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A Comparison of Acoustical Performance Between Traditional and Modern Church

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Abstract: Due to various worship approaches, churches' plans and designs have evolved over time. In traditional churches, the chancel is where the preacher and choir are while the nave is where the audience is seated. The modern churches on the other hand usually follow the auditorium layout, where the chancel is replaced by a stage. The stage serves as a space for the musical worship and performances, other than preaching by the pastors. In acoustical terms, the chancel and the stage are known as the sound source and the audience is the sound receiver. It is essential to understand the relationship between the differences in the characteristics of traditional and modern churches and the impact on their acoustical performance. Two churches with different layout (cruciform and rectangular) from traditional and modern churches in Malaysia were selected to run a computer simulation using ODEON Room Acoustic Software. The results were then reviewed and analyzed in acoustical parameters: (i) Reverberation Time (RT) and (ii) Speech Transmission Index (STI). Smaller church scored better in STI thus it is better for speech driven worship service as while bigger church scored better in RT thus it is more ideal for musical worship. In addition, the existing materials found in modern churches improved the overall acoustical performances. In conclusion, the church acoustical performance is affected by factors like the volume, distance between the sound origin, receivers and the surrounding walls, total absorption area and types of surface material and its absorption coefficient.

Keywords: Church, acoustics, speech intelligibility, speech transmission index, reverberation time

1. Introduction

Churches play an important role as a great social building worldwide and they have a special design language. In the beginning, as stated in the Book of Acts, Christians have been gathering in private houses before the existence of churches during the first century [1]. There was a transitional period during the tetrarchy (293 - 312 CE) when the congregation size surpassed the limited space of private homes, resulting in the needs of non-residential architectural buildings for these Christian communities, namely warehouses or municipal halls [2]. There was a turning point in church architectural design and construction in the fourth century.

Churches are built as religious places of worship and they have a complex challenge when it comes to acoustical design. From mosques to churches, acoustic comfort is regarded as an important consideration in historic religious buildings [3]. Room acoustics is a fairly new field of study. The top priorities of classical room acoustics are optimal music perception verbal communication [4]. Since its introduction (Sabine 1868 - 1919) more than a century earlier, experimental evidence established by Schroeder, Beranek, Barron, Ando, and Bradley have supported very accurate

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variables for the room acoustics of concert venues and auditoriums in regard to the ideal environments of the audience to be ascertained [5]. Churches provide a diversified purpose acoustically. Their environments must accommodate both speech and music, which appear to be conflicting at times [6].

As most churches' liturgy consists of chanting for the majority of the service, singing is the dominant mode of sound transmission in Eastern Orthodox churches. The massive Cathedrals of Catholics in the Roman Empire, primarily during the Renaissance, featured acoustic conditions with a significant reverberation for instrumental worship and singing. Unlike modern churches, ancient churches and temples needed fewer reverberation rooms as their congregational activities were primarily focused on preaching and biblical studies [7].

The Protestant Reformation began in early 1517, leading to the destruction of the Roman Catholic Church's hierarchical structure in Western Europe and to the revolutionization of a new division of Christianity. Ever since the beginning of this century, speech intelligibility has thus become crucial compared to the previous medieval cathedral for the acoustic performance of worship services [8]. In the early 1940s, more churches were constructed in remote areas, resulting in less concern for noise control [9]. The new project soon seemed to be financially successful due to the affordable types of materials used. The people, however, began to realize that they required better acoustical equipment.

As the church begins to expand in size, bigger musical equipment is required, and a bigger space is needed to satisfy the growing crowds. This resulted in a few elements of church design having started to differ. In addition, contemporary musical instruments and electronic devices, for instance, electrical guitar, keyboards, drum sets are required on the top of the existing traditional pipe organs. All these considerations resulted in making the right investment in achieving good acoustical performance of the churches and to create the need for acoustics experts to fit these systems properly [7].

