, *et al.,* 2012).

BIM have numerous benefits over conventional 3D CAD (Zhang, *et al.,* 2013; Eadie, *et al.,* 2013). Some of the features of 3D CAD and BIM are compared in Table 2. BIM platform uses a 3-dimensional object-oriented computer aided design (CAD) model to create and manage real-time virtual building elements as BIM objects (Zhang, *et al.,* 2013). BIM objects represent building geometry, geographic information, spatial and functional relationships between various building elements which can be displayed in multiple views and can be used for analyzing domain issues (Eadie, *et al.,* 2013). BIM stores data in its internal database as a digital file and that can be shared between several applications (Bryde, *et al.,* 2013). To develop a building information model, a number of BIM software applications are available such as Autodesk Revit, Graphisoft and Bentley (Azhar, *et al.,* 2008). BIM software provides Application Programming Interfaces (API) for designing and customizing applications according to desired needs whereas traditional CAD software does not provide such functionalities (Eadie, *et al.,* 2013). BIM also supports Industry Foundation Classes (IFC), an open building exchange standard which provides comprehensive support for facility management operations (Azhar, *et al.,* 2008).

BIM technology is based on powerful object-oriented approach that has been developed to tackle issues related to information management and interoperability. Moreover, it provides effective sharing and exchange mechanism of building information through entire building lifecycle (Motamedi, *et al.,* 2014). In recent years, there have been many initiatives to adopt BIM approach in construction and facility management processes for safety management (Azhar and Behringer, 2013).

Table 2: Differences between 3D CAD and BIM (Zhang, et al., 2013; Eadie, et al., 2013)

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	×	✓

3. Radio Frequency Identification (RFID) and Wireless Sensor Networks (WSNs)

Radio Frequency Identification (RFID) and Wireless Sensor Networks (WSNs) are two important technologies for ubiquitous wireless computing that have attracted great attention in recent years. Their use revolutionizes diverse application areas and provides limitless future potentials (Jedda, *et al.*, 2012; Lin, *et al.*, 2013). A brief introduction of both the technologies has been given below.

RFID is an automatic identification and data collection technology which transmits and receives metadata through radio waves (Montaser and Moselhi, 2014). An RFID system consists of three major components: RFID tag; RFID reader/writer; and the application residing in a computer (Lin, *et al.*, 2014). RFID tag, also known as transponder (transmitter/responder), is composed of a microchip, an antenna and enclosure (Wong and Guo, 2014) for processing, communicating and storing information in a non-volatile memory (Sardroud, 2012). RFID tags when attached to objects give unique e-coding for counting and identification purposes (Azevedo, *et al.*, 2014). RFID tags can be categorized as active, passive or semi-active based on the battery supplied or can be classified as read only or read-write tags (Hong-da, 2012). RFID is a promising technology which has existed for years in the construction industry and has the potential to become ubiquitous in the coming years for a variety of applications (Fan, *et al.*, 2014).

A Wireless Sensor Network (WSN) is a system that consists of Radio Frequency (RF) transceivers, microcontrollers and power sources. There are different types of sensors available to monitor a wide variety of parameters such as temperature, humidity, light, pressure, motion etc. (Othman and Shazali, 2012). Recent advancements in WSNs have led to the development of low power, low cost and multifunctional sensing nodes to enable sensing with data processing (Yang, *et al.*, 2014). WSN with self-configuring, self-healing and self-diagnosing capabilities have been developed to enable applications that RFID technology could not address (Zhang and Arora, 2003). WSNs are used for a variety of applications, such as: smart buildings; environmental monitoring; facility monitoring and maintenance; site security; safety management; and various other applications (Andonovic, 2009; Hussain, *et al.*, 2009; Zhang, *et al.*, 2007). Currently there are two major wireless standards are available for WSNs which are Bluetooth (IEEE 802.15.1) and ZigBee (IEEE 802.15.4) (Wielens, *et al.*, 2008; Wang, *et al.*, 2010). Both these standards operate within the Industrial Scientific and Medical (ISM) band of 2.4 GHz, which provides huge spectrum allocation and license free operations. It is also possible to establish a WSN using Wi-Fi (IEEE 802.11) protocol however, this protocol is usually utilized in PC-based applications and do not offer power efficient solutions (Mendez, *et al.*, 2011).

As mentioned earlier, RFID technology has been deployed extensively in industrial applications mainly for identification and tracking the location of workers or equipment (Vaha, *et al.*, 2013; Kelm, *et al.*, 2013). It has been extremely beneficial in the areas of construction management and facility management particularly for improved real-time information traceability and visibility (Motamedi, *et al.*, 2013). However, the application of RFID technology is limited to logistics, inventory control and supply chain management (Gulcharan, *et al.*, 2013). WSNs on the other hand, are cost effective networks that may consist of an array of small sensors which gather and provide environmental conditions for critical applications including health and safety management (Heller and Orthmann, 2014). Moreover, major advantages of WSNs over RFID include longer reading range and flexibility in designing and configuring various network topologies according to desired needs (Liu, *et al.*, 2008). However, battery life and reliability of performance in real-time environments are critical issues in WSNs that need specific attention when designing such solutions.

