A Methodology for Indoor Human Comfort Analysis Based on BIM and Ontology

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Abstract –

In the operations and maintenance (O&M) stage of a building, thermal comfort and acoustic comfort are essential for the health and productivity of occupants. There are many complaints about the indoor human comfort in office buildings due to inappropriate indoor temperature or noise. Building information modeling (BIM) technology is an efficient means for helping facility managers to capture complete information from the design and construction stages and deliver this valuable information to the operation stage. In addition, WELL building standard is a performance-based system for monitoring, measuring, and certifying metrics of the environment of buildings that impact human wellbeing and health. It is potential that leveraging environment condition data and BIM data to improve the indoor human comfort level based on WELL building standard. However, there is a lack of study on improving the indoor human comfort level using BIM technology and WELL building standard.

Therefore, this study proposes the methodology of applying BIM technology and WELL standard to improve the thermal comfort and acoustic comfort. BIM provides geometric and semantic information for different BIM engineering analysis software to simulate comfort zones in office buildings. Ontology engineering approach is adopted to establish the knowledge and relationship among observation data from sensor network, occupant behavior, indoor human comfort index, and indoor human comfort situation. Ontology can address the information interoperability among these different domains. In addition, an illustrative example is studied to verify the feasibility of the proposed methodology. The results indicate the methodology can be applied to evaluate the indoor human comfort based on thermal comfort and acoustic comfort index. Finally, some recommendations are given to facility managers to improve the indoor human comfort level.

Keywords –

Acoustic Comfort; Building Information Modeling; Ontology Approach; Thermal Comfort; WELL Building Standard

1 Introduction

The physical factors related to human comfort in office buildings includes temperature, acoustics, air quality, layout and lighting [1]. Thermal comfort is essential for the places where people work and live. 11% of the office buildings met the acceptable criteria based on a survey in USA in 2006 [2]. Six essential variables influence the thermal comfort of human beings, such as radiant temperature, metabolic rate, humidity, dry bulb temperature, air speed, and clothing or other insulation [2]. Moreover, other psychological parameters also have a large role in affecting the level of thermal comfort, for example, individual expectations. People feel different comfortable levels when they are in the same condition. It means thermal comfort is subjective. Currently, a new standard, WELL building standard [3], supports an approach combining many strategies to handle the occupant issues related to thermal comfort.

The sound in the building environment, especially in open plan offices, is the major source of complains from occupants [4]. The noise and sound have a big influence on occupants' working motivation [5], behavior, and intellectual performance [6], which indicates that the optimization of the sound has a high priority. The speaking in acoustic aspect in the office is a complicated case and it is relevant to human comfort and working efficiency. Not only physical properties and acoustic descriptor, but also the condition of environments can determine the acoustic comfort. The objective of WELL building standard is to enhance the satisfaction, social interaction, and productivity, by reducing exterior noise intrusion and indoor noise level [3].

Based on many studies [4] [5], acoustic comfort and thermal comfort are of importance in the office buildings. When the acoustic in the room cannot meet the criteria of acoustic standard, it has bad influence on the people's satisfaction, the emotion, and physical activities. However, a methodology to study the indoor human comfort in the operations and maintenance (O&M) stage is lacking. Moreover, they rarely studied the trade-off between thermal comfort and acoustic comfort.

Currently, a new technology can be applied to simulate the indoor building environment, building information modelling (BIM). BIM is defined as "a digital representation of the building process and is used to facilitate the exchange and interoperability of information in digital format" [7]. BIM can be used to monitor the indoor thermal condition and acoustic condition combining with sensor technology, which are useful for the automated evaluation and analysis of human comfort based on WELL standard. BIM supports different types of engineering analyses (e.g. thermal comfort and acoustic comfort analysis), which are helpful for improving the building operations in terms of human comfort [8]. BIM can improve data interoperability and collaboration between different participants and different engineering software to facilitate the human comfort analysis process [8].

