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Monitoring thermal comfort in subways using building information modeling

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ABSTRACT

Metro transit systems have gained a lot of importance because of the large number of passengers depending on that vital mode of transportation. Most of metro transit systems contain subways which need to be efficiently ventilated in order to maintain health and comfort of passengers. Therefore, it is necessary to monitor the thermal comfort inside subways. Subways are large facilities that require an efficient and huge ventilation system. Monitoring thermal condition for the subway is an important issue because of the variations that may occur in different spaces within the subway. These variations may affect energy consumption and the level of thermal comfort for the passengers as well. This research presents an application that utilizes wireless sensor network (WSN) and building information modeling (BIM) in order to monitor thermal conditions within a subway. BIM-based model is used to visualize the readings of air temperature and humidity levels in the subway spaces. Whereas, WSN is used to measure air temperature and humidity at different spaces within the subway via a group of transmitter nodes attached with different sensors. A case study is presented in order to illustrate the capabilities of the system developed. Finally, conclusion and future recommendations to expand this research is presented.

1. Introduction

Recently, world's transportation systems are booming because of a lot of reasons such as population's increase, need to reach new areas, and the need to increase the efficiency of transportation system. One of the most important modes of transportation is rapid transit systems. Across the world, many countries possess giant network of rapid transit system which contains underground stations (subways) and above ground stations. For example, London underground network has 11 lines with 270 stations [1]. Another example, Egypt has three lines of its metro system in Cairo consisting of 57 stations and 17 of them are underground [2]. As for underground stations, air temperature in underground stations is higher than air temperature in the outdoor environment and as a result subways require an efficient ventilation system or HVAC system. The large number of commuters that gave rapid transit system significant importance requires different subway authorities to maintain the commuters' satisfaction and well-being. One of the most important aspects that the authority shall maintain, assess and predict is the thermal comfort of passengers. It is important to ensure that different thermal comfort conditions are within acceptable limits.

A lot of subways were built long time ago, for example, London underground began operation in 1863. Other countries started their rapid transit system more recently. The age of different subways and maintenance strategies are the main factors, affecting the performance of different systems in a subway [3]. Ventilation or HVAC systems are one of the systems that are affected by the age and maintenance strategies and practices. If ventilation/HVAC system is not maintained properly, the energy consumption increases, the thermal comfort of passengers decreases and the rate of satisfaction between passengers decreases. As number of passengers increase within a subway, the temperature of air increases and as a result the degree of thermal comfort decreases among passengers.

Surveys and mathematical models are the two main methods that are used in order to assess the degree of thermal comfort among occupants of a building and the expected comfort temperature. Lee et al. [4] have examined the relationship between the learning performance of students and indoor environmental quality (IEQ). The study took place in Hong Kong Polytechnic University teaching rooms which were air conditioned. They examined the IEQ of the university in terms of thermal comfort, indoor air quality and

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visual and aural levels. Measurement devices were used in order to collect data from certain lecture halls every 30 min. The authors distributed a survey among students in order to measure the level of satisfaction between students. EPIQR (energy performance, indoor air quality and retrofit) is an European project that is used to assess and determine the energy performance of buildings, indoor air quality and possible replacement/maintenance actions. The developed tool allows the user to answer a questionnaire related to IEQ in his/her facility associated with the facility information (e.g., address and age of persons living in the apartment). It acts as a diagnosis and analysis tool for the complaints and it takes corrective actions [5]. The development of this tool was a great attempt to associate information about facility with questionnaires and complaints; however, this attempt does not include any digital representation or geometric modeling for the facilities. TOBUS (a decision making tool for office building and upgrading solutions) is another tool that contains nine modules to model building dimensions and geometry and other useful information about the facility. One of the modules is concerned with the assessment of the indoor air quality in which it collects data from questionnaire answered by occupants of the building. After that data can be analyzed and TOBUS can indicate complaints and major problems. TOBUS can provide statistics about different complaints and problems [6,7]. Kim et al. [8] have monitored and predicted indoor air quality (IAQ) of subways. Air pollutants, air temperature and humidity were measured at a subway in Korea. The authors have monitored and assessed the effect of different seasons on the IAQ in metro systems using seasonal models. A multivariate analysis of variance test (MANOVA) is developed in order to know if different seasons influence the IAQ of subways. A measurement device is installed at the platform level of the subway and continuously measures different parameters.

