Improve Indoor Acoustics Performance by Using Building Information Modeling

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Abstract

Indoor acoustics is usually an important criterion of evaluating the performance of building rooms such as concert halls, lecture rooms, and wards. Indoor acoustic simulation during architecture design and before room decoration can improve room acoustic performance. However, 3D room modeling usually takes much time before acoustic simulation. Building information modeling (BIM) is currently widely applied through life cycle of a building because it dramatically improves modeling efficiency by providing both geometric and semantic information. This study aims at integrating BIM technology with acoustic simulation to improve indoor acoustic performance. A BIM model containing information of three main factors affecting indoor acoustic, namely architecture geometry, speaker position, and decoration materials, is built and slightly modified so that it can be used to conduct acoustic simulation. Acoustic simulations with different architecture geometries, speaker locations, and decoration materials were performed to study how indoor acoustic performance was affected by examining variation of reverberation time, which is an important indoor acoustic evaluation criteria. Sensitivity analysis of the three main factors that affect indoor acoustics was also conducted. Finally, the acoustic simulation results with BIM and without BIM were compared. It was found that the simulation results were the same and the acoustic simulation time was reduced by using BIM.

Keywords –
Architecture design, BIM, Decoration Materials, Indoor Acoustic Simulation, Speaker Position

1 Introduction

Acoustic performance is an important aspect that has to be carefully considered in the design and construction process of buildings, especially for buildings with specific acoustic requirements, such as lecture rooms or concert halls. Once a building is constructed, it would be very costly in both finance and manpower to fix inappropriate acoustic performance. Therefore, it is necessary to conduct acoustic simulation and prediction to help designers and engineers to analyze the acoustic performance of a building in the design stage.

To evaluate the acoustic performance of a building, a couple of parameters are commonly used, including reverberation time (RT), sound intensity level, noise, sound uniformity and intelligibility [41]. This study focuses on the reverberation time since it is one of the most important indicators and can be calculated by relatively simple equations. Reverberation time is defined as the time required for reflections of a direct sound to decay 60dB. The preferred reverberation time is dependent on the purpose of buildings. For classrooms, the recommended reverberation time is tenths of seconds [33], whereas for larger buildings such as concert halls, this value usually varies from 1 to 2 seconds [26,27].

Although many simulation methods are available, prediction of building acoustic performance is still a very complicated work. In real situations, reverberation time of a room is affected by many factors, including room size [4,23], enclosure shape [13], materials of walls and ceilings [32], absorption of seats and audiences [11,12,25]. In the acoustic design process, all those factors require careful considerations. In most cases, it is extremely hard to find proper values for all those parameters in a short time. Plenty of time is required in the process of trials and errors.

Building information modeling (BIM) has been commonly used in the architecture, engineering, and construction (AEC) industry. With BIM technology, an accurate virtual model of a building is constructed digitally [18]. A building information model contains precise geometry and relevant data needed to support through the lifecycle of the buildings. Many studies on BIM have been conducted at different building life cycle stages such as design [39], construction [24,29,30], operation and maintenance [6,7,36], and demolition [14,31], which have shown that BIM can provide geometric and semantic information of buildings accurately and effectively at any stage. Therefore, in this study, BIM is integrated with acoustic simulation tools to evaluate and improve the acoustic performance of concert halls.

This study aims at improving the acoustics performance of concert halls by integrating BIM with existing acoustic simulation software. The rest of this paper is organized as follows. Section 2 presents the literature review. The integration of BIM and acoustic simulation software is illustrated in Section 3. Section 4 uses an example to illustrate the proposed methodology. Discussions and conclusions are included in Section 5.

2 Literature Review

2.1 Reverberation Time Prediction

Prediction of acoustic performance of a building has been studied for over a hundred years. The most commonly used reverberation time prediction formulas were proposed by Sabine [34] and Eyring [19], respectively. Their equations were derived from different considerations but the same assumptions. In the following decades, based on their works, a series of improved methodologies were developed to solve problems in different cases [5,9,20]. After 1960s, introduction of computer modelling greatly increased the efficiency and availability of building acoustic simulation [35,38].

