BIM-BASED ACOUSTIC SIMULATION FRAMEWORK

Chengde Wu, PhD Student, chdwu22@gmail.com
Mark. J. Clayton, Professor, dr.mjclayton@gmail.com
College of Architecture, Texas A&M University, College Station, TX, USA

ABSTRACT

A simulation system based on Building Information Modeling (BIM) software can speed the prediction of the acoustic performance of an indoor space during the schematic building design stage. This claim is demonstrated by a software prototype that is composed of four modules: BIM data extraction module, frequency analysis module, sound effect simulation module, and auralization/visualization module. After giving a BIM of a room additional custom parameters to express acoustic qualities of materials, the BIM data extraction module retrieves necessary information such as room dimensions, and absorption coefficients of surfaces. The frequency analysis module identifies dominant frequencies in a sample sound track file. The sound effect simulation module reads extracted BIM data and the frequency composition information and calculates reverberation time and sound intensity level (SIL). The auralization/visualization module applies the results from the previous step to modify the sound track with the calculated reverberation and SIL. It also maps these effects on the plans to help visualize the performance of the room. By repeating the analysis, the software can generate different sound tracks to simulate different listening positions or the effects of different finish materials, providing information to support design decisions about the size, shape, and finishes of a room. The software is intended for relatively simple spaces, such as conference rooms, lecture halls, lobbies and offices, while more complex and sophisticated software is appropriate for concert halls, theaters and other performance spaces. The prototype software shows that integration of acoustic analysis into BIM could enable architects to easily simulate acoustic performance during schematic design stage, achieving better designs more quickly.

Keywords: room acoustic simulation, Building Information Modeling (BIM), frequency analysis, sound effects

1. INTRODUCTION

Acoustics is an important factor to consider when designing facilities requiring high acoustic performance, but may be overlooked in more common office buildings or educational facilities. Once a building is built, it can be very costly to fix if it has inappropriate acoustic effects. Architects and engineers could be aided by easy ways to simulate building acoustics before construction. Scale models and computer models are being used, especially for design of performance spaces and lectures halls, but the methods are expensive and require expert consultants.

As the industry adopts Building Information Modeling (BIM), it may be possible to incorporate acoustic analysis into design processes in a more seamless way. This research focuses on the connection of BIM and acoustic simulation to speed the acoustic analysis and enable its application to common architecture such as small auditoriums, conference rooms, lobbies, and classrooms. We believe this will help architects to incorporate acoustic analysis in more building design efforts at earlier stages.

2. PREVIOUS RESEARCH

Acoustic simulation was introduced in the early 20th century by using scale models. With the emergence of computer, simulation method has switched to computer models since 1960s. The introduction of Building

Information Modeling in the last few years may provide new opportunities for incorporating acoustic analysis into the design process.

2.1 Measuring acoustic performance

Acoustic performance of an indoor space is usually evaluated by several indicators. Major indicators include reverberation time, sound intensity level, noise, flutter, and intelligibility. This research limits the scope to reverberation time and sound intensity level because they can be calculated with relatively simple equations yet they are the most important in determining performance. Figure 1 shows that preferred reverberation time has a wide range depending on different room functions.

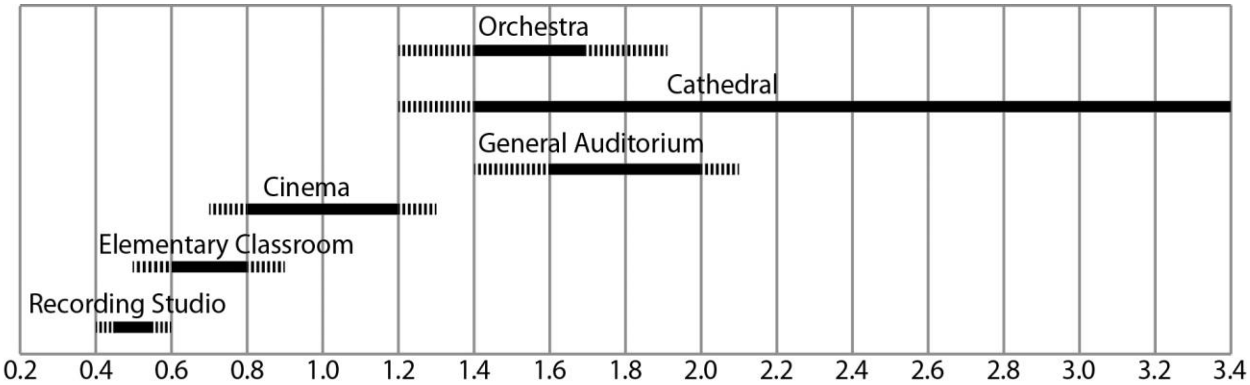


Figure 1: Proper reverberation time (in seconds) depending on room functions (Grondzik et al. 2010)

2.2 Scale models

In 1913 Sabine first used ultrasonic waves to test 2D section of scale model (Sabine 1913). A variety of other methods employing scale models have also been used (Rindel 2002). Davis and Kaye tested water ripple (Davis et al. 1927), Satow tested light beams on reflective surfaces (Satow 1929, from Rindel 2002), Spandöck used sound signal in a scale model (Spandöck 1934, from Rindel 2002), more recently in 1986, laser beam was tested. The scale of the models used in the research has ranged from 1:5 to 1:200.