The human knowledge can be conveted to a machine-readable knowledge in explicit format using ontology [9]. Ontology contains three main aspects, classes (entities/ concepts), properties or attributes of the classes or entities, and the relationships between entities or attributes. A knowledge base consists of the ontology combining with classes, properties and relationships. Ontology enables people to reuse the existing knowledge in different domains, and ontology also provide prototyping and sufficient details of knowledge in many domains [10]. Some researchers have leveraged ontology approaches to solve the information interoperability problem in the AEC/FM industry, such as Chen et al. [11] developed an ontology-based method and addressed the information interoperability between facility management and BIM. Moreover, an ontotology method is developed by Adeleke & Moodley [12], which aimed to monitor and control the indoor environment for a real case in Durban, South Africa.

This paper focuses on the problem of improving indoor human comfort, especially in acoustic and thermal comforts. This study explored the trade-off between acoustic comfort and thermal comfort. It leveraged BIM technology and ontology approach to improve the indoor human comfort level. In Section 3, a novel methodology to analyse the thermal comfort and acoustic comfort is proposed based on BIM and ontology engineering. The final recommendations in Section 4 will benefit the renovation and decoration of office buildings.

2 Research Background and Related Work

2.1 Indoor Human Comfort Standard

Currently, there are many standards related to indoor human comfort. Standards; EN-ISO 7730: 2005 [13], ASHRAE55-2013 [14], Fanger's Model of thermal comfort is a refer of EN 15251: 2007 [15]. However, only physiological reactions are considered in the Fanger's model for the physical aspects in the indoor environment. Thermal comfort means the level of satisfaction when people feel the heating level of the indoor or outdoor environment. Thermal comfort in various levels of humidity and temperature in different seasons is defined in ISO 7730:2005 standard [13].

Based on thermal comfort checklist [13], there are serval indexes for thermal comfort assessment are includes in the thermal comfort checklist, such as metabolic rate, humidity, air temperature, air movement, radiant temperature, and changes to the environment. EN 15251:2007 standard [15] entitled "Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings". Thermal environment, acoustics, indoor air quality, and lighting are designed for indoor conditions and for setting limits, which ensures the Energy Performance of Buildings Directive do not compromise the comfort of occupants in the pursuit of energy reduction.

The new section "Open plan offices" of the standard ISO 3382 [16] "Measurement of room acoustic parameters" was released in 2012. It describes innovative measures for the acoustic condition qualification with a high correlation of the sound environment in the subjective perception. The third section of ISO 3382 summarized that the distance dependent qualities are the suitable acoustic measurement in open offices, for example, sound pressure level, spatial decay rate, and distraction distance.

However, these standards are not comprehensive to evaluate the indoor human comfort. WELL building standard is a performance-based system for monitoring, measuring, and certifying metrics of the environment of buildings that impact human wellbeing and health [3].

The WELL building standard seven aspects of wellness, i.e., Air, Light, Comfort , Nourishment, Water, Fitness, and Mind [3]. The development of WELL Certified™ leads to a good environment of buildings and helps people to enhance the sleep, mood, fitness, nutrition, performance and comfort of the occupants. WELL building standard aims to implement technologies, programs, and strategies and encourage the active lifestyles, healthy as well as reducing the opportunity of appearance of harmful pollutants and chemicals [3].

2.2 Study on Thermal Comfort and Acoustic Comfort

Noise is an unpleasant aspect of the indoor or outdoor environment as the commonly experienced. The influence of noise on human comfort w studied in many years. Physiological responses to acoustic stimulation studied by Candas and Dufour [17] showed that the vasoconstriction is affected by high noise level, and it may increase the metabolic rate of human and muscle tension. Santos and Gunnarsen [18] claimed that two or more parameters of indoor environment are relevant to the optimal levels of human comfort. They studied the trade-off between temperature and noise considering the parameters of the window opening or draft. The outcomes show that the decrease of 1 °C in operative temperature has the same effect of decreasing of approximate 7 dB in noise level. They claimed that the noise from HVAC system can reduce occupants' willingness to lower the temperature in a warm environment. Another finding, that the change in noise level of 3.9 dB has the same effect on human comfort when changing 1 °C in operative temperature (in a range of 23 – 29 °C), was proposed by Clausen & Carrick [19].

