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Acoustical Evaluation of Multipurpose Hall by Using Computer Simulation: A Case Study of Tunku Canselor Hall, Universiti Malaya

Hoong Yoong Le[1], & Nazli bin Che Din[1,2*]

[1]Department of Architecture, Faculty of Built Environment, Universiti Malaya, 50603 Kuala Lumpur, Malaysia,
[2]The Centre for Building, Construction & Tropical Architecture (BuCTA) Faculty of Built Environment, Universiti Malaya, 50603 Kuala Lumpur, Malaysia.

[*]Corresponding email: nazlichedin@um.edu.my

ABSTRACT

Dewan Tunku Canselor (DTC), Universiti Malaya, is a large hall serving multiple speeches and musical performance facilities. Musical performance and speeches in a multi-purpose hall needed to be as intelligible, desirable, and engaging as possible. However, speech and musical performance required different acoustic configurations, and it is difficult to accomplish both simultaneously. Therefore, the appliance of acoustic strategy plays an important role in regulating overall acoustic performance. Many research organisations have focused on acoustics in multi-purpose halls. However, there is a lack of research on acoustic performance in Malaysia. In addition, DTC is one of the most iconic buildings and registered as one of the UNESCO Heritage Buildings in Malaysia. A lot of renovation and refurbishments have been conducted; however, the available acoustic performance to serve speeches and performance remains questionable. This paper demonstrated the acoustical performance of the available information about DTC by using computer simulation. Apart from reviewing the acoustic performance, this study denoted related alterations to improve the existing condition based on recommended criteria. This study is based on ODEON software computer simulation to analyse the specific parameter, i.e., reverberation time (T30) and speech transmission index (STI). This research validated that the current acoustical performance of DTC did not achieve optimum performance as a multi-purpose hall. Then, a recommended modification model to improve the performance arises upon the research findings and simulation results. Based on literature reviews, the proposed acoustic solution attained the best results by gaining optimum reverberation time in architectural acoustic.

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INTRODUCTION

Dewan Tunku Canselor (DTC) is a landmark for Universiti Malaya (UM) and is listed under the National Heritage. The yearly convocation ceremonies for graduation have been held for many years and hosting numerous university functions, including theatres performances, seminars, and conferences.

It caught fire on 29 June 2001, and the DTC hall was not used until the completion of repair and renovation [1]. During the renovation, the principle of conservation was applied to retain the authenticity of the building's original design. Thus, all architectural features in DTC were retained, and the original design was maintained. However, the interior renovation work included acoustic treatment was based on the new requirement to ensure that DTC is able to host multi-purpose functions as required to facilitate, such as the annual convocation ceremony, speech, musical performances, and conferences.

Meantime, there have been many studies worldwide about acoustics in multi-purpose halls involving physical measurement and/or simulation, which has aided us in solving acoustic issues and designing better hall spaces [2-5]. However, a less significant study has been made to examine the acoustical performance in the multi-purpose hall in Malaysia, particularly in heritage buildings such as DTC, and their acoustics performance as a multi-purpose hall remains unknown.

This study aims to investigate the acoustical performance in the main hall of the DTC, UM, as shown in Figure 1, with the aid of using computer simulation to assess the acoustic quality of the multi-purpose, and the results were compared in evaluation criteria. Selected acoustical parameters were chosen to emphasize their impact on the pre-and post-acoustic alteration.

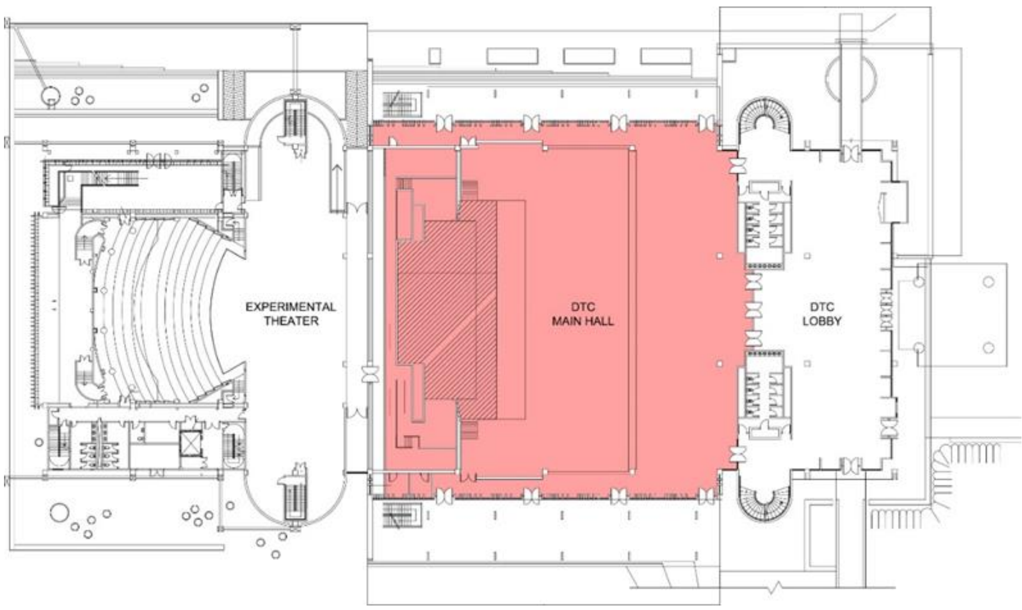


Figure 1. Plan view of Dewan Tunku Canselor.

