Acoustical simulation, design and experimental investigation of a classroom: A case study

Mohammad Reza Torabi[a], **Ali Loghmani**[b*]

[a]*BSc Student, Department of Mechanical Engineering, Isfahan University of Technology, Isfahan, Iran*

[b]*Assistant Professor, Department of Mechanical Engineering, Isfahan University of Technology, Isfahan, Iran*

ARTICLE INFO	ABSTRACT
	To improve teaching and learning conditions, room acoustics tries to adjust the educational environment. This research addresses the room acoustics of a small classroom in the Department of Mechanical Engineering at the Isfahan University of Technology. It has been studied by modeling and simulating the classroom in the COMSOL software using the ray tracing method, and the reverberation time has been calculated. The model is validated by field measurements and using the impulse response function according to ISO 3382-2 in terms of the reverberation time. Then, it is compared to Eyring's and Sabin's empirical relationships, as well. The acoustics modes of the classroom have been obtained using the modal analysis in the COMSOL software. ANSI/ASA S12.60 is employed to design a suitable acoustical environment for the classroom and absorption panels and bass traps are utilized to reach the desired condition. After applying the adjustments, the reverberation time reached the recommended standard value, which increases the sound quality. Other acoustical parameters such as Definition (D_50), Clarity (C_50) and Sound Transmission Index (STI) have been calculated before and after the acoustic correction. Results revealed that speech intelligibility has fallen in the acceptable range.

1. Introduction

In order to achieve suitable conditions for speech communication, which is the most important part of the learning process in the classroom and other educational environments, it is necessary that architectural and mechanical design provide suitable conditions for acoustic characteristics [1]. Many studies have shown that inappropriate acoustic design in the classroom can directly affect the understanding of speech and reduce the learning efficiency of students, and in addition, it can cause audio problems for the teacher who needs to speak up to compensate for acoustic problems [2]. A lot of noises and echoes can be an obstacle to

* Corresponding author:

E-mail address: a.loghmani@iut.ac.ir (A. Loghmani)

understanding speech so it slows down the speed of teaching and reduces understanding and learning [3].

In recent years, many studies have been done in the field of acoustics and various criteria have been created for all types of rooms and environments. Since it is related to feelings and Human conditions, acoustics have also entered the fields of physiology and psychology to better study the conditions and perform activities to improve the environment [4]. For these reasons, the issue of classroom acoustics has attracted researchers' attention in different countries, and it has led to the creation of regulations for educational places. Therefore, designers, architects and builders are required to comply with the regulations to prevent high background noises and echoes that can reduce understanding; thus, learning is controlled and the teacher's speech reaches the people with an appropriate loudness and clarity [5]. Yang and Hodgson [6] in response to the complaint of teachers in a preschool, examined it acoustically and evaluated the reverberation time, background noise, and speech level, with the teachers' subjective reaction questionnaire. They simulated eight different modes, including increasing the absorption of surfaces and reducing the volume of the simulated room, and predicted the reverberation time. Astolfi et al. [7] investigated the acoustical parameters in eight small high school classes, in which different analytical models for the class such as Sabin, Eyring, and Hodgson's experimental model were used. Numerical simulation using the ODEON 6.5 software was also compared with the results obtained through field measurements for two situations: an empty class and a class with students. Nijs and Rychtáriková [3] proposed a predictive model for speech intelligibility, which was introduced with the U50 parameter based on objective parameters, such as reverberation time and signal-to-noise ratio. Also, the architectural guide for the maximum reverberation time has been obtained and compared with the existing suggested values, and the minimum necessary value for the reverberation time has been surveyed. Awad et al. [8] evaluated the classes of three universities in Egypt with three methods of field measurement including a sound level meter, simulation in ODEON software, and Sabin and Eyring mathematical formulas. In this research, the sound level, noise level, reverberation time and signal-to-noise ratio were examined and compared with the values found in ANSI S12.60 [1] and BB93 [9] standards. Pääkkönen et al. [10] investigated the classrooms and corridors of a school and examined the reverberation time, A-weighted sound pressure level and sound isolation, as well as other acoustical parameters, and compared them with the Finnish standard SFS 5907. Fantozzi et al. [11] investigated a class of the Engineering Department at the University of Pisa and calculated reverberation time using the analytical relationships of Sabin and Eyring, and the class was simulated using EASE 4.4 software. Fantozzi et al. performed the necessary measurements in accordance with ISO 3382-2 standard [12] and in the "precision" method, which used interrupted noise for this measurement. Russo and Ruggiero [13] investigated three different acoustic designs for a classroom in Italy. They specified the necessary parameters for modeling in CadnaR software by measuring the acoustical parameters of reverberation time, sound clarity and sound transmission index according to ISO 3382-2 standard [12] and using the impulse response method. Then, by comparing different modes, they chose the optimal design, and after implementation with the desired panels, they again measured and compared with the designed values obtained from the simulation. Prodeus and Didkovska [14] investigated two small and medium classes, assuming that the effect of background noise on speech intelligibility is negligible compared to the effect of reverberation time. Then, they studied the effect of people's distance from the wall and their locations, on the speech intelligibility by employing the measured impulse response. Abraham and Ravishankar [15] evaluated different correction combinations for eight classes in order to find the optimal reverberation time by a step-by-step method, which after each correction, the reverberation time and the

speech clarity with the parameter C_{50} have been obtained and the calculated reverberation time has been compared with ANSI S12.60 standard.

Previous studies have shown that room acoustics analysis is of great importance for enhancing speech intelligibility and learning quality. Generally, those studies have used just one or two approaches (theoretical, simulation, or experimental) for investigating the effect of acoustical treatment on speech intelligibility and they neglected the treatment for low frequencies. However, in this research, a comprehensive analytical, numerical and experimental study of the acoustical performance of a classroom, a case study of a small classroom in the Department of Mechanical Engineering at the Isfahan University of Technology, has been done. The classroom is modeled and simulated in the COMSOL software and validated by experimental measurements. Two different experimental methods are performed and compared to the measured reverberation time. Room modes are calculated by means of frequency analysis. Using low-frequency modes, the proper location for the bass traps is selected. To achieve compliance with standards and improve the acoustic response in the low and mid frequencies, different configurations for the absorption panels are investigated. Finally, for evaluating the effectiveness of the adjustments, field measurements are done again and the results are compared with those of the simulations and standards.

2. Modeling and simulation

In order to obtain a suitable level of speech intelligibility in a classroom, it is necessary to have an accurate prediction of the reverberation time and sound pressure level. Diffuse field theory with Sabin's and Eyring's formula is the most common theoretical relation which has been evaluated in previous studies [7]. In this research, in addition to using diffuse field models, simulation in the COMSOL software is also performed and the necessary acoustic parameters are obtained.

To obtain the reverberation time, with the assumption of a diffuse field, in which the sound pressure distribution in the classroom is uniform, three formulas are used as follows [4].

Sabin's formula by ignoring the air attenuation:

$$T_{60} = 0.161 \frac{V}{A} \tag{1}$$

Sabin's formula by taking into account the air attenuation:

$$T_{60} = 0.161 \frac{V}{S\bar{\alpha} + 8a_{air}V} \tag{2}$$

Eyring's or Eyring-Norris's formula:

$$T_{60} = 0.161 \frac{V}{-Sln(1 - \bar{\alpha}) + 8a_{air}V} \tag{3}$$

In this research, the required analysis has been carried out in the ray acoustics (rac), which is one of COMSOL's environments. In ray acoustics, ray tracing could be studied to obtain the required room acoustic properties.