A couple of computer models have been developed for acoustic simulation, such as particle tracing models [40], rays tracing model [37], beam tracing model [21], and hybrid model [38]. Based on those simulation models, effects of different factors were investigated. Using the acoustic rays and particle tracing technology, Passero and Zannin [32] evaluated the acoustic quality of real open-plan office and improved the acoustic condition of the office by performing modifications on the office room. Their study concluded that divider panels between the work stations and ceilings with high sound-absorbing materials could ensure the acoustic quality. With ray-based programs, Bistafa and Bradley [9] predicted the reverberation time of a classroom model and analysed the effects of different construction materials. Vorländer [40] considered the uncertainties of computer acoustic simulations.

2.2 Industry Foundation Classes (IFC)

Industry Foundation Classes (IFC), which is defined in ISO/PAS 16739 [2], is currently the main neutral file format for data exchange among BIM software [1]. IFC is designed to represent as much building information as possible through the life cycle and to facilitate the data transfer among various BIM-supported software, thereby is used in this study. The latest version of IFC is IFC 4, which includes 766 entities [3]. Related information is stored in terms of entities such as the *IfcProject*, *IfcSite*, *IfcWall*, *IfcSpace*, etc. *IfcSpace* is usually used to represent an area or volume that provides a certain function within a building. *IfcSpace* has been studied to extract spaces from buildings to conduct indoor navigation [17], indoor path planning [28], emergency response [10], and indoor localization [15]. Since acoustic simulation requires the volume of the concert, *IfcSpace* is also studied in this paper.

2.3 BIM Applications on Acoustic Simulation

BIM has been commonly applied through the lifecycle of buildings. However, as for acoustic simulation, only a few studies are reported. For example, Deng et al. [16] integrated BIM and 3D geographic information system (GIS) to combine traffic noise evaluation in both outdoor and indoor environments in a single platform. A high level of detailed information from BIM such as interior walls and interior rooms was used in a 3D GIS platform. Wu and Clayton [41] presented a BIM-based software prototype that can speed the prediction of the acoustic performance of an indoor space at the building design stage. In this study, BIM was used to provide related building information to calculate the current acoustic performance of the indoor environment based on RT and sound intensity level (SIL). However, no comparisons among different designs of architecture geometry, decorated materials, and speaker locations have been conducted. Besides, the presented software prototype has to refer to multiple platforms. Therefore, BIM-based acoustic simulation studies to improve the indoor acoustic performance are still limited.

3 Methodology

In this study, a BIM-based methodology is proposed (see Figure 1) to improve indoor acoustic performance. First, an IFC file is exported from the concert BIM model. Then, information including architecture geometry, speaker location, and decorated materials is extracted from the IFC file and serves as the input to set up acoustic simulation environment. Finally, acoustic simulations with different architecture geometries, speaker locations, and decorated materials are conducted according to the RT of concert hall to improve its acoustic performance. More details of the methodology are introduced in the following sections.

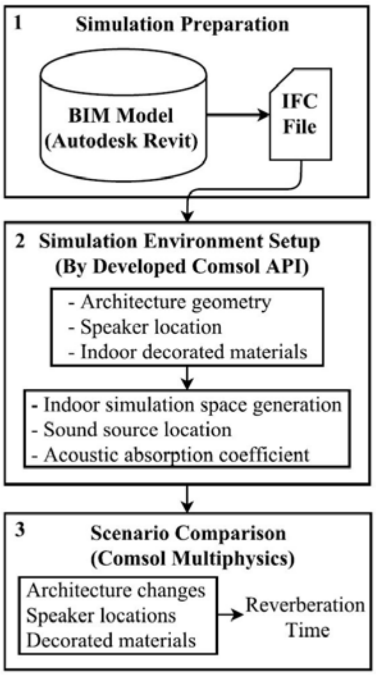

Figure 1. The proposed methodology.

3.1 Simulation Preparation

The BIM model of a building project is usually available at the early stage of its lifecycle in the AEC industry. Acoustic performance therefore can be evaluated and improved in an efficient manner by directly using the building information from BIM model. In this study, the 3D architectural model is built by Autodesk Revit, which is commonly used BIM software in the AEC industry. Through Revit, the building information can be easily extracted and exported into IFC format.