2.3 Computer models

Researchers have used computer models to simulate room acoustics since the 1960s. Major computer models include Wave Equation Models, Image Source Model, Markoff Chain Model, Particle Tracing Models, Ray Tracing Models, Cone Tracing Models, Radiosity Models, and Hybrid Models (Rindel 2002). Much progress has been made in computer models, so that they are accurate enough to simulate all frequencies. (Volander 2012).

There are a number of software applications for acoustic simulation: Odean, Catt, EASE, Ramsete, SoundPlan, VNoise, SEAM 3D and others. These applications import pure geometry from 3D CAD or SketchUp and permit the user to assign absorption coefficients to each face. Although these applications require additional work to assign acoustic properties to each face, some of them are proven to be excellent in accuracy (Volander 2010, Bradley 2007).

2.4 BIM-based acoustic simulation software

Conventional Computer-Aided Design (CAD) software in architecture has primarily been used for drafting. Recently, it is changing from drafting to modeling that represents not only the geometric description of the building, but also physical qualities, geometric relationships, economic qualities and other parameters. Compared to CAD, Building Information Modeling (BIM) is a richer representation of actual buildings, because BIM is composed of building components such as walls and columns, rather than graphic primitives such as lines and arcs. Because BIM software can represent all building information, both graphical and non-graphical, BIM has the capability to integrate many processes which were not easily addressed using conventional CAD systems. BIM has been used to support energy analysis, cost estimating, construction simulation, and facility management, as well as design documentation. In theory it should be possible to integrate acoustic simulation into BIM software.

Although the commercial software for acoustic simulation listed above in some cases will allow import of geometry representations produced by CAD programs, none of them can make use of rich BIM that includes acoustic data. A review of acoustic simulation software suggests that Autodesk Ecotect is able to directly accommodates BIM data. However, it also can obtain only geometric data from the BIM and is unaware of acoustic qualities that may be embedded in the BIM. Ecotect imports gbXML files and uses the data in acoustic simulation. After importing the geometry, acoustic properties must be assigned to each face because gbXML does not contain information about acoustic properties. In addition, Ecotect does not account for the frequency composition of sound source. Some other research has been conducted to connect BIM with architectural acoustic simulation (LePage 2010), but connecting BIM with acoustic simulation remains a research issue.

Scale models usually take weeks to get the result of acoustic simulation (Rindel 2002). Existing computer software systems have reduced simulation time to a few days while preserving or increasing accuracy. The BIM-based acoustic simulation application programmed in this research is able to reduce the simulation time to a few minutes.

3. RESEARCH METHODS

This paper describes model-based research methods to produce a proof-of-concept of integrating acoustic situation into a BIM to enable designers to gain feedback regarding acoustic performance. The initial step was to review literature to gain an understanding of the theory and equations behind acoustic analysis of architectural spaces, various methods of analog and digital acoustic simulation, and the software development tools that can aid the production of a prototype. A software prototype was constructed using Autodesk Revit, the Revit API, the DirectX toolkit, and C# programming in Visual Studio. Our research has employed test cases of determining the reverberation and sound level intensity in a building and a lecture hall . Tests have been informally conducted to confirm that the process is very fast and accurate. This paper focuses on the development of the software prototype.

The software-aided design process is conceived as consisting of fundamental steps of collecting necessary data about acoustic qualities of the architecture, simulating sound propagation, modifying a sound sample with the simulation results, and listening to simulated sound (known as auralization) and inspecting the sound characteristics both numerically and graphically. A supporting step is to analyze the sound sample to identify the dominant frequencies that will be most affected by the acoustic qualities of the space. Necessary input data can be extracted from BIM model and sound source, shown in figure 2 as “BIM Data Extraction” and “Frequency Analysis” (Section 3.1 and 3.2). We used equations to simulate two of the major acoustic indicators: reverberation time and sound intensity level (Section 3.3). When simulation results are ready, we can apply the calculated values to sample sound track and listen to the final sound effect (Section 3.4). Figure 2 shows detailed simulation process.

3.1 BIM data extraction

To perform acoustic simulation, we only need a small portion of the information from a BIM model. There are four sets of necessary input data when performing acoustic simulation of an indoor space: geometry of the room, finish materials of the room and the absorption at various frequencies, sound source, and audience. Geometric data of the room include volume of the room, each face of the room, and the area of each face. Necessary material property is the sound absorption coefficient at series of octave band frequencies. Necessary data for sound source include the position and the power of the sound source assuming it is omni-directional. For audience information, we only need the position of the audience if subjective factors are neglected. In this research we modeled a building in Revit Architecture and extracted necessary data from the model by software written with the Revit Application Programming Interface (API) using the C# language.