Ray acoustics can be used to calculate the path, phase and sound intensity, which is valid for high frequencies where the wavelength is much smaller than the geometric dimensions [16]. The dimensions proposed for the analysis of a certain frequency should be four times the wavelength corresponding to the evaluated frequency [17].
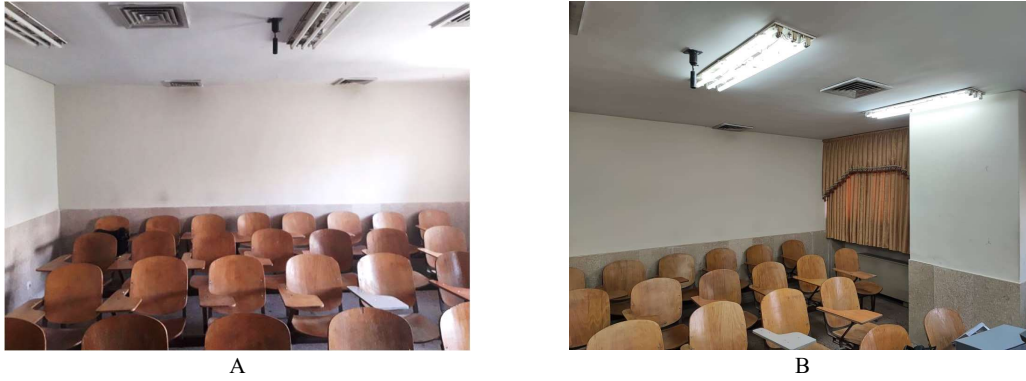
A   B

Fig.(1): Two views of the classroom before adjustment.

The case study of the present work is a classroom in the Department of Mechanical Engineering at the Isfahan University of Technology as shown inFig.(1). After the necessary measurements of its various dimensions, the class is drawn in the "Generative Shape Design" environment of the CATIA software as illustrated in Fig.(2).
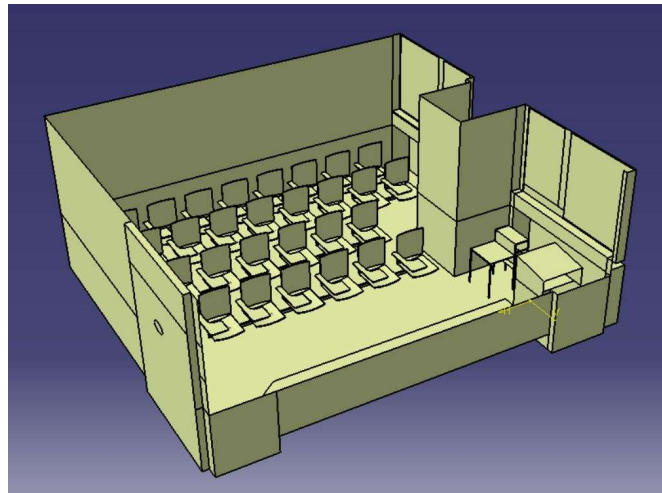

Fig. (2): The classroom model in CATIA

After modeling the classroom, the model is imported into the geometry section of the COMSOL software. The required parameters for simulating the model and the position of the receivers and transmitters are summarized in Table (1) and Table (2), respectively. They are entered in the "Global Definition" section.

Table 1. Classroom's parameters

name	Expression	Value	Description
rho0	1.2[kg/m^3]	1.2 kg/m^3	Density
c0	343[m/s]	343 m/s	Speed of sound
f0	500[Hz]	500 Hz	Band center frequency
lam0	c0/f0	0.686 m	Wavelength at f0
P0	0.03[W]	0.03 W	Source power
Vol	92[m^3]	92[m^3]	Room volume

r_rec	0.3[m]	0.3 m	Receiver radius
dt	0.01[s]	0.01 s	Time interval
Nrays_min	(4.34/r_rec)^2*Vol/pi/c0/dt	1786.8	Recommended minimum number of released rays
Nrays	1000*ceil(Nrays_min/1000)	2000	Number of released rays
s_default	0.05	0.05	Scattering coefficient of flat surface

Table 2. Receiver and source positions

name	Expression	Value	Description
x_s1	2[m]	2m	Source 1 x-coordinate
y_s1	-0.7[m]	-0.7m	Source 1 y-coordinate
z_s1	1.9[m]	1.9m	Source 1 z-coordinate
x_s2	4[m]	4m	Source 1 x-coordinate
y_s2	-0.7[m]	-0.7m	Source 1 y-coordinate
z_s2	1.9[m]	1.9m	Source 1 z-coordinate
x_r1	5.35[m]	5.35m	Receiver 1 x-coordinate
y_r1	3.7[m]	3.7m	Receiver 1 y-coordinate
z_r1	1[m]	1m	Receiver 1 z-coordinate
x_r2	0.83[m]	0.83m	Receiver 2 x-coordinate
y_r2	3.7[m]	3.7m	Receiver 2 y-coordinate
z_r2	1[m]	1m	Receiver 2 z-coordinate
x_r3	3.8[m]	3.8m	Receiver 3 x-coordinate
y_r3	3[m]	3m	Receiver 3 y-coordinate
z_r3	1[m]	1m	Receiver 3 z-coordinate

Table 3. Absorption coefficient of the materials[17, 18]

Frequency (Hz)	Gypsum	Terrazzo	Wood	Large pane glass	Small pane glass	Steel	Drapery	Opening
125	0.013	0.01	0.15	0.18	0.04	0.05	0.07	1
250	0.015	0.01	0.11	0.06	0.04	0.1	0.31	1
500	0.02	0.015	0.1	0.04	0.03	0.1	0.49	1
1000	0.03	0.02	0.07	0.03	0.03	0.1	0.75	1
2000	0.04	0.02	0.06	0.02	0.02	0.07	0.7	1
4000	0.05	0.02	0.07	0.02	0.02	0.02	0.7	1

Table. 4. Air Attenuation coefficients [19, 20]

Frequency (Hz)	Air Attenuation ($\frac{Np}{m} \times 10^{-3}$)
125	0.056269
250	0.16419
500	0.33283
1000	0.56949
2000	1.2284
4000	3.7347