Acoustical Design for Multi-Purpose Hall

In multiple usage hall spaces primarily for musical and speeches, there is the need for acoustical properties to support both intelligible and sufficient long reverberation time for musical performance. The acoustic requirements for both usages are contradicted with each other. For speeches, it is similar to the lecture room and auditorium (mainly in speech activity) the requirement for reverberation is about 0.8 s harmonious to achieve speech intelligibility whereas, longer reverberation time to attain delightful and vivid listening for musical performance.

For a multi-purpose hall that accommodates speeches and performance, it must allow good verbal and musical communication. Assuming that, it has poor acoustics if it makes both communications difficult. It is challenging for the multi-purpose hall to achieve good speech intelligibility and good music acoustic at once due to the acoustic design considerations tackle on either one of the multi-purpose activities; potentially, it will lead to another imbalance situation. i.e., speech intelligibility achieved, however, neglected the desirable listening for music or not live enough. In order to accomplish both, it could be possible to lead to three solutions where to reduce or increase reverberation time to meet both hearing requirements, implement an adjustable absorption system in the room or adopt electronic enhancement for the sound system.

Room Volume and Shape

In multi-purpose hall design, the basic room shape and volume must be primary design considerations to provide an optimum acoustic environment. In acoustic, room volume is one major element that determines reverberation time. Therefore, an excellent acoustic system to serve multi-purpose facilities needed to be equally balanced, and it should be relatively harmonious to maintain desirable reverberation for multiple acoustic needs.

It is crucial to have appropriate order of volume for its use in obtaining optimum listening conditions. A mixed usage hall of musical and speeches both require different room volumes to achieve optimum listening. Hence, it is hard to fulfil both at optimum at once. The musical played in a hall with too small room volume is likely to lack fullness, whereas speech in a hall with a very large volume for its seating capacity is expected to lack clarity. The preliminary shape of volume can be depending on the visual or seating consideration. However, to emphasize lateral reflections, rectilinear and square plans are better and lightly preferred. Besides the arrangement providing excellent sightlines, it is compelling to minimize the distance to the performing area.

The geometrical consideration on the section is one criterion to determine the ratio of the volume in terms of height. Therefore, the ratios of the room’s length to its width as well as the ratios of room’s height to width are the meaningful deliberation for the multi-purpose hall should be well considered during preliminary stages.

Section shape with appropriate acoustic treatable to provide good listening. It can provide a good distribution of strong early reflections and diffusion. The reverberation time of the stage should be approximately equal to that of the hall. Reverberation will linger when surfaces surrounding the stage are shaped to inter-reflect or scatter sound rather than to reflect sound toward the absorptive audience. The use of ray-diagram as an analyzing method is one solution that can orientate the ceiling and sidewalls correctly, especially near the proscenium. Ceiling and wall surfaces should provide practical sound reflections and diffusion—volume and form like vaults, domes, concave surface shapes should be avoided.

Reverberation Time (RT)

Absorption in acoustic is effective in reduce or eliminate undesirable sound reflection off the surface. The optimum reverberation time (RT) for a room is related to both the room volume (V) and the amount of total absorption (A) in the room. In a multi-purpose hall, reverberation time requires speech intelligibility to have a low range of RT and music performance which should have a high range of RT than an equivalent volume room used mainly for particular usage [6]. However, a multi-purpose hall serves speech giving and musical performance (Figure 2).

For speeches to achieve better hearing, reverberation times should be less than 1.2 s from 250 Hz to 4000 Hz for large space volume, and it requires less than 0.8 reverberation time. Long reverberation times may reduce speech intelligibility in the same way it can mask speech signals. However, occupied hall for musical performance, reverberation time at mid frequencies (i.e., an average of reverberation at 500 Hz and 1000 Hz), the reverberation time should be at 1.6 s to 2.4 s and longer reverberation time for the case of the empty hall. Music in rooms with appropriate reverberation times may sound full-toned.

Through, the reverberation time for multi-purpose use should be around 1.4 s to 1.9 s at mid-frequencies. Consequently, a mid-frequency reverberation time of 1.8 s at 500 Hz may be appropriate for music activities, where blending is needed, and not be too long for speech activities, mainly if an adequately designed sound-reinforcing system is used.

