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Investigation of the Acoustics Performance of the University's Lecture Rooms by using Economical and Feasible Design Improvement Strategies

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ABSTRACT
Students encounter difficulties in speech comprehension because of unfavorable classroom acoustics conditions, which subsequently affect their cognitive development and academic performance. Therefore, optimal listening conditions are required to ensure that listeners perceive and recognize speech effectively. This invites numerous studies to explore plausible acoustic interventions and treatments as an initiative to remediate the issue. Thus, this study seeks to a) identify the actual acoustic conditions in two (2) classrooms in the Faculty of Built Environment, Universiti Malaysia Sarawak, and b) establish economical acoustic design strategies for future improvements. This quantitative study embarks on on-site acoustic measurements to evaluate the reverberation time and background noise level of the selected classrooms. The data from the on-site measurement is applied for 3D model verification for the simulation process. The establishment of plausible design treatment alternatives is further analyzed through simulation using ODEON software. The simulation process yielded the effects of a) material surface treatment and b) sound field amplification systems on several acoustic parameters. The findings reveal that the surface treatment using low-cost material and the installation of sound field amplification significantly enhanced the classroom acoustic quality and are feasible to be implemented for future improvements.

1.0 INTRODUCTION

Conducive classroom surroundings are essential to facilitate effective teaching and learning processes. A conducive learning environment is influenced by a variety of environmental factors, including lighting, thermal comfort, and indoor air quality; but the most important factor has always been acoustic conditions (Palau & Mogas Recalde, 2019). Most of the teaching and learning practices involve auditory learning, which requires students to use their sense of hearing effectively to articulate the information delivered by the teachers. According to the American Speech-Language-Hearing Association (2005) and Rosenberg et al. (1999), approximately 45-70% of the student's time spent in classrooms involves speech comprehension. Classrooms with poor acoustic quality degrade students' learning attainments, which involve reading and listening, especially for young children. Students of younger age groups have yet to develop auditory sensitivity to formant and voice onset times compared to adults (Astolfi et al., 2019). According to Cediel and Neira (2014) in a poor acoustic environment, teachers are susceptible to vocal dysfunction due to an involuntarily increased voice level (Lombard effect). Therefore, to improve students' learning development and teachers' well-being, good acoustic quality in a classroom is required.

Referring to classroom acoustics guidelines established by American National Standards Institute (2010) and Building bulletin 93 (2015), a classroom with optimal acoustics performance must achieve reverberation time of less than 0.8 seconds and background noise not exceeding 35dB(A). However, due to language differences, the criteria for other acoustical factors in each country vary significantly. The acoustic requirements in Chile, Norway, Denmark, and other countries, particularly for reverberation time, are set at 0.6 seconds. Meanwhile, 0.8 seconds of reverberation time has been adopted as the benchmark for Germany, France, Italy, and China (Park & Haan, 2021). In some countries like South Africa and India, a standard guideline for classroom reverberation time has yet to be established (Van Reenen & Karusseit, 2017) (Gupta, 2015) and this includes Malaysia.

Several acoustic parameters require serious attention while designing a classroom. The main four prominent factors to be acknowledged for classroom acoustic design are reverberation time (RT) (Sarlati et al., 2014) background noise (Mogas et al., 2021) and Speech Transmission Index (STI) (Escobar & Morillas, 2015). According to Picard and Bradley (2001), and Nijs and Rychtarikova (2011), speech quality in classrooms has been reported to deteriorate when reverberation times exceed 0.5 or 0.6 seconds. This condition is due to the masking effect of late reflections on the direct and early sound produced and consequently degrades speech intelligibility.

Speech intelligibility refers to the effectiveness of speech communication measured. This is measured through the percentage of word comprehension. The prediction of speech intelligibility of the listeners in a classroom can be quantified by using STI. The STI value varied from "0" to "1" and represented by the quality rating scale from "bad", "poor", "fair", "good", and "excellent". It was found that the STI value is directly influenced by the reverberation time, signal-to-noise ratio (SNR) (Houtgast, 1980) and excessive noise level (Peng & Wu, 2018).

Excessive amount of ambient noise levels is more concerning than improper room acoustic quality (Bradley & Sato, 2008). Most of the background noise in a classroom comes from outdoor activities, learning activities inside the classroom, and electrical appliances inside and outside the classroom. According to a study conducted by Haron et al. (2021), the ambient noise level in a school classroom in Malaysia surpassed 70 dBA as a result of heavy traffic during peak hours. Classrooms equipped with open louvre windows facilitate the easy dissipation of traffic noise into the classrooms. Hodgson et al. (1999) found that the noise level recorded in unoccupied and occupied classrooms was between 39-42 dB and 40-45 dB respectively. The value depicts that the acoustic conditions of the classrooms were affected by the noise generated by the ventilation system (Mydlarz et al., 2013). As a result of the ventilation system's operation, both STI and SNR values were reduced (Longoni et al., 2017).

The acoustic quality of a particular space is influenced by a few factors namely, the surface material, background noise, room volume, and so forth. According to previous studies, the selection of surface material plays a significant role in producing an ideal acoustic quality in a classroom. Using materials with higher reflective properties will create excessive sound reflection and thus more reverberant conditions. According to

Zhou et al., (2021), using high-absorptive materials for ceilings and walls remarkably reduced the reverberation time of a classroom. Apart from that, employing adequate absorbers in an enclosed space managed to reduce the background noise by 5 dB.

The STI in the classroom can be enhanced by using suitable absorptive materials, especially at frequencies that are important for speech intelligibility (Eldakdoky & Elkhateeb, 2017). Besides that, the suitable configuration of absorptive material must be clearly indicated to achieve optimal reverberation time (Cucharero et al., 2019) and STI (Li & Xu, 2022). Based on Ene and Catalina (2021), the STI value was improved by installing absorptive materials on rear and sides of the classroom's wall.

Various studies that emphasized surface treatment in classrooms have been conducted in the past. Arvidsson et al. (2020) conducted surface treatment by employing a 40 mm thick glass wool product as a treatment for both the ceiling and walls. The glass wool was put in a suspended manner, attached to both the original ceiling and the wall. The treatment was found to have a substantial effect on reducing the RT by 0.7 seconds, 0.6 seconds, and 0.3 seconds at frequencies of 500 Hz, 1000 Hz, and 2000 Hz, respectively. In their study, Peng et al. (2020) examined the impact of employing a mineral fiber acoustic ceiling on RT and STI in two classrooms. A 15 mm mineral fiber acoustic ceiling, with a noise reduction coefficient (NRC) of 0.6, was placed on the ceiling surface. It was installed with back cavities of 535 mm and 335 mm. The findings demonstrated a significant decrease in RT in both classrooms, with reductions of 0.65 s and 0.61 s, respectively. Furthermore, the STI experienced a substantial enhancement following the treatment, with Classroom A's score increasing from 0.55 to 0.74 and Classroom B's score increasing from 0.58 to 0.75.

The building material's price hike has become a global issue, and it has gotten worse due to the recent pandemic. As stated by Chew (2021), the skyrocketing cost of building materials has resulted in an increase in construction costs of up to 20%. The same trend was observed for acoustic materials on the global market. According to Statista Research Department (2022), the current price of acoustic and thermal materials tremendously increased up to 155.9% from 2015. Thus, affordable acoustic treatment alternatives are essentially required to accommodate the needs in establishing acoustically conducive learning spaces.

There is no doubt that a significant number of global studies have been undertaken on surface treatment for enhancing acoustic performance. However, most of the suggested remedies relied on commercially available absorptive materials, which are less economically viable. An inquiry into the use of cost-effective materials for surface treatment is necessary to achieve optimal acoustic conditions for students and teachers while minimizing expenses.

Therefore, the purpose of this study is to evaluate the impact of potential low-cost treatment strategies on acoustic conditions, particularly the RT and STI of lecture rooms for future improvements. This study can be used as a reference by end users and organizations in offering cost-effective design solutions for creating acoustically favorable learning environments.

2.0 METHOD

Located in northwest Borneo Island, Universiti Malaysia Sarawak (UNIMAS) is one of the public universities in Malaysia and was established in 1992, as presented in **Figure 1**. The educational facilities were built in 2004 in accordance with a contemporary design concept. Initially, the building was known as the External Laboratory Complex, operated by the Faculty of Resource Science and Technology (FRST), and all facilities were dedicated to lab experimental purposes. Later, the building was refurbished to accommodate the administration as well as state-of-the-art teaching and learning facilities for the newly established faculty, Faculty of Built Environment (FBE). Two (2) lecture rooms, namely QS Studio 2 and QS Studio 4, located at the FBE, UNIMAS were selected for the acoustics evaluation as shown in **Figure 2**.

The measurement was conducted during end-semester breaks to avoid any interference from students' activities within the building area. The lecture rooms are exclusively allocated to students enrolled in the Quantity Surveying Program, for the purpose of lectures and studio work. The building is encompassed by and is seamlessly integrated with the natural surroundings, rendering it suitable for educational activities with minimal environmental noise disruption. The lecture rooms are situated at a considerable distance from the adjacent road, resulting in less vehicular congestion. Therefore, it is essential to investigate the acoustic conditions of the newly refurbished learning facilities that involves a transformation in room designation to ensure a conducive learning environment can be provided. The evolving architectural characteristics and functions necessitate a comprehensive evaluation and intervention of the acoustic conditions in learning spaces to align with the current lecture-based teaching and learning approach.

This study has potential limitations. The on-site acoustic evaluation process focused on measuring the reverberation time (RT) and background noise level (BNL) of the lecture rooms. These two (2) parameters are vital to creating acoustically conducive learning spaces with an ideal speech intelligibility quality. Despite the potential inclusion of certain parameters, such as speech clarity (C50) in the acoustic evaluation, their exclusion from the present study is justified by equipment limitations. These parameters may be revisited in subsequent investigations. Besides that, the current study only incorporates data from mid- to high-frequency regions. Due to the unavailability of an omnidirectional speaker, the balloon burst method was used. Although the balloon burst method is one of the best alternatives to an omnidirectional speaker, there are some limitations, as the sound produced at lower frequencies deviates and does not meet the standard criteria. While low-frequency regions are undoubtedly relevant in many classroom activities, this study specifically focuses on mid- to high-frequency regions. This emphasis aligns with the ANSI/ASA S12.60 standard requirements, which prioritize lecture-based activities, as well as the unavailability of an omnidirectional speaker.