Energy consumption depends mainly on the efficiency of the energy-related systems such as HVAC and refrigeration systems, lighting and daylighting controls, domestic hot water systems, and renewable energy systems. According to Lu et al. [9] HVAC system in a subway station can consume more than 40% of the total power. So, a major way to save energy for the HVAC systems is to design optimal control strategies to minimize the overall energy consumption while still maintaining the satisfied indoor thermal comfort and healthy environment [10]. Freire et al. [11] has examined the indoor thermal comfort control problem in buildings equipped with HVAC (heating, ventilation and air conditioning) systems. He proposed different strategies to reduce energy consumption and maintaining acceptable indoor air conditions related to thermal comfort. One of these strategies tries to find the optimal value for the HVAC consumption while maintaining acceptable thermal comfort conditions to reduce energy consumption.

Building information modeling (BIM) is considered as a way in order to represent the physical characteristics of different elements in digital form [12,13]. BIM has several advantages; therefore, many research studies have been directed to the possible applications of BIM. Azhar et al. [14] have developed a framework that aims at utilizing one of the valuable advantages of BIM, multi-disciplinary information, with LEED accreditation process. The authors stated that the accreditation process using BIM will be more efficient and precise than other traditional methods. The framework depends on exporting the BIM-based model using Revit software to Integrated Environmental Solutions (IES) software in order to perform different analysis on the facility and create LEED documentation. Lee et al. [15] have integrated the BIM-based model of the project and a group of sensors in order to create a navigation system that helps in solving blind lifts problems. The developed system is capable to determine the location of the lifted object with respect to the project and other existing buildings. The authors have used laser and encoder sensors and video camera in order to visualize the lifted object and determine information about its location. The location of the object is then integrated with the BIM-based model and updated in real time manner. Zhang et al. [16] have developed a tool that checks safety in construction models using BIM-based models taking advantage of the information existing in the BIM-based model such as quantities and schedules. The authors have used the safety measures and guidelines such as the measures and guidelines given by OSHA as a rule check that can used with Revit or other BIM software. The safety checking system developed by the authors is updated at the same time the BIM model is updated throughout different construction phases in order to identify different hazards. Schlueter and Thesseling [17] have used BIM in order to calculate the energy performance of buildings using information from different disciplines. Calculations are done by a tool developed by C# programming language and integrated with a BIM software. The authors use BIM capabilities of storing different information and parameters in order to do energy and energy performance calculations at early design stages. BIM has allowed the authors a rapid assessment of energy performance at early design stages.

BIM-based models contain a lot of useful information about different project elements. A specific chiller in a subway can be associated with information like dimensions, materials, year of manufacturing, URL link for the manufacturer and much other information. This integration between geometric properties of different elements and their other non-geometric properties offers the opportunity of fast information retrieval. A lot of meaningful information can be extracted from the BIM-based model, as elements is not only represented by its geometric parameters as CAD drawings do but also associated with useful information such as the place of the element and its material [18]. BIM-based models offer a better visualization for facilities, improved coordination between different specialties and integration of other facility management applications. Most of BIM software packages offer the user the ability to add customized parameters or functions in order to add more information and expand the BIM-based model capabilities. Indoor environmental quality (IEQ) monitoring can be used as an application of BIM-based model. Readings of air temperature, humidity, air velocity, noise level, illumination level and gas levels can be associated with the BIM-based model. The BIM based model allows integrating the previous readings in spatial manner. For example, readings can be associated with every lecture hall in a university which gives a better visualization and understanding for different problems. Marzouk and Abdelaty [3] have proposed a framework for the integration between wireless sensor network (WSN) and BIM-based model in order to assist asset managers in facilities inspection. WSN is very useful and effective way in order to collect data within a facility in addition it is easy to install within an existing facility. Most, if not all, of subways have a building management system (BMS) which is a customized system designed specifically for a certain building/facility in order to manage certain tasks within the facility. BMS can be used in order to control the temperature of the facility and control many other systems within the facility. However, these tasks done by the BMS can easily be done with a customized BIM-based model. BIM-based model complements the use of BMS with more comprehensive features. This research aims at integrating WSN with BIM-based model in order to partially monitor and assess IEQ. The developed system is capable to measure temperature and humidity in a subway by the installation of WSN and linking information with BIM-based model in a spatial manner. The system also proposes linking simple mathematical model with the BIM software in order to predict the level of thermal comfort among passengers. The research provides a novel approach toward the expansion of BIM applications in facility management.