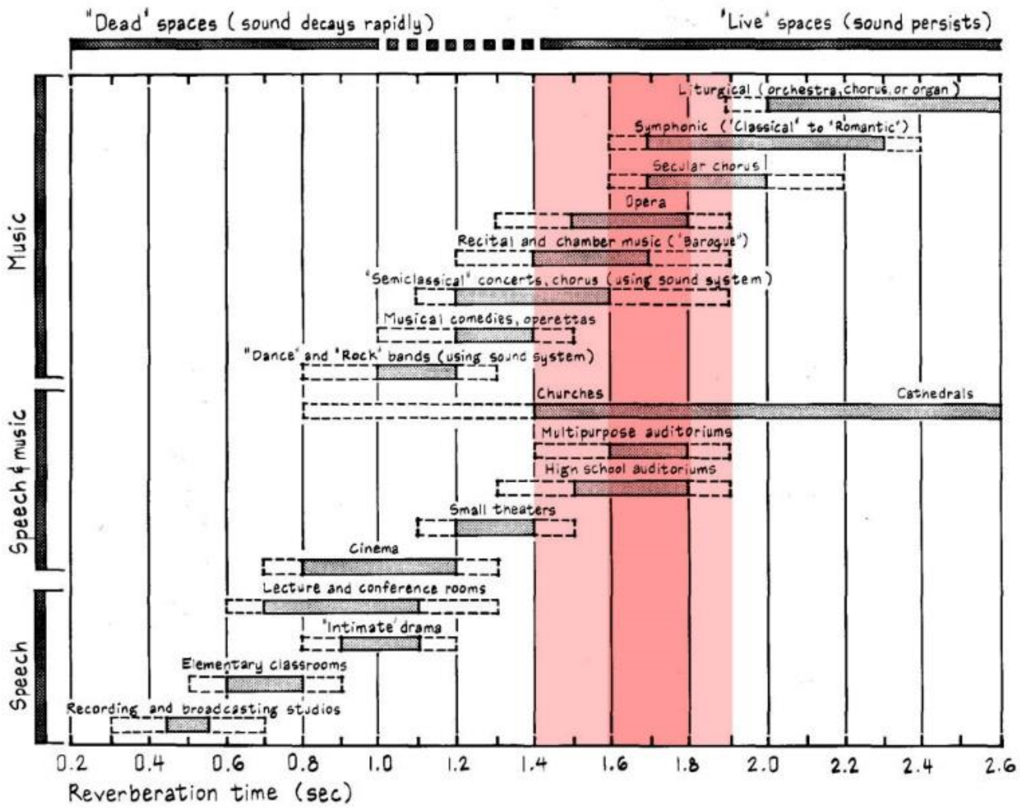


Figure 2. Optimum reverberation time at 500/1000 Hz for auditoriums and similar facilities [7].

Speech Transmission Index (STI)

The Speech Transmission Index (STI) is a physical metric well correlated with the intelligibility of speech degraded by additive noise and reverberation. The traditional STI uses modulated noise as a probe signal and is valid for assessing degradations resulting from the speech signal's linear operations. Speech intelligibility is a sound quality descriptor that can be used to analyse the suitability of space where speech is crucial (e.g., room related to speech delivering). The speech intelligibility properties of space are able quantified either through a listening test or through physical measurements. STI represents the ability of a transmission channel to transfer across the features of a speech signal by measuring some physical parameters of the channel, e.g., a room. STI is a well-established objective measuring predictor of how the transmission channel parameters impact speech intelligibility quantifiable. Figure 3 illustrated STI as a numerical representation of communication channel characteristics with values ranging from 0 to 1. For most applications, an STI of at least 0.5 is recommended on this scale [8]. An STI of 1 indicates excellent sound transmission, whereas 0 indicates no signal recognition [9].

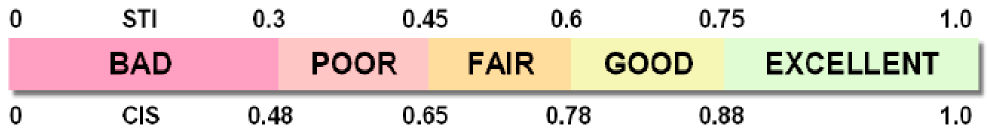


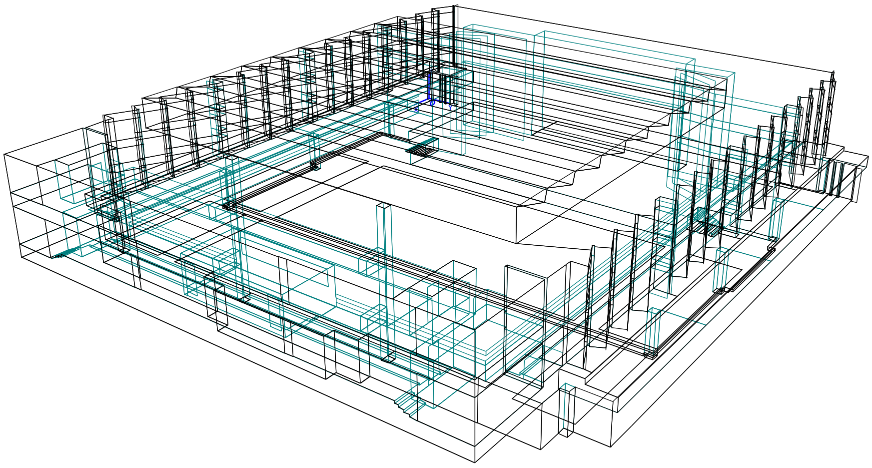
Figure 3. Speech Transmission Index indicator [10]

RESEARCH METHODOLOGY

Design of Experiment

The immediate purpose of carrying out this research aims to identify the existing acoustical performance of DTC as a multi-purpose hall. By determining the acoustic performance of multi-purpose usage of speeches and musical performance. The research method focuses on computer simulation; it starts with replicating the original building form and exact hall feature into digital format. The DTC main hall's original building plans were obtained and translated into a simplified 3-dimensional model as shown in Figure 4 by using Google SketchUp®; then, the computational analysis is performed in ODEON 13.02 Industrial version [11].

All features and details such as surface walls and ceiling panels are models in the 3-dimensional (3D) model. Architectural details, such as framing, were excluded during the 3D modelling process [11-12] because such detail does not create any prominent early reflections to the receivers [13-14]. First, its validity must be checked, including the consistency of modelling data with the correct format. The process involves a water tightness test of the room through the 3D Billiard window. A water tightness test is to check whether the room model is completely enclosed to ensure the accuracy of the simulation. In this research, the materials setting needs to replicate the existing material used to achieve a nearly similar condition as the case study.