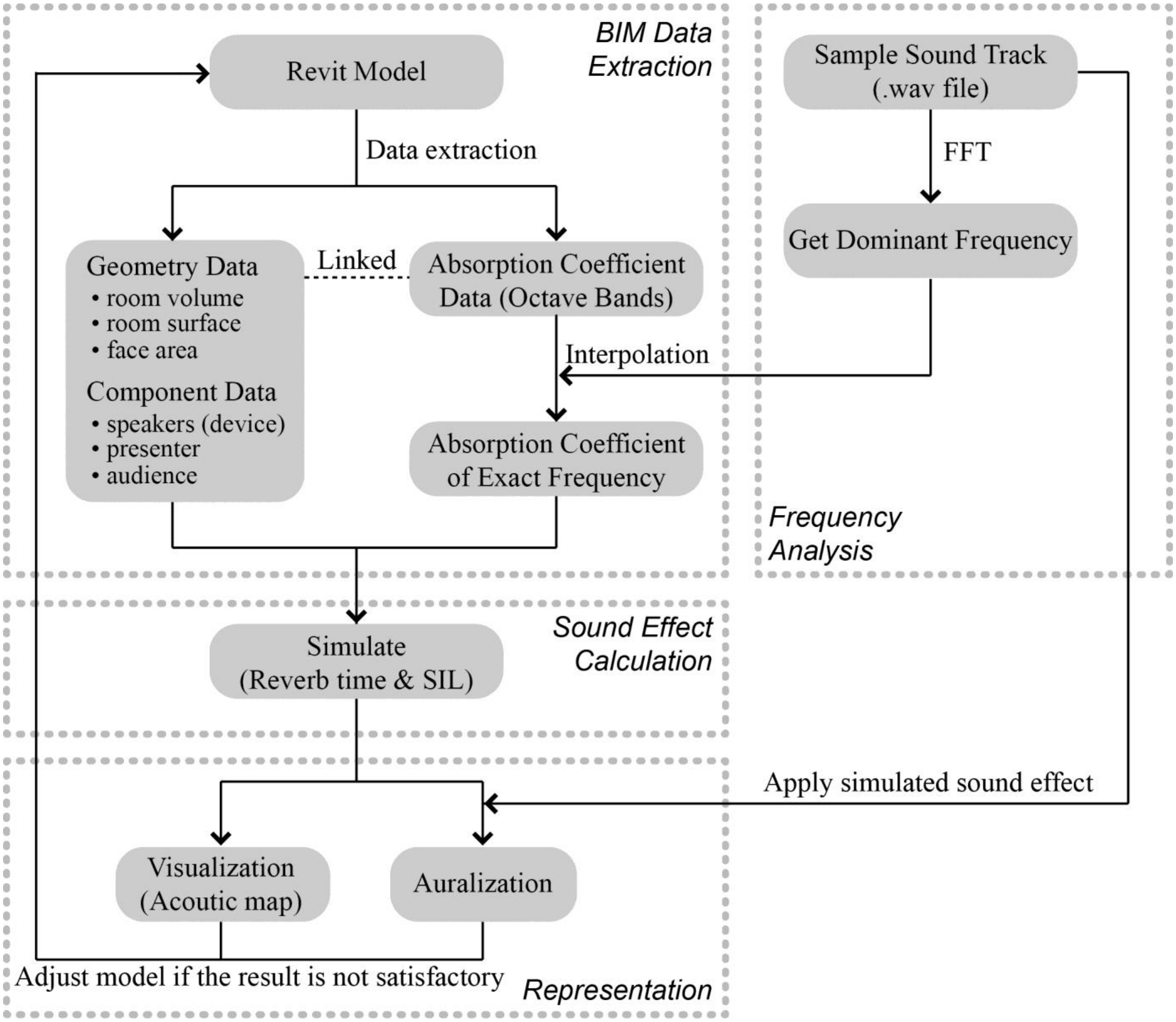


Figure 2: Simulation process diagram

3.2 Frequency analysis

Absorption coefficient of building materials is different at different frequencies (table 1). To know how much sound energy a specific building material absorbs, we need to know the frequency composition of the sound source. The software user may select a sound track file in .wav format that is similar to the situation we want to simulate (lecture, concert, etc.), and find the dominant frequency of the sound track. It is then possible to calculate actual absorption coefficient of the material at the dominant frequency by linear interpolation.