As time passes, the modern churches comprise several activities based on the congregational style of the church. For instance, the scale of Roman Catholic cathedrals increased, resulting in high reverberant acoustic environments for worship music and chants [10]. However, these cathedrals do have to perform the task of delivering God’s message and speeches, which require a greater need for intelligibility of speech. It is critical to generate appropriate speech communication that can be clearly understood from any seating arrangement in the church; or else, members will experience isolation. Everyone in the prayer service should be experiencing the same acoustical environment since everyone is considered same in God's temple [10]. Thus, it is a challenge for acoustical design in churches as there needs to be a balance between both good speech intelligibilities in the sermon and instrumental worship [11].

Poor acoustic parameters, which contribute to bad speech communication, generate two major issues. First, they decrease learning performance. Second, they could cause tiredness, anxiety, and health concerns (headaches and sore throats) within pastors who are required to adapt for inadequate acoustic environments by increasing their volume, for instance [12]. The quality of oral communication can be measured by the ‘speech intelligibility’. This figure represents the percentage of spoken content effectively understood by the average audience. It has been recommended that speech intelligibility should exceed 97% for ordinary people working in their first language. According to research, the reverberation time for ordinary people should be lower than 0.7s in order to achieve 100% speech intelligibility [12].

It is the fact where churches have been evolving even until today according to its congregational style and additional function such modern worship. Hence, church layout design needs to take into consideration all its functions in order to achieve a good acoustic quality. A systematic parametric study is constructed to perform the analysis of acoustical performance for traditional and modern churches. In addition, other design characteristics such as material and acoustical system found in the modern churches will be included. The acoustical performances will be simulated using computer software simulation and results will be reviewed and analyzed according to the parameters: i) Reverberation Time (RT) and ii) Speech Transmission Index (STI). These criteria will help to determine the acoustical performance of the churches.

1.1 Reverberation Time (RT)

In a confined environment, sound will echo through the room for a period of time even after the origin has ended producing energy [10]. Reverberation time (RT) is defined as the time taken for the sound level to drop by 60dB after the sound source has ceased. According to Fig. 1, RT between 1.2 to 2.6 seconds to is recommended for churches and cathedrals depending on their liturgy style. Table 1 showed some results of RT in relation to the volume based on studies done by [6], [13]- [15]. For modern church worship, the optimum RT is between 1.2-1.6 seconds (concert using sound system). A lower RT is needed for speech intelligibility [16].

1.2 Speech Transmission Index (STI)

The Speech Transmission Index (STI) is a tool used to analyze the intelligibility and efficiency of speech transmission in a room. The highest STI index is 1, indicating the best speech intelligibility, while index close to 0 indicating a poor speech intelligibility [18].