Type (Building)	Type (Shape)	Volume, m^3	Max Height, m	Area, m^2	No. of Seat
Hall	Rectangular	21602.15	12.70	1883.7	3000

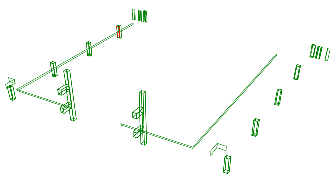
Figure 4. Simplified 3-dimensional model of Dewan Tunku Canselor.

Material

The method of assign material and selection is determined by the actual material used in DTC. Materials are possible to assign directly from the material library in ODEON. Each surface of a model needs to assign a material type before the simulations can be carried out. Due to the limitation of material use information in the ODEON material library and difficulty identifying the information during data collection, the simulation applies the material with the nearest absorption coefficient (α) property to the actual on-site material. In this research, the materials used in the DTC needed to identify conducive to simulate the nearest situation in each room model. Table 1 showed that the following materials were selected and used in the materials assignation process for this study.

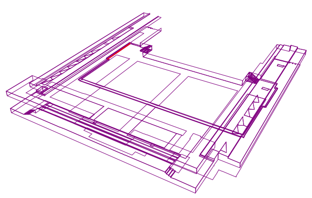
Table 1. The sound absorption coefficient of materials assigned for each surface

Column Surface: Smooth unpainted concrete



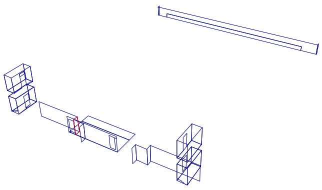
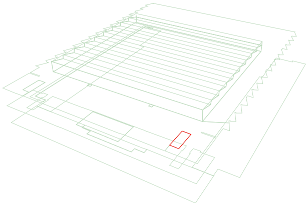
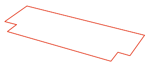
Frequency (Hz)	α
250	0.01
500	0.02
1000	0.02
2000	0.02
4000	0.05

Column Surface: Smooth unpainted concrete



Frequency (Hz)	α
250	0.04
500	0.07
1000	0.06
2000	0.06
4000	0.07

Wall Panel surface: Thin plywood paneling

	Frequency (Hz)	**α**
	250	0.21
	500	0.1
	1000	0.08
	2000	0.06
	4000	0.06
Ceiling board surface: Plasterboard on frame, 13 mm boards, 100 mm empty cavity		
	Frequency (Hz)	**α**
	250	0.11
	500	0.05
	1000	0.03
	2000	0.02
	4000	0.03
Stage flooring surface: 6mm pile carpet bonded to closed-cell foam underlay (ODEON Library: Parkin, Humphreys, & Cowell, 1979)		
	Frequency (Hz)	**α**
	250	0.09
	500	0.25
	1000	0.31
	2000	0.33
	4000	0.44

Set-up ODEON Sound Source and Receiver

Before conducting the simulations by ODEON, the sound source and receiver need to be defined in the order. In this research, the sound source replicated the exact speaker setting, multiple points of Electro-Voice-EVF1152s-94 Passive.CF2 setting was used as the sound source (Table 2).

Table 2. Sound power of Electro-Voice-EVF1152s-94 Passive.CF2

Frequency,Hz	250	500	1000	2000
Sound power, dB	105.6	103.7	100.1	99.7

The sound source was replicated and placed precisely the location of the speaker point in DTC. Then, the receiver locations were occupied uniformly in the whole area of the seating area of DTC. Thus, the room was composed of position rows of the front, middle, and rear, and each row was divided into three parts: right, center, and left sides. Figure 5 demonstrated the location of the sound sources and receiver points for the room model.

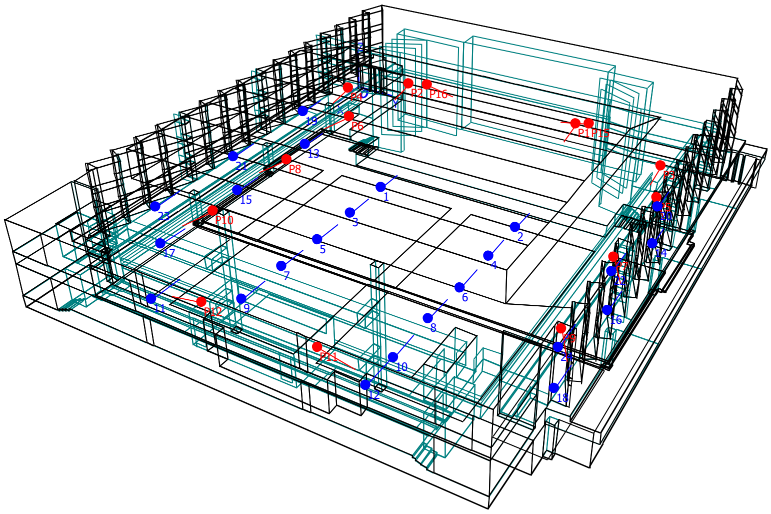


Figure 5. Location of sound source and receivers in the churches (red: source; blue: receiver).