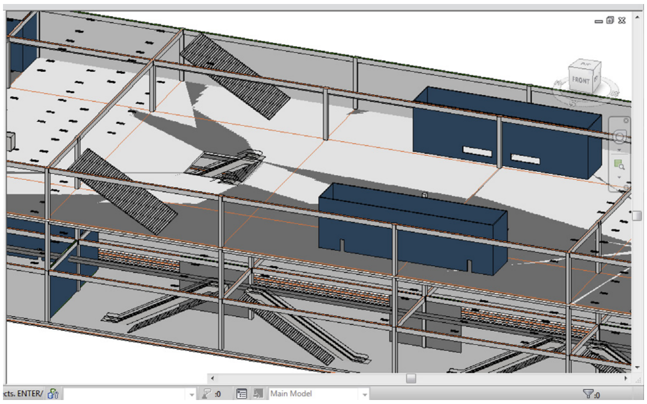

Fig. 1. Modeling different elements of subway in BIM-based model.

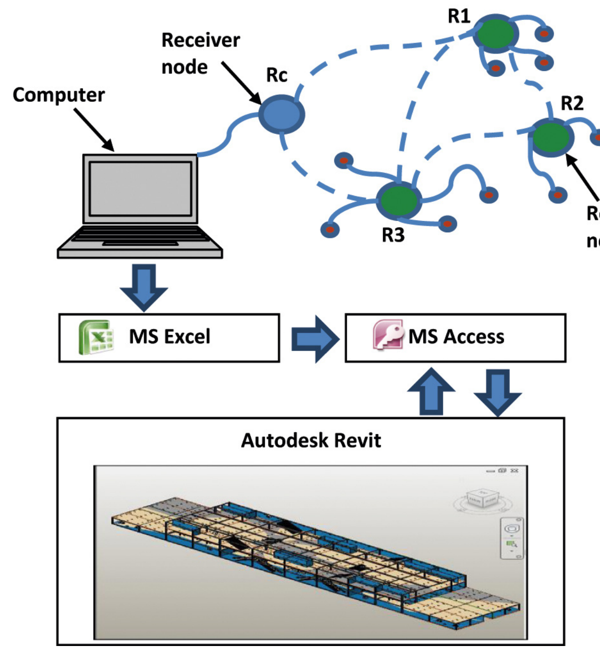

Fig. 2. Data flow in the proposed BIM-based model.

2. System overview

In this section, an overview for the integrated BIM-WSN system is illustrated. The BIM-WSN system is capable of establishing a communication channel between the BIM based model and different sensors installed in a subway. The system is composed of two main components. The first component is the BIM based model for a subway. The model shows different elements and levels for a subway and at every specific space there is a dummy element called thermal comfort monitor which doesn't exist in reality. The main role of the thermal comfort monitor is to store data gathered by the WSN in the BIM based model in a spatial manner as depicted in Fig. 1. The thermal comfort monitor has the following parameters: temperature (indoor/outdoor), humidity, comfort temperature and date of latest update. The temperature parameter varies whether it is indoor temperature or indoor temperature according to the location of the thermal comfort monitor. Comfort temperature is a parameter that shows the temperature of air at which most passengers are satisfied. Finally, the latest update parameter shows the latest date when information is exported to the BIM-based model.

The second component in the system is the WSN which is a group of router nodes with different sensors attached. Temperature and humidity sensor is attached to the router node and temperature and humidity readings are sent to the receiving node. The receiving node is connected to a computer so readings can be imported the BIM based model. Various wireless technologies (e.g., Zigbee, Wifi, Bluetooth, Ultra Wide Band, and Infrared) can be used to send and receive data. The developed WSN, in the proposed application, uses Zigbee because of its low data rate and high range. Data rate is the size of data transferred per time (second). In the developed application, the size of data transferred is small so it is more convenient to use Zigbee. The range of XBee®, which is Zigbee module produced by Digi International, can reach 40 m for indoor applications [19] which is more than sufficient for the developed application. Each router and receiver node has its own address in order to determine channel of communication and prevent data conflict. An Arduino Uno microcontroller board is used connected to temperature and humidity sensor. As there is no function in the Arduino compiler that can open an MS Excel sheet to enable data exchange, an external program (named Gobetwino) is used. Gobetwino is a generic proxy that have the ability to open an excel file and send the readings directly to the excel file [20].