Moreover, many researchers have studied on the comfort-based control of HVAC system. A neural network was applied to come up with a thermal comfort based on HVAC system control in study Liang and Du [20]. A predictive thermal comfort model is introduced to the controlling using HAVC systems by Freire, Oliveira [21]. However, people paid little on the negative effects of HVAC system in acoustic comfort level. Some survey results were described by Reffat and Harkness [22], and they found that acoustic comfort has the equal importance of thermal comfort for the occupants in office buildings. Many occupants have to suffer from the noise from HVAC system, because the mechanical system is unavoidable and the reinstalling of HVAC system costs high. Frontczak and Wargocki [23] studied on multiple sensations and they found that the acoustic comfort and thermal comfort are the most essential parameters for human sensations.

The control of acoustic and thermal comfort affects to the multiple comforts, and people have studied this topic for many years. Even though people studied the acoustic performance, the coverage of room ceiling and the effect of HVAC system, such as Machner [24]. They indicated the different materials of ceiling have different influence on the acoustic comfort and thermal comfort. A few of researchers studied the trade-off between thermal comfort and acoustic comfort. The big problem is that there is lack of study on the trade-off between acoustic and thermal comfort for the design and control of HVAC system.

3 Methodology

3.1 Proposed Methodology

This study has drawn from various research areas, including BIM engineering software, WELL building standard, wireless sensor network for indoor human comfort management, and ontology engineering. The methodology includes the following four aspects:

(1) The geometric and semantic information from BIM models is used for indoor human comfort simulation and analysis.

(2) The various sensing networks and sensing devices are applied to monitor the indoor environment.

(3) BIM engineering software are implemented to simulate the indoor thermal comfort zones and acoustic comfort zones.

(4) Ontology approach is adopted to prototype the knowledge of indoor human comfort management and occupant behavior interaction. Ontology approach is also applied to provide information from sensor network for indoor human comfort management.

The information process of the proposed methodology for indoor human comfort analysis is illustrated in Figure 1. In the process, the geometric information of BIM models is extracted into CAD files, such as .dwg files, .dxf files, and .sat files. These files are available for BIM engineering analysis software, including Autodesk CFD and COMSOL Multiphysics [25].

When using these two software for indoor comfort evaluation, the first step is to identify materials of building structures and main components, because different materials have different influences on thermal comfort and acoustic comfort [24]. For example, the noise level from HVAC system when the ceiling is made of baffle is higher than the noise level from HVAC system when the ceiling is made of master matrix. Similarly, the materials of wall, floor, furniture, door, and window are identified.

In the second step, the space function of each room are determined based on usage situation. The sensor data obtained from ontology schema of indoor human comfort, for instance, temperature setting in HVAC system, and noise from outside, are as the parameter input and boundary setting of BIM engineering analysis software.