The results obtained from on-site measurements were used in simulations using ODEON acoustics software to develop several treatment strategies for the lecture rooms. Figure 3 illustrates the details of the research activities involved in the current study. The details of both lecture rooms are presented in **Table 1**.

Figure 1. Location of the Faculty of Built Environment, UNIMAS. (Source: google maps)

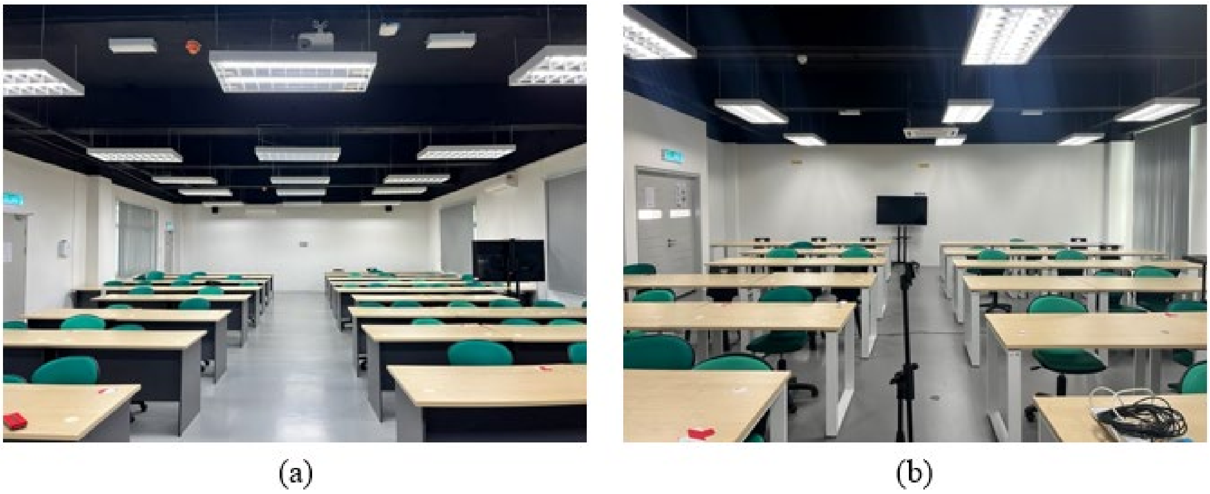

Figure 2. Interior view of (a) QS Studio 2 and (b) QS Studio 4 classrooms

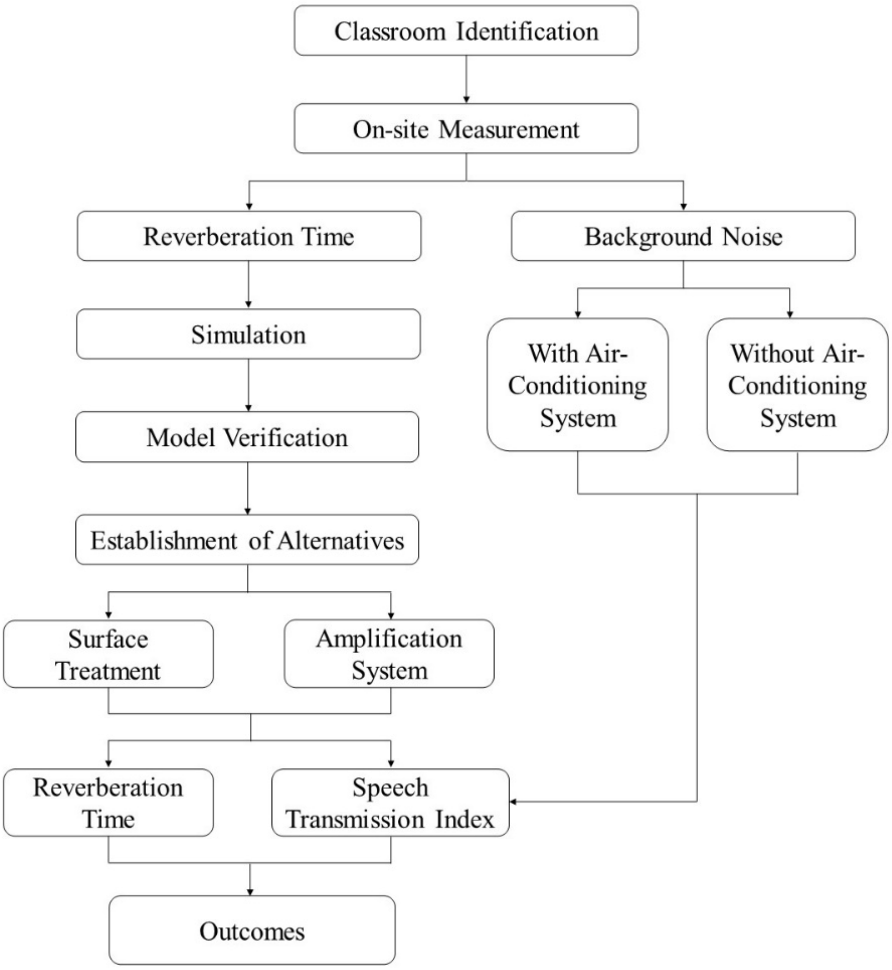

Figure 3. Flowchart of research activities

Table 1. Detail summary of room surface materials for QS Studio 2 and QS Studio 4

Components	Surface Materials	Surface area (m^2)		Volume (m^3)	
		QS Studio 2	QS Studio 4	QS Studio 2	QS Studio 4
Floor	Painted and glazed concrete	124.3	105.5	552.1	409.3
Wall	Painted plastered brick wall	151.9	117.6		
Ceiling	Painted smooth concrete	125.6	93.4		
Beam	Painted smooth concrete	74.8	52.6		
Column	Painted smooth concrete	8.6	12.3		
Door	Single leaf hollow door / Solid door	3.8	3.8		
Window	Aluminium casement window with vertical blind	21.3	21.2		
Table	Laminated chipboard	98.5	30.6		
Whiteboard	Glossy surface whiteboard	3	3		

2.1 Measurement of background noise level (BNL) and noise criteria (NC)

To evaluate the background noise level and continuous equivalent sound levels, LAeq was measured in unoccupied lecture rooms under two different conditions: 1) with the operation of air conditioning system and 2) without the operation of the air conditioning system. Prior to the measurements, all windows and doors were fully closed, which represented the actual learning environment. Six receiver locations representing the student's position were determined as shown in **Figure 4**. At every receiver location, the BNL was measured for 2 minutes, and the data was recorded every second. The sound pressure level was recorded using a Cirrus CR:171B sound level meter positioned 1.2 meters from the floor level (the student's ear level). The average A-weighted sound pressure level for both lecture rooms was calculated, ranging from 63 Hz to 8000 Hz. Noise criteria curves (NC) for each lecture room were obtained from the sound spectrum of the maximum sound level measured.

2.2 Measurement of reverberation time (RT)

The balloon burst method was employed for RT evaluation. Due to the unavailability of omnidirectional speakers, the balloon burst method was chosen for the study. Certain studies using balloon burst method demonstrated good correlation results when compared to expected RT outcomes (Rusiana et al., 2015), particularly for reverberant and large room (Jambrosic et al., 2008). The balloon method is one of the most reliable and affordable alternatives for the omnidirectional source, as it fulfills the directivity requirements of omnidirectional speakers at mid- to high frequency. However, at lower frequencies, the directivity of sound produced from the balloon deviates and does not meet the standard requirement (Papadakis & Stavroulakis, 2019). Therefore, only RT results ranging from 500 Hz to 8000 Hz were considered for verification and simulation processes.

Several researchers had adopted balloon burst method for RT measurement in their study. For instance, a study conducted by Rabelo et al. (2014) had employed balloon burst method to determine the RT condition of classrooms in Brazil. For RT measurement, the same location of sound source and receivers used in BN measurement was utilized. A sound source using a 75-cm-circumference balloon was placed 1.7 meters from floor level at the lecturer's teaching position. Six (6) receiver points were initially identified, and a Blue Solo 01dB sound level meter was placed at 1.2 meters from floor level at each pre-determined location. The location of the sound source and receivers are displayed in **Figure 4**. The RT (T30) data was analyzed from recorded sound impulses from balloon popping using dBBati32 software, which was connected to a Blue Solo 01dB sound level meter. For each receiver point, the procedure was repeated twice. Due to the incapability of balloon to produce low frequency region, the reverberation time results were captured for frequencies ranging from 125 Hz to 8000 Hz. The equipment configuration schematic drawing can be referred to in Figure 5.