Temperature and humidity data are gathered in a timely manner. Time delay which is the difference in time between two successive readings is set in order to control the number and timing of measurements. Once readings are recorded, two options are available: (1) sending readings to receiver node and (2) leaping readings from node to node in the network till they reach receiver node. According to the space between the receiver node and the router node, one of the two aforementioned options is selected. If the router node and the receiver are in range which is 40 m [19] (i.e., both are connected directly), the first option is most applicable, otherwise, the second option is executed. First, readings are recorded in an external file associated with time of measurement. Having raw data in Microsoft Excel format aids in processing and mining acquired data. For Example, the average values of temperature and humidity can be easily computed and other sorts of sophisticated data analysis can be developed. Afterwards, some selected data from MS Excel can be associated with a database using SQL server or Microsoft Access. It is important to notice that project information shall be exported from Autodesk Revit to Microsoft Access or Microsoft SQL server first, then, the l data are exported from Microsoft Excel to a database. Using the Revit database link enables importing and exporting of information between a database software and Autodesk Revit.

Fig. 2 illustrates a schematic diagram that shows data flow in the proposed BIM-based model. The data flow diagram is divided into two main levels: level one represents the flow of data between different router nodes, receiver and a computer. Router nodes and receiver node are abbreviated by "R" and "Rc", respectively. Referring to Fig. 2, it is worth noting that "R1" and "R3" are in the range of the receiver node, therefore, data flow directly from "R1" and "R3" into the receiver node "Rc". Whereas, "R2" is out of range of the receiver node, so data have to flow to "R1" and "R3" and then flow to the receiver node. After data have been sent to the receiver node, the receiver node converts the data type in order to be used by the computer. A module is developed using C# language in order to achieve connectivity between the Microsoft Excel file that contains the readings and the Microsoft Access database. The main role of the module is to calculate the average of the readings in the Excel file every specific time period set by the user. After calculating the average, the module saves the calculated average into the database in order to be monitored by the user.

3. Assessment of thermal comfort

Thermal comfort of enclosed space depends on various factors. According to Health and safety Executive (HSE) [21], air temperature, radiant temperature, air velocity, humidity, clothing insulation and metabolic heat are the six basic factors that affect thermal comfort of occupants. As for subways, radiant temperature is not considered a factor that affect thermal comfort of passengers because there are no objects or devices that emit heat into indoor air of subway. The developed system allows measuring air temperature and humidity at different places in subways. Further, temperature and humidity sensors can be installed at air inlets of a subway in order to measure temperature and humidity of outdoor air. After gathering data (temperature and humidity) along the subway and integrating these data with the BIM-based model, partial assessment of thermal comfort is performed. Through the installation of a router node at the air inlet in the subway, it is possible to measure the outdoor temperature. Several studies have investigated the relation between the outdoor temperature and comfort indoor temperature and determination of thermal comfort using the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) [22–26].

Inefficiencies of the HVAC system and different density of passenger are the main reason for variations in temperature and humidity levels within a subway. For example, at the platform level, more people exist compared to an intermediate level (level between the ticket hall level and the platform level). As a result, it is expected to find that temperature and humidity levels have higher values compared to intermediate levels. Another advantage of the developed system is that it can determine problems' locations that might exist in the HVAC system through tracking different air temperature in the subway. As temperature and humidity readings are recorded in database and integrated with BIM-based model in a spatial matter, it is possible to compare the degree of thermal comfort according to a specific place or the whole subway. This allows the subways' operators to review the different temperature and humidity levels at different levels and locations of the subway using the BIM-based model and save energy by fixing the problems that might exist in the HVAC system. Thermal comfort temperature is calculated according to Auliciems and deDear [22] model as per Eq. (1).

$$T_{n,o} = 17.6 + 0.31\,T_o \tag{1}$$

where $T_{n,o}$ is the neutral temperature based on mean outdoor temperature and T_o is the outdoor air temperature.

The BIM-based model is capable also to compare thermal comfort temperature with average air temperature of the subway. Calculating the average air temperature of the subway leads is an indication for passenger satisfaction or comfort. It is more common that passengers spend more time at the platform level rather than the intermediate level. Sometimes, passengers may find the ticket hall level crowded and they have to stay in lines. Conclusively, time spent by passengers in a subway varies according to the several factors such as: time during the day, working days or weekends, average number of passengers using subway and time between arrivals of trains. So, it would be misleading to calculate the average air temperature of the whole subway without taking in consideration time spent by passenger at different levels. In order to estimate time taken by passenger at each activity a simple module is created using C# language. Commonly, there are three categories of subways; one level subways, two levels subways and three levels subways. The one level subway consists of only the platform level including the ticketing hall. The two levels subway consists of two levels; one is the platform level and the other the ticketing hall level. The last category of subways consists of platform level, intermediate level and ticketing hall level.