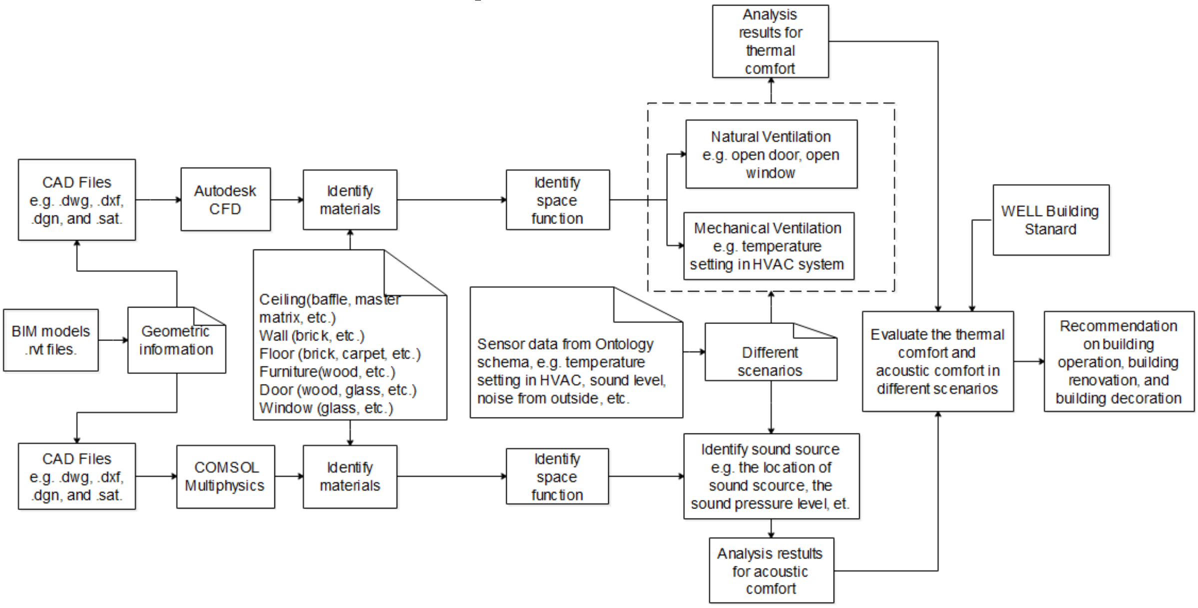

Figure 1. The information process of proposed methodology for indoor human comfort analysis

In the third analysis step, several scenarios (natural ventilation or mechanical ventilation, door open or window open, exterior noise or internally generated noise) are determined to simulate the thermal comfort and acoustic comfort. The simulation results are analysed to evaluate the indoor human comfort level based on WELL Standard. Finally, some recommendations are given for facility managers to improve building operations, building renovation, and building decoration.

3.2 Criteria of Thermal Comfort and Acoustic Comfort

In this paper, the criteria of thermal comfort and acoustic comfort in WELL standard are studied based on [14, 26], and the Indoor Air Quality Certification Scheme in Hong Kong [27]. Table 1 illustrates the requirement of acoustic comfort index based on WELL standard, while Table 2 shows the requirement of thermal comfort index.

Table 1. The requirement of acoustic comfort index

Index	The Requirement of Index	Standard
Exterior noise intrusion	Average sound pressure level from outside noise intrusion <50 dBA.	WELL Standard
Internally generated noise	Open office spaces and lobbies < 40 dBA; Enclosed offices < 35 dBA; Conference rooms and breakout rooms: <30 dBA	WELL Standard
Reverberation time	Conference rooms: 0.6 s Open workspaces: 0.5 s	WELL Standard
Sound masking	Open workspaces: 45 - 48 dBA. Enclosed offices: 40 - 42 dBA	WELL Standard

Table 2. The requirement of thermal comfort index

Index	The Requirement of Index	Standard
Ventilation effectiveness	CO_2 < 800 ppm	WELL Standard
Air flush	Indoor temperature > 15 °C Relative humidity < 60%.	WELL Standard
Humidity control	30% <Relative humidity < 50%	WELL Standard
Air quality monitoring and feedback	20 < Indoor temperature < 25.5; 40 < Relative humidity < 70 Air speed < 0.3 m/s; CO_2 < 800 ppm CO < 1.7 ppm; PM 10 < 20 ug/m3 NO2 <40 ug/m3; O3 < 50 ug/m3	Indoor Air Quality Certification Scheme 2003
Ventilated thermal environment	Air speed > 0.2 m/s, 1.0 met < Metabolic rates < 1.3 met; 0.5 clo < Clothing insulation < 1.0 clo	ASHRAE Standard 55-2013 Section 5.3

Natural thermal adaptation	Clothing insulation < 0.7 clo 1.0 met < Metabolic rates < 1.3 met 0.5 clo < Clothing insulation (Icl) < 1.0 clo 10°C < Outdoor temperature < 33.5 °C 19 °C < Floor surface temperatures< 29 °C	ASHRAE Standard 55-2013 Section 5.4

3.3 Ontology Implementation

This paper adopts ontology approach to represent the main concept of indoor human comfort management, as shown in Figure 2. The developed ontology provides representation support for the actions/ activities of the occupant, the observations of sensors in the indoor environment and the description of building environment [28]. The observations of sensor give the measurement values of sensor in certain properties (e.g., air quality, sound level, humidity, temperature, and CO_2 concentrations) of the environment. While the description of environment provides data or information such as features in the office buildings, types (e.g., type of ceilings), and quantities (e.g., number of windows), etc. Figure 2 illustrates the main concepts of the developed of indoor human comfort ontology.