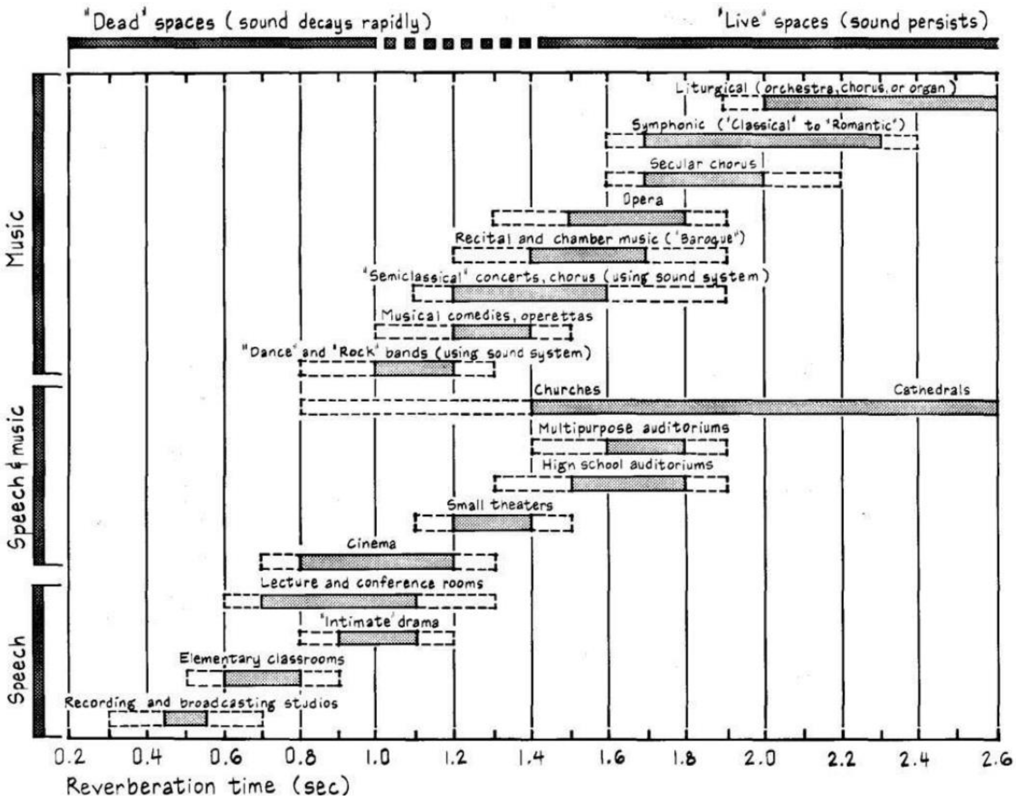


Fig. 1 - Recommended reverberation for various room and function [17]

Table 1 - Results of reverberation time in relation to the volume in various case studies

No.	Church	Location	Denomination Architectural Style	Volume (m³)	Mean Reverberation Time T30, (s)		Reference
					500Hz	1000Hz	
1	Santi Luca e Martina	Italy	Baroque	10000	3.3	-	[6]
2	San Lorenzo	Italy	Baroque	12000	4.1	-	[6]
3	Sant'Agnese in Agone	Italy	Baroque	14500	5.0	-	[6]
4	St. Pius C	Italy	Catholic	3000	4.95	4.73	[14]
5	Roman Catholic Diocese Church	Jordan	Catholic	5457	2.25	2.08	[15]
6	Fille-Dieu	Switzerland	Catholic	5600	4.65	4.20	[13]
7	St. John	Portugal	Catholic	6048	3.31	3.22	[13]
8	Sacred Heart of Jesus Church	Jordan	Catholic	7326	2.35	2.20	[15]
9	Sacre-coeur	Switzerland	Catholic	9137	6.83	6.47	[13]
10	Fossanova Abbey	Italy	Gothic	17000	6.6	-	[6]
11	Messianic Church	Brazil	Modern/ contemporary	993	1.20	-	[6]
12	Church of São Carlos Borromeu	Brazil	Modern/ contemporary	2100	1.35	-	[6]
13	Church of Santa Maria Assunta	Italy	Modern/ contemporary	6300	6.3	-	[6]
14	Church of San Giovanni Battista	Italy	Modern/ contemporary	9000	7.7	-	[6]
15	"Dives in Misericordia" Jubilee Church	Italy	Modern/ contemporary	10500	7.3	-	[6]
16	Bom Jesus dos Perdões	Brazil	Neogothic	5501	4.61	-	[6]
17	Romanel	Switzerland	Protestant	477	1.75	1.84	[13]
18	Cheseaux	Switzerland	Protestant	575	1.75	1.84	[13]
19	Lutheran Good Sheperd Church	Jordan	Protestant	1024	2.30	2.05	[15]
20	Pasquart	Switzerland	Protestant	4472	2.74	2.77	[13]
21	Sacra di San Michele	Italy	Romanesque	7000	5.0	-	[6]

Fig. 2 - Speech Transmission Index and Common Intelligibility Scale [25]

2. Research Methodology

The aim of this research is to perform the analysis of acoustical performance for traditional and modern churches through a systematic parametric study. A total of four churches were selected to run a simulation to identify the current level of acoustical performance of traditional and modern churches.

One of the earlier literature reviews on room acoustic modeling was released by Schroeder [19]. This research focuses on music hall auralization, which was utilized for renovation, and suggested that computer technology will transform the architecture of music halls. As highlighted by Naylor [20], there was a surge in room acoustic modeling development in the early 1990s. Most of the existing industrial modelling software, such as ODEON, CATT-Acoustic and EASE were developed in that period. Since then, many published studies have proposed innovations in modeling techniques, as well as case studies focused at verifying such techniques [21].