4. RESEARCH METHODOLOGY

Initially, an extensive literature review, including surveying the landscape of BIM and its integration with RFID and wireless sensor technologies, has been carried out. This examination has suggested that sensing technologies have been used to develop applications for real time monitoring of construction sites and hazard preventions. Literature review was followed by a series of semi-structured interviews with industry experts to map the capabilities of BIM and wireless sensor technologies to the information needs of health and safety managers. This was followed by a prototype development as a proof of concept. The prototype explores integration of commercial BIM software with sensor data to create a self-updating BIM model. The developed prototype system uses BIM for visualization purpose and TelosB motes for sensor data acquisition. The development environment that is used for prototype development consists of: Crossbow`s TelosB mote (Wireless Sensors); Autodesk Revit Architecture 2013 (BIM Software); Microsoft Visual Studio.Net (Software Development Environment); and Microsoft SQL Server (Database Management System). BIM enables the integration of real-time sensor data with building information due to its inherent feature of integration with external databases (SQL Server in this case). Consequently, this data link is established by assigning room element's automatically created uniqueID from Autodesk Revit to its associated sensor values. BIM model, designed in Autodesk Revit Architecture, then displays the latest real-time sensor data to visualize the status of various locations. The developed prototype system has been successfully tested in a building by placing TelosB mote in two different locations. Finally, industry experts have evaluated the developed prototype system on the basis of system: effectiveness; practicality; usability; proactivity; and financial feasibility. Figure 2 illustrates the research framework adopted for the development of real-time environmental monitoring, visualization and notification system for safety management.

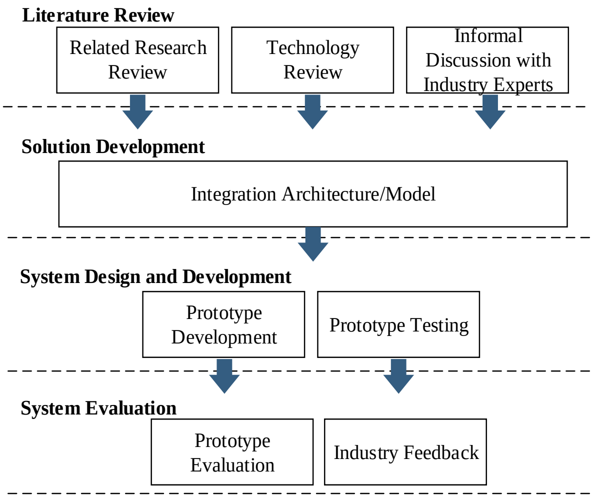

FIG. 2 Research Methodology Framework (Adapted from (Aziz, 2004)

5. BIM-RFID/SENSORS BASED INTEGRATED SOLUTIONS

BIM software, BIM database, RFID tag/sensor information and software application are the key elements of any BIM and RFID/sensor integrated system (Meadati, *et al.*, 2010). This integration is only possible by Application Programming Interfaces (API) offered by BIM as well as by RFID/sensors systems. A summary of BIM-RFID/sensor integrated solutions is listed in Table 3. These BIM-RFID based integrated solutions are primarily focusing on identification, tracking, progress monitoring of workers and equipment, building energy performance etc., nevertheless these solutions do not fulfill the requirement to sense and monitor environmental conditions to ensure safety at worksites or in buildings. Woo, *et al*. (2011) has attempted to propose a robust computational platform based on XML parsing engine for monitoring building environments using an Ethernet data logger. However, this method of collecting environment data for the built environment is time consuming, labor intensive and will not able to cope with the analysis of sensor data for effective facility management and decision making tasks (Porter, *et al.*, 2005 and Geo Scientific Ltd., 2001). Wireless and continuous data acquisition about building facilities is essential and preferred over wired technologies for acquiring lifecycle information and therefore supporting overall safety management in buildings.

Attar, *et al*. (2011) proposed the concept of sensor enabled cubicles for visualizing building performance in terms of its physical attributes of environment. Analog outputs from different sensors have been digitized using interface board and is sent to an embedded computer. Web based database is maintained by collecting data by an 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 accommodate user centric approach of visualization, since every user (building occupant, facility manager or owner) has role specific requirements for deploying sensor network, which needs to be explored.

Cahill, *et al.* (2012) and Ozturk, *et al.* (2012) also highlighted the importance of sensor networks deployment in buildings for the purpose of decreasing the operational and maintenance costs of buildings. Incorporating sensors in buildings for facility management operations like monitoring energy performance will be a next step towards intelligent buildings. Guven, *et al*. (2012) presented a framework based on BIM and sensors to provide the damage and vulnerability information of a facility that is under the threat of multi-hazard emergency situations.

As discussed in Table 3, there are many BIM-RFID/sensors based systems are available for construction and facility management operations. However, these systems primary focus on building energy monitoring and management. The integration of BIM with sensors for health and safety management is still need to be explored. Commercially available BIM softwares (BIM solutions by Autodesk, Bentley and Graphisoft etc.) provide a platform for simplified integration of BIM and real-time sensor data for health and safety management. BIM and sensor data integration along with mobile notification system can help to improve environmental safety in building by providing more illustrative building layouts in terms of BIM model and safety plans, as well as by supporting communication at the occurrence of hazardous situations, such as informing building H&S managers and site staff about making safety arrangements in response to warnings received on their mobile devices.