The absorption coefficients of the materials in 1/1 octave are specified based on Table (3). In order to consider air absorption for Sabin's and Eyring's formula as well as the numerical simulation, the coefficients of Table (4). have been used according to ISO 9613-1 standard [20]. After defining the surfaces and applying the boundary conditions, absorption and diffusion coefficients have been applied, the final model is shown in Fig.(3).
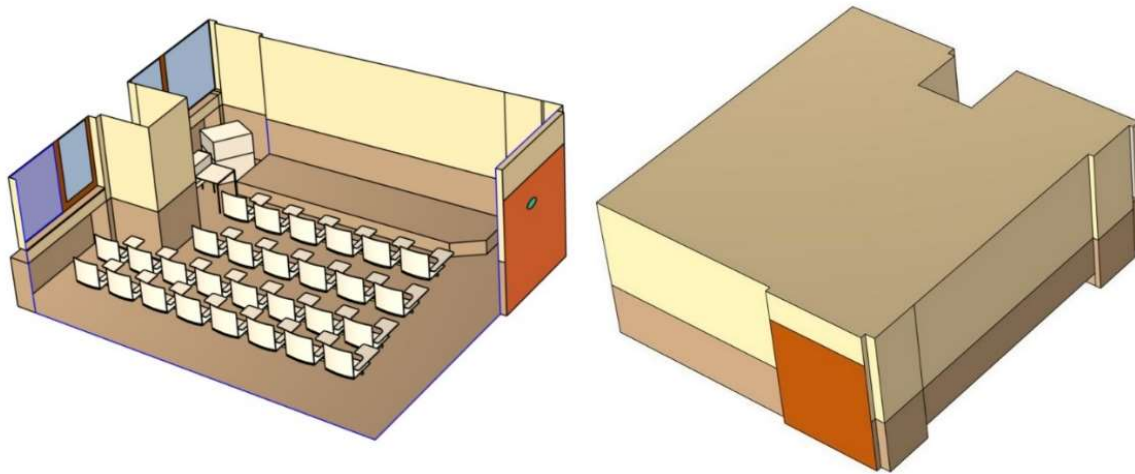

Fig. (3) The classroom model in COMSOL

The ray acoustic in the COMSOL software can calculate the reverberation time and other parameters related to the room acoustics. In this analysis, instead of solving the differential equation and using the finite element method, waves or rays are traced from the sound source, and when dealing with meshed surfaces, the relations related to the absorption, reflection and diffusion are applied to the rays and then they leave the contact points and continue to move. To this end, it is required to mesh the surfaces to define the boundaries of the room as illustrated in Fig.(4).
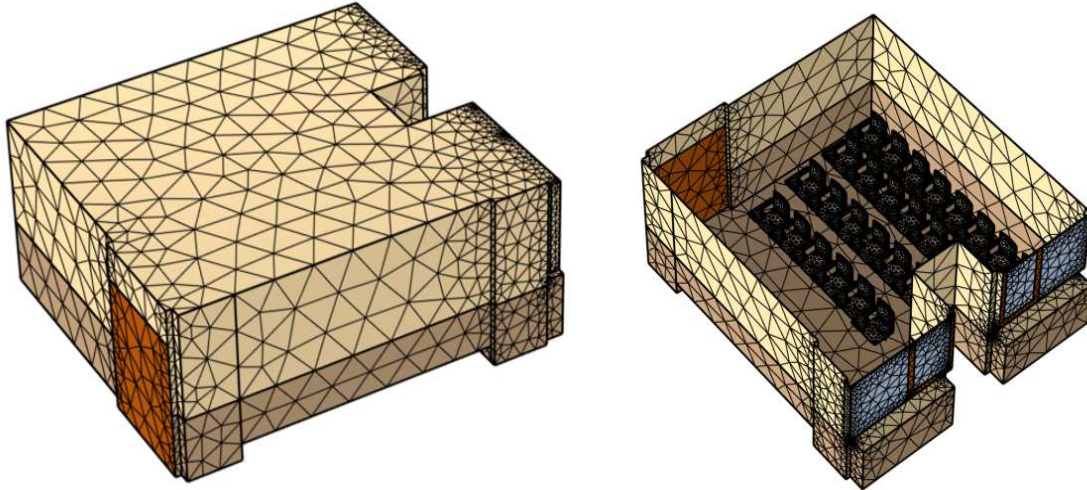
Fig. (4) Meshed model of the classroom.

In the ray acoustic analysis, the greater the number of rays to be analyzed, the higher accuracy can be expected; however, high number of rays increases the time of calculations, which is not desirable. The recommended number of rays in order to limit the impact response error to 1 dB in each time interval Δt, is given in Equation (4) [21].

$$N_{rays} = 4.34^2 \frac{V}{\pi r^2 c \Delta t} \tag{4}$$

where V is the room volume, r is the radius of the receiver and c is the speed of sound.

When a ray goes out of the defined geometry or when its power or intensity is less than a defined value, it is removed from the analysis to reduce the calculations. This threshold is defined in the "Ray Termination" option of the software. In this research, the geometric and power criteria are used in such a way that when the power of each of the rays is 60 decibels lower than the initial state, it will be terminated as shown in Equation (5) [21].

$$Q_{th} = \frac{P_0}{N_{rays}} \times 10^{-6} \tag{5}$$

where, P_0 is source power and N_{rays} is the number of released rays.

According to Table (5) [22], a minimum of six source-microphone combinations are required for achieving engineering accuracy. In this research, the six combinations are generated by using two locations for the source and three locations for the receiver.

Table 5. Minimum number of positions and measurements [22]

	survey	engineering	precision
Source-microphone combinations	2	6	12
Source-positions	≥1	≥2	≥2
Microphone-positions	≥2	≥2	≥3
No. decays in each position (interrupted noise method)	1	2	3

The positions of the sound sources and the receivers, respectively, are given in Figure (5) and Figure (6), considering a radius of 0.3 meters for the receivers in order to simulate the position of a person and considering the omnidirectional spherical source.
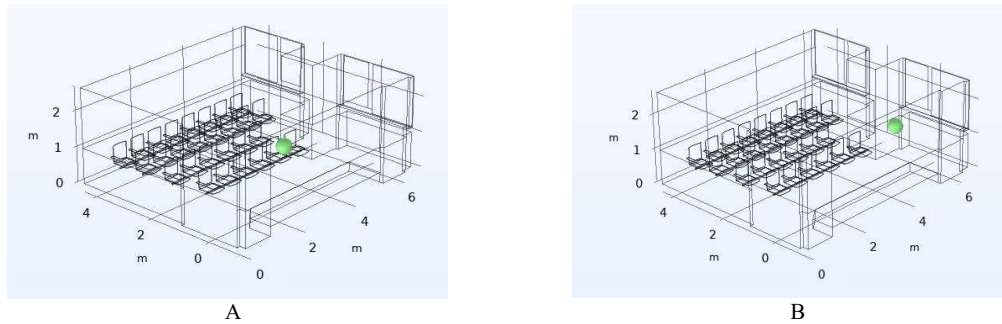