The IFC file, which is based on EXPRESS data structure, contains the geometric information, object location, and the types of all elements in a building. *IfcSapce* entity, as introduced in Section 2.2, is used to obtain the geometry of the concert hall. The local placement property of the speaker in the IFC file can provide its location with a coordinate (*x*, *y*, *z*). As for decorated materials, whose sound absorption coefficients are vital for acoustic simulation, they can be determined by the types of the wall and seats.

3.2 Simulation Environment Setup

Acoustic analysis is conducted by a commercial finite element solver COMSOL Multiphysics. To run an acoustic analysis, three parameters are needed to setup the simulation environment including indoor simulation space, sound source location, and acoustic absorption coefficient.

Firstly, necessary information for acoustic analysis is extracted from the IFC file through a developed COMSOL application programming interface (API), including architecture geometry, speaker location, and indoor decorated materials. The COMSOL API file is programmed based on Java. Through the API, all operations and manipulations performed in COMSOL Desktop can be reflected in programming lines. To run COMSOL simulation case, a Java class file (.class) is built through Jave IDE. Java Development Kit (JDK) and COMSOL server are used to compile the Jave-file that COMSOL generates.

Secondly, all the three parameters for acoustic analysis are generated from the information extracted from the IFC file. The architecture geometry and speaker location can be directly used in COMSOL as the indoor simulation space and sound source location, respectively. Furthermore, indoor decorated materials are mapped to the corresponding acoustic absorption coefficients through a developed plug-in.

3.3 Acoustic Simulation

A typical acoustic simulation can be divided into three parts: a sound source which is used to mimic realistic sound generation, the propagation media (air in most cases) with boundary settings in the simulated space and the 'microphone' which receives sound response information. The interested parameters and results can be obtained through post-processing of the three parts. Since RT is one of the critical factors for evaluating performance of a concert hall, it is studied in this project.

In this project, the reverberation time is calculated by the Eyring-Norris's equation (in SI units):

$$\mathrm{RT}_{60} = 0.161\frac{V}{-S\log_{10}(1-\frac{A}{S})}, \qquad (1)$$

where V is the room volume, S is the total area of all interior surfaces in the room, A is the total sound absorption in the room, which can be expressed as:

$$\mathrm{A} = \sum a_i S_i \qquad (2)$$

where S_i is the area of each surface in the room, including the walls, doors, windows, floor and so on, and a_i is the corresponding absorption coefficient of each surface. For the same material, the absorption coefficient is dependent on sound wave frequency (as listed in Table 1). Hence, the reverberation time of a room will differ within different frequency ranges.

Table 1 Absorption coefficient of several building materials and sectional areas at different frequencies [8,22].

Materials	Absorption Coefficients					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Brick, unglazed, painted	0.01	0.01	0.02	0.02	0.02	0.03
Carpet, heavy, on concrete	0.02	0.063	0.14	0.37	0.60	0.65
Concrete block, painted	0.10	0.05	0.06	0.07	0.09	0.08
Wood floors	0.15	0.11	0.10	0.07	0.06	0.07
Seats area (Mitaka Hall)	0.44	0.52	0.52	0.41	0.41	0.37
Seats area (TOC Concert Hall)	0.41	0.36	0.37	0.33	0.25	0.21

Based on the three parts in acoustic simulation, the settings and study cases are listed as follows. Two point sources are set in simulations to mimic loudspeakers arranged on both lateral sides inside the hall. The sources will be fixed on the ceiling and moved from the first row to the last row of seating area so that the influence of sound source positions on RT can be evaluated.

As for the propagation media and boundary conditions, the whole space will be filled with the air which matches with realistic situations of all the existing concert halls and boundaries will be set based on the characteristics of interested cases, such as sound absorption coefficient settings of walls, floors, seats and so on. In this study, RT of concert hall with decoration materials with varied sound absorption capabilities will be studied and associating regularity will be concluded. It should be mentioned that the acoustic response will vary at different frequency ranges. Hence, the sound absorption coefficient of each area will be considered in a reasonable range which can cover acoustic response over broadband.

At the last, to evaluate the effects of geometry of concert hall, other similar halls with the same volume but different shapes will be simulated for comparison.

4 Illustrative Example

4.1 Introduction to Concert Model

In order to validate the proposed BIM-based methodology, a real concert hall in the Hong Kong University of Science and Technology (HKUST), which is a space with volume of about 2230 m^3, was used (see Figure 2). After necessary parameters were collected through a site visit, the BIM model of the concert hall was created in Autodesk Revit based on the geometric information of seating area, walls, floors, etc. (see Figure 2).