2.1 Churches Selection

To investigate the characteristic of the acoustical performance in traditional and modern churches, two churches with different layout (cruciform and rectangular) from traditional and modern churches in Klang Valley, Malaysia were selected. The churches chosen had a total capacity of less than 1000 audience, which is typically ideal for churches that use purely natural sound sources [17]. The churches selection also took into consideration the congregation's capacity to ensure a fair comparison between the traditional and modern churches.

Table 2 - Summary of churches' physical measurements.

No.	Church	Abb.	Hall Dimension (m)			Calculated Parameter	
			Length	Width	Height	Volume, V (m^3)	Number of Seats
1	Traditional Church A	TCA	40.22	11.58	10.90	3887.58	600
2	Traditional Church B	TCB	31.05	8.48	12.52	2213.68	280
3	Modern Church A	MCA	36.26	24.19	9.37	5842.69	650
4	Modern Church B	MCB	18.82	12.70	4.20	1234.56	250

2.2 Churches Modeling

First, the floor plans of various churches were collected. The plans of churches TCA and TCB were all referenced from the Measured Drawings completed by the students of the Faculty of Built Environment, Universiti Malaya that is stored in the Faculty Library's Archives. Whereas plans for churches TCB and MCB were obtained from the staff in Modern Church A & B with permission from the pastor. The churches were then modelled into 3-dimensional drawings using the SketchUp 3D software. SketchUp software was chosen because of its compatibility with the requirements ODEON. In the 3D modelling design, architectural details such as ornaments, cornice, framing etc. were excluded as it does not create significant impact to the audience [22], [23].

Once accessed in ODEON, the water tightness test is run to check if there is any "opening" found the model. This step is important to ensure the model is properly modelled and enclosed to minimize error, hence getting a more accurate result. The churches were designed and modelled according to the ODEON instruction manual in order to minimize the error hence obtaining the best outcome:

- X-axis directed towards the congregation
- Y-axis directed to the right as seen from the congregation
- Z-axis pointing towards the top

2.3 Materials Assignment

The surfaces of the churched models need to be assigned with the material, which can be done using ODEON software itself. The software comes with a series of materials in its library, which contains data such as the material absorption coefficient in different frequencies. Two different simulations were carried out to evaluate the relationship between different surface materials, different sound sources, RT, and Speech Intelligibility, by using ODEON Room Acoustic Software 16.02 Industrial version. In the first set of simulation, the materials used were standardized in all churches as a constant variable for avoiding the significant differences of materials used in order to identify the acoustical impact of the different church layouts. While in the second set of simulation, existing materials such as acoustic panels, carpet and fabric seats found in modern churches were assigned to identify the actual condition of the modern church acoustical performance.

Table 3 - Summary of churches geometry, plans and sections

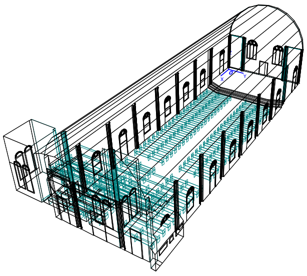
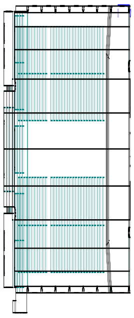
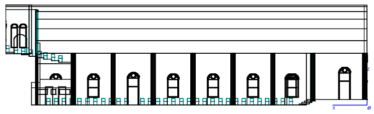
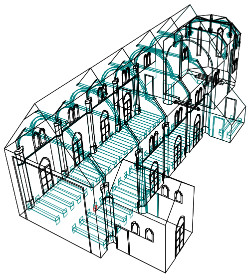
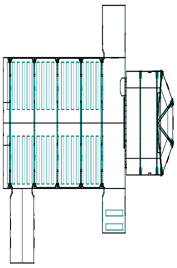
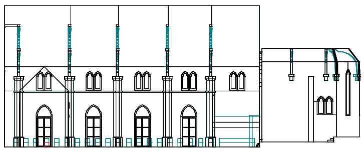
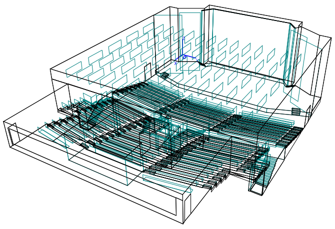
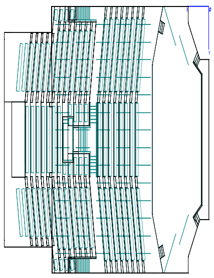
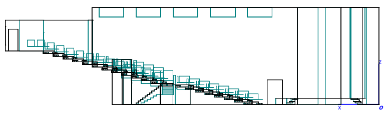
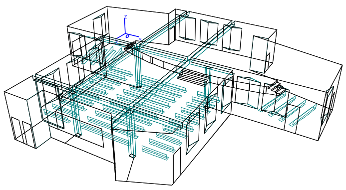
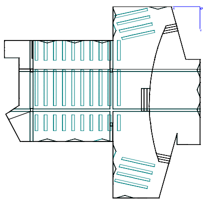
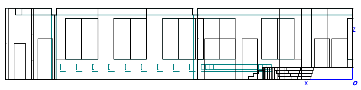
Abb.	Church	Plan	Section
TCA	Traditional Church A 		
TCB	Traditional Church B 		
MCA	Modern Church A 		
MCB	Modern Church B 		