A   B

Fig. (5) Sound Sources Positions: A) first source; B) second source.
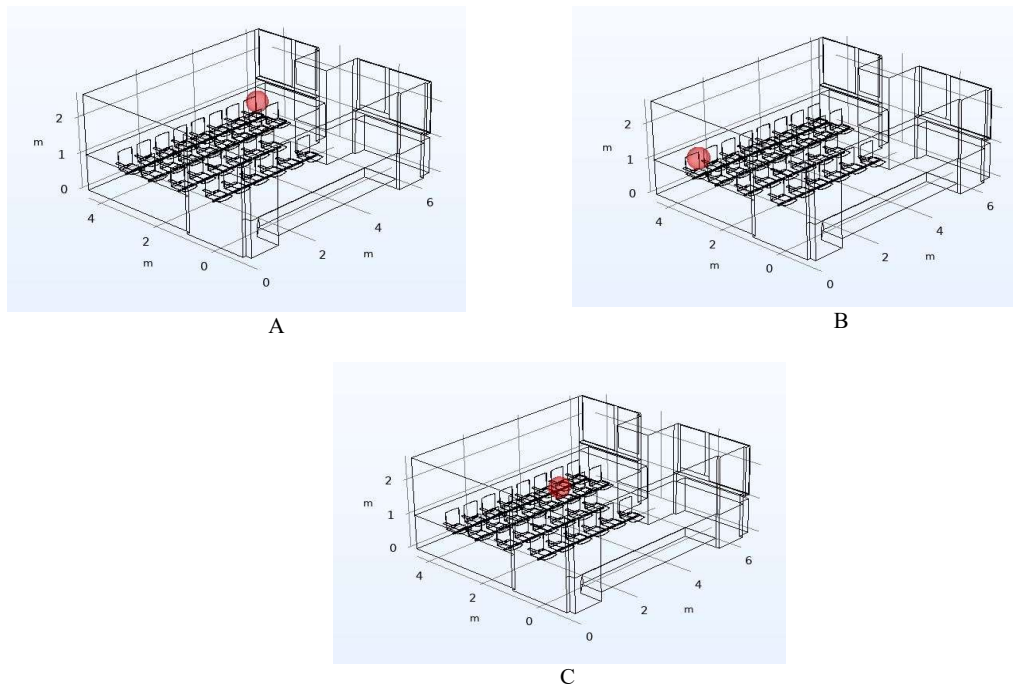

A   B

C

Fig. (6) Receiver positions: A) first receiver; B) second receiver; C) third receiver.

3. Experimental setup

To validate the results obtained from the simulation, as well as measure the classroom background noise based on ISO 3382-2 [12], experimental tests have been performed. In this measurement, the impulse response is used to obtain the decay curve and the reverberation time, and a one-minute sound has been recorded to obtain the background noise.

A class-1 microphone with a diameter of ½" with a nominal sensitivity of 38.9mV/Pa at a frequency of 250Hz is employed for the measurements. Furthermore, a calibrator with dual 94 and 114 dB sound pressure outputs is used to check the calibration of the measurement microphone. For data analysis, Dewesoft data acquisition is used to obtain the decay curve, reverberation time, and octave bands of the background noise. These instruments can be seen in Fig.(7)..

A

B

C

Fig. (7) A) Microphone; B) Calibrator; C) Data acquisition

In this research, two methods have been used to produce the impact sound: bursting a balloon and clapping hands. The measurement has been carried out with two types of sound sources described in six combinations of sound source and microphone according to the positions mentioned in the simulation section. Since the impact sound is not too loud relative to the background noise, RT_{20} is calculated, in which the sound level decay curve is checked in the range of 5 to 25 decibels lower than the initial sound, and then RT_{60} is obtained based on the RT_{20}. This process is done by the software, which is related to the assumption of linearity of the decay curve according to Equation (6).

$$RT_{60} = 3RT_{20} \qquad (6)$$

4. Results and discussion

In this section, the results of the simulations and field measurements, and a discussion about the agreement between the analytical, numerical and experimental results are presented.

4.1.Ray tracing

Ray tracing characterizes the paths and the way that rays move in simulations, which can be plotted for any frequency and at any time. In Figure(8), ray tracing is plotted at 2, 5 and 10 milliseconds for a frequency of 125Hz for source number one.
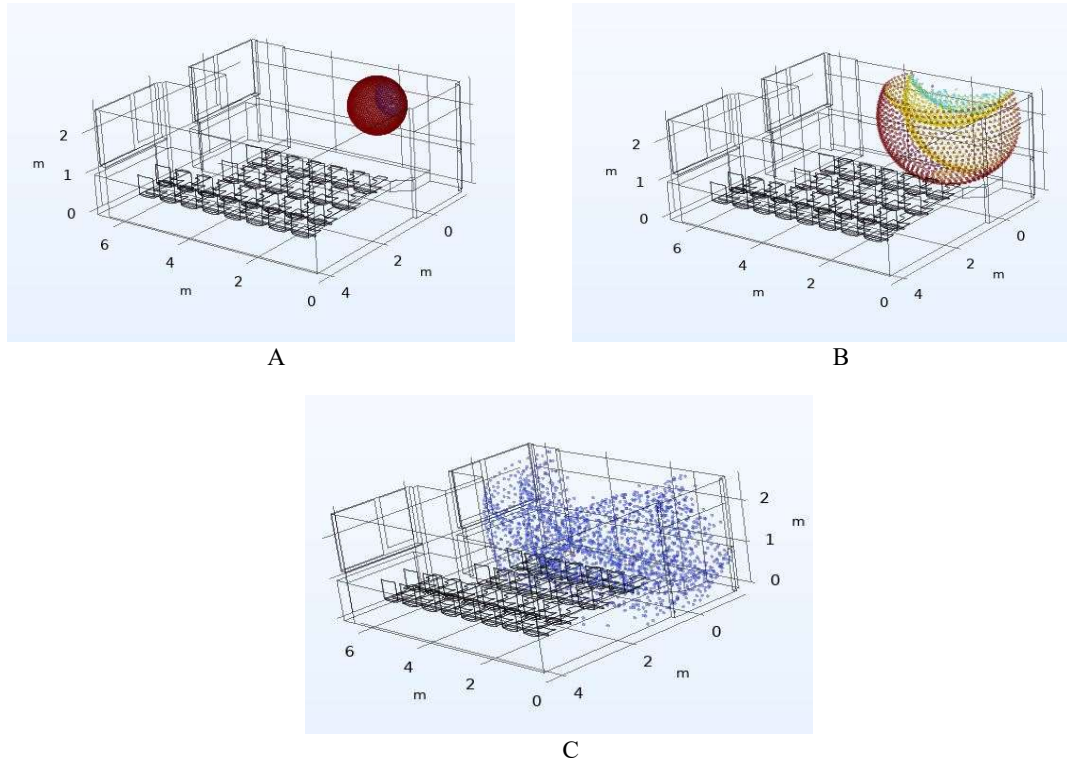
A

B

C

Fig. (8) A) 125 Hz ray tracing at 2ms; B) 125 Hz ray tracing at 5ms; C) 125 Hz ray tracing at 10ms.

4.2. Impulse response and reverberation times

In order to obtain the acoustic parameters of the class, it is required to obtain the impulse response curve. It can be drawn for each combination of sound source and receiver; thus, totally creates six graphs. As an example, the impulse response curve for source number one and receiver number one is depicted in Figure(9).