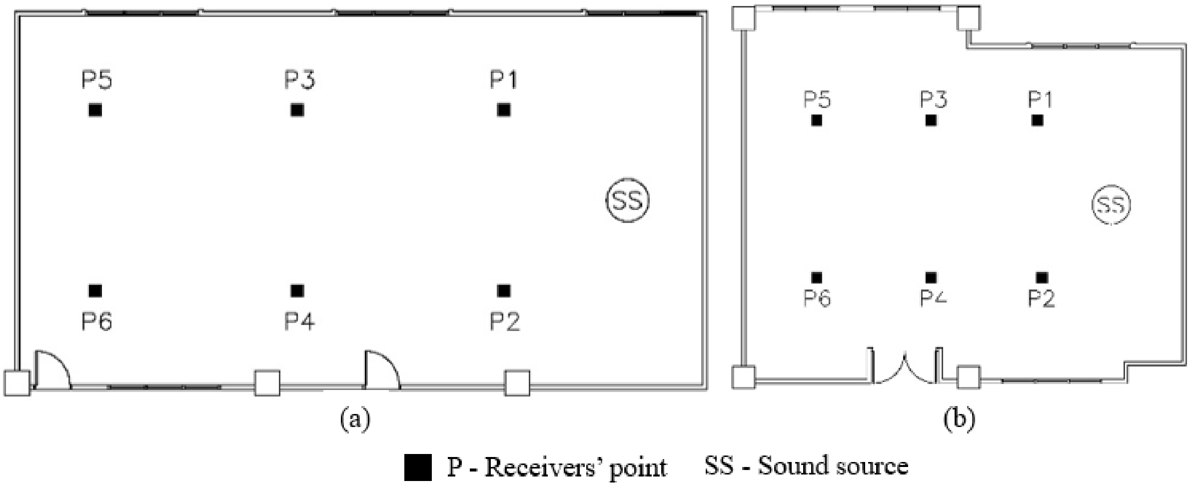

Figure 4. Sound source and receivers' location for the classroom (a) QS Studio 2 and (b) QS Studio 4

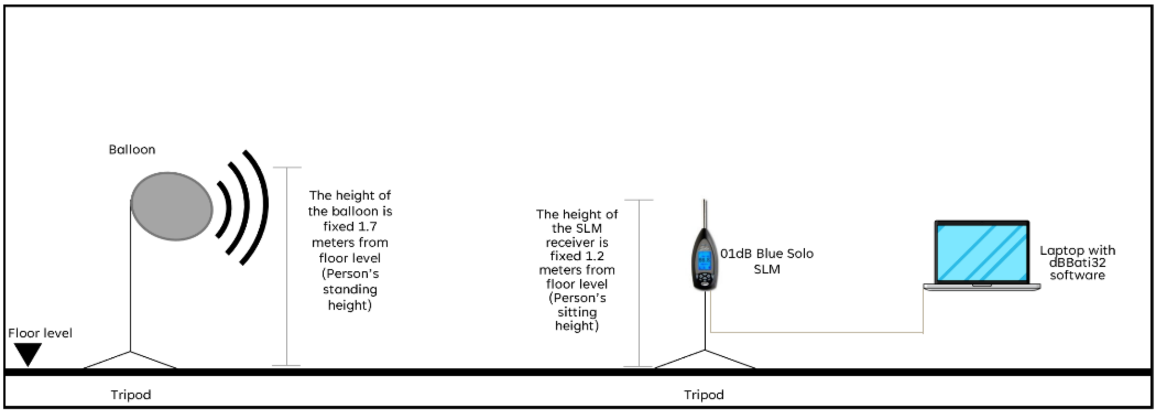

Figure 5. Schematic drawing of equipment configuration for RT measurement

2.3 3D modelling and verification

The 3D models for both lecture rooms were produced using Sketchup Pro® software before the verification process, as shown in Figure 6. According to Jalil et al. (2019), reduction of surface areas of about 80% for ODEON simulation model simplification is acceptable. Nevertheless, the percentage of surface reduction varied according to some factors that might affect the validity of the results such as individual modelling techniques, model settings in the simulation software, and the accuracy of scattering as well as the absorption coefficient of the materials. After the 3D model for the lecture rooms was completed, the model verification process was carried out using ODEON room acoustic software Version 17. The verification process ensured the model's validity and consistency with the data obtained from on-site measurements of the lecture rooms. Room parameters, material selection, and the sound source and receivers' locations were accurately configured according to on-site measurements. The 3D model created required verification to ensure the geometry was free from errors. The verification was made by analyzing water tightness using the 3D investigate Rays function. Before the simulation work began, the impulse response length and the number of late rays were determined using the quick estimate function in ODEON. For this study, the model verification process was performed by comparing the reverberation time between the on-site and simulated results. For engineering-type accuracy, the relative difference between two sets of reverberation time data must be less than 10%. The simulation work for acoustic treatment alternatives commenced after the relative difference in RT results complied with the standard requirement.

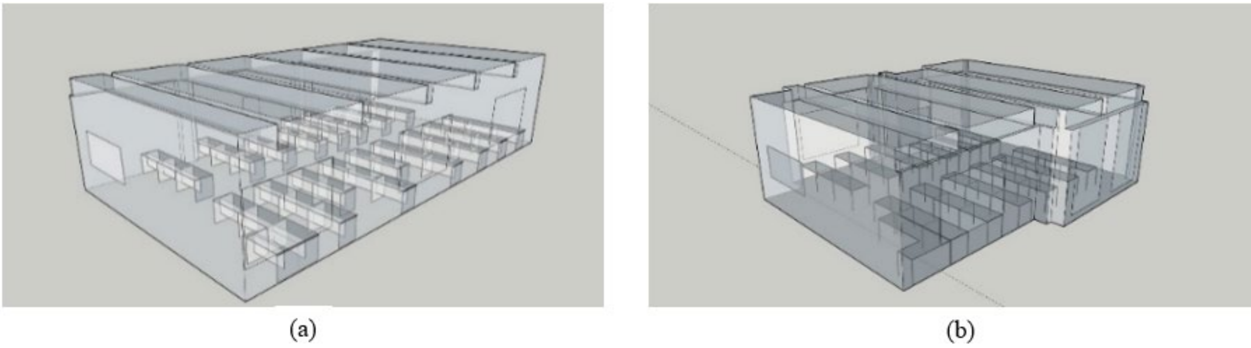

Figure 6. 3D modelling perspectives of (a) QS Studio 2 and (b) QS Studio 4

2.4 Simulation works for acoustics treatment alternatives

The simulation focused on the effect of surface treatment and the installation of sound amplification systems on the lecture rooms' acoustic conditions. Modifications to the surface materials involved ceilings, walls, and windows using low-cost materials, as shown in **Figure 7**. Seven (7) low-cost treatment alternatives (M1 – M7) and one (1) commercial treatment (M8) were configured and proposed for future reference and comparison. The RT data of 1/1 octave band settings from 125 Hz to 8000 Hz were recorded and analyzed further. The detailed configuration for surface treatments is presented in **Table 2**. In a prior investigation conducted by Abdullah et al. (2020), the ODEON software was utilized to implement acoustic improvements in university classrooms located in Malaysia. The simulation incorporates gypsum board and perforated plywood as materials for treating the walls and ceilings. For the present study, the corkboard was affixed directly to the wall, while the velvet curtain was positioned above the hanging lighting fixtures with an 880 mm gap from the original ceiling level to prevent any disturbance in the distribution of light. The fabric material was placed over the wire-rope cable, which was securely attached to the side walls, resulting in a curved shape. The influence of sound amplification systems on the speech transmission index (STI) was determined by establishing four (4) speakers that were positioned at the front and rear of the lecture rooms, as illustrated in **Figure 8**. A natural raised sound source (ANSI_RAISED_SPEECH_ NATURAL.SO8) was used for the simulation. The details of sound power across each frequency are shown in **Table 3**. For STI evaluation, the input of background noise was required. Two different background noise conditions, with and without the operation of the air conditioning system, were used to identify the effect on STIs. The STI results obtained for amplified and non-amplified lecture rooms were compared and analyzed.

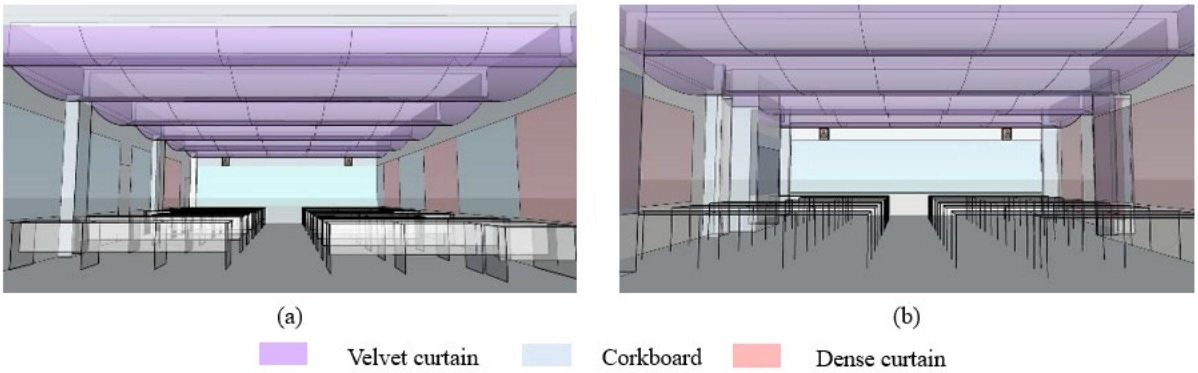

Figure 7. Acoustic treatment areas based on different components in the (a) QS Studio 2 and (b) QS Studio

Table 2. Summary of acoustic treatment alternatives for the lecture rooms

Treatment	Affected Surface Area	Surface material	Absorption Coefficient (α)	Surface area (m^2)		Approximate surface covered (%)	
				QS Studio 2	QS Studio 4	QS Studio 2	QS Studio 4
M1	Wall	25mm corkboard	0.4	46.8	29	31	25
M2	Ceiling	Velvet curtain	0.35	143.3	107.6	100	100
M3	Window	Dense curtain	0.35	21.3	21.2	100	100
M4	Ceiling + Wall	Velvet curtain + 25mm corkboard	0.35 & 0.4	190.1	136.6	62	58
M5	Ceiling + Window	Velvet curtain + Dense curtain	0.35 & 0.35	164.6	128.8	100	100
M6	Wall + Window	25mm corkboard + Dense curtain	0.4 & 0.35	68.1	50.2	39	36
M7	Ceiling + Wall + Window	Velvet curtain + 25mm corkboard + Dense curtain	0.35, 0.4 & 0.35	211.4	157.8	65	62
M8	Ceiling + Wall	Classic Tone panel + Fabric panel broadband	0.85 & 0.95	143.8	110.3	62	58