As discussed in Table 3, there are many BIM-RFID/sensors based systems that are available for construction and facility management operations. However, these systems primarily focus on building energy monitoring and management. There is a need to explore further the integration of BIM with sensors for health and safety management. Commercially available BIM software for example, solutions by Autodesk, Bentley and Graphisoft etc., provide a platform for simplified integration of BIM and real-time sensor data for health and safety management. This integration along with mobile notification system can lead to improved environmental safety in buildings by providing more illustrative building layouts in terms of safety plans, as well as timely communication of alerts in case of any hazardous situation.

Table 3: BIM and RFID/Sensors Integrated Solutions

Primary Purpose	***RFID/sensor technology***	***Location***	***Findings***	***Reference***
Automated management of life cycle information of buildings	*RFID tags on stationary components*	*Building-Outdoor*	*Generated 4-D virtual reality model, examined construction interfaces and conflicts in design phase and monitored construction installation works in real-time.*	*Cheng, et al. (2011)*
Fixed Assets localization	*RFID tags on stationary components*	*Building-Indoor*	*Located RFID tagged building components without RTLS Services.*	*Motamedi, et al.(2011)*
Movable Assets localization	*RFID tags on movable components*	*Building-Indoor*	*Located movable RFID tags without RTLS Services.*	*Motamedi, et al.(2012)*
Tracking of valuable assets in real-time	*RFID tags on stationary components*	*Building-Indoor*	*Maintained Database of valuable assets by tracking using passive RFID tags*	*Costin, et al.(2012)*
Building Energy Monitoring	*Electricity consumption sensors*	*Building- Indoor*	*Highlighted importance of BIM-based Baseline Building Model for monitoring building environments.*	*Woo, et al. (2011)*
Real Time Building Energy Monitoring	*Energy sensors*	*Building- Indoor*	*Proposed solution to reduce energy usage in a building.*	*Alahmadi, et al. (2011)*
Visualization of Building Performance	*Energy sensors*	*Building – Indoor*	*Achieved Real-time visualization of building performance data.*	*Attar, et al. (2011)*
Optimization of Building Operations	*Energy sensors*	*Building – Indoor*	*Monitored sensor data and identified relevant IFC objects that could support sensor data*	*Cahill, et al. (2012)*
Post Occupancy Evaluation (POE) in Residential Buildings	*Energy sensors*	*Building – Indoor*	*Monitored real-time building related energy performance*	*Ozturk, et al. (2012)*
Providing guidance for evacuation during emergency	*Gyroscope, ultrasonic and distance sensors*	*Building – Indoor*	*Presented a framework to provide the damage and vulnerability information of a facility that is under the threat of multi-hazard emergency situations.*	*Guven, et al. (2012)*

6. REAL-TIME ENVIRONMENTAL MONITORING, VISUALIZATION AND NOTIFICATION SYSTEM

Based on literature review and case studies (discussed in Table 3), an integration model for real-time environmental monitoring, visualization and notification system is developed (see Figure 3) which focuses on the following:

- Monitoring and aggregating the temperature and humidity sensor values using TelosB motes placed at different locations in a building;
- Saving the aggregated sensor values with location and timestamps to a centralized database server (SQL Server);
- Populating the BIM model in Autodesk Revit with relevant sensor data for real-time visualization of a building; and
- Smartphone based notifications and sound alarms in the building if sensor data exceeds defined thresholds (listed in Table 1).

Prototype System Functionality

A prototype system for real-time environmental monitoring, visualization and notification is developed which uses off-the-shelf BIM software and modifies it to visualize and manage real-time sensor data in its native environment. The prototype system is programmed to interface with Autodesk Revit Architecture 2013, a BIM software solution, which comes with Application Programming Interfaces (API) and Software Development Kit (SDK). These features make the Revit Architecture a good choice to write custom software applications to achieve desired research objectives.

For sensor data acquisition, IEEE 802.15.4 compliant TelosB motes by Crossbow are used because of open-source and energy efficient sensor suit, which includes integrated temperature, humidity and light sensors. Low cost TelosB motes are powered by two AA batteries and use Universal Serial Bus (USB) port for programming and communication with the host computer. The main reason behind the selection of TelosB motes is its ability to sustain harsh environmental conditions particularly when enclosed with sealed waterproof protective casing (Hill, *et al.*, 2005 and Bathula, *et al.*, 2009) However, sensors and antenna should be fit onto the protective casing so that sensing and transceiving capabilities of motes do not get compromised (TinyOS, 2011).