Table1: Absorption coefficient of common building materials at different frequencies (Egan 1988)

Materials	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Concrete or terrazzo	0.01	0.01	0.02	0.02	0.02	0.02
Brick, unglazed	0.02	0.02	0.03	0.04	0.05	0.07
Glass, ordinary window	0.35	0.25	0.18	0.12	0.07	0.04
Gypsum board, 5/8 inch thick	0.55	0.14	0.08	0.04	0.12	0.11
Carpet, heavy, 5/8 inch thick	0.37	0.41	0.63	0.85	0.96	0.92
Wood, 1 inch panel with airspace behind	0.08	0.24	0.57	0.69	0.71	0.73

French mathematician Jean Baptiste Joseph Fourier (1768-1830) proved that any continuous periodic signal can be represented as the sum of properly chosen sinusoidal waves (Smith, 1998). Discrete Fourier Transform (DFT, equation 1), one of the four Fourier Series, is widely used in Digital Signal Processing across many disciplines. DFT converts time domain of the sound signal to frequency domain of the same signal.

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-i2\pi kn/N}. \qquad (1)$$

Early DFT algorithms are very computationally consumptive. In this research, we used Fast Fourier Transform (FFT), the fastest algorithm to perform DFT. Figure 3 shows the time domain graph of a mono-tone sound wave with 250 Hz frequency (left), and the frequency domain graph of the same sound wave after FFT (right). We can see a spike at 250Hz.

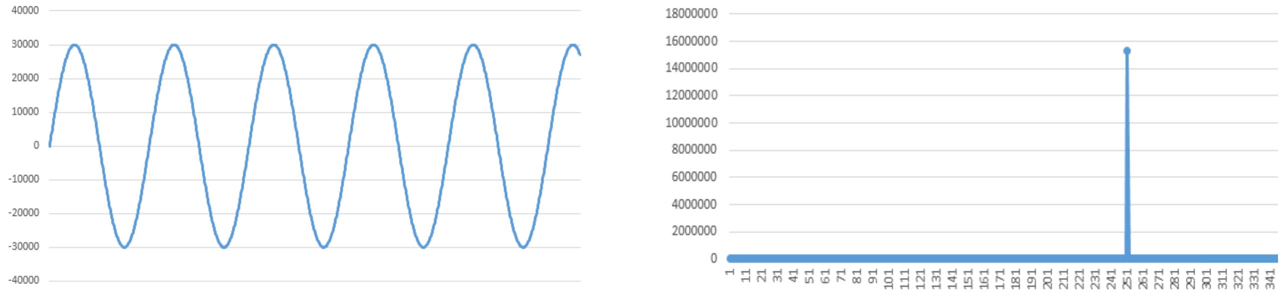


Figure 3: Time domain of the digital sound signal at 250Hz (left) and frequency domain of the same signal (right)

3.3 Simulating sound effects

After extracting BIM data and analyzing dominant frequency of the sound track, the software simulates the sound in the space based on two of the major acoustic indicators: reverberation time and sound intensity level (SIL). Reverberation time is calculated by Sabine’s equation:

$$\mathrm{RT60} = k \bullet V / A \qquad (2)$$

Where Factor k (constant) = 0.049 (IP) or 0.161 (SI)
V = room volume
$A = \alpha_1 \bullet S_1 + \alpha_2 \bullet S_2 + \alpha_3 \bullet S_3 + \ldots$
α = absorption coefficient of each surface material
S = surface area

Sound intensity is calculated using inverse square law, i.e., sound intensity (w/m2) is the reciprocal of distance square (equation 3). In this prototype software, only direct sound source is applied to calculate sound intensity.

$$I = P/(4\pi r^2) \tag{3}$$

Where I = sound intensity
P = power of the sound source
r = distance from the sound source

3.4 Auralization and visualization

3.4.1 Auralization

The values of reverberation time and sound intensity level enable approximation of how the specific sample sound track would sound to the audience at the spot of the space. By applying these sound effects to the sample sound track, the building designer gains a sense of how it would sound if the space is built. In this research, we used MS DirectX to adjust sound intensity level and apply reverberation effect to the sample sound track file.

3.4.2 Visualization

Based on the simulation result from simulation step, the application also generates sound intensity level map and reverberation map for visual judgment. Sound intensity level map (figure 13) shows the sound intensity change throughout a room, and reverberation map (figure 15) shows the different reverberation time of each room in a building. Visualized maps may help designers to detect acoustic flaws of their building and may help them to design indoor space with better acoustic effects.

4. TESTING

The envisioned design process aided by software has been tested using a worked example of an auditorium (figure 4) and Langford C building (figure 15) at Texas A&M University

4.1 Revit model

We modeled an auditorium in Revit Architecture, shown in figure 4 and 5. In the model, there are two speakers (electric devices) hanging on the wall, a presenter, and an audience. In the section view, figure 5, we can see the boundary of the space which is necessary for the simulation. In Revit Architecture, acoustic properties are not included in the material library as parameters. We created custom parameters to hold absorption coefficients of the building materials