By obtaining the impulse response curves, it is possible to calculate the reverberation time (RT_{60}) for each combination of sound source and receiver (six combinations) and any octave band in the range of 125 to 4000 Hz. For example, the reverberation time curve related to the sound source and receiver number one along with the curves related to reverberation time prediction by Sabin's and Eyring's formula (Equations (1), (2), and (3)) are given in Fig. **(**10) that the theoretical results are in good agreement with the simulation results.
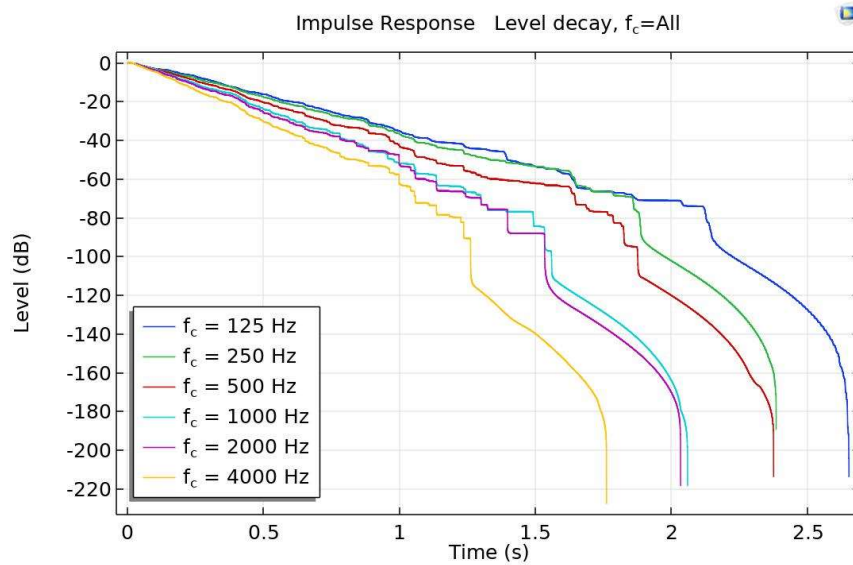
Fig. (9) Impulse response corresponding to the source and receiver number one.
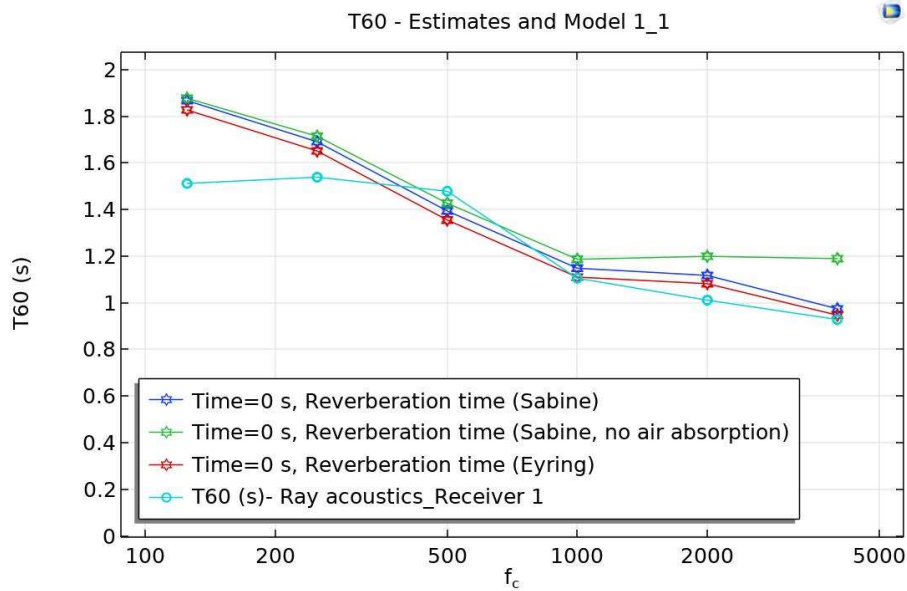

Fig. (10) Estimated and simulated reverberation time for the sound source and receiver number one.

In the experimental measurement, for the combination of the source and microphone number one with the balloon bursting case, the recorded sound and the curve of the pressure level decay over time are shown in Fig. (. Furthermore, the data related to the corresponding reverberation time are shown in Table(6).
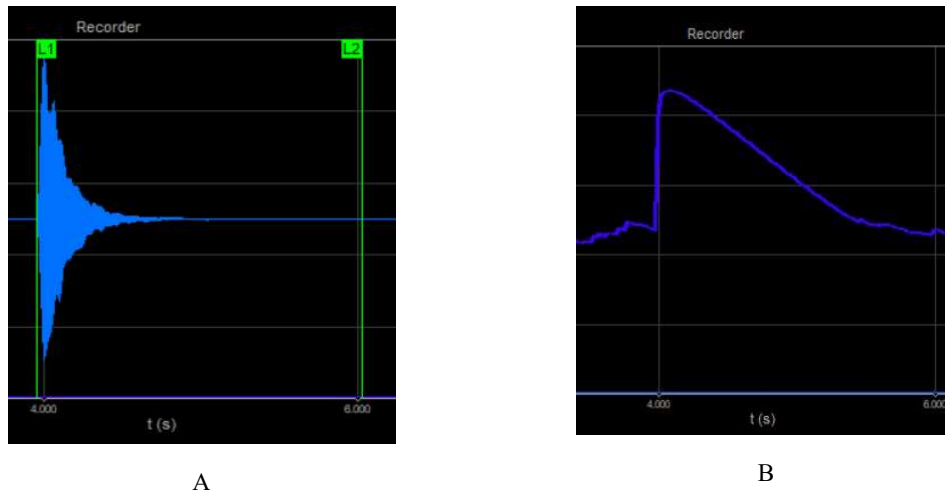
A

B

Fig. (11) Results of the sound source and microphone number one (balloon bursting case), A) time-wave sound; B) sound pressure level drop

In Table , the simulation results are averaged between six different sound source and receiver combinations. Also in Table 6 and Table 7, reverberation time measured by two impulse sound sources of balloon bursting and clapping are given. By comparing the results of simulation and field measurement, the results show the accuracy of the simulated model, except in special cases such as a frequency of 125Hz for the clapping source, which can be caused by the inappropriateness of this source in low frequencies as an impact source.

Table. (6) Reverberation time corresponding to the sound source and microphone number one (balloon bursting case)

Frequency (Hz)	$RT_{60}(s)$
125	1.746
250	1.076
500	1.119
1000	0.865
2000	0.834
4000	0.731

Table 7. Simulated and averaged reverberation time among six sound source and receiver combinations.

Frequency (Hz)	125	250	500	1000	2000	4000
RT_{60} (s)	2.07	1.65	1.36	1.07	1.03	0.94

Table 8. Measured reverberation time (balloon bursting type case)

Frequency (Hz)	125	250	500	1000	2000	4000
RT_{60} (s)	2.04	1.38	1.17	0.9	0.86	0.72

Table 9. Measured reverberation time (clapping hands case)

Frequency (Hz)	125	250	500	1000	2000	4000

RT_{60} (s)	2.29	1.51	1.09	0.92	0.83	0.81

4.3. Background noise

In order to measure the background noise, the sound of the class is measured three times for one minute. The result with A-weighting is given in Fig. (1).
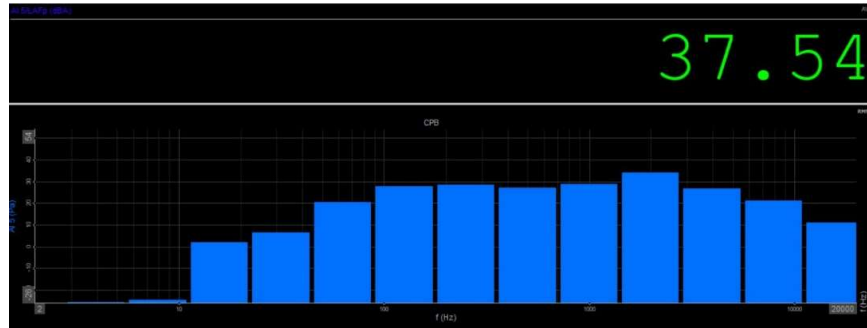

Fig. (1) One-minute sound background noise with A-weighting.