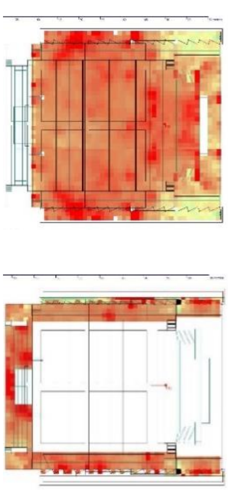
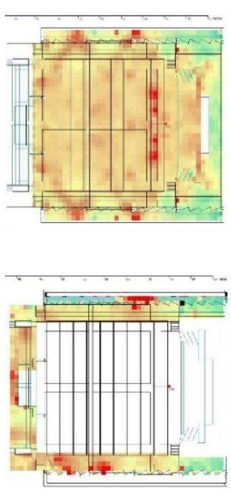
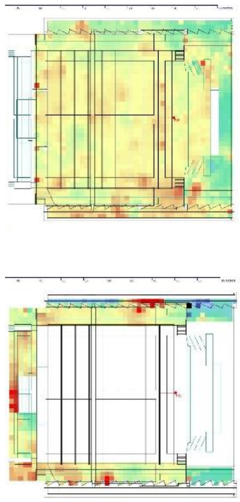
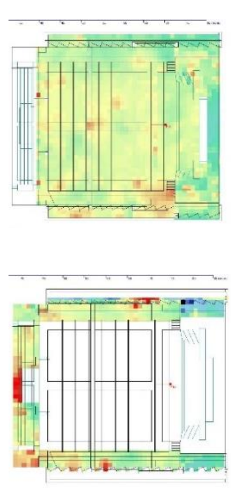
RESULTS AND FINDINGS

Simulation 1: Existing Acoustic Performance in Dewan Tunku Canselor (DTC) Reverberation Time (RT)

In practice, it is become a common approach to measure the time that it takes for a sound to decrease by 20 dB or 30 dB only, and then to extrapolate the result to 60 dB. Therefore, for make better comparison with the future undertaking measurement in-situ, T30 was used in this simulation analysis. Based on the obtained data in Table 3, all averaged RT values have fluctuated as frequency increases. The lowest frequency achieved the highest reverberation time. However, the reverberation time at 2000 Hz shows the lowest simulated T30, an average of 1.29 s. Zannin & Zwites [15] stated that the room reverberation is shorter at higher frequencies and longer in lower frequencies. Therefore, this phenomenon may be related to the materials in use, and it shows the material property may not be well absorbed in the low frequencies' region.

A multi-purpose hall has various uses, for example, speech and musical performances. Acoustic design has an important role in the acoustic quality and functionality of a multi-use hall and significantly affects user comfort and satisfaction [16]. In order for a multi-purpose hall to achieve as good for both speech and musical performance, broadly, the value of RT needed to reach between 1.4 s to 1.9 s at 500 Hz to 1000 Hz, as shown in Figure 2 and Table 4. The optimum reverberation time for a multi-purpose hall is between 1.6 s to 1.8 s at 500 Hz to 1000 Hz. However, the RT value between 1.4 s to 1.6 s and 1.8 s to 1.9 s is considered good and acceptable [7].

Table 3. Results of T30 (s), and grid response across four-octave bands

	Reverberation time, T30 across four-octave bands			
Grid Respond				
Frequency, (Hz)	250	500	1000	2000
Average RT, T30	1.72	1.45	1.34	1.29

Based on Figure 6, the highest RT achieved by receiver 20 (R20) is 1.55 s at the frequency of 500 Hz and 1.44 s at 1000 Hz. It shows that R15 to R18, R19, and R21 did not reach the optimum tolerance range at the frequency of 500Hz. Furthermore, most of the receiver points did not achieve an acceptable tolerance range except R3, R20, R22, and R24 at a frequency of 1000 Hz. The average T30 at 500 Hz is 1.45 s, and the 1000 Hz is 1.35 s. It demonstrated averaged RT at 500 Hz achieved acceptable tolerance, yet; it shows insufficient RT at 1000 Hz. The current range of simulated RT results may suit the function relative to a recital or semi-classical concert; however, to achieve the average optimum range for a multi-purpose hall, it is essential to reach 1.6 to 1.8 s. However, the results show that raising the over RT, especially at high frequency, is required to achieve better hearing pleasure for multi-purpose hall usage.

Table 4. Acceptable values of criteria applied to DTC for multi-purpose hall assessment

Criteria	**Optimum range**	**Tolerance range**
Reverberation time (s)	1.6 – 1.8	1.4 – 1.6 & 1.8 – 1.9