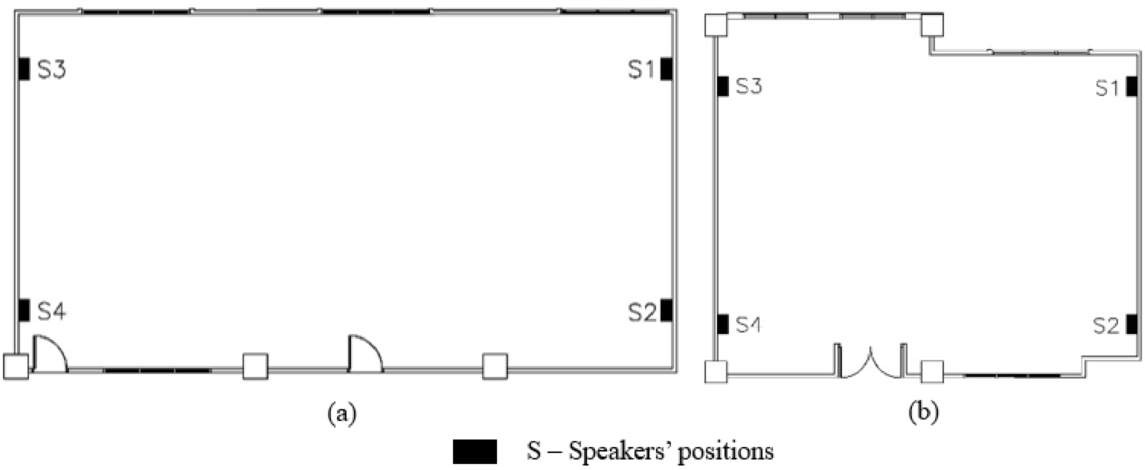

Figure 8. Speakers' location in the (a) QS Studio 2 and (b) QS Studio 4

Table 3. Details of ODEON sound source

Frequency (Hz)	63	125	250	500	1000	2000	4000	8000
Sound power (dB)	48	59	69.5	74.9	71.9	63.8	57.3	48.4

3.0 RESULTS

3.1 On-site measurement

3.1.1 Background noise level (BNL) and noise criteria (NC)

For background noise and noise criteria measurement, six similar locations to reverberation time measurement were computed and averaged. This study specifically omits the assessment of noise levels outside and instead concentrates solely on the ambient noise within, with the aim of examining the effects of both environmental noise and mechanical ventilation noise in lecture rooms. A continuous equivalent sound pressure level, LAeq were recorded for 2 minutes with 1 second interval time. During the measurement, the lecture rooms were 1) unoccupied 2) closed doors and windows and 3) with and without air-conditioning systems. The results indicate that the ambient noise for both classrooms without air-conditioning system are lower than the maximum requirement of 35 dB(A) established by American National Standards Institute (2010) and Building bulletin 93 (2015). This is resulted from the fact that the classrooms are located far from the main road and surrounded by a natural setting. However, the LAeq increased from 28.8 dB to 53.4 dB for QS Studio 2 and from 25.6 dB to 55.5 dB for QS Studio 4 when the air-conditioning system was turned on. This shows that the noise generated from ventilation system was the main source of the BNL increment.

Despite the establishment of legislation regarding background noise in classrooms, most learning spaces did not satisfy the recommended requirements. The average background noise level observed in school classrooms in Colombia was 73.2 dB, as determined by a measurement conducted by Montoya & Mejía (2021). Moreover, according to Gremp & Easterbrooks (2018), the average recorded ambient noise in 42 empty classrooms was 48.18 dB, beyond the recommended threshold for youngsters. **Figure 9** depicts the BNL results based on 1/1 octave band frequency settings and time scale of two minutes recording period. While **Figure 10** illustrates the NC results for both selected lecture rooms under different room conditions. The results show that the NC rating for QS Studio 2 and QS Studio 4 are NC-25 and NC-23 respectively which are below the maximum recommended value of NC-35 when the air-conditioning systems were not operated. Nevertheless, in a condition where the air-conditioning systems were operated, the NC rating tremendously increased to NC-46 and NC-48 for QS Studio 2 and QS Studio 4.

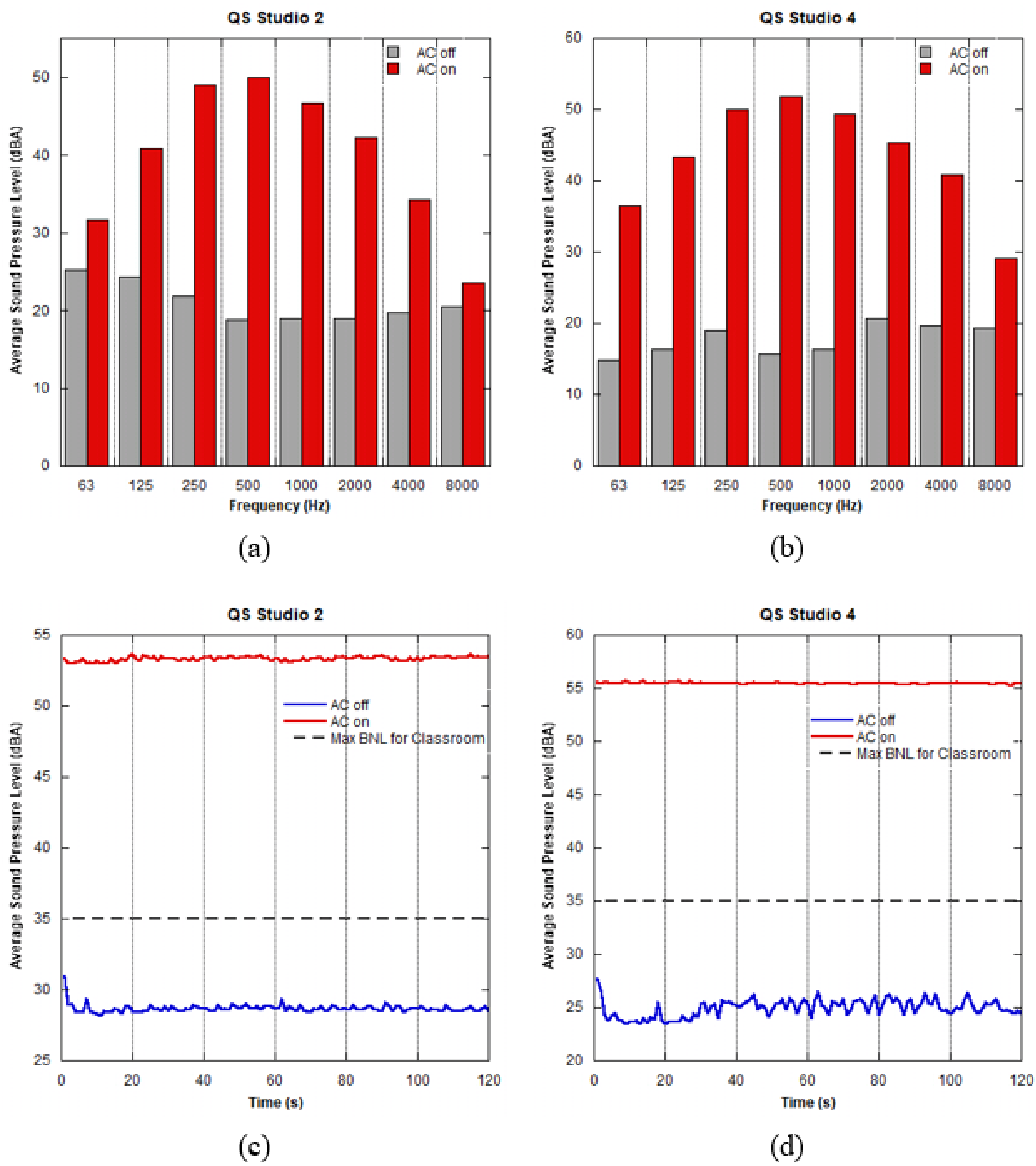

Figure 9. Comparisons of average background noise level (BNL) based on 1/1 octave band frequencies (a & b) and 2 minutes time scale (c & d)

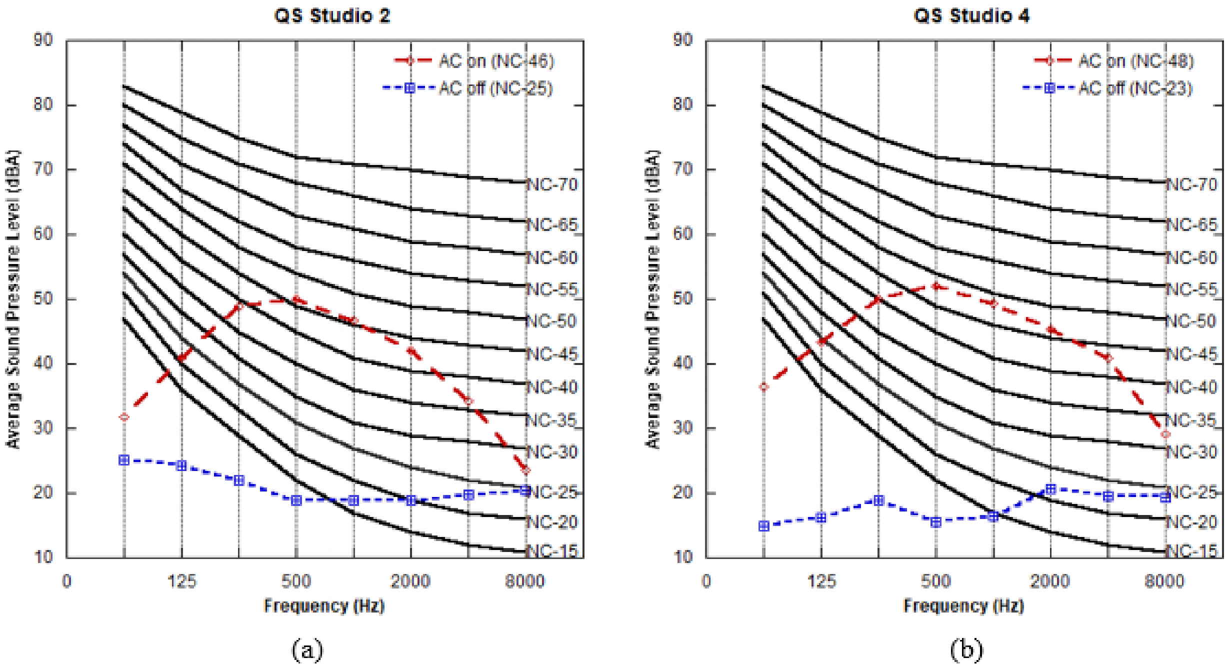

Figure 10. Comparisons of NC curves in different room conditions for (a) QS Studio 2 and (b) QS Studio 4