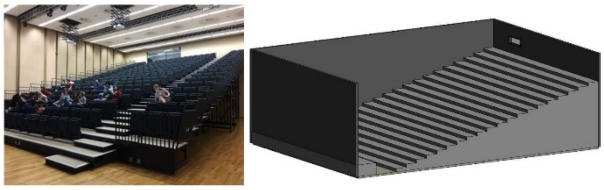

Figure 2. Example concert hall and its BIM model in Revit.

The initial model used in COMSOL simulations was a simplified prototype of the above-mentioned concert hall. The main characteristics including walls, floors, seating area and stage were extracted for improving acoustic performance based on the proposed methodology. To evaluate the influence of speaker locations and properties of decoration materials, a series of positions of sound source and varied reasonable materials of each component were considered. Besides, to obtain the effect of concert hall geometry on acoustic property, the original model was modified into fan-shaped with the same relative placements of stage and seating area, identical height in *z* direction and the same volume, as shown in Figure 3.

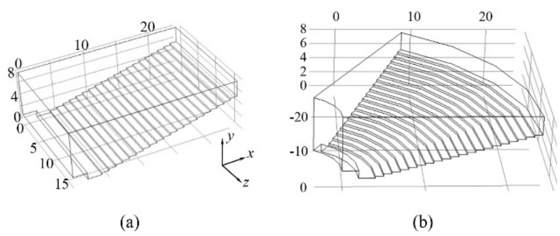

Figure 3. COMSOL models of concert halls. (a) Initial model from concert BIM model; (b) Modified model for study the effect of geometry

4.2 Simulation Results

4.2.1 Effects of Position of Sound Source

To study the influence of positions of sound source on RT, the sound absorption coefficients of the interested regions, i.e., floor, walls and seating area, are set as an initial case (α_{floor}=α_{wall}=0.05, α_{seats}=0.3). It is assumed that the two loudspeakers hanged on the ceiling are moved backward synchronously. Figure 4 shows the simulation results, where the *x* axis indicates the distance between the front wall and the sound sources and the *y* axis represents the RT. The results show that the RT is almost the same with various positions of sound sources.

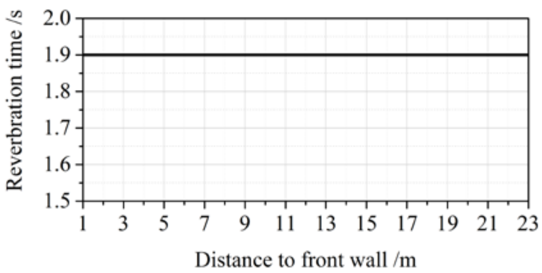

Figure 4. Reverberation time response of varied position of sound source.

4.2.2 Effects of Geometry of Concert Hall

To evaluate the effects of geometry of concert hall on RT, the original model is modified. The size of the cross-section in *x-y* plane remains the same and it is revolved so that the new concert hall has the same internal volume as the original one (2230 m^3), which is shown in Figure 3. Here, the sound absorption coefficients setting are the same as the initial case mentioned in Section 4.2.1 and the two speakers are hanged at the initial position (1 m from the front wall). For the original concert hall, the RT based on the above-mentioned settings is 1.9 s, however, this value changes to 1.61 s. It indicates that the change of concert hall geometry, which results in variation of the total sound absorption coefficient, also exerts important influence on RT and it should be designed carefully after determining the whole volume.

4.2.3 Effects of Sound Absorption Coefficients

The acoustic properties of decoration materials play an important role on performance of a concert hall. The sound absorption coefficients of materials have deciding effects on RT. In this study, the walls and seating area occupy the most area inside the concert hall. Hence, they are considered as two vital factors and studied in detail on the premise that the α_{floor} =0.05 (initial case). The walls are always made of concrete or woods with varied thicknesses. Their sound absorption coefficients usually lie between almost 0.01 and 0.1. In terms of seats, they are usually made of porous material, which is soft and comfortable. The sound absorption coefficients can locate in a wider range, from almost 0.1 to about 0.5. Considering these two variables, the reverberation time of the simulation model shown in Figure 3(a) is evaluated. Figure 5-6 give the dependence of reverberation time on sound absorption coefficients of seating area and walls, respectively. It can be seen that as sound absorption coefficients of the walls and seating area increase, the reverberation times reduce.