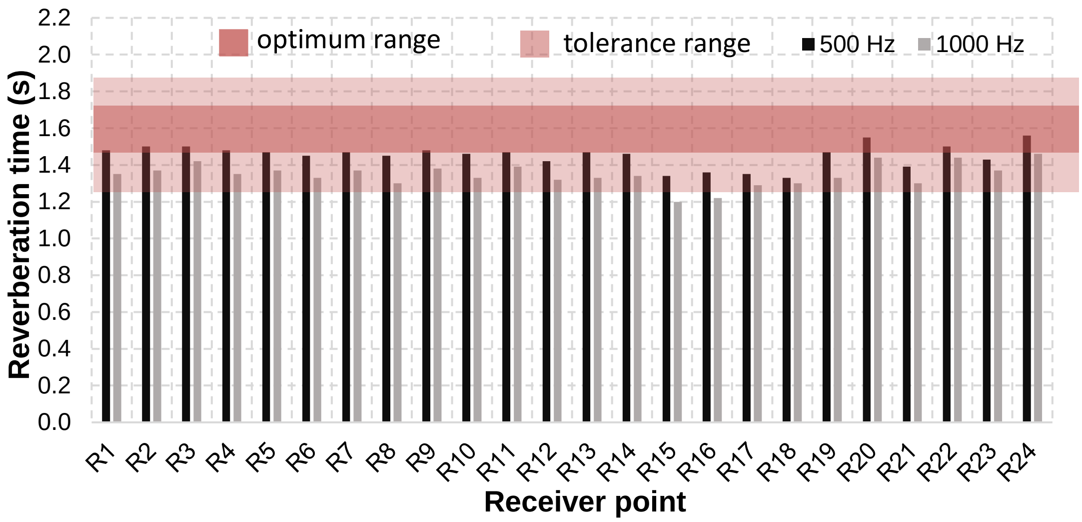


Figure 6. Comparison of T30 simulated results in the different receiving points with optimum and tolerance range reverberation time at 500 Hz & 1000 Hz

From the viewpoint of auditory sensation, harmoniously, for loudness level to attenuate uniformly over the frequency range, the high and low frequencies reverberation time must be longer. However, it becomes short at high frequencies because of air absorption, which is a condition in that sounds are usually heard [17]. Therefore, if the reverberation at high frequencies is made long, the acoustic environment feels unnatural. Also, to reduce the percentage articulation of speech, a shorter reverberation at low rather than mid frequencies is preferred.

The overall absorption area and room volume determine the reverberation time in a room. Room volume has a direct relationship with its RT value. As room volume increase, RT increase. Next, RT relies on the total absorption area. In order to achieve optimum reverberation time, it requires raising the current RT value. Absorption area or value may need to reduce whereby the room volume is fixed, and hard to expand the volume size to achieve a longer reverberation time.

Speech Transmission Index (STI)

Sufficient acoustic quality of speech communication is essential in many different situations and places; classrooms in schools, auditoriums, multi-purpose halls, etc. Speech transmission index (STI) is an objective method for the prediction and measurement of speech intelligibility

According to Figure 7, the lowest STI simulated value of 0.54 at R2 can be considered fair in the speech transmission index. Meanwhile, all STI simulated values were compared at each receiver position in the room model; a higher value of STI was found in R11 and R12, both receiver points located on the balcony with low ceiling condition. Additionally, the two receiver points are near to the location of sound sources P11 and P12. Therefore, a better STI simulated value was found when the receiver is near the sound source.

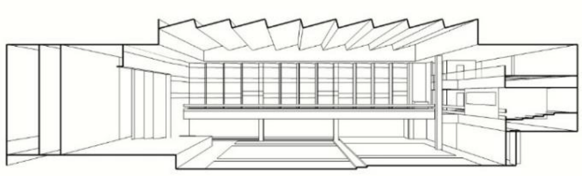
Generally, it is noticeable that some of the point receivers away from the sound source have lower STI values at the center of the multi-purpose hall. However, the average of all receiver points concluded the STI value of 0.62, which generally achieved the good in STI.

Based on the ODEON simulation, the STI value on the balcony area is better than the STI below the balcony, and the direct sound source impacts the receiver. Furthermore, the location of the sound source influences the STI value, whereby better STI value increase when it is appropriate near the sound source, and it decreases with the distance from the sound source. Thus, the current acoustic performance of DTC as a multi-purpose hall fulfils partially of optimum acoustic criteria whereby it achieved good value in averaged STI. However, in terms of RT, the current condition is only best for music and performances.

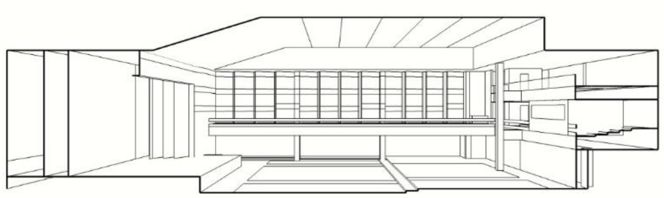
Figure 7. Comparison of STI results at the different receiving points.

Simulation 2: Proposed Acoustic Performance in Dewan Tunku Canselor (DTC) Reverberation Time (RT)

The first simulation of the experiment summarized that the present acoustic performance of DTC is equally acceptable in STI. However, the results gained from reverberation time T30 show that it did not achieve overall balance in speech and musical performance criteria. Therefore, even though it demonstrates a good performance for speech activity, it can conclude that the value of reverberation time needed to be increased for achieving the functionality in musical performance and having optimum hearing experience for a multi-purpose hall.