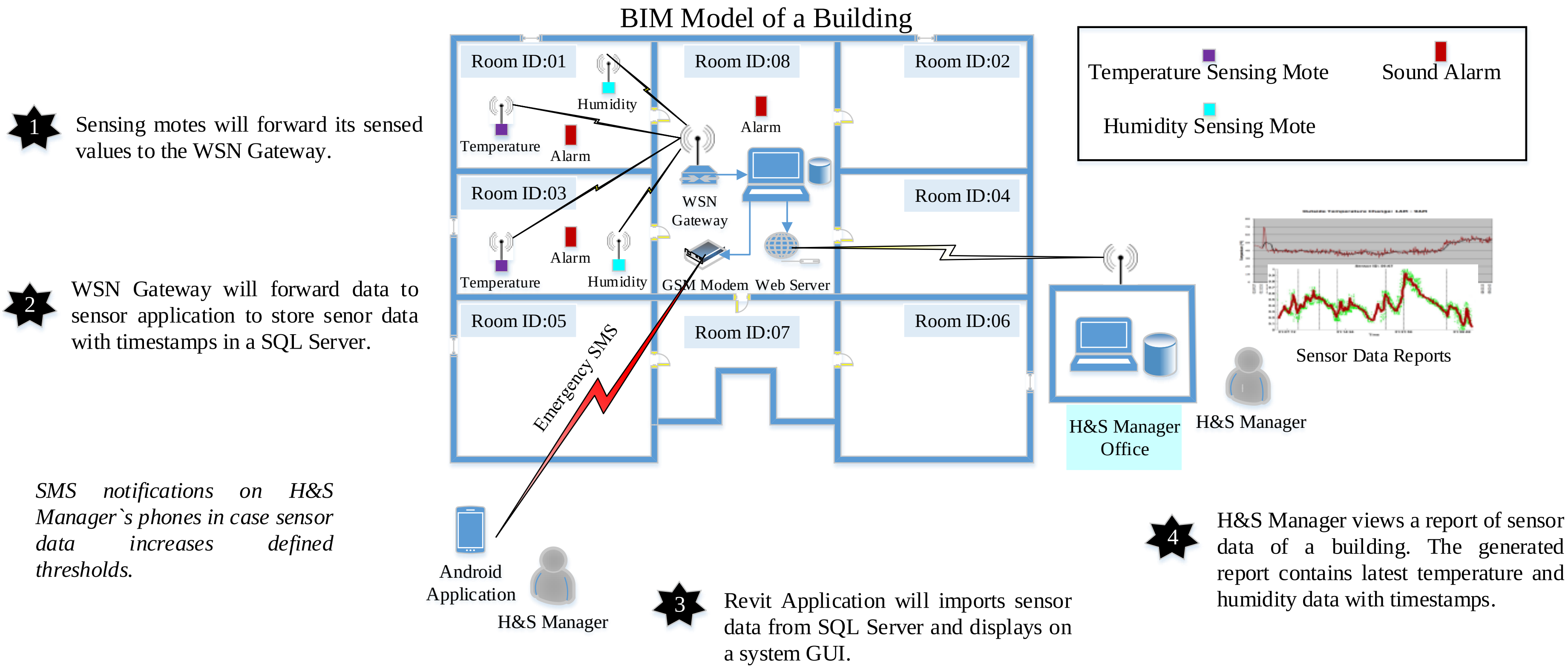

FIG. 3 Integration Model of Real-Time Environmental Monitoring, Visualization and Notification System

Prototype System Database Schema

Database has been configured using Microsoft SQL Server to store updated sensor data, managed by the Autodesk Revit software via Revit database link. The tables designed for prototype system provide a basic framework to define relationship between BIM objects (rooms) and acquired sensor data.

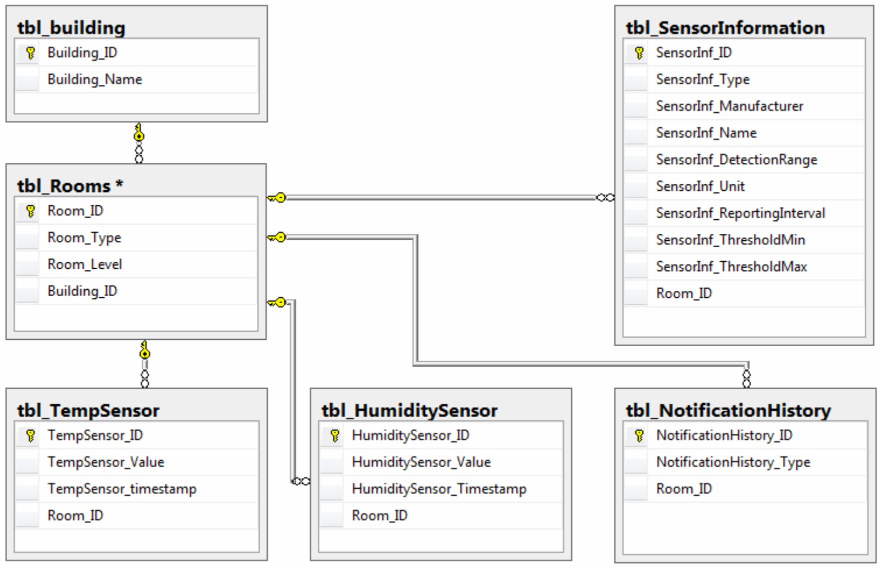

FIG. 4 Database Schema of Real-time environmental monitoring, visualization and notification prototype system

Figure 4 describes the database tables of real-time environmental monitoring, visualization and notification prototype system. "tbl_building" table uniquely identifies every building. "tbl_Rooms" table contains details on room tagged for environmental monitoring. This room is tagged by the H&S manager by selecting the "Tag Room" option located in Room & Area section in Autodesk Revit software. "tbl_TempSensor" and "tbl_HumiditySensor" tables list the details of temperature and humidity sensors. Whereas, "tbl_NotificationHistory" table holds the information about the generated notifications due to increase/decrease in the sensor values from defined thresholds.

The UI of prototype system provides an access to the database and to the tables to define/modify relationships. Real-time environmental monitoring, visualization and notification prototype system displays a series of data grid views which displays the most updated sensor values (see Figure 6).