3.1.2 Reverberation time (T30)

The reverberation time was measured in both unoccupied and furnished conditions, using a balloon as a sound source. Only frequencies ranging from 500 Hz to 8000 Hz were considered, as the results deviate at a lower frequency range as shown in Table 4 and Table 5. RT results indicate that both classrooms fail to comply with the international standard requirement. The recorded RT for QS Studio 2 and QS Studio 4 was 1.73 and 1.89 seconds, respectively. These results are excessively higher than the maximum requirement of 0.7 s established by the American National Standards Institute (2010) and 0.8 s as required by Building Bulletin 93 (2015). The substantial difference in the results is because of the use of reflective materials in the lecture rooms. Both lecture rooms have painted cement-rendered floors, painted brick walls, and painted concrete ceilings. All the surfaces mentioned above have low absorption coefficients, thus more sound energy is reflected within the lecture rooms. A study by Jo et al. (2022) found that classrooms wall equipped with sound-absorbing boards demonstrate optimal reverberation time (RT) conditions in comparison to classrooms with painted cement surface. Furthermore, classes that utilize carpet flooring attained the recommended RT value of 0.6 seconds, in contrast to classrooms equipped with marble flooring (Ahmad, 2020). As stated by Puglisi et al. (2021), to achieve the optimum RT, a sufficient number of absorptive materials is recommended to be employed on the wall, ceiling, and floor. The deficiency of RT in both lecture rooms potentially decreased students' ability to perceive and comprehend the speech.

Table 4. Reverberation time (T30) data of on-site measurement for QS Studio 2

Frequency	Receiver 1			Receiver 2			Receiver 3			Receiver 4			Receiver 5			Receiver 6		
	1st	2nd	μ	1st	2nd	μ	1st	2nd	μ	1st	2nd	μ	1st	2nd	μ	1st	2nd	μ
500	2.21	2.46	2.34	2.13	2.34	2.24	2.5	2.51	2.51	2.29	2.29	2.29	2.34	2.48	2.41	2.62	2.51	2.57
1000	2.03	2.09	2.06	2.01	2.02	2.02	1.97	1.97	1.97	1.89	1.95	1.92	1.96	1.96	1.96	2.04	2.08	2.06
2000	1.85	1.78	1.82	1.79	1.84	1.82	1.72	1.8	1.76	1.74	1.74	1.74	1.84	1.79	1.82	1.75	1.77	1.76
4000	1.49	1.51	1.50	1.54	1.48	1.51	1.41	1.47	1.44	1.56	1.49	1.53	1.47	1.56	1.52	1.59	1.56	1.58
8000	0.99	0.98	0.99	0.99	1.00	1.00	0.96	0.96	0.96	1.01	0.96	0.99	0.96	0.92	0.94	0.92	0.99	0.96

*1st and 2nd refer to the first and second measurement data

Table 5. Reverberation time (T30) data of on-site measurement for QS Studio 4

Frequency	Receiver 1			Receiver 2			Receiver 3			Receiver 4			Receiver 5			Receiver 6		
	1st	2nd	μ	1st	2nd	μ	1st	2nd	μ	1st	2nd	μ	1st	2nd	μ	1st	2nd	μ
500	2.82	2.7	2.76	3.10	3.15	3.13	2.58	2.64	2.61	2.64	2.91	2.78	2.40	2.62	2.51	2.57	2.47	2.52
1000	2.13	2.17	2.15	2.14	2.11	2.13	2.14	2.14	2.14	2.14	2.04	2.09	2.06	2.10	2.08	2.08	2.05	2.07
2000	1.83	1.88	1.86	1.85	1.85	1.85	1.84	1.84	1.84	1.90	1.86	1.88	1.87	1.85	1.86	1.82	1.88	1.85
4000	1.68	1.64	1.66	1.65	1.63	1.64	1.64	1.68	1.66	1.79	1.74	1.77	1.65	1.62	1.64	1.70	1.68	1.69
8000	1.16	1.11	1.14	0.98	1.07	1.03	1.16	1.16	1.16	1.15	1.07	1.11	1.03	1.00	1.02	1.06	1.09	1.08

*1st and 2nd refer to the first and second measurement data

3.2 Simulation

3.2.1 Model verification

The purpose of conducting the verification process is to ensure the 3D models accurately represent the actual condition of the lecture rooms. A comparison of reverberation time data between on-site measurement and simulation was carried out for the verification process. The RT comparison was evaluated through their respective relative difference of Just Noticeable Differences (JND). Rindel et al. (2013) stated that the recommended JND for RT must be less than 5% relative differences. Nonetheless, as specified by Bistafa and Bradley (2000), 10% is the most practical maximum relative difference for engineering type accuracy for RT. The mean RT from 500 Hz to 8000 Hz for both measured and simulated data was calculated and compared. Figure 11 depicts the comparison of RT for QS Studio 2 and QS Studio 4 lecture rooms for the verification process. From the findings, both lecture rooms' models have met the requirement for a relative difference of less than 10%, as stated in Table 6. This indicates that both models were acceptable to be used for the prediction of treatment strategies.

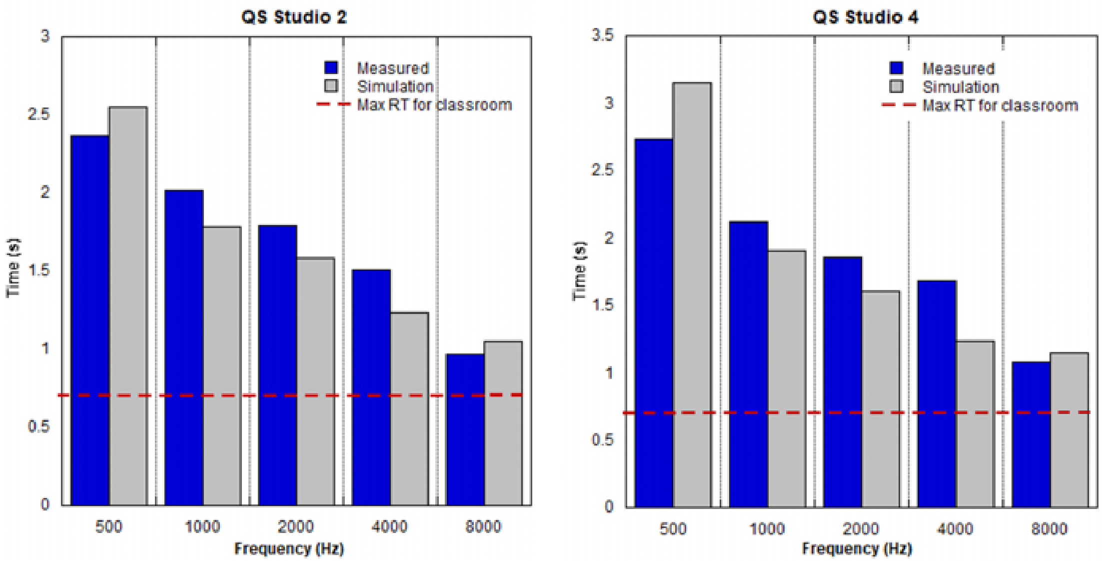

Figure 11. Comparisons of reverberation time results between measured and simulated for verification

Table 6. Just Noticeable Difference (JND) of RT between measured and simulated for QS Studio 2 and QS Studio 4

Classroom	Reverberation time (Mean 500 – 8000 Hz)		JND (%)	Recommended JND (%)
	On-site	Simulation		
QS Studio 2	1.73	1.64	5.3	<5% (Rindel et al., 2013)
QS Studio 4	1.89	1.82	3.8	<10% (Bistafa & Bradley, 2000)

3.2.2 Effects of Surface treatment on reverberation time

Figure 12 illustrates the comparisons of simulated RT results for untreated original lecture rooms (M0), different low- cost treatment alternatives (M1-M7) and commercial treatment (M8) by using ODEON software. The commercial acoustic treatment was purposely included in the study to compare the treatment cost. The detailed treatment configuration is shown in Table 2. Given the unavailability of established classroom acoustics requirements in Malaysia, the current findings are being compared to international standards. From the findings, all the proposed treatments can reduce the reverberation time across all octave bands. However, only M4, M5, M7 and M8 treatments managed to meet the maximum RT of 0.7 s as established by ANSI/ASA S12.60 specifically for speech purposes. It shows that treatment alternatives that involve ceiling modification significantly impact the reduction of RT for both lecture rooms to provide better speech intelligibility as compared to a single treatment on wall and window surfaces.

The substantial decrease in RT for configurations M4, M5, M7, and M8 is due to the large surface area of the ceiling that is treated by highly absorptive materials, which prevents the sound from continuing to reverberate. Moreover, a notable reduction in RT is attributed to the impact of decreasing the height of the ceiling. As mentioned by Acoustical Society of America (2000), installing a new lay-in ceiling suspended from the original ceiling is one of the treatments that can reduce the RT to desirable condition. In addition, the simulation method demonstrated that optimal RT conditions in classrooms can be attained by substituting reinforced concrete walls and microfiber ceilings with gypsum board and perforated plywood that is 12 mm thick (Abdullah et al., 2020). An adequate number of absorptive materials are required to be placed on the ceiling, walls, and floors to achieve a suitable RT for classrooms (Sundaravadhanan et al., 2017). However, floor treatment using absorptive materials such as carpet is not recommended by several countries due to hygiene regulations (Valentine et al., 2002). In summary, the findings indicate that the treatment configuration of M4, M5, and M7 results in optimal RT for both classrooms and can be considered for future acoustic improvement.