O	Original room model

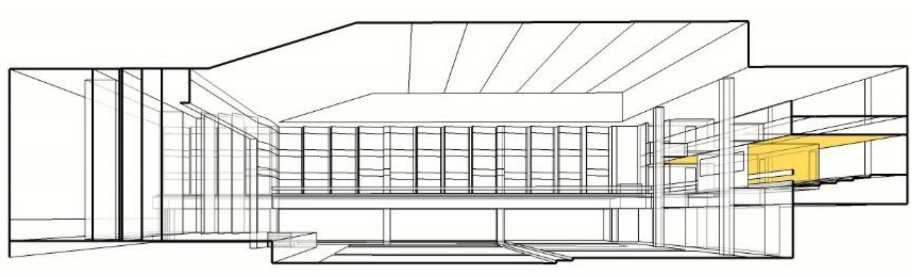


A1	Single sloped and increase height ceiling

Figure 8. Section drawings of existing DTC room and modification

Material	50mm Fabric panel with wool infill

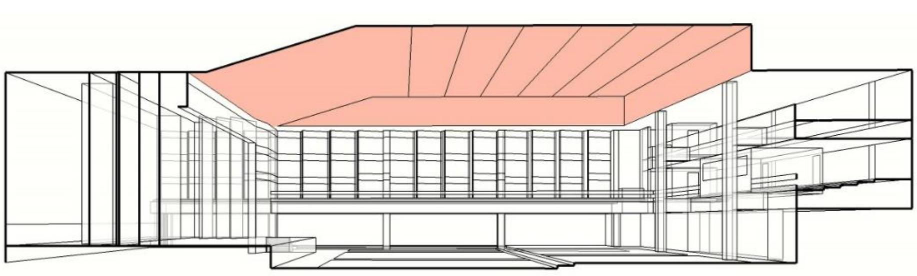
Room model



Frequency (Hz)	250	500	1000	2000	4000
α	0.72	0.53	0.42	0.62	0.55

Material	Plasterboard on frame, 13 mm boards, 100 mm empty cavity

Room model



Frequency (Hz)	250	500	1000	2000	4000
α	0.11	0.05	0.03	0.02	0.03

Figure 9. The sound absorption coefficient of materials applied in modification room model A1

According to the basic theory and equation of reverberation time, the Sabine formula identifies the two main parameters on which reverberation time depends. First, in order to increase reverberation time according to the formula, the room volume needed to be increased. Hence, modifications on the ceiling design and height (Figure 8) are a wise solution, and at the same time, it provides weaker early reflection. Next, the material's total room absorption can be reduced to achieve a longer reverberation time.

An alteration model was made based on the theoretical lengthening reverberation time by increasing the room volume. The modification in room model, A1, shows a single sloped follow with a raised flat ceiling conducive to poor early reflection and resulted in long reverberation time in theory. This model is used to evaluate the relationship between high volume ceiling and acoustical performance. This experiment's sound source and receiver position remain in the same setting as the original model (O). Most of the materials' properties remain similar to the previous simulation except for the new elevated ceiling, surrounded wall, and ceiling above R11 and R12. Figure 9 represent the changes and modification of material applied in room model A1. Using a 50 mm fabric panel with wool infill to replace the original plasterboard on the ceiling reduces the high reverberation time in a low volume under-balcony space. In addition, by increasing the (A) absorption coefficient, the reverberation time can be reduced.

Table 5. Comparison RT result of the original model and modification model of DTC.

Room Model	Average Reverberation Time, T30 (s)			
	Frequency			
	250	**500**	**1000**	**2000**
O	1.72	1.45	1.34	1.29
A1	1.62	1.74	1.80	1.53

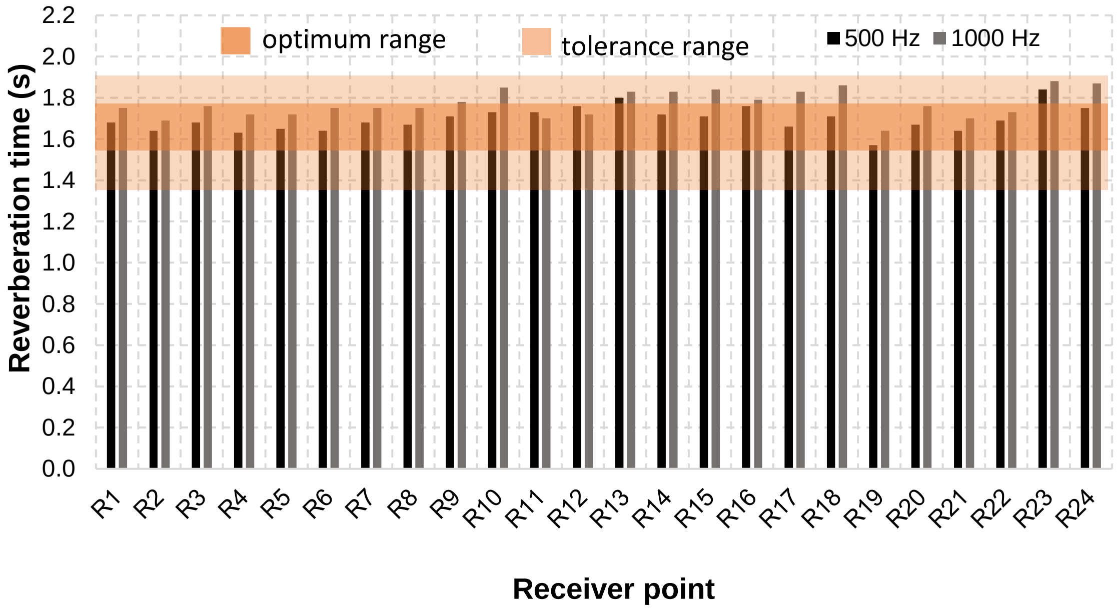


Figure 10. Comparison of T30 simulated results of different receiving points in modification room model A1 with optimum and tolerance range at 500 Hz & 1000 Hz.

The T30 results are shown in Table 5 across four-octave bands (250 Hz - 2000 Hz). In Table 5, room modification of A1 shows significant improvement in the reverberation time. The RT value across four-octave bands was relatively increased except at 250 Hz. Overall, the averaged RT of Simulation 2 gains better reverberation time compared to the original room model.