Table 4 - Sound absorption coefficient of standardized materials assigned in all churches, first set of simulation.

Building Component and Materials Assigned	Frequency, f (Hz)			
	250	**500**	**1000**	**2000**
Floor: Material 2003, ceramic tiles. Perforation = 12%. mineral wool in cavity	0.44	0.68	0.79	0.56
Wall: Material 1005, smooth brickwork, 10mm deep pointing, pit sand mortar	0.09	0.12	0.16	0.22
Ceiling: Material 4053, perf. 27 mm gypsum board (16%), d= 4.5mm 300mm from ceiling	0.55	0.60	0.90	0.86
Concrete column: Material 103, concrete block, painted	0.05	0.06	0.07	0.09
Chair: Material 110033, audience on wooden chairs, 1 per sq. m	0.24	0.56	0.69	0.81

Window: Material 10006, glass, ordinary window glass	0.25	0.18	0.12	0.07
Door: Material 10007, solid wooden door	0.10	0.06	0.08	0.10

Table 5 - Sound absorption coefficient of existing materials found in modern churches, second set of simulation

Building Component and Materials Assigned	Frequency, f (Hz)			
	250	**500**	**1000**	**2000**
Acoustic panel: Material 12300, 15mm hard preset mineral fiber plate	0.61	0.64	0.75	0.91
Curtain: Material 8006, curtain (0.2 kg/m2)	0.06	0.39	0.63	0.70
Carpet: Material 7004, carpet heavy on concrete	0.06	0.14	0.37	0.60
Fabric seats: Material 11007, audience, heavily upholstered seats	0.8	0.86	0.89	0.90

2.4 Define Sound Sources and Receivers

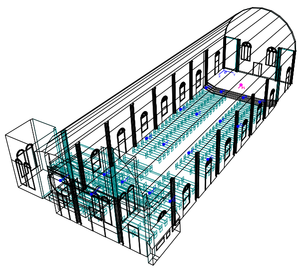
In the first and second simulations, a single sound source point was assigned at the center of the stage using the sound of a natural raised sound (BB93_RAISED_NATURAL.SO8) in ODEON software. Natural raised sound was chosen to illustrate the preaching session by a pastor in a church without using sound reinforcement systems. The sound source was placed at 1.5m height as the mouth height of a typical person [17]. In the third simulation, two sound sources (Loudspeaker SLS_LS8800) are installed at 6m height at R2 and 3.6m height at C2, following the actual loudspeaker system installed in both modern churches.

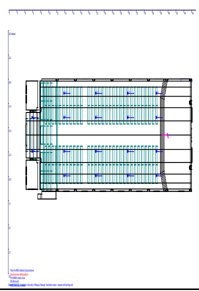
The receivers were spread across the hall in a uniform position. In general, the halls of the churches were categorized into three zones: left, center and right. Each zone was divided into front, middle and rear rows. Table 6 shows the arrangement of the sound origin and recipient for the churches.