Due to space constraints, only the examples of RT grid mapping at 1000 Hz for untreated and treatment alternatives for both lecture rooms are described in Figure 13. As typical human ears are more responsive to sound produced at 1000 Hz, which reflects the standard threshold of hearing, only RT grid mapping of 1000 Hz was chosen (Olajide Olasoji & Francis Akingbade, 2008).

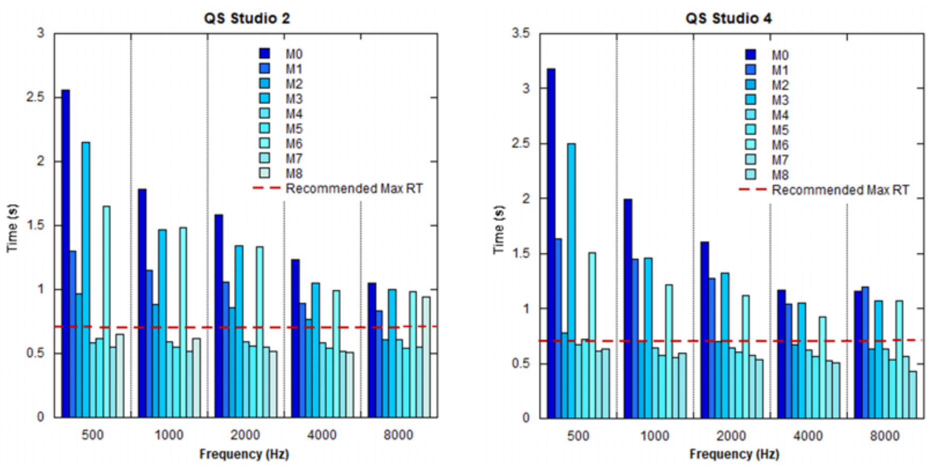

Figure 12. Comparisons of reverberation time results between untreated and different acoustic treatment alternatives for a) QS Studio 2 and b) QS Studio 4

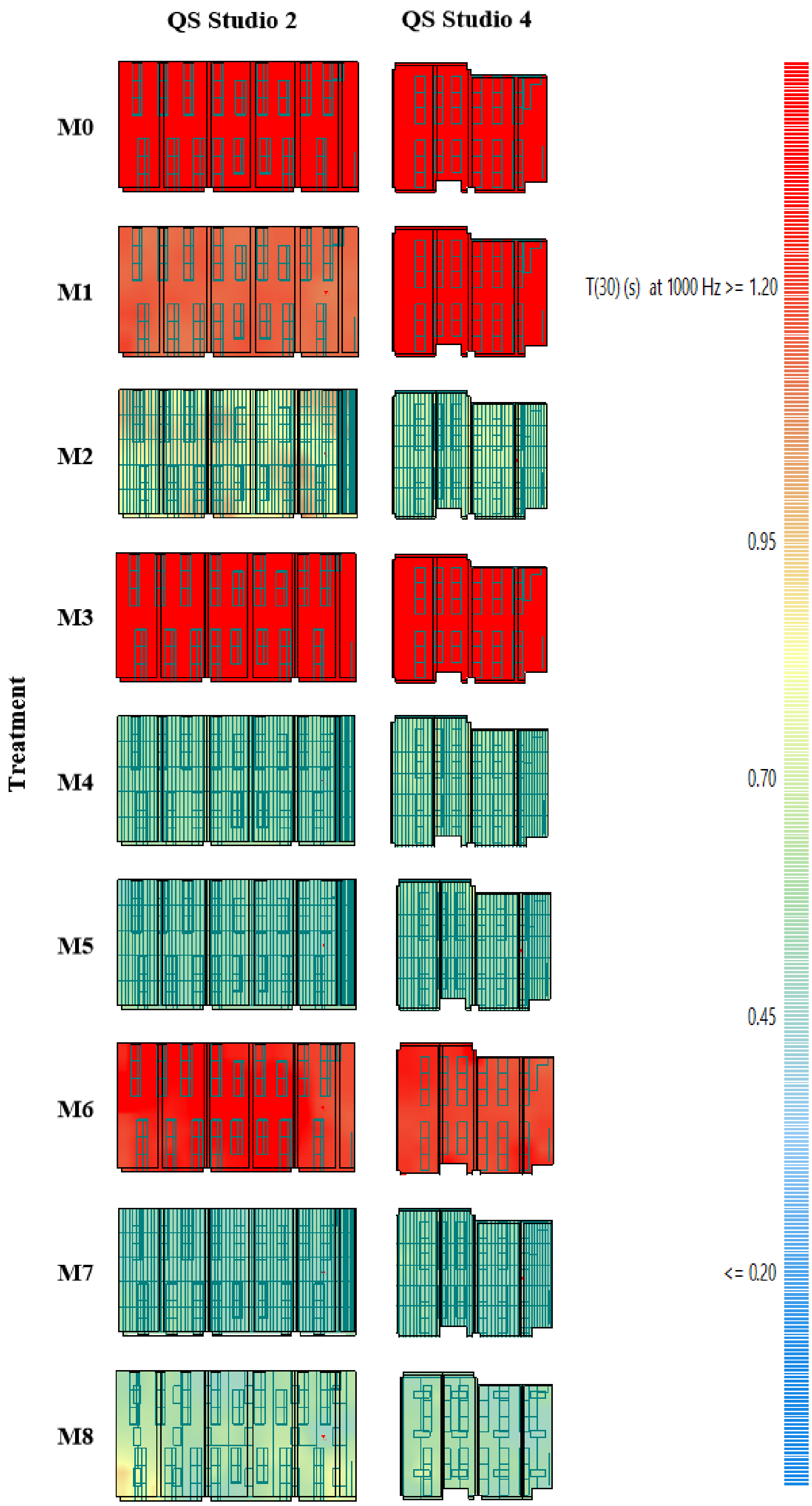

Figure 13. Reverberation time grid mapping of QS Studio 2 and QS Studio 4 at 1000 Hz for different treatment alternatives

3.2.3 Effects of sound amplification system on speech transmission index

All the treatment alternatives as well as untreated lecture rooms configurations were used for the speech transmission index (STI) evaluation. The effects of employing sound amplification systems on STI results in both lecture rooms was evaluated in two conditions: a) with the operation of the air-conditioning system (high BNL) and b) without the operation of the air-conditioning system (low BNL). Two speakers were placed at a height of 2.7 metres above the floor and a distance of 1.2 metres from the side walls in the front and rear of the lecture rooms. The simulation utilized the directivity pattern of the BOSE M101 speaker, which accurately reproduced the natural-raise voice spectrum. The study did not take into account the amplification components and processing system due to the constraints of the simulation software function. **Figure 14** depicts the comparison of STI results between unamplified and amplified classrooms in a high background noise environment while **Figure 15** shows the comparison of STI results in a low background noise environment. From the results, an insignificant improvement in STI ratings was observed between amplified and unamplified lecture rooms. However, the STI ratings further improved from "poor" to "fair" in less reverberant lecture rooms, particularly in M4, M5 and M7 configurations. According to a study conducted by Trinite & Astolfi (2021) the use of sound amplification systems in classrooms enhances the speech intelligibility, as long as the reverberation time (RT) is decreased to its optimal level.

Furthermore, the rising trend of STI ratings keeps on increasing to "good" in low background noise lecture rooms (without air-conditioning system). Di Loreto et al. (2023) conducted a study to examine the influence of the air-conditioning system on STI. The findings suggest that the functioning of the air-conditioning system generates extra noise into the room, which ultimately impairs the intelligibility of speech. The results indicate that the operation air-conditioning system introduces additional noise into the room and eventually degrades the speech intelligibility. This indicates that the STI ratings of the classrooms are greatly influenced by the RT, background noise level, and sound amplification systems. Therefore, to ensure optimum STI can be achieved, i) the RT should fulfill the standard requirement of 0.7 s, ii) the BNL must be reduced to a maximum level of 35 dB (A), and iii) sound amplification systems must be employed to optimize the sound signal.

The example of average STI grid mapping for frequency ranging from 125 Hz to 8000 Hz for QS Studio 2 conditions is presented in **Figure 16**. The spatial distribution of STI mapping describes the quality of speech in the lecture rooms. The STI behavior is categorized based on the color scale of orange red (bad), (poor), yellow (fair), light green (good) and dark green (excellent). As stated by Mealings (2016), for children aged 12 and above, the recommended STI rating must be greater than 0.6 (good) in order to satisfy favorable speech intelligibility quality in the classroom.