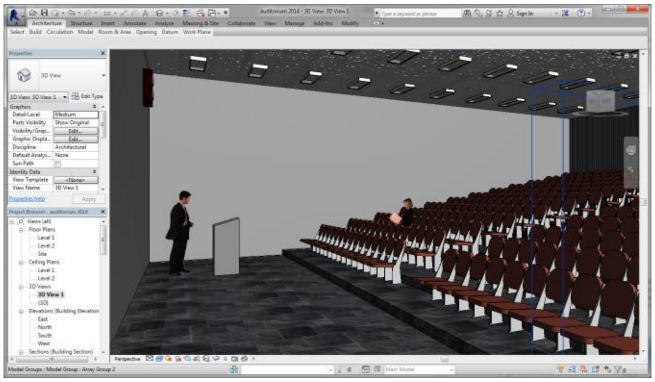


Figure 4: Perspective of the auditorium

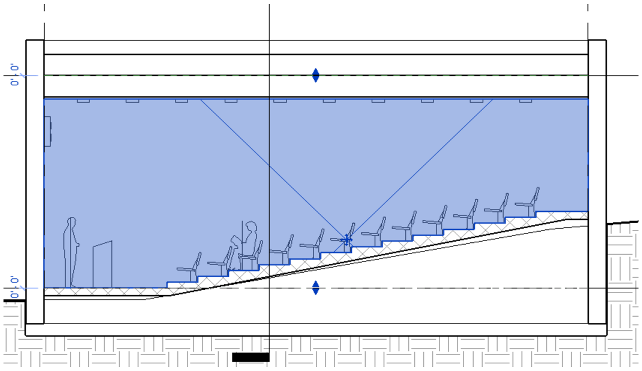
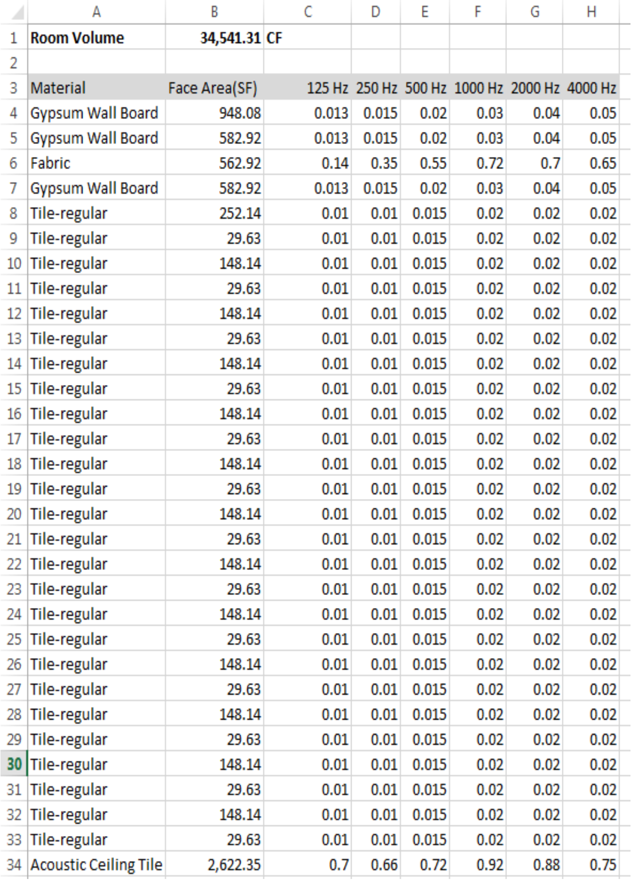


Figure 5: Section of the auditorium

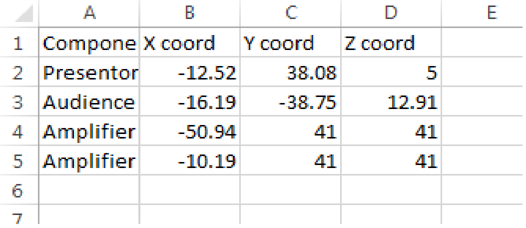
4.2 BIM data extraction

BIM data extraction module retrieves all necessary information for simulation from the Revit model. The software, developed in the Revit API, identifies the room that the user has selected and retrieves all building components which form the boundary of the room, such as walls, ceilings, and floors. The software iterates each component and gets the absorption coefficients from the finish materials. Figure 6 shows extracted data for reverberation calculation. The software also finds sound sources and audience that are inside the room. Figure 7 shows position of each component used in sound intensity level calculation.