To compare the background noise with the standard values, the background noise measured in octave bands between 63Hz to 8000Hz with A-weighting is given in Table 8. It is about two decibels higher than the recommended value; however, it is acceptable according to the standard [1].

Table 10. Background noise

Frequency (Hz)	63	125	250	500	1000	2000	4000	8000	Overall
Avg. (dBA)	21.98	27.19	29.46	30.35	30.60	30.19	25.09	17.35	**37.29**

4.4. Frequency analysis and classroom modes

As a vibration system, the room has special acoustics modes and eigenfrequencies that are separate at low frequencies and can have a great impact on the frequency response. The modes are created when a sound wave propagates in the space so that reflected waves interfere and the sound field is reinforced. As a result of these modes, the frequency response curves have peaks at low frequencies, called resonance frequencies [23]. In case these modes are not controlled, as a result, they lead to acoustic problems in these frequencies.

The "Pressure Acoustics, Frequency Domain" module is used to solve and obtain the eigenfrequencies and modes of the room by introducing the geometry and specifying the number of necessary frequencies and the middle frequency [16]. For example, equal pressure levels of the mode corresponding to the frequency of 125.39Hz are shown in Fig. (13).
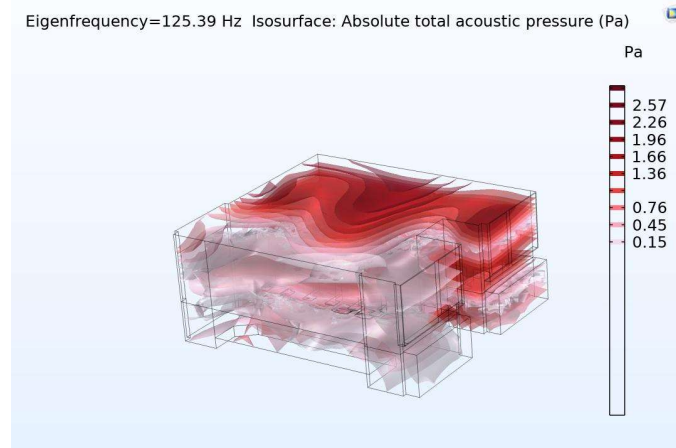
Fig. (2) Isosurface corresponding to the eigenfrequency of 125.39Hz.

4.5. Design and selection of acoustic treatment

In section 4.2, it was demonstrated that the current reverberation time is different from the standard value and it should be reduced to reach the recommended value. In order to reduce the reverberation time, and in general, the echoes inside the room, which is due to successive reflections, it is necessary to increase the absorption of the room. Adding absorbing surfaces (absorbers) on the reflective surfaces can adjust the acoustic treatment of the room. In addition, as shown in section 4.4, at low frequencies, acoustics resonances occur. For controlling the class modes and the high reverberation times related to low frequencies, it is required to install bass traps at the locations with high acoustic pressure, corresponding to the eigenfrequencies [1, 17].

Table 11. Limits on the A- and C-weighted sound levels of background noise and reverberation times in unoccupied furnished learning spaces [1].

Learning space	Greatest one-hour average a- and c-weighted sound level of exterior source background noise (dB)	Greatest one-hour average a- and c-weighted sound level of exterior-source background noise (dB)	Maximum permitted reverberation time for sound pressure levels in octave bands with mid-band frequencies of 500, 1000, and 2000 Hz (s)
Core learning space with enclosed volume ≤ 283 m^3 ($\leq 10000\ ft^3$)	35/55	35/55	0.6s
Core learning space with enclosed volume > 283 m^3 and $\leq 566\ m^3$ (> 10000 ft^3 and $\leq 20000\ ft^3$)	35/55	35/55	0.7s
Core learning spaces with enclosed volumes >566 m^3 ($>20000 ft^3$) and all ancillary learning spaces	40/60	40/60	No requirement

According to ANSI/ASA S12.60 [1], which introduces the criteria of acoustic performance, recommended reverberation time and background noise are given in Table 9. According to this standard, the reverberation time for the mid-frequencies of 500, 1000 and 2000 should be less than 0.6 seconds for a classroom with a volume below the 283 m^3. The frequency of

500Hz can be used as an index for the acoustic design of the classroom since the current reverberation time at this frequency has the largest difference from the desired value in the standard. In other references, the suggested reverberation time is between 0.6-0.8 seconds [17].

Table 12. Number of used panels/bass traps

Panel/Bass trap	Egg Crate (50 × 50 cm)	FlexiA	MD55	Azteka Diffuser	Super Bass 90	Mega Fuser
Number of panels	29	8	20	1	3	2

Several types of panels and bass traps, in different configurations, are examined by simulating in COMSOL software, and the best design is chosen in terms of reaching the desired reverberation time and minimum cost. According to the references, the efficiency of a sound-absorbing material can be affected by its distribution and pattern. For instance, the "Checkerboard Pattern" can improve efficiency because of the diffraction of sound energy around perimeters and more absorption provided by the exposed panel edges [17].
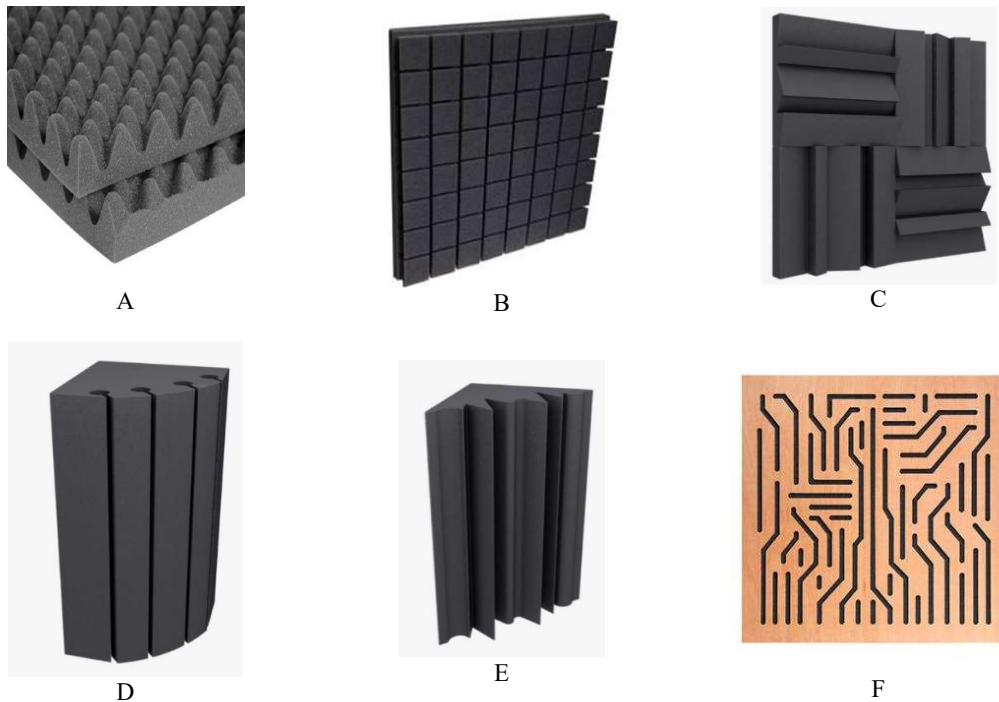

A   B   C

D   E   F

Fig. (14) Panels and bass traps: A) Egg crate; B) Flexi-A; C) MD55; D) Super Bass Trap 90; E) Mega Fuser; F) Azteka Diffuser.