Sensors ID Assignment and Relationships with BIM elements

The most important function required for "real-time environmental monitoring, visualization and notification prototype system" is to link building elements (rooms) to physical temperature and humidity monitoring sensors that can collect the environmental data about rooms (workspaces) (Riaz, *et al.*, in press). This function is achieved by utilizing the built in powerful "Tag Room" feature of Autodesk Revit software. The following below numbers illustrate the chronology of interaction, and correspond to the numbers in Figure 5:

1. Using the Revit software, H&S manager first tag the rooms (workspaces) on a BIM model, which need environmental monitoring. Tagging a room is achieved in Revit native environment by using "tag room" feature located in the drop-down menu of "room and area panel".
2. After tagging the rooms (workspaces) in BIM model, find the unique identification (ID) of the tagged rooms by using the feature of "IDs of selection" in the drop-down menu of "inquiry" in the "modify" tab of Revit software.
3. Assign the ID of the tagged room found using above step 2 to the wireless sensor which has been embedded in a building element, exactly the same as of the room. In the designed prototype, two

TelosB mote comprising of temperature and humidity sensors are tagged to two rooms for environmental monitoring.

4. Once the ID assignment to wireless sensors is done, prototype system will now able to display the location and IDs of the tagged rooms on a GUI, which can be invoked using "external tools" menu from the Revit UI.

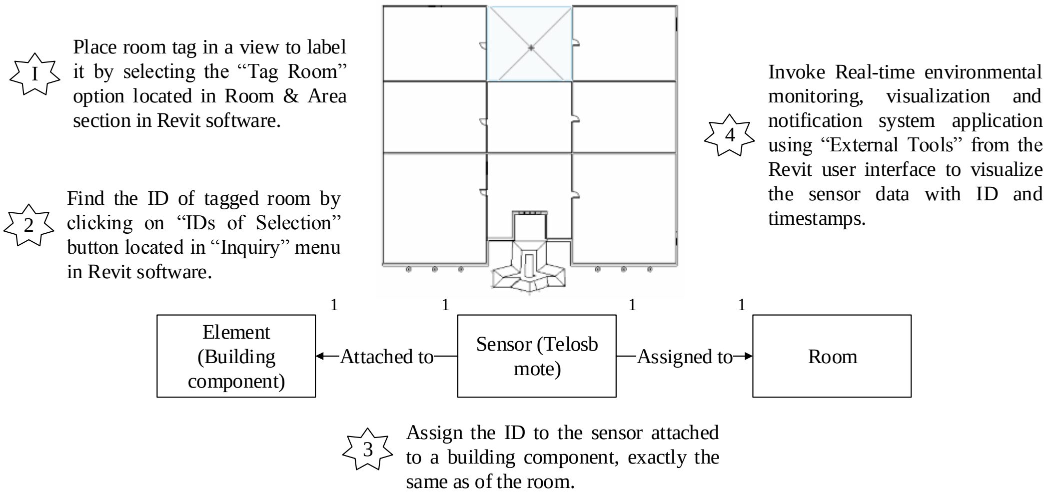

FIG. 5 Sensor Attachment and Assignment Relationships

The assignment of the room element's automatically-created unique ID from Autodesk Revit to each associated sensor will create a database link for real-time monitoring. Using a database link is powerful because whether or not the BIM is updated separately from the sensor data, it does not affect its relationship to the sensor data. In order to visualize the data using a live Revit model and live sensor information, prototype GUIs are designed in a way that H&S managers can query the BIM data, and using the known relationships to the sensor information, GUI can display the correct sensor information for the associated room (Riaz, *et al.*, in press). Due to the BIM database structure that enables this querying which can be done for an entire building simply that doesn`t exist with traditional 3D CAD softwares.

Prototype System User/Data Interaction

A self-updating GUI entitled as "real-time environmental monitoring, visualization and notification system" has been designed as a Revit Add In (an external application), which can be invoked by pressing external tools button from Revit Architecture software and will start updating itself with latest values of sensors as shown in Figure 6. The GUI of Revit External Application is designed using C# language and consists of a list of all the rooms' information which is tagged by a user. Data grid views are added to show the sensor data of temperature and humidity from their database tables. In order to develop a prototype system, two TelosB sensing motes and one TelosB gateway mote has been used to make a WSN in two rooms in a building. TelosB motes are supported by TinyOS open source operating system developed by UC Berkeley and supports self-configuring sensor networks.

Sensor acquisition application using C# language is created to read the wireless sensors placed in workspaces with their Room IDs. Sensor application is programmed to read USB port and to provide connectivity to wireless sensor gateway. After reading the sensors data, values of temperature and oxygen are stored with timestamps in an SQL Server database. The time interval of saving a sensor data in a database can be increased or decreased by a user as required (see Figure 7). If oxygen and humidity sensor data increases or decreases the defined thresholds (in case of temperature it is set as 30 ºC and in case of humidity it is set as 70 % in any physical workspace) then designed prototype system will show red color triangles on a BIM model. Notifications will be generated in Revit Architecture and to H&S Manager`s mobile device. The occurrence of notifications will be saved in a database for future accident analysis (see Figure 8). The designed GUIs will help the H&S managers to actually visualize the workspaces and observe their associated real-time environmental sensor data.