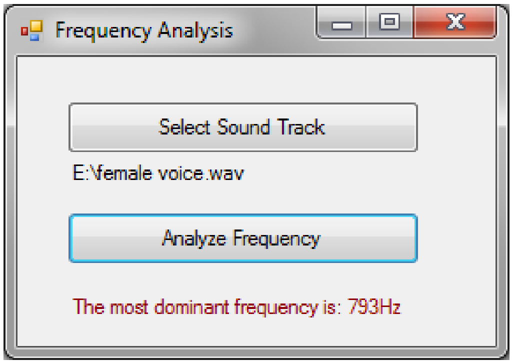
	A	B	C	D	E	F	G	H
1	**Room Volume**	**34,541.31**	**CF**					
2								
3	Material	Face Area(SF)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
4	Gypsum Wall Board	948.08	0.013	0.015	0.02	0.03	0.04	0.05
5	Gypsum Wall Board	582.92	0.013	0.015	0.02	0.03	0.04	0.05
6	Fabric	562.92	0.14	0.35	0.55	0.72	0.7	0.65
7	Gypsum Wall Board	582.92	0.013	0.015	0.02	0.03	0.04	0.05
8	Tile-regular	252.14	0.01	0.01	0.015	0.02	0.02	0.02
9	Tile-regular	29.63	0.01	0.01	0.015	0.02	0.02	0.02
10	Tile-regular	148.14	0.01	0.01	0.015	0.02	0.02	0.02
11	Tile-regular	29.63	0.01	0.01	0.015	0.02	0.02	0.02
12	Tile-regular	148.14	0.01	0.01	0.015	0.02	0.02	0.02
13	Tile-regular	29.63	0.01	0.01	0.015	0.02	0.02	0.02
14	Tile-regular	148.14	0.01	0.01	0.015	0.02	0.02	0.02
15	Tile-regular	29.63	0.01	0.01	0.015	0.02	0.02	0.02
16	Tile-regular	148.14	0.01	0.01	0.015	0.02	0.02	0.02
17	Tile-regular	29.63	0.01	0.01	0.015	0.02	0.02	0.02
18	Tile-regular	148.14	0.01	0.01	0.015	0.02	0.02	0.02
19	Tile-regular	29.63	0.01	0.01	0.015	0.02	0.02	0.02
20	Tile-regular	148.14	0.01	0.01	0.015	0.02	0.02	0.02
21	Tile-regular	29.63	0.01	0.01	0.015	0.02	0.02	0.02
22	Tile-regular	148.14	0.01	0.01	0.015	0.02	0.02	0.02
23	Tile-regular	29.63	0.01	0.01	0.015	0.02	0.02	0.02
24	Tile-regular	148.14	0.01	0.01	0.015	0.02	0.02	0.02
25	Tile-regular	29.63	0.01	0.01	0.015	0.02	0.02	0.02
26	Tile-regular	148.14	0.01	0.01	0.015	0.02	0.02	0.02
27	Tile-regular	29.63	0.01	0.01	0.015	0.02	0.02	0.02
28	Tile-regular	148.14	0.01	0.01	0.015	0.02	0.02	0.02
29	Tile-regular	29.63	0.01	0.01	0.015	0.02	0.02	0.02
30	Tile-regular	148.14	0.01	0.01	0.015	0.02	0.02	0.02
31	Tile-regular	29.63	0.01	0.01	0.015	0.02	0.02	0.02
32	Tile-regular	148.14	0.01	0.01	0.015	0.02	0.02	0.02
33	Tile-regular	29.63	0.01	0.01	0.015	0.02	0.02	0.02
34	Acoustic Ceiling Tile	2,622.35	0.7	0.66	0.72	0.92	0.88	0.75

Figure 6: Extracted room data from BIM to spread sheet



	A	B	C	D	E
1	Compone	X coord	Y coord	Z coord	
2	Presentor	-12.52	38.08	5	
3	Audience	-16.19	-38.75	12.91	
4	Amplifier	-50.94	41	41	
5	Amplifier	-10.19	41	41	
6					
7					

Figure 7: Extracted component data from BIM to spread sheet



E:\female voice.wav

The most dominant frequency is: 793Hz

Figure 8: Sample sound track frequency analysis module interface

4.3 Sample sound track frequency analysis

The frequency analysis module analyzes the frequency composition of a sample sound track and sorts out the dominant frequency. Figure 8 is the interface of frequency analysis module, figure 9 is the time domain of the sample sound track, and figure 10 is the frequency domain of the same sound track. In figure 8 and 10, we can see that the dominant frequency of the sample sound track is 793 Hz.

4.4 Simulating sound effects

After collecting all necessary information, the software is ready to calculate reverberation time and sound intensity level. Absorption coefficient is calculated by linear interpolation based on the identified dominant frequency of the sample sound track (Figure 11). Figure 12 shows the result of reverberation time and sound intensity level calculation.