Table 13. The absorption coefficient of panels and bass traps

Frequency (Hz)	Egg Crate (thickness 5.5 cm)	FlexiA	MD55	Azteka Diffuser	Super Bass 90	Mega Fuser
125	0.15	0.14	0.12	0.10	0.57	0.24

250	0.31	0.35	0.4	0.25	0.65	0.53
500	0.73	0.64	0.63	0.43	0.57	0.46
1000	0.9	0.78	0.7	0.65	0.47	0.39
2000	0.92	0.84	0.75	0.69	0.42	0.35
4000	0.91	1	0.9	0.75	0.41	0.34

The employed panels of the best design are shown in Fig. (14) and the number of panels and their properties are listed in Table 10 and Table 11, respectively. The configuration of the panels in the final design is depicted in Fig.(15). In this figure, blue panels are Egg Crate, green panels are FlexiA, purple panels are MD55, the orange panel is Azteka Diffuser, black bass traps are Super Bass 90 and green bass traps are Mega Fuser. The predicted reverberation time of the classroom is listed in Table14. By comparing the results of with those before the acoustic adjustment, it can be seen that the reverberation time in the simulation has decreased significantly. By comparing with the desired values in the standard [1], it can be seen that in the frequencies of 1000Hz and 2000Hz, the reverberation time has reached less than 0.6 seconds and there is a small difference (0.08 seconds) at the frequency of 500Hz.
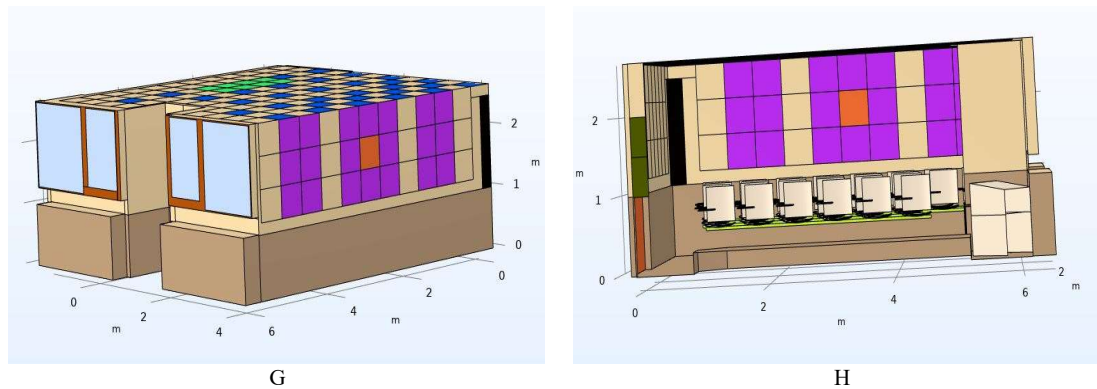

| G | H |

Fig. (3) Configuration of installed panels in the classroom

Table 1. Simulated and averaged reverberation time among six sound sources and receiver combinations after treatment.

Frequency (Hz)	125	250	500	1000	2000	4000
RT_{60} (s)	1.63	0.99	0.68	0.58	0.59	0.51

After installing the panels and bass traps in the classroom, as shown in Fig. (4, the parameters of the classroom were measured again and the results are summarized in Table 15 and Table 16. By comparing the measured results with the simulation results, it is clear that the reverberation time has decreased as expected. In addition, the measured values are a little lower than the simulation values. This mismatch in results is similar to the initial measurement stage, before modifying the room. Simplifications applied at the stage of modeling and the difference between the absorption coefficients used for the simulation and the real values, are the possible causes of the mismatch.

Table 2. Measured reverberation time after treatment (balloon bursting type case)

Frequency (Hz)	125	250	500	1000	2000	4000
RT_{60} (s)	1.52	0.74	0.62	0.49	0.42	0.37

Table 3. Measured reverberation time after treatment (clapping hands case)

Frequency (Hz)	125	250	500	1000	2000	4000
RT_{60} (s)	1.59	0.85	0.6	0.44	0.42	0.37

By comparing the obtained results with the recommended values (T, at 500 Hz frequency, the reverberation time has reached the recommended value of 0.6 seconds. At the frequencies of 1000Hz and 2000Hz, it has become less than the recommended value of 0.6 seconds. According to the application of the class and standard ASA/ANSI S12-60 [1], it is desirable and it can increase speech intelligibility. The reduction of the reverberation time for low frequencies is lower than the high frequencies. If the reduction for low frequencies is unsatisfactory, adding more bass traps is a possible solution.
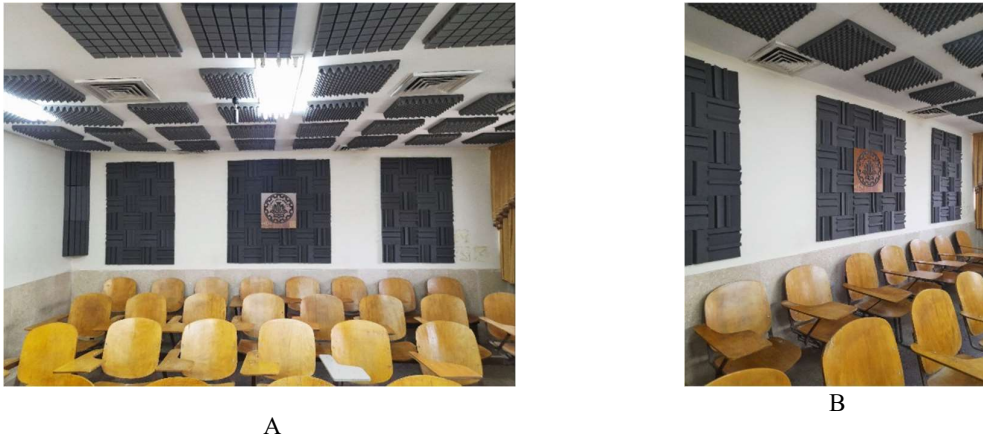

A

B

Fig. (4) Two views of the classroom after acoustic adjustment. Early reflections and speech intelligibility parameters

Reflections of the produced sound waves in the space are not perceived as a distinct repetition of the original sound wave if its delay and loudness do not exceed certain limits. Therefore, these reflections, also known as early reflections, just make the sound appear more extended and louder. Early reflections improve speech intelligibility in the space. The two parameters used to specify the early reflections are "Definition or Deutlichkeit (D_{50})" and "Clarity Index (C_{50})", which are presented in Equations (6) and (7) for the impulse response of the room, $g(t)$,[4]:

$$D_{50} = \frac{\int_0^{50ms}[g(t)]^2 dt}{\int_0^{\infty}[g(t)]^2 dt} \tag{6}$$

$$C_{50} = 10\log\left(\frac{\int_0^{50ms}[g(t)]^2 dt}{\int_{50}^{\infty}[g(t)]^2 dt}\right) dB \tag{7}$$

Another acoustical descriptor that is commonly used to indicate speech intelligibility is the "Sound Transmission Index (STI)" which is an objective measurement to predict speech intelligibility. It is based on the modulation transfer function (MTF)[4, 24].