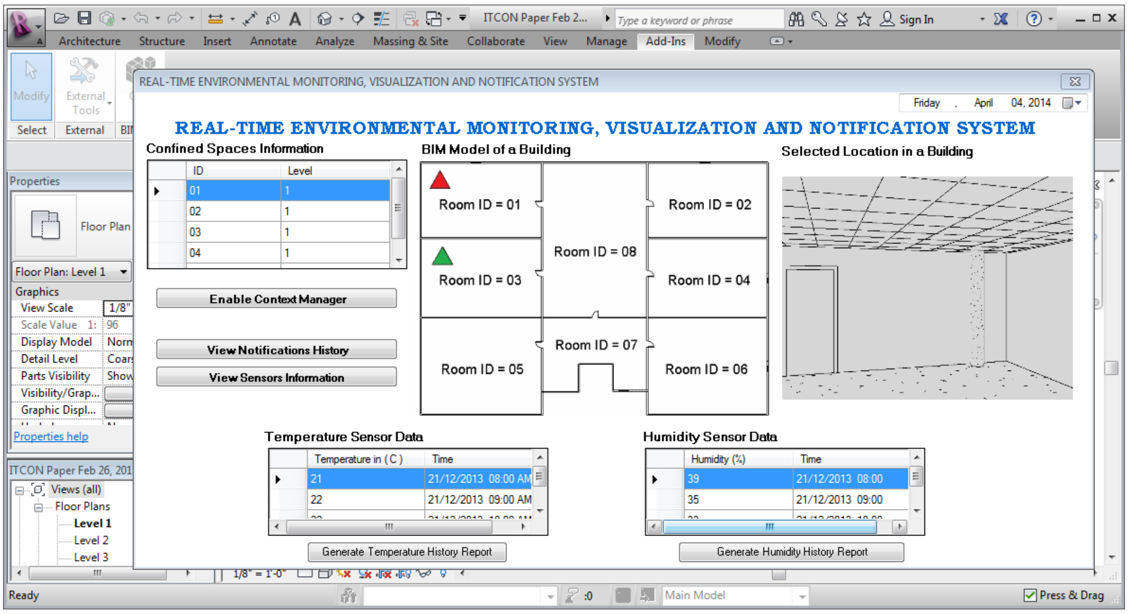

FIG. 6 Invoked External Application from Revit GUI

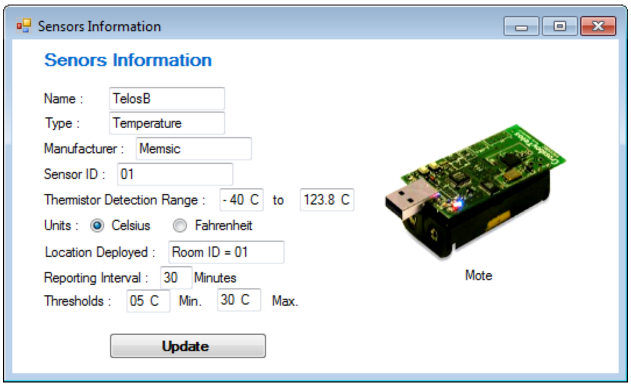

FIG. 7 Visualizing the Sensors Information

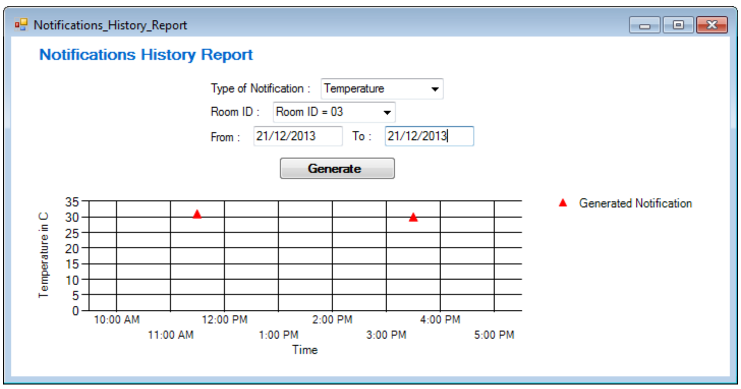

FIG. 8 Visualizing the Generated Notifications History

Prototype System`s Operating modes

Real-time environmental monitoring, visualization and notification system comprises of heterogeneous power sources in which some nodes (sound alarms) are plugged in to wall due to their higher power consumption and other nodes (temperature, humidity) are working on batteries. Application demands of prototype system pose some requirements on power management to have energy efficiency in battery controlled nodes (sensing motes) which are,

- Sensors used to collect temperature and humidity attributes should adapt their operational states according to the occupancy of workers in workspaces. During work shifts, H&S manager may need a high rate for temperature and humidity values for worker safety analysis whereas a low rate or turn off sensors if there is no activity in workspaces.

- Prototype system should provide openness to H&S manager, who should be able to set contexts and sensors` thresholds values at run time which are unique to different work scenarios. These sensors` thresholds will play an important role in generating sound and SMS based notifications to H&S managers on the occurrence of hazardous situations in work spaces.