As mentioned earlier, reverberation time in a multi-purpose hall is considered optimum, essentially ranges from 1.6 to 1.8 s, with the tolerance range from 1.4 to 1.9 s. Figure 10 shows that all receivers achieved tolerance range or improved reverberation time for a multi-purpose hall. Furthermore, receivers R1 to R9, R11, R12, R16, and R20 to R22 have significantly reached the optimum range of reverberation time in both 500 Hz and 1000 Hz.

Speech Transmission Index (STI)

Table 6 shows that the A1 room model slightly declined averaged STI compared with the original room model based on the simulation. Theoretically, speech intelligibility decreases with decreasing direct-to-reverberant ratio. If the signal-to-noise ratio conditions are constant, intelligibility scores increase with a decreasing time for reverberation [18]. The increase in overall volume for room model A1 has lengthened the reverberation time while also causing the STI to decrease. However, the decline of STI from 0.62 to 0.60 s generally still fall under good performance in the STI.

Table 6: Comparison of STI result of the original model and modification model of A1.

Room Model	Average Speech Transmission Index, STI
O	0.62
A1	0.60

CONCLUSIONS

The primary purpose of investigating the acoustical performance of Dewan Tunku Canselor (DTC) as a multi-purpose hall for speeches and musical performance has been performed by a series of simulations. Several original and modification room models' simulations demonstrate that fine adjustment can improve acoustic performance in achieving optimum range reverberation time cause mainly by increasing the room volume and adjusting the material absorption coefficient. The modification room model results showed increment of almost 17% in 500 Hz and 26% in 1000 Hz. Also, almost 3% increment can be found in STI result compared to original model. For comparisons to selected parameters, simulations were done in both room models, providing a credible understanding of good acoustic performance based on the recommended criteria. Further simulations and measurements in different parameters are now being pursued intensively.

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REFERENCES

[1] M. A., Zuraini, “Rehabilitation of the Tunku Canselor Hall, University of Malaya, Kuala Lumpur, Malaysia”, The ICOMOS & ISPRS Committee for Documentation of Cultural Heritage CIPA 2003 XIXth International Symposium: New Perspectives to Save Cultural HeritageAt: Antalya, TurkeyVolume: XIX, 2003.

[2] M. Barron, and K. Sven, "A possible acoustic design approach for multi-purpose auditoria suitable for both speech and music." Applied Acoustics, 115, 42-49, 2017, doi.org/10.1016/j.apacoust.2016.08.018

[3] M, Cairoli, "Architectural customized design for variable acoustics in a multipurpose auditorium." Applied Acoustics, 140, 167-177, 2018, doi.org/10.1016/ j.apacoust.2018.05.026

[4] H. Z. Alibaba, and M. B. Ozdeniz, "Acoustical Renovation of University Multipurpose Halls: The Case of Lala Mustafa Paşa Hall." Sustainability 11, no. 5: 1397, 2019, doi.org/10.3390/su11051397

[5] M. Cairoli, "The architectural acoustic design for a multipurpose auditorium: Le Serre hall in the Villa Erba Convention Center." Applied Acoustics 173, 107695, 2021, doi.org/10.1016/j.apacoust.2020.107695

[6] M. D., Egan, Concepts in Architectural Acoustics, New York: McGraw-Hill, 1972.

[7] M. D., Egan. Architectural Acoustics, Florida, United States, J. Ross Publishing, 2007.

[8] ISO 9921:2003 Ergonomics – Assessment of speech communication. International Organization for Standardization, Geneva, Switzerland (2003).

[9] Templeton, D. (Ed.), Sacre, P., Mapp, P., Saunders, D., Acoustics in the Built Environment. Oxford: Butterworth-Heinemann Ltd. 140-142, 1993.

[10] H. J., Steeneken, and T. Houtgast. "A physical method for measuring speech-transmission quality." The Journal of the Acoustical Society of America 67.1, 318-326, 1980.

[11] C. L., Christensen, and G. Koutsouris. "ODEON room acoustics software version 12." Basic, Industrial, Auditorium and Combined Editions, 2013.

[12] S. Siltanen, T. Lokki, L. Savioja, and C. L. Christensen, “Geometry reduction in room acoustics modeling”, Acta Acustica united with Acustica, 94(3), 410-418, 2008, doi.org/10.3813/AAA.918049

[13] J. S. Bradley, H. Sato, and M. Picard, “On the importance of early reflections for speech in rooms”, The Journal of the Acoustical Society of America, 113(6), pp.3233-3244, 2003.

[14] N. A., Abd Jalil, B. C. D., Nazli, N. Keumala, and A. S. Razak, “Effect of model simplification through manual reduction in number of surfaces on room acoustics simulation”, Journal of Design and Built Environment, 19(3), 31-41, 2019.

[15] P. H. T., Zannin, and D. P Z., Zwirtes. "Evaluation of the acoustic performance of classrooms in public schools." Applied Acoustics 70.4, 626-635, 2009.

[16] F. M., Sharaf, "An Approach to Improve Acoustic Performance in Multipurpose Halls." Journal of American Science 10.3s, 2014.
[17] Z. Maekawa, J. Rindel, and P. Lord, Environmental and architectural acoustics. CRC Press, 2010.
[18] W. Yang, and J. S. Bradley. "Effects of room acoustics on the intelligibility of speech in classrooms for young children." The Journal of the Acoustical Society of America 125.2, 922-933, 2009.