Table 4. Recommended and averaged values of acoustical descriptors for speech intelligibility

Acoustic descriptor	Recommended value	Before treatment (Averaged value)	After treatment (Averaged value)
D_{50}	≥ 50	33.4	63
C_{50}	$\geq 0\ dB$	$-3\ dB$	$2.36\ dB$
STI	≥ 0.62	0.51	0.67

By calculating these averaged parameters before and after the corrections, Table 4 summarizes these averaged values alongside the recommended ones [13, 24]. As can be seen, all the parameters improved and fell within the recommended range, which indicates the improvement of the acoustical conditions for speech. Additionally, Fig. 17) reveals that after the treatment, speech intelligibility or syllable intelligibility reached over 90 percent, which is very suitable for communication [4, 17].
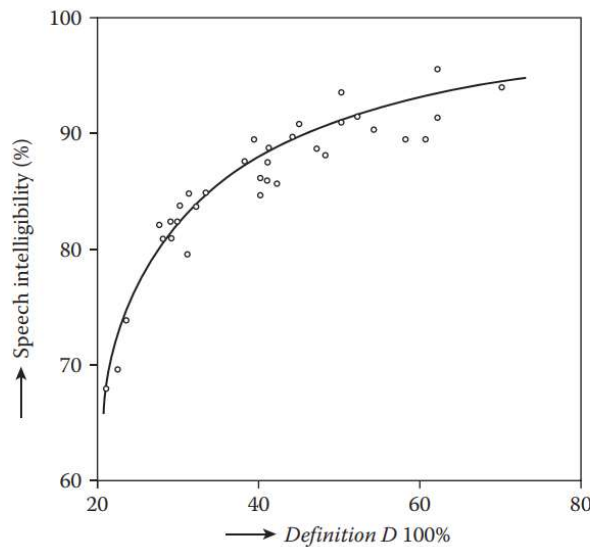

Fig. (5) Syllable intelligibility and definition relationship [4]

5. Conclusion

In this research, modeling and simulation of a classroom in the Department of Mechanical Engineering at the Isfahan University of Technology was done to obtain the acoustical treatment of the class and to modify it. The classroom was modeled in CATIA and by importing the geometry into the COMSOL software and applying the boundary conditions, acoustical simulation was performed using the ray tracing method. The reverberation time and modes of the classroom were obtained. To validate the simulation results, field measurements were conducted to experimentally check the classroom parameters according to ISO 3382-2 [12]. By comparing the results obtained from the field measurements with those of the simulation, and Sabin's and Eyring's theoretical relations, it was determined that the model is acceptable and can be used for the classroom acoustical design. The parameters

were compared with the recommended values in ANSI/ASA S12.60 [1], and by designing and simulation, absorption panels and bass traps were selected to be used to modify the classroom to reduce the reverberation time and improve speech intelligibility. After installing the panels and bass traps in the classroom, the acoustical parameters of the classroom were re-measured and compared with the designed values. The average reverberation time between two different sources at 500Hz frequency is reduced from 1.13 to 0.61 seconds, at 1000Hz from 0.91 to 0.47 seconds, and at 2000Hz frequency from 0.85 to 0.42 seconds. It has been found that it is in accordance with the initial purpose of the research, that is, to reach the recommended values of the standard. Acoustical descriptors improved as follows: D_{50} increased from 33.4 to 63, C_{50} increased from -3 dB to 2.36 dB and STI increased from 0.51 to 0.67. The result of these improvements translates to better speech intelligibility for the classroom as a learning space.

References

[1] A. Standard, ANSI/ASA S12. 60-2010/Part 1 American National Standard Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools, Part 1: Permanent Schools, in: USA: Acoustical Society of America, 2010.

[2] M. Hodgson, Rating, ranking, and understanding acoustical quality in university classrooms, Journal of the Acoustical Society of America, 112 (2002) 568-575.

[3] L. Nijs, M. Rychtáriková, Calculating the optimum reverberation time and absorption coefficient for good speech intelligibility in classroom design using U50, Acta Acustica united with Acustica, 97 (2011) 93-102.

[4] H. Kuttruff, Room acoustics, sixth edition, 2016.

[5] ASA, Classroom Acoustics 1: A resource for creating learning environments with desirable listening conditions, in, 2003.

[6] W. Yang, M. Hodgson, Acoustical evaluation of preschool classrooms, Noise Control Engineering Journal, 53 (2005) 43-52.

[7] A. Astolfi, V. Corrado, A. Griginis, Comparison between measured and calculated parameters for the acoustical characterization of small classrooms, Applied Acoustics, 69 (2008) 966-976.

[8] H.S. Awad, H.H. Farag, M.A. Hanafi, D.S. Taha, Architectural acoustics in educational facilities: An empirical study on University Classrooms in Egypt, in: Proceedings of Meetings on Acoustics, 2012.

[9] BB93, Building Bulletin 93: acoustic design of schools - performance standards, in, 2003.

[10] R. Pääkkönen, T. Vehviläinen, J. Jokitulppo, O. Niemi, S. Nenonen, J. Vinha, Acoustics and new learning environment - A case study, Applied Acoustics, 100 (2015) 74-78.

[11] F. Fantozzi, M. Rocca, N. Spinelli, Assessment of reverberation times in university classroom: Comparison between analytic formulae, software simulations and measurements, in: Building Simulation Conference Proceedings, 2019, pp. 10-17.

[12] ISO, ISO 3382-2:2008 Acoustics — Measurement of room acoustic parameters — Part 2: Reverberation time in ordinary rooms., in, 2008.

[13] D. Russo, A. Ruggiero, Choice of the optimal acoustic design of a school classroom and experimental verification, Applied Acoustics, 146 (2019) 280-287.

[14] A. Prodeus, M. Didkovska, Objective Assessment of Speech Intelligibility in Small and Medium-Sized Classrooms, in: 2020 IEEE International Conference on Problems of Infocommunications Science and Technology, PIC S and T 2020 - Proceedings, 2021, pp. 27-32.

[15] A.K. Abraham, M.S. Ravishankar, A case study of acoustic intervention in classrooms, Building Acoustics, 28 (2021) 293-308.

[16] COMSOL Multiphysics Acoustics Module User's Guide, version 6.0 2021.

[17] M.D. Egan, Architectural Acoustics, J. Ross Pub., United Kingdom, 2007.

[18] R.F. Barron, Industrial noise control and acoustics, CRC Press, 2002.

[19] T.J. Cox, P. D'Antonio, Acoustic Absorbers and Diffusers, in, Spon Press,(2003 or 2004), 2009.

[20] I. Standard, ISO 9613-1:1993 Acoustics — Attenuation of sound during propagation outdoors — Part 1:, in: Calculation of the absorption of sound by the atmosphere, 1993.

[21] M. Vorlaender, Auralization. Fundamentals of Acoustics, Modeling, Simulation, Algorithms and Acoustic Virtual Reality, 2008.

[22] ISO, Acoustics — Measurement of sound insulation in buildings and of building elements — Part 5: Field measurements of airborne sound insulation of façade elements and façades, in, 1998.

[23] M. Kleiner, J. Tichy, Acoustics of small rooms, 2014.

[24] IEC, IEC 60268-16: Sound system equipment—Part 16: Objective rating of speech intelligibility by speech transmission index, in, 2011.