To satisfy above requirements, a context aware power management mechanism is introduced in the prototype system. Context-aware power manager, residing in sensor data acquisition application controls the power management operations for the system. For battery controlled sensing motes, real-time environmental monitoring, visualization and notification system provides two types of power management operating modes: those rely on H&S managers` directives and those based on context awareness mechanism, which can be activated using "Enable Context Manager" button in the main prototype UI (see Figure 6). First, H&S managers can directly control each sensing mote. Sensing motes can be turned on/off and their rate for collecting sensor values is directly configured and controlled (see Figure 7). Second, power management operating mode adapts the behavior of the work spaces` environment located in a building. Initially, H&S manager need to define sensor thresholds for power management. If there is no abrupt change in collected sensor values then sensing motes should be command to transmit sensor value with an increased delay and their rate for saving sensor values in a database is only increased when there is a significant change is detected in a sensor value. This context-aware operating mode aims at increasing effectiveness and usability of developed prototype by taking atmospheric context into account and hence provides more efficient power and storage management solution to AEC industry.

Prototype System Mobile Application

Another objective of "real-time environmental monitoring, visualization and notification system" is to allow H&S manager to remotely monitor sensor data of workspaces located in a building using mobile devices. Real-time environmental monitoring, visualization and notification system Mobile Application has been designed using Android, an open source platform for mobile devices (see Figure 9).

Android platform is chosen because it provides comprehensive set of tools and frameworks to design mobile applications easily and efficiently. Moreover, this platform will command nearly half of worldwide smartphone operating system market by the end of year 2012 (Gartner, 2012). Application is designed using Eclipse, an integrated development environment and it is tested in Android Virtual Device (AVD). Wi-Fi (standard IEEE 802.11) is used for connectivity with a web database and access to database is protected with a username and password. By using the mobile application, H&S Manager can easily monitor the real time sensor data of workspaces and can help in responding to time sensitive emergency situations occurring in buildings or construction sites.

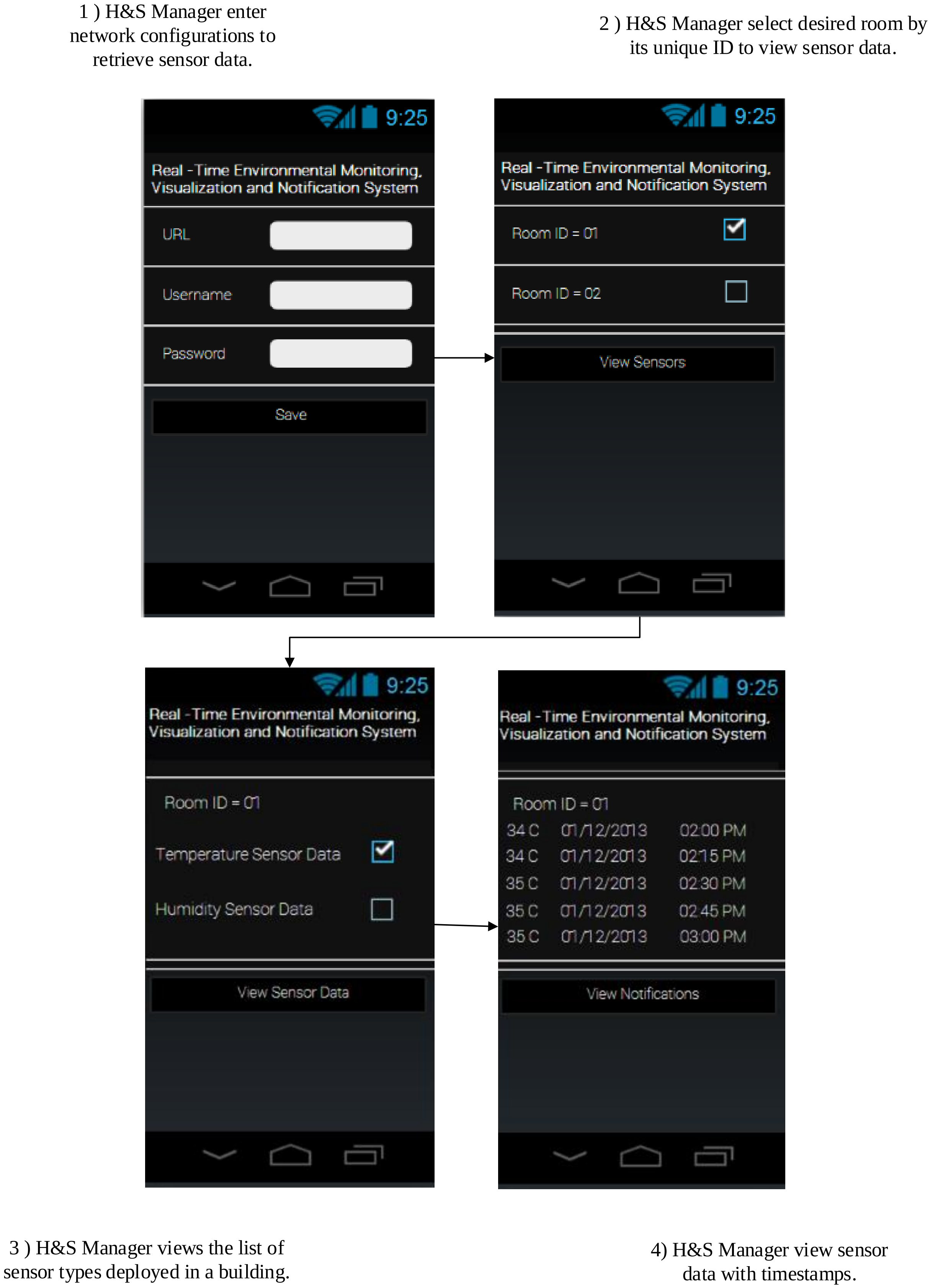

FIG. 9 Mobile Application of Real-Time Environmental Monitoring, Visualization and Notification System

7. PROTOTYPE EVALUATION – INDUSTRY FEEDBACK

The questionnaire which was developed for the evaluation of "real-time environmental monitoring, visualization and notification prototype system" requested quantitative information from the respondents. The construction industry evaluators were carefully selected with verification that they have an understanding of the emerging BIM framework and sensor technology. A survey was conducted with these contributors who were employees of contractors (25) and consultants (3). Although, the sample size was small, but it covers the whole spectrum of people associated with the construction safety management and a familiarity of BIM platform.