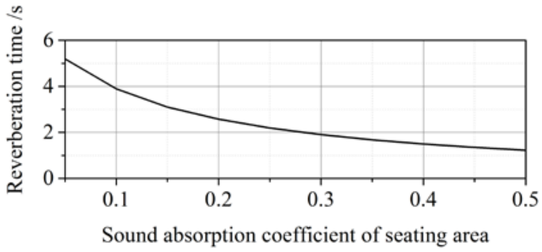

Figure 5. Reverberation time response of various sound absorption coefficients of seating area (α_{wall}=0.05).

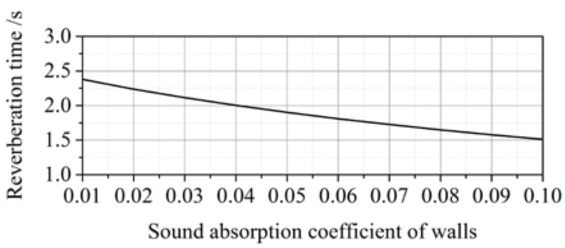

Figure 6. Reverberation time response of various sound absorption coefficients of walls (α_{seats}=0.3).

Furthermore, the combination of materials of walls and seating area is simulated and optimized. As shown in Figure 6, the sound absorption coefficients of both walls and seating area are considered simultaneously. Given an optimization objective, such as a RT of 1.8 s, proper combinations of materials of walls and seating area can be easily obtained (dashed line shown in Figure 7).

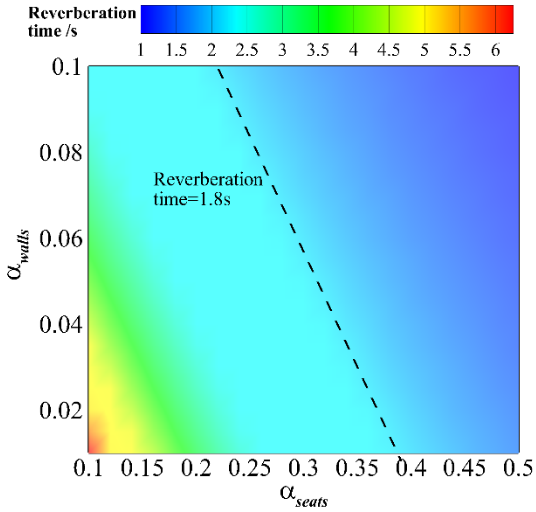

Figure 7. Reverberation time response of various sound absorption coefficients of walls and seating area.

In addition to conducting the acoustic simulation of concert hall by using BIM, the same acoustic simulations has also been conducted manually. It shows that the simulation results obtained from both methodologies are the same. However, acoustic simulation with BIM takes less time at the simulation environment setup stage. Therefore, using BIM to conduct acoustic simulation can help evaluate and improve the acoustic performance of concert hall in an efficient manner. Besides, with the proposed BIM-based methodology, the more complex the concert hall is, the more time can be saved for the acoustic simulation.

5 Discussions and Conclusions

This paper integrates BIM with existing acoustics simulation software to improve acoustic performance of concert halls by utilizing the rich building information from concert BIM model. API of the simulation software COMSOL Multiphysics is used to develop algorithm that can extract building information directly from IFC file, which is exported from Autodesk Revit, and to set up the acoustic simulation environment automatically. This developed methodology reduces the time of simulation environment setup. Scenario comparisons has also been conducted to provide guidance for the decisions on architecture geometry, speaker location, and decorated materials. To validate the proposed BIM-based methodology, the example concert model was created to set up the simulation environment. Simulation comparisons show that the same test results can be obtained, while the simulation environment setup time was increased. In addition, the simulation environment setup time saved by the proposed BIM-based methodology increases with the complexity of concert halls.

However, there are still some limitations in this study. The building information extraction algorithm works well only on regular architecture geometry. To make the proposed methodology more general, extraction algorithm should be furtherly improved. In addition, the developed function of decorated materials-sound absorption coefficient mapping only contains a few commonly used decorated materials. More potential materials should be included in the future work.

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