Table 6 - Sound source (red dot) and receivers (blue dots) positions in the churches

Church — **Sound Source and Receivers Points**

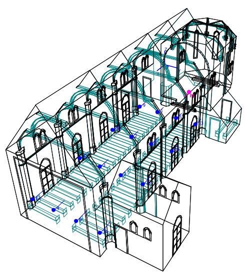
TCA: Traditional Church A

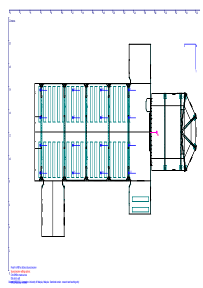




Source (x, y, z)	Receivers (x, y, z)			
	R1	R2	R3	R4
6.00, 5.80, 1.50	8.80, 4.00, 1.20	16.00, 4.00, 1.20	24.00, 4.00, 1.20	32.00, 4.00, 1.20

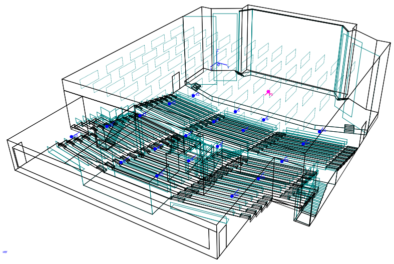
TCB: Traditional Church B

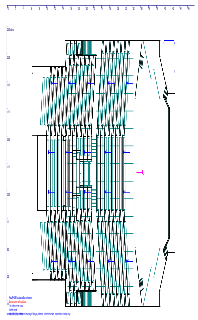




Source (x, y, z)	Receivers (x, y, z)			
	R1	R2	R3	R4
7.50, 7.68, 1.50	12.90, 6.40, 1.20	18.30, 6.40, 1.20	23.70, 6.40, 1.20	30.00, 6.40, 1.20

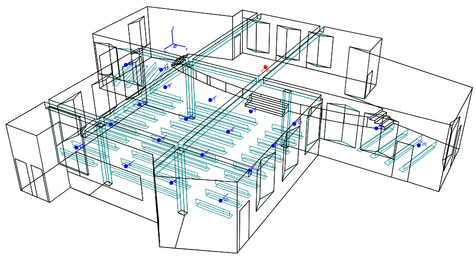
MCA:
Modern
Church A

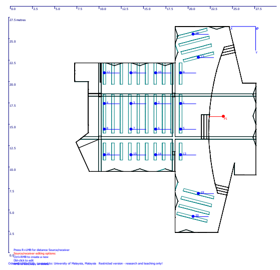




Source (x, y, z)	Receivers (x, y, z)			
	R1	R2	R3	R4
8.00, 12.00, 2.10	12.80, 10.20, 1.20	17.60, 10.20, 2.40	22.80, 10.20, 3.50	27.60, 10.20, 4.80

MCB:
Modern
Church B





Source (x, y, z)	Receivers (x, y, z)			
	R1	R2	R3	R4
3.60, 10.50, 1.90	8.40, 9.00, 1.20	11.20, 9.00, 1.20	14.00, 9.00, 1.20	17.00, 9.00, 1.20

3. Results and Discussion

3.1 Reverberation Time (T30)

Since conducting a thorough acoustic measurement survey in occupied scenarios would be quite challenging, the impact of occupancy on acoustical parameters is commonly studied using acoustic simulation software applications. There are just a few studies analyze the impact of occupancy, and usually they are referring to smaller areas [24]. The findings were reviewed and analyzed using the reverberation time (T30) parameter at various frequencies, but mainly focusing at 1000Hz as it is the frequency where human ears are most sensitive to [25]. According to [17], a good RT value for churches and cathedrals is between 1.4s to 2.6s, while 0.8s to 1.4s is considered a fair value.

Based on Fig. 3, MCA had the best RT compared to three other churches with a value of 1.48s at 1000Hz. TCA and TCB had RT values of 0.74s and 0.64s respectively, close to fair value of 0.8s while MCB did not achieve good or fair value across all frequencies. MCA has twice the RT value at 1000Hz compared to TCA due to its 50% bigger volume despite having the same type of layout. This shows that the RT is greatly impacted by the room's volume, which is shown by Sabine's formula of RT, T = 0.161 (volume/ total sound absorption area). Thus, as the room's volume increases, the RT increases as well.