The questionnaire was designed to evaluate the system for: effectiveness; practicality; usability; proactivity; and financial feasibility. The respondents' choices of answers ranged on a Likert scale of -2 to +2, where: -2 = strongly disagree; -1 = disagree; 0 = neither agree nor disagree; +1 = agree; and +2 = strongly agree. The responses were quantitatively analyzed using a t-test (see Table 4 for mean of responses and p-value). The results are statistically significant in all cases (p-value is less than 0.05) except in the case of 'usability' of the prototype system (p-value is 0.19 > 0.05). This suggests that the respondents do not consider the Graphical User Interface (GUI) of the prototype system as very user friendly for the use of an average construction worker. Therefore, particular attention needs to be given to the interface design during the implementation stage of the system. Moreover, respondents are significantly in agreement with the effectiveness of the application where they find it useful and relevant for industry needs. They concur that the system will contribute in reducing the environmental H&S hazards on construction sites and will help towards a proactive H&S management system that will enable managers to *learn* to improve H&S management practices.

Table 4: Evaluation Results

No.	*Evaluation Criteria*	*Mean of Responses*	*p-value (one tailed)*
1	***Effectiveness***	*0.6667*	*0.0009*
2	***Practicality***	*0.5795*	*0.0001*
3	***Usability***	*0.1477*	*0.1927*
4	***Proactiveness***	*0.4318*	*0.0111*
5	***Financial Feasibility***	*3.364*	*7.99E-14*

As the system evaluation results suggests, the respondents felt that real-time environmental monitoring, visualization and notification prototype system is most likely to positively impact the construction industry for safety management and which ultimately affects the way the construction process is conducted. The data fusion between BIM and wireless sensor technology will serve to be an in invaluable accomplishment that can be utilized for future applications for safety management. However, more research needs to be conducted in order to make system interoperable with existing sensor systems by reducing its cost of deployment and simplifying the system user interfaces. Additionally, quantifying the impact of a prototype system through real world construction case studies will offer a more compelling argument for real-time environmental monitoring, visualization and notification prototype system adoption by AEC firms than simply the perceptions described here.

8. CONCLUSION AND FURTHER RESEARCH

The developed prototype application investigates the integration of BIM with wireless sensors and mobile computing. The research has highlighted significance of monitoring workspaces since working in hot and humid environments is one of the leading cause of death of workers in buildings and in construction sites. In order to address the atmospheric hazards, real-time environmental monitoring, visualization and notification system promotes a proactive H&S management system where the information requirements of H&S management can be addressed. Designed prototype system is implemented within the native environment of Autodesk Revit software and it takes the advantage of Revit UI to work. Prototype system works as an extension to commercial BIM software (Revit) that does not requires users to have any special trainings to learn a new interface of Revit. Engineering firms that currently use BIM software (Revit) in the construction process can easily operate prototype system for environmental safety management by simply installing designed prototype system as Revit Add In. This unique feature of interoperability makes real-time environmental monitoring, visualization and notification system an attractive option for the AEC industry investing in BIM technology as this feature was not found in the past and current literature. As previous research prototype systems presented in Table: 2 are the stand-alone systems designed specifically for energy management in buildings that requires additional trainings which may discourage its use and adoption in the industry. Designed prototype system uses central SQL Server for persistent data storage so that building supervisors and H&S managers connects to a centralized database to retrieve updated real-time sensor data throughout the building lifecycle. The designed application is at initial stage of development and incorporation of activity and other gas monitoring sensors will add more value to a designed system to reduce deaths and injuries occurring in workspaces. Sensor reliability and energy efficiency are two of the most important parameters requiring careful consideration when developing a system such as real-time environmental monitoring, visualization and notification system.

After designing and development of prototype system, it has been evaluated in terms of system`s effectiveness, practicality, usability, proactivity and financial feasibility by industry experts. There are many ways in which the application can be improved. For example, an important function that can be added in the developed prototype system is tracking the location of workers in construction sites using RFID technology. Application of RFID technology will not only increase worker safety but will also prevents unauthorized access to hazardous areas in the construction site and avoiding accidents caused by the incautious workers. Installing the RFID readers at the entrances will detect the entry of workers into hazardous zones and when the workers are inside a zone, a prototype system shows a location of worker on a BIM model. In this way, H&S managers will better monitor the allocation of workers to each zone more efficiently and ensuring safety of workers by visualizing the real-time sensor data of hazardous zones on their smart phones. Furthermore, developed Android application can also be enhanced to allow the H&S managers to remotely read just threshold values and time intervals of saving sensor values in a database to avoid memory overflow. These enhancements can give a more proactive approach to deal with atmospheric related hazards.

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