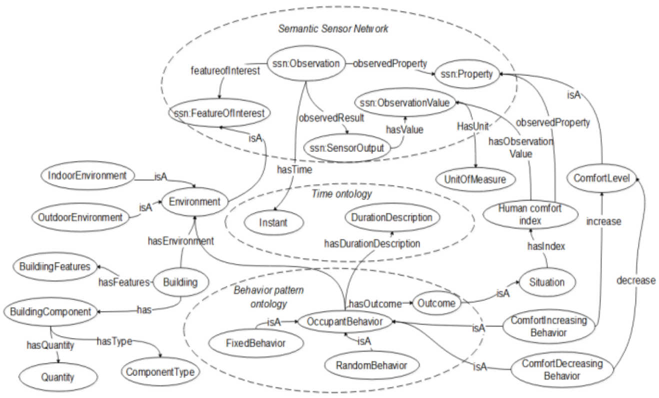

Figure 2. The main concepts of the developed indoor human comfort ontology

In the ontology schema, reasoning-based ontology can automatically determine the indoor acoustic comfort index and thermal comfort index. Sensor data is used to evaluate the proposed ontology, and the condition date can be queried from ontology for analysing the human comfort situations and determine control actions. This ontology schema enables the support for data representation and ontology reasoning on both occupant actions and the observations of sensor for indoor human comfort analysis. The ontology also represents the semantic indoor human comfort index regarding to thermal comfort and acoustic comfort.

The Unified Modelling Language (UML) diagram can represent the information in the proposed ontology schema. The office includes the space and the occupant. The office has two situations: occupied and empty. The number of occupants is one important factor to evaluate the human comfort. In order to monitor the environment condition of the office space, the temperature sensor, humidity sensor, CO_2 sensor, and sound sensor to monitor the value of each comfort index. The space has quantity of sensors, semantic type of various sensors, and different units of sensor values. For example, there are five temperature sensors in one specific office and the unit of temperature is " °C ". Similarly, there is one sound sensor in this office. The parameter of the sound sensor is acoustic pressure level and the value of acoustic pressure level is 35 dB. The UML diagram of data representation for sensors is illustrated in Figure 3, as follows.

Based on the ontology approach, the adequate sensor measurements for indoor human comfort are represented in the proposed ontology schema. It provides representation and reasoning services to analyse indoor human comfort situations based on measurements and WELL building standard. It determines human actions/ behavior to reduce the influence from bad environment. In the case, we will evaluate the proposed indoor human comfort ontology to test sensor data and query it for different situations relevant to each of scenarios.

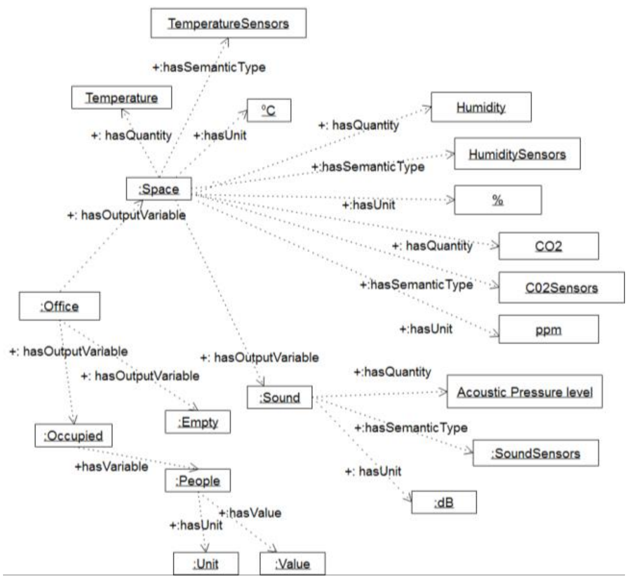

Figure 3. The data representation of sensor information for human comfort management

3.4 Using BIM Authoring Software to Evaluate Indoor Human Comfort

Different BIM-based engineering analysis software are incorporated in the proposed framework in order to evaluate and improve indoor human comfort level based on WELL standard. For example, Autodesk CFD can be applied for indoor thermal analysis, and COMSOL Multiphysics is used for noise impact assessment. Specifically, the application procedure of using BIM-based engineering analysis software to evaluate and improve indoor thermal comfort and acoustic comfort in buildings is illustrated as follows.