There are three main activities that are performed by passengers in any subway. These activities are: buying a ticket, moving from level to another (according to the subway number of levels) and waiting for the train. Each activity consumes time from the passenger and it varies depending on some factors such as number of passengers using the subway, distance to move from one level to another, delay in train arrival and unexpected malfunctions in ticketing machines. The mentioned factors affect the time spent by passenger doing each activity. The module helps subways operators to determine an approximate percentage of total time spent by a passenger in a subway. First, the module asks the operator to choose the type of the subway. Accordingly, the operator is allowed to insert the minimum and maximum time for activities according to his/her experience. Further, the operator has a flexibility to skew the generated random time with a certain degree either toward the minimum value or the maximum value.

In order to use the module, the operator selects the number of levels in the subway as one level subway. As a result, the user is only allowed to ticket buying time and train waiting time. By specifying a probability of 0.6 for train waiting time, it implies time value will be slightly above time average. The same concept applies for the ticket buying time. The module generates a random time between the minimum and maximum time according to a normal distribution with mean determined by the user according the probability inserted and a variance of half the distance between the minimum and maximum values. After generating random times for each activity, the module calculates the total time spent by a passenger in a subway. The module also calculates the percentage of time spent by the passenger at each task that he/she performs. Subsequently, the operator can use these percentages in calculating the weighted average of air temperature and humidity levels in a subway. Through using these percentages, more weight is given to locations where a passenger spends more time in these locations.

4. Case study

A case study for Cairo Metro is developed in order to illustrate the capabilities of the developed system. A router node and a receiver node are installed at three different underground stations in order to measure air temperature and humidity level at the platform level. It is worth mentioning that the three stations are successive which indicates that outdoor air temperature and humidity levels are very similar among the three stations. Air temperature and humidity levels were measured afternoon for four consecutive working days. A DHT11 digital temperature and humidity sensor was used to measure temperature and humidity levels. The measurement accuracy for the aforementioned sensor is ±2.0 °C and ±5% for relative humidity. Data gathered by the router node is logged into Microsoft Excel file to calculate average and standard deviation are calculated. Table 1 lists the average and the standard deviation of air temperature and humidity level at the platform for the three stations. The EN ISO 7730 recommends that the humidity level shall in the range of 30–70% [24]. Table 1 lists the average and standard deviation of humidity level at the three stations. Humidity levels for the three stations are very similar and between the recommended range given by EN ISO 7730.

Data gathered from the receiver node that represents air temperature and humidity in the three stations in the first day as shown in Fig. 3. Humidity levels for the three stations are very similar to each other. Some sort of error in reading may occur according to the quality of sensor used, for example the humidity level in station #2 has suddenly dropped to 28% which is unrealistic reading compared with other readings for the same station. As for air temperature; station #1 has the highest average temperature, station #2 has the second highest air temperature and station #3 has the

Table 1
Average and standard deviation of air temperature and humidity in the three stations.

	Station #1				Station #2				Station#3			
	Temperature (°C)		Humidity (%)		Temperature (°C)		Humidity (%)		Temperature (°C)		Humidity (%)	
	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD
Day 1	32.95	0.86	47.32	2.30	28.56	1.25	44.63	1.45	25.57	0.84	44.24	1.80
Day 2	33.02	0.78	47.19	2.36	28.77	1.49	44.40	1.54	26.00	0.93	44.81	2.60
Day 3	33.10	0.84	47.58	2.03	28.95	1.87	44.31	1.01	25.93	0.92	45.31	2.31
Day 4	33.19	0.85	47.27	2.26	28.48	1.32	44.73	1.50	25.75	0.86	44.75	1.4