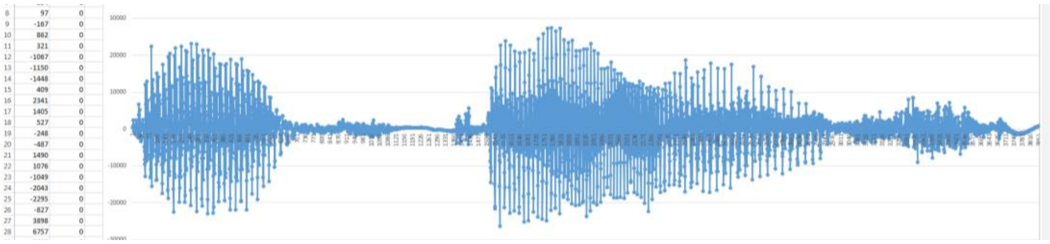


Figure 9. Time domain of the sample sound track

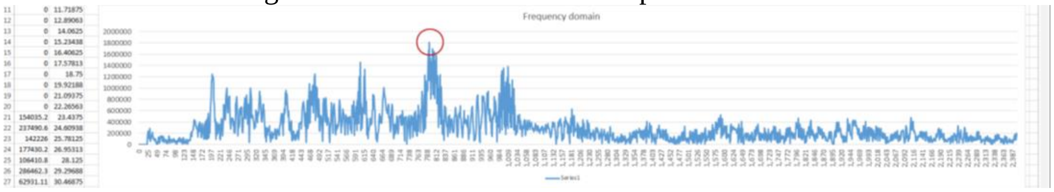
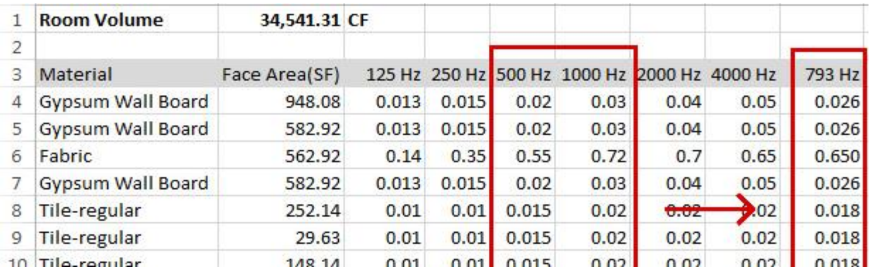


Figure 10: Frequency domain of the sample sound track



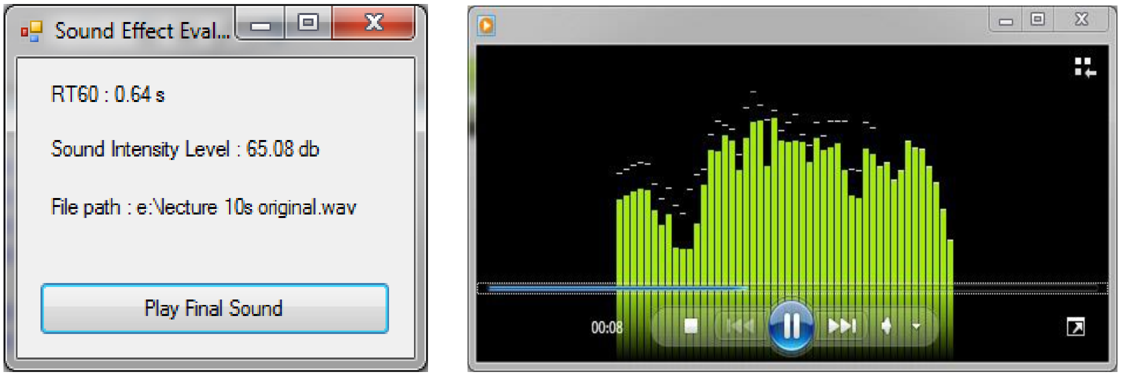
1	Room Volume	34,541.31	CF						
2									
3	Material	Face Area(SF)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	793 Hz
4	Gypsum Wall Board	948.08	0.013	0.015	0.02	0.03	0.04	0.05	0.026
5	Gypsum Wall Board	582.92	0.013	0.015	0.02	0.03	0.04	0.05	0.026
6	Fabric	562.92	0.14	0.35	0.55	0.72	0.7	0.65	0.650
7	Gypsum Wall Board	582.92	0.013	0.015	0.02	0.03	0.04	0.05	0.026
8	Tile-regular	252.14	0.01	0.01	0.015	0.02	~~0.02~~	.02	0.018
9	Tile-regular	29.63	0.01	0.01	0.015	0.02	0.02	0.02	0.018
10	Tile-regular	148.14	0.01	0.01	0.015	0.02	0.02	0.02	0.018

Figure 11: Interpolation of the absorption coefficient based on dominant frequency

4.5 Auralization and visualization

4.5.1 Auralization

Auralization module enables us to listen to the sound effect of the room at the audience member's seat. This module reads the value of reverberation time and sound intensity level from simulation result and applies it to the sample sound track. Figure 12 shows the values of reverberation time, sound intensity level (left) and playing the sound track at the same time (right). With partly sound-absorbing materials (acoustic tiles on the ceiling and glass fiber on the back wall), reverberation time in the auditorium was 0.64 seconds and the sample sound track was sounded highly intelligible. After changing all surfaces to reflecting materials (gypsum boards on the walls and the ceiling, ceramic tiles on the floor), reverberation time soared above 5 seconds. Consequently, the sample sound track was very reverberant and the intelligibility dropped significantly. When the audience is set to the last row of the auditorium, sound intensity level dropped to 59.57dB which is an easily noticeable aural change.