(1) The inputs include geometric information (e.g. length, area) and semantic information (e.g. quantity, materials) from BIM models.

(2) The inputs include real-time data (e.g., temperature, humidity, CO_2, noise from outside) obtained from ontology schema of sensor network.

(3) Reports and code from other resources, such as building operation records, are used to set different scenarios for simulation and evaluation.

(4) The inputs are used in BIM engineering software for different types of engineering analysis (such as acoustic impact analysis and indoor thermal analysis). For example, the indoor noise, layout of one room, material of ceiling and wall can be used in COMSOL Multiphysics to simulate indoor acoustic comfort zone.

4 Illustrative Example

4.1 Case Background

In order to validate the proposed methodology, two conference rooms in the academic building of HKUST are used as the example to illustrate the methodology. The layout of two conference rooms is shown in Figure 4. The ceiling is made of baffle and the wall is made of concrete. X door, Y door, Z door and one wall of right room are made of glass, indicated in Figure 4. The left room is open office space and right room is enclosed offices.

Assume there are eight people speaking around two tables (highlighted in blue in Figure 4) in left room in this case. The sound source is internally generated noise, defined from the surface of two tables. The parameter setting in COMSOL Multiphysics is as follows: walls of two rooms are sound hard boundary. The density of air is 1.25 kg/m3 and the speed of sound is 343 m/s. The sound frequency of internally generated noise is 90HZ. The glass doors are open.

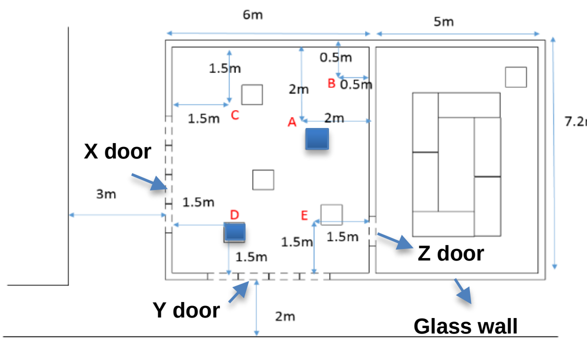

Figure 4. The layout of two conference rooms

The BIM model of two conference rooms is built using Autodesk Revit 2018, as shown in Figure 5. According to the methodology in Figure 1, the BIM model is successfully transferred into COMSOL Multiphyiscs software for acoustic comfort simulation.

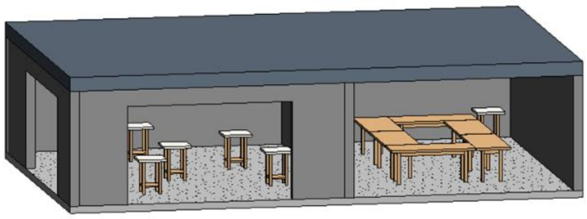

Figure 5. BIM model in Revit

4.2 Simulation Results

The sound simulation result is illustrated in Figure 6a and Figure 6b. The sound pressure level in left room ranges from 45 dB to 55 dB. The sound pressure level in right room is less than 40 dB. Based on WELL standard, open office lobbies and spaces are occupied regularly and/or contain workstations, and the noise criteria in maximum level is 40 dB [3]. The maximum noise criteria of the enclosed offices is 35 dB [3]. Therefore, the sound pressure level in these two conference rooms are higher than the maximum noise criteria. People feel very noisy when there are eight people speaking. The glass door should be closed if they have meeting in left room. Otherwise, the bad influence will affect the normal work in near offices and the lobby.

Apart from the acoustic effect of people speaking, in order to validate acoustic comfort and thermal comfort without people in different situations, two scenarios are designed: (1) HVAC system is on and (2) HVAC system is off. Sensing devices are used to detect the thermal comfort and acoustic comfort index in four testing points, A, B, C, and D. The values of comfort index in four testing points are obtained from the designed ontology schema, and the values are shown in Table 3.