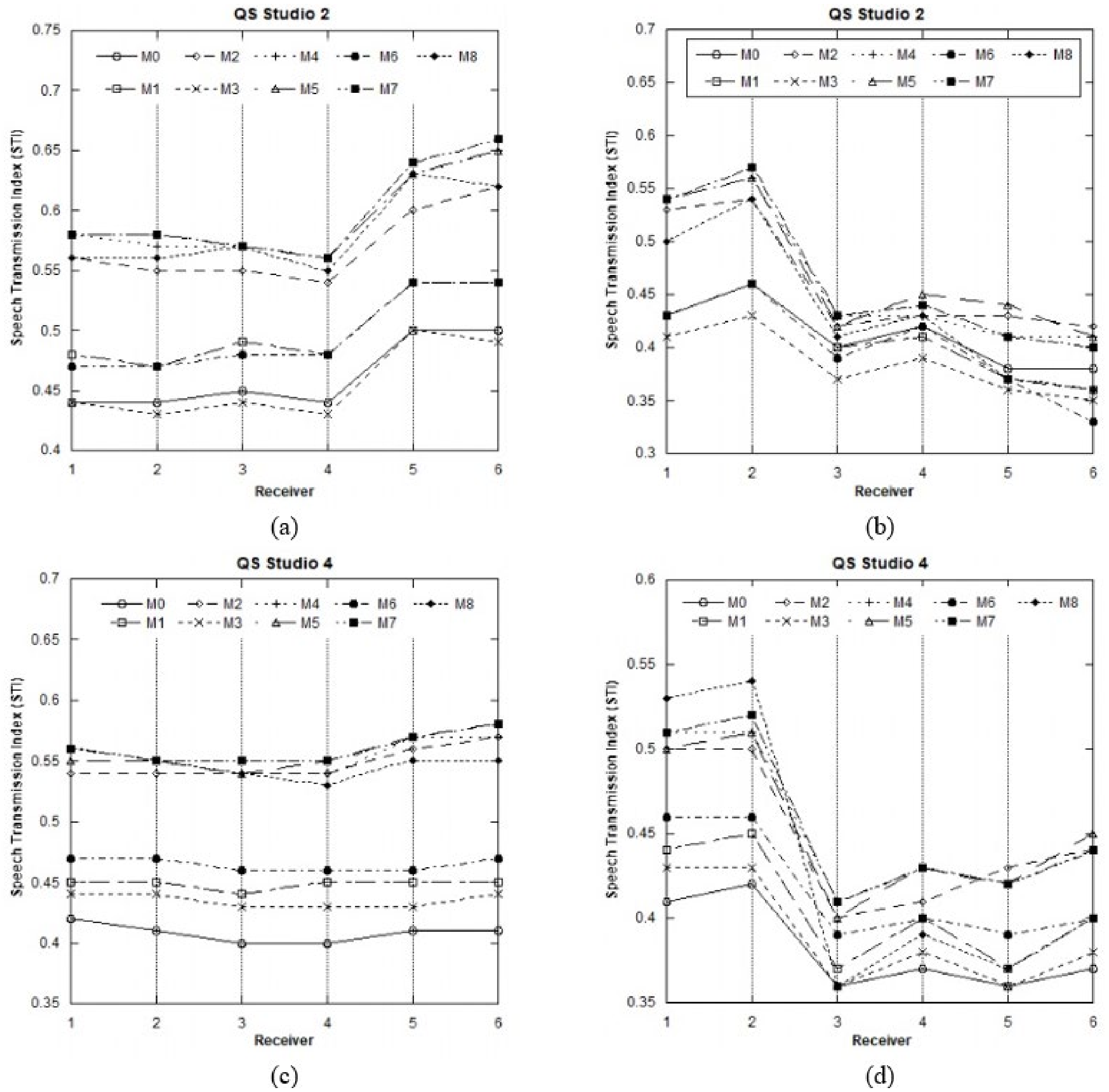

Figure 14. Comparisons of STI value of (a & c) amplified and (b & d) unamplified classrooms in different treatment alternatives in high background noise environment

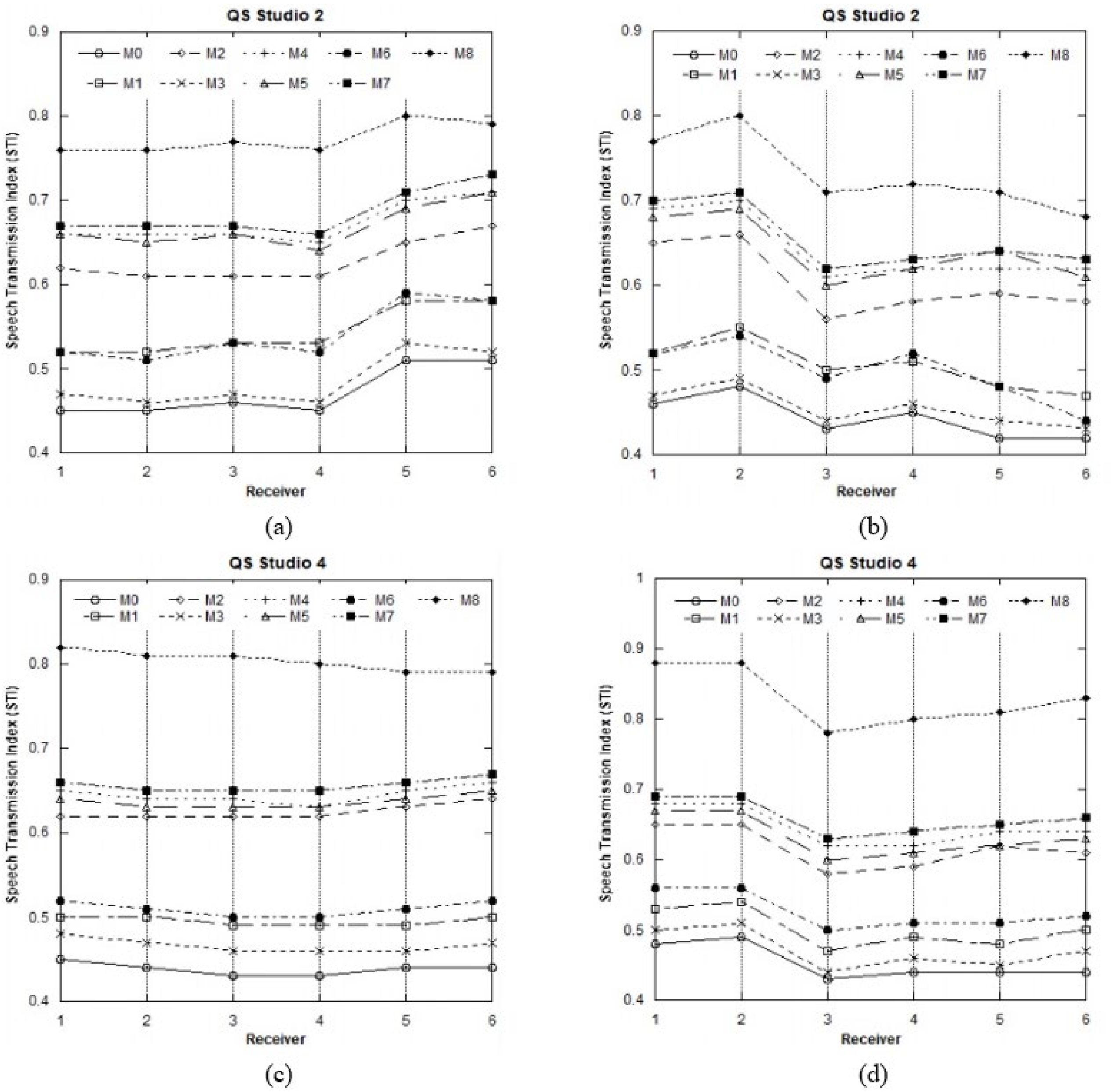

Figure 15. Comparisons of STI value of (a & c) amplified and (b & d) unamplified classrooms in different treatment alternatives in low background noise environment

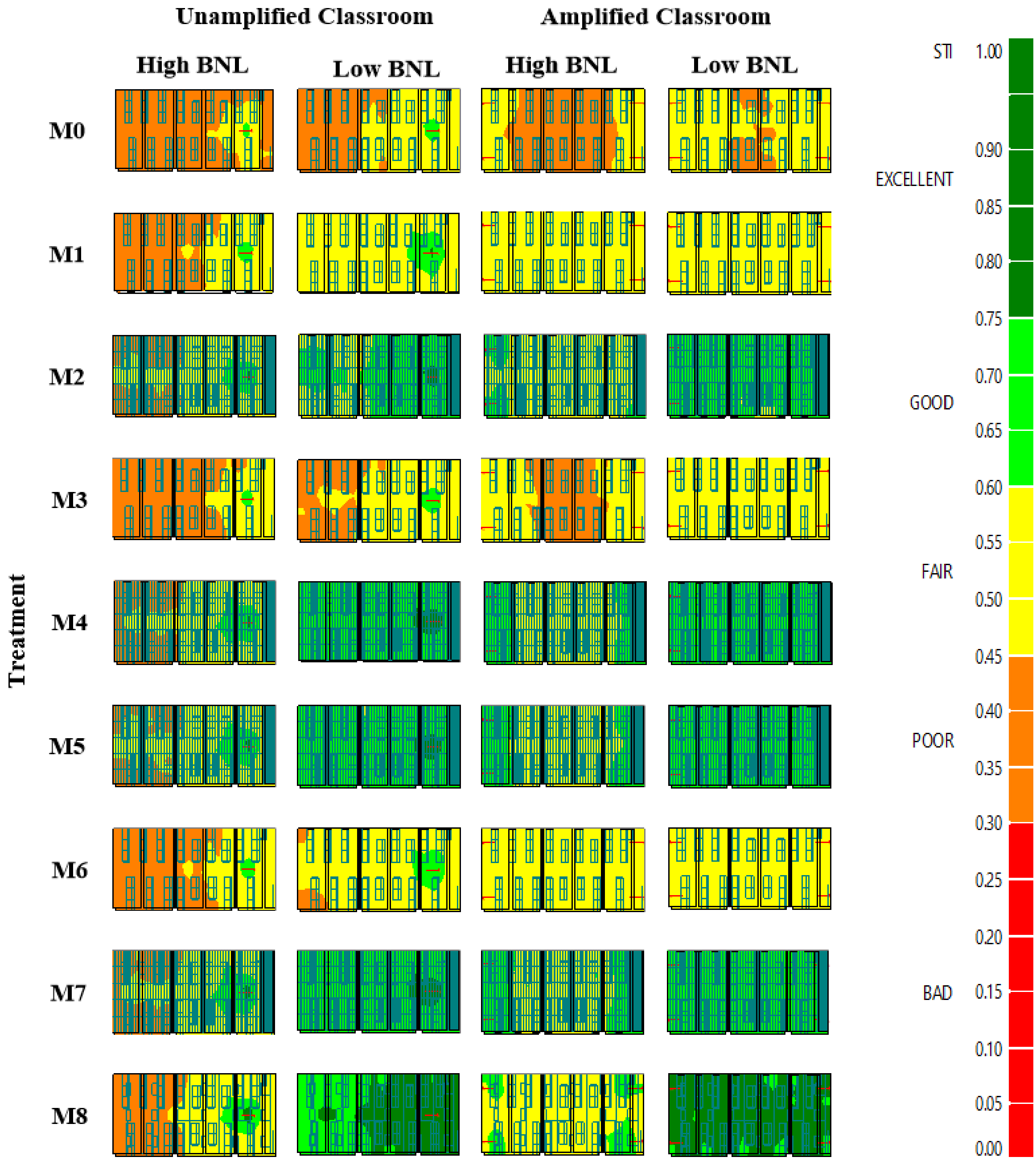

Figure 16. Comparisons of STI grid mapping between the current condition and different acoustic treatment alternatives of QS Studio 2 based on unamplified and amplified configurations in a high and low background noise level

3.2.4 Cost estimation for acoustics treatment

From the acoustic treatment alternatives simulation results, apart from commercial treatment (M8), only low-cost treatments of Mod-4, 5, and 7 managed to improve the acoustic conditions of the lecture rooms according to American National Standards Institute (2010) requirements. Therefore, the cost estimation calculation merely focuses on the comparisons between low-cost and commercial treatment alternatives as mentioned beforehand. The detailed calculation of the treatment cost for both lecture rooms is described in Table 7 and Table 8. The data shows that the M5 acoustic treatment is the least expensive alternative and can be constructed for RM6180.53 and RM5008.28 for QS Studio 2 and QS Studio 4 respectively. The commercial treatment costs for QS Studio 2 and QS Studio 4 are expected to total RM29750.00 and RM23670.39 respectively. This suggests that more than RM18000 can be saved by implementing treatment M5 in both lecture rooms. The total cost for M5 treatment can be reduced even more provided that the treatments are made voluntarily by the staff and students, and do not involve other incurred costs such as labor as well as profit and overhead costs.