RT60 : 0.64 s

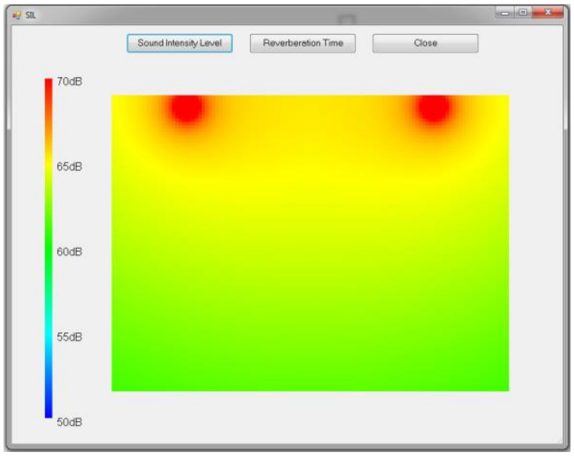
Sound Intensity Level : 65.08 db

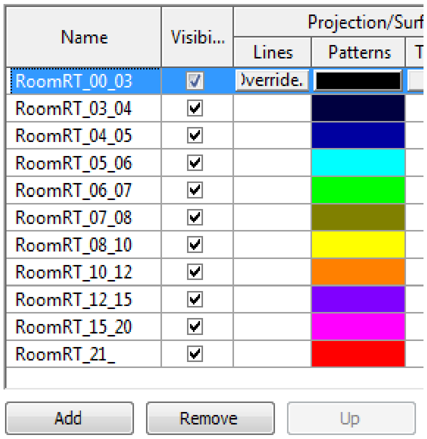
File path : e:\lecture 10s original.wav

Figure 12: Auralization module interface (left) and playing the sound file (right).

4.5.2 Visualization

Visualization module shows sound intensity level map (figure 13) and reverberation map (figure 15, left). Sound intensity level map shows the variation of sound intensity in a room. The effects of the two speakers are clearly depicted. The reverberation map is produced by iterating all rooms in the building automatically, and applying colors to the rooms by filters in Revit. The difference of the colors in figure 14 and figure 15 is because Revit internally reduces the saturation of the filter colors for rooms. Any space that is not defined as a room in Revit is shown in white (figure 15). Reverberation time schedule (figure 15, right) is also created at the same time for reference. This could change the design process by empowering designers to always consider acoustic effects of the building they are designing.





Name	Visibi...	Projection/Surf		
		Lines	Patterns	T
RoomRT_00_03	☑	)verride.	⬛	
RoomRT_03_04	☑		⬛	
RoomRT_04_05	☑		🟦	
RoomRT_05_06	☑		🟦	
RoomRT_06_07	☑		🟩	
RoomRT_07_08	☑		🟫	
RoomRT_08_10	☑		🟨	
RoomRT_10_12	☑		🟧	
RoomRT_12_15	☑		🟪	
RoomRT_15_20	☑		🟪	
RoomRT_21_	☑		🟥	

Figure 13: Sound intensity level map of the auditorium

Figure 14: Filters applied to rooms in Revit

Name	Number	RT60	Area	Volume
Auditorium	105	0.61	1659 SF	18244.58 CF
Classroom	111	0.64	706 SF	8359.68 CF
Viz Dept.	108	0.61	957 SF	11325.11 CF
Prof.	104B	0.54	123 SF	1457.57 CF
Prof.	104C	0.56	166 SF	1966.51 CF
Room	104	0.58	240 SF	2837.93 CF
Prof.	104A	0.55	132 SF	1563.56 CF
Hazard Cent	106C	0.43	207 SF	2435.10 CF
Hazard Cent	106B	0.41	108 SF	1268.83 CF
Hazard Cent	106D	0.42	54 SF	630.87 CF
Hazard Cent	106A	0.44	313 SF	3682.93 CF
Men		0.58	102 SF	1210.47 CF
Women		0.60	163 SF	1928.93 CF
Janitor		0.53	47 SF	559.05 CF
Prof.	107A	0.51	147 SF	1737.59 CF
Prof.	107B	0.51	138 SF	1633.25 CF
Prof.	107C	0.51	86 SF	1012.32 CF
Room	111A	0.57	55 SF	649.59 CF
Classroom	109	0.64	1186 SF	14035.88 CF
Hazard Cent	110	0.62	926 SF	10962.62 CF

Figure 15: Reverberation map (left) and schedule (right) of Langford C building

5 CONCLUSION

The examples suggest that acoustic analysis of rooms for reverberation and sound intensity level can be completed in a few minutes from a BIM using the prototype software. This research focused on connecting BIM data with acoustic simulation to increase the level of automation. We were able to extract necessary data from Revit model, analyze the frequency of the sound source, and get the result of the simulation result in a few minutes. Any update made in the Revit file was able to be re-simulated immediately. A designer can conduct "what-if" scenarios very rapidly, gaining a sense of what materials and surfaces can produce the best soundscape. This system will help architects to simulate acoustic effects of the buildings they design in early design stage. It may also help to convey concepts in acoustics to students.

Future work includes 1) improving the accuracy of the software, 2) experimenting how the software changes design process, 3) adopting more realistic ways of auralization and visualization such as virtual reality by which we can simulate buildings in real time.

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