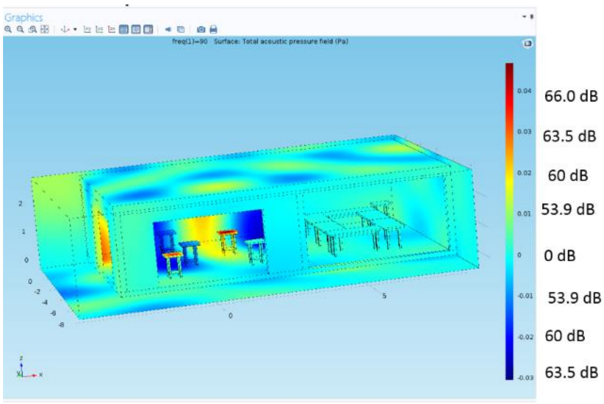

Figure 6a. The overall sound simulation results

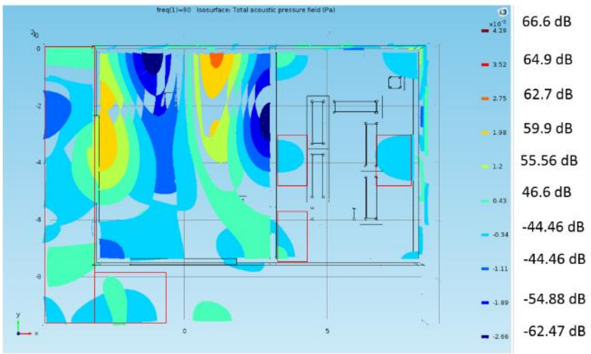

Figure 6b. The plan view of sound simulation results

According to thermal comfort index in Table 2, when temperature is more than 20 °C and less than 25.5 °C, relative humidity is 30% to 50%, and CO_2 is below 800 ppm, occupants feel comfortable [3].

When the HVAC system is off, temperature values in four testing points (A, B, C, and D) are slightly higher than 25 °C, which is near the maximum value. Humidity is 62.2% to 63.2% and CO_2 is from 542 ppm to 651 ppm. Humidity is higher than the acceptable level, and CO_2 is within the acceptable limits. The exterior noise is around 42.3 to 45.2 dB, which is higher than the maximum criteria of 40. Therefore, in this situation, occupants feel a little hot, moist and a bit noisy.

Table 3. The value of thermal comfort index

Testing point	**A**	**B**	**C**	**D**	
Index	HVAC System Off				
Temperature (°C)	25.3	25.1	25.1	25.5	
Humidity (%)	62.8	63.2	62.9	62.2	
CO_2 (ppm)	544	651	561	542	
Sound pressure level (dB)	43.6	45.2	42.5	42.3	
Index	HVAC System On				
Temperature (°C)	22.6	21.5	22.4	23.5	↓
Humidity (%)	50.5	50.6	47.2	45.6	↓
CO_2 (ppm)	533	533	537	521	↓
Sound pressure level (dB)	50.5	50.6	47.2	45.6	↑

When the HVAC system is on with setting the outlet temperature 20 °C, the indoor temperature decreases to 21.5~23.5 °C. Simultaneously, the humidity reduces to 45.6~50.6% located in acceptable area and CO_2 concentration decreases to 521~537 ppm. This indicates occupants would feel more comfortable than the former situation. However, the noise from HVAC system though baffle ceiling increases the sound pressure level by 3~7dB. If occupants prefer to reducing the temperature level rather than reducing noise level, they would feel more comfortable when the HVAC is on. Otherwise, they would feel more comfortable when the HVAC system is off.

5 Conclusions

Thermal comfort and acoustic comfort are essential for the productivity and health of occupants in the O&M stage of a building. This paper leverages the advantages of BIM technology and ontology engineering approach to study indoor human comfort. A novel methodology is proposed to analyse the thermal comfort and acoustic comfort based on BIM technology and WELL Building Standard.

The process of methodology is explained in detail in this paper. BIM provides geometric and semantic information and information interoperability function for different engineering analysis software to simulate comfort zones in office buildings. In addition, ontology schema is developed to represent the knowledge of sensor observation domain and indoor human comfort managemnt domain. Ontology approach addresses the information interoperability problem between sensor data and indoor human comfort management. Finally, an illustrative example is studied to verify the feasibility of the proposed methodology. The results indicate that the methodology can be successfully applied to evaluate the indoor thermal comfort and acoustic comfort based on BIM and ontology approach.

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