Table 7. Cost estimation of different acoustic treatment alternatives for QS Studio 2

Item	Detail calculation			
	M4	**M5**	**M7**	**M8**
Material	**Velvet curtain** RM26.00/m^2 x 143.3m^2 = RM3725.80 **Corkboard** RM227.00/m^2 x 46.8m^2 = RM10623.60 **Accessories** RM150.00 Total = RM14499.40 Add 5% wastages: RM14499.40 + RM724.97 = **RM15224.37**	**Velvet curtain** RM26.00/m^2 x 143.3m^2 = RM3725.80 **Dense curtain** RM21.50/m^2 x 21.3m^2 = RM457.95 **Accessories** RM150.00 Total = RM4333.75 Add 5% wastages: RM4333.75 + RM216.69 = **RM4550.44**	**Velvet curtain** RM26.00/m^2 x 143.3m^2 = RM3725.80 **Corkboard** RM227.00/m^2 x 46.8m^2 = RM10623.60 **Dense curtain** RM21.50/m^2 x 21.3m^2 = RM457.95 **Accessories** RM150.00 Total = RM14957.35 Add 5% wastages: RM14957.35 + RM747.87 = **RM15705.22**	**Classic Tone Panel** RM54.00 x 127.6 m^2 = RM6380.00 **Suspended ceiling including frame =** RM70.00 x 127.6 m^2 = RM8932.00 **Fabric Panel Broadband** RM120.00 x 16.2 m^2 = RM1944.00 Total = RM17256.00 Add 5% wastages: RM17526.00 + RM862.80 = **RM18388.80**
Labour	3 manpower: RM100.00/day x 2 days x 3 nos = **RM600.00**	3 manpower: RM100.00/day x 2 days x 3 nos = **RM600.00**	3 manpower: RM100.00/day x 2 days x 3 nos = **RM600.00**	5 manpower: RM200.00/day x 5 days x 5 nos **= RM5000.00**
Profit and overhead	20% profit and overhead: (Material + labour cost) x 20% (RM15224.37 + RM600.00) x 20% = **RM3164.87**	20% profit and overhead: (Material + labour cost) x 20% (RM4550.44 + RM600.00) x 20% = **RM1030.09**	20% profit and overhead: (Material + labour cost) x 20% (RM15705.22 + RM600.00) x 20% = **RM3261.04**	20% profit and overhead: (Material + labour cost) x 20% (RM18388.80 + RM5000.00) x 20% **= RM4677.76**
Total	Material + labour + profit **RM18989.24**	Material + labour + profit **RM6180.53**	Material + labour + profit **RM19566.26**	Material + labour + profit + 6% consultation fee **RM29750.00**

Table 8. Cost estimation of different acoustic treatment alternatives for QS Studio 4

Item	Detail calculation			
	M4	**M5**	**M7**	**M8**
Material	**Velvet curtain** RM26.00/m^2 x 107.6m^2 = RM2797.60 **Corkboard** RM227.00/m^2 x 29m^2 = RM6583.00 **Accessories** RM150.00 Total = RM9530.60 Add 5% wastages: RM9530.60 + RM476.53 = **RM10007.13**	**Velvet curtain** RM26.00/m^2 x 107.6m^2 = RM2797.60 **Dense curtain** RM21.50/m^2 x 21.2m^2 = RM455.80 **Accessories** RM150.00 Total = RM3403.40 Add 5% wastages: RM3403.40 + RM170.17 = **RM3573.57**	x **Velvet curtain** RM26.00/m^2 107.6m^2 = RM2797.60 **Corkboard** RM227.00/m^2 x 29m^2 = RM6583.00 **Dense curtain** RM21.50/m^2 x 21.2m^2 = RM455.80 **Accessories** RM150.00 Total = RM9986.40 Add 5% wastages: RM9986.40 + RM499.32 = **RM10485.72**	**Classic Tone Panel** RM54.00 x 93.2m^2 = RM5032.80 **Suspended ceiling including frame =** RM70.00 x 93.2m^2 = RM6524.00 **Fabric Panel Broadband** RM120.00 x 17.1m^2 = RM2052.00 Total = RM15036.80 Add 5% wastages: RM15036.80 + RM751.84 = **RM13608.80**
Labour	3 manpower: RM100.00/day x 2 days x 3 nos = **RM600.00**	3 manpower: RM100.00/day x 2 days x 3 nos = **RM600.00**	3 manpower: RM100.00/day x 2 days x 3 nos = **RM600.00**	4 manpower: RM200.00/day x 5 days x 5 nos **= RM5000.00**
Profit and overhead	20% profit and overhead: (Material + labour cost) x 20% (RM10007.13 + RM600.00) x 20% = **RM2121.43**	20% profit and overhead: (Material + labour cost) x 20% (RM3573.57 + RM600.00) x 20% = **RM834.71**	20% profit and overhead: (Material + labour cost) x 20% (RM10485.72 + RM600.00) x 20% = **RM2217.14**	20% profit and overhead: (Material + labour cost) x 20% (RM13608.80 + RM5000.00) x 20% **= RM3721.76**
Total	Material + labour + profit **RM12728.56**	Material + labour + profit **RM5008.28**	Material + labour + profit **RM13302.86**	Material + labour + profit + 6% consultation fee **RM23670.39**

4.0 DISCUSSION

The on-site acoustic evaluation revealed the actual acoustic conditions of two lecture rooms at the Faculty of Built Environment, Universiti Malaysia Sarawak. For reverberation times, it was found that both lecture rooms failed to achieve the standard guideline established by ANSI/ASA S12.60 and Building Bulletin 93. This shows that surface treatments are required to increase the sound absorption characteristics of the lecture rooms. As for BNL, it was found that neither lecture rooms met the recommended guidelines from

ANSI/ASA S12.60 and Building Bulletin 93, which set the maximum value of 35 dB(A) during the operation of air-conditioning systems.

According to the simulation for treatment alternatives, modifications that involve ceiling surfaces made of low-cost material had a significant impact on decreasing the reverberation time compared to wall and window surface modification. While a slight improvement in reverberation time was found in treatment Mod 1, 3, and 6 which focus on wall and window surface modification. This indicates that ceiling treatment plays a vital role in determining the lecture rooms' reverberation time because of the large surface area. A similar situation was observed in a prior study when the use of mineral-fiber acoustical ceiling tiles in a classroom led to a notable improvement in RT. As specified by Acoustical Society of America (2000), one way to achieve the desired condition of reducing the RT is by creating a new lay-in ceiling that is suspended from the existing ceiling.

The effect of employing sound amplification systems in both lecture rooms shows a significant improvement in the STI ratings. The study discovers that the STI ratings increased in conditions of a) low background noise and b) amplified classrooms and c) low reverberation time. By employing sound amplification systems in the lecture rooms, the STI ratings improved from "poor" to 'good", provided that the reverberation time and background noise level were in favorable conditions. In previous studies, improvements in speech intelligibility in a classroom equipped with a sound amplification system were observed. However, in a reverberant classroom, speech perception decreased. This shows that using a sound amplification system can be effective, provided that the room acoustics are fixed in ideal conditions (Trinite & Astolfi, 2021).

Generally, the findings of this study disclose poor acoustic comfort in both lecture rooms, and future improvement is attainable by using low-cost treatment alternatives. As shown in Tables 6 and 7, it is possible to improve the current acoustics conditions of the lecture rooms for a total cost of less than RM6500.00 and can be saved up to RM23000.00 in comparison to the commercial treatment. The exorbitant cost of commercially available absorptive materials has posed a significant obstacle to implementing classroom acoustic treatment. The utilization of inexpensive materials possessing favorable absorbent properties is undeniably practical while also considering the aesthetic appearance of the specific areas. Thus, the proposed treatment alternatives from the study can be referred to as a basic guideline to improve current lecture rooms' acoustic conditions. Hence, a conducive learning environment can be established to foster effective teaching and learning processes.

5.0 CONCLUSIONS

The on-site acoustic assessment was carried out in two lecture rooms at UNIMAS. Subsequently, ODEON room acoustic simulation software was utilized to conduct a sequence of acoustical simulations on low-cost surface treatments and sound amplification systems alternatives for RT and STI. The findings revealed that the actual RT conditions for both lecture rooms exceed the maximum recommended value, but they have significantly improved and comply with international standard guidelines by implementing surface treatment in certain areas. Furthermore, the STI ratings were improved from 'poor' to 'good', and this improvement was largely influenced by the RT conditions of the room, the level of background noise, and the use of sound amplification systems. While the current acoustic conditions of both lecture rooms do not satisfy the standard regulations, the recommended criteria can be met by implementing cost-effective acoustic treatment alternatives. Further investigation will be pursued into the details of the material's configurations in different room dimensions and other acoustical parameters, such as speech clarity.

6.0 ACKNOWLEDGEMENTS

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