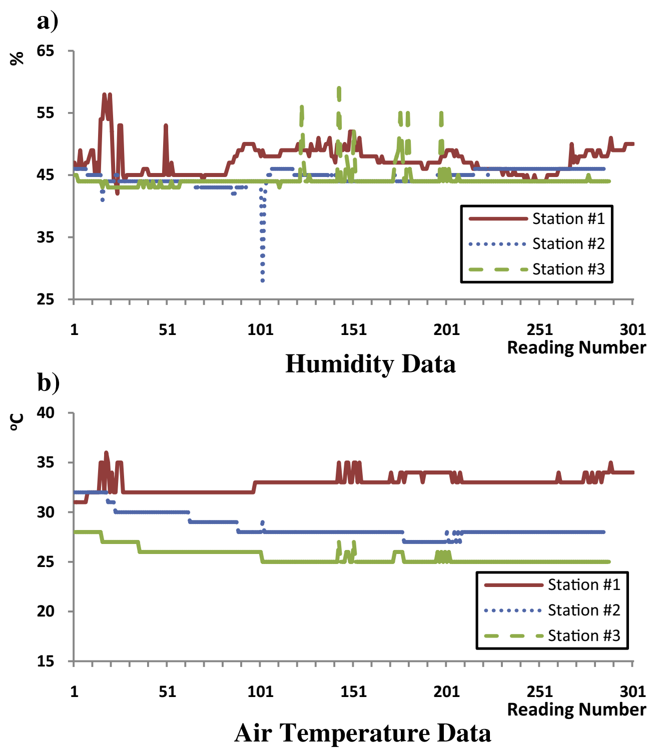

Fig. 3. Three stations data in the first day.

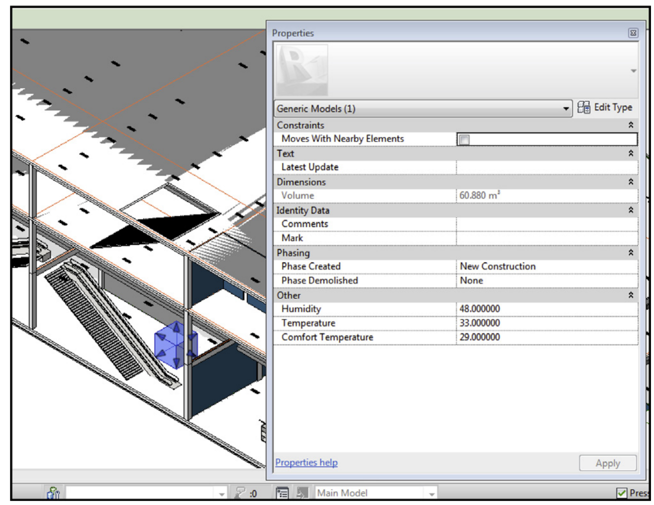

Fig. 4. Different readings at platform level in BIM-based model.

lowest air temperature. Level of passengers' crowdedness is most probably the main reason for this variation in air temperature. It was noticed during the time of measurement that station #1 had the largest number of passengers while station number #3 has the lowest number of passengers.

The average air temperature for the three stations is very similar among the four days. It is obvious that station #1 has the highest air temperature among the three stations and station #3 has the lowest air temperature. Through the four days of measurement, it was noticed that station #1 was the most crowded stations among the three stations and stations #3 is the less crowded stations. Using accurate number of passengers associated with each station, subway authorities can use these data as prediction indicator for the level of thermal comfort for passengers and to determine inefficiencies of HVAC systems among different subways which help in reducing energy consumption by taking predictive actions.

The next step after calculating the average air temperature and average humidity levels at the platform level is to export this data to Microsoft Access or Microsoft SQL server. The Microsoft Excel files can be linked with the database software in order to import the values of different parameters automatically at a certain time period. For example, air temperature and humidity level are exported to Microsoft Access database. It is important to export the information BIM-based model including all its elements, associated with their parameters as a first step. The database updates air temperature and humidity levels. Revit Database link is an external tool that is used in order to export all elements and their parameters within a project in database software. Average air temperature, humidity and comfort air temperature now can appear in the BIM-based model allowing the operator to predict the level of thermal comfort at different locations in the subway as per Fig. 4. In fact, the thermal comfort unit placed in the BIM-based model shall reflect the location of the transmitter node in order to enhance the visualization capabilities of the BIM-based model. The operator now can check different air temperature and humidity levels at certain space in a certain level and compare it with expected thermal comfort temperature.

5. Conclusions

Monitoring of indoor environmental quality in subways is a crucial issue for subways authorities. This is attributed to different factors including; large number of subways users, long time periods spent by passengers, and the criticality of this mode of transportation. The integration between BIM and WSN offers great advantages to the developed monitoring system. The integration provides a better visualization for the subway different elements and spaces associated with indoor air temperature and humidity levels. It also provides the ability for the subway operators to know the spaces that most probably have thermal comfort problems. Through the formation of the database containing air temperature and humidity readings, it is possible to track thermal comfort problems in the subway. As such, better control of the subway HVAC system is achieved in an effort to ensure the efficient consumption of energy. A case study was presented to illustrate some of the capabilities of the system. Data gathered by the WSN is analyzed and useful information was exported to BIM-based model.

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