Both modern churches with existing materials (MCA2 and MCB2) assigned had lower RT values across all frequencies compared to standardized materials (MCA and MCB) as shown in Fig. 4. This showed that the existing materials such as carpet, curtain, acoustic panels, and fabric seats absorb sound better compared to the materials like ceramic tiles and wooden seats used in traditional churches. MCA2 had RT value 1.20s at 1000Hz, which is in the range of good RT value for musical comedies and concert using sound system. This value proved that the existing materials were designed to cater for the modern church demand, which focus on the live band worship session. MCB had an RT value of 0.45s with existing materials, with a difference of just 0.05s at 1000Hz, due to its smaller volume compared to MCA.

In general, the value of reverberation time, RT of all churches decreased as the frequency increased from 250Hz to 2000Hz. Based on Fig. 5, MCA3 had a lower RT value compared to MCA2. This was mostly due to the position of the loudspeakers facing directly to the acoustic sponges hung on the ceiling, causing some sound energy to be absorbed by the acoustic sponges, thus resulting in lower RT value. In the MCB2 and MCB3, the biggest RT value difference was only 0.03s at 1000Hz. This explained that in a smaller volume of building, both sound sources had very insignificant impact in RT. Some recommended alterations such as applying absorptive treatment of the rear wall and installing scattered elements on the side walls to reduce echoes may improve the acoustical performance [26].

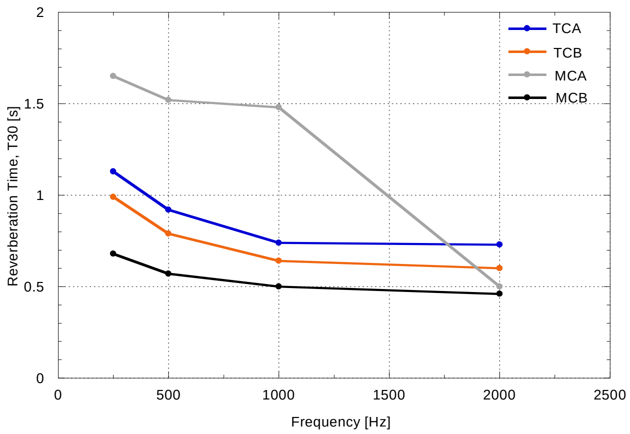


Fig. 3 - Reverberation Time (T30) between churches with standardized materials (Sound source: BB93_Raised_Natural)

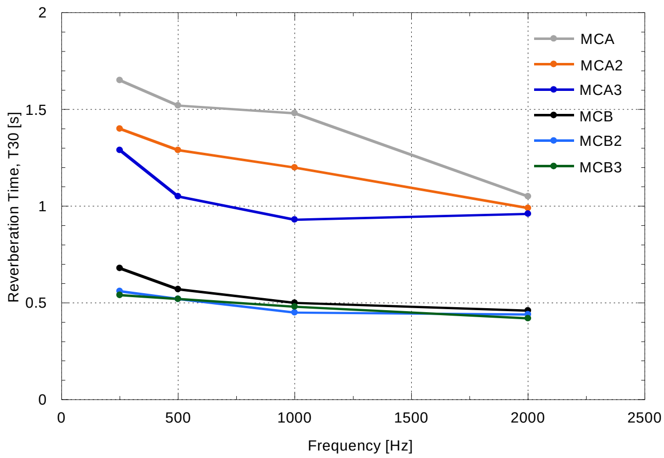


Fig. 4 - Reverberation Time (T30) between modern churches with existing materials in BB93_Raised_Natural and Loudspeaker SLS_LS8800

3.2 Speech Intelligibility

Fig. 5 and Fig. 6 showed the Speech Transmission Index, STI values in three different simulation settings, from raised natural sound in standardized materials across churches, to existing materials and loudspeaker system used in modern churches. It has been recommended that speech intelligibility should achieve 97% for ordinary people working in their first language. The speech quality is determined by the speaker's speech volume, the spacing between the speaker and the audience, and the room's acoustic performance [12]. According to [18], the highest STI index is 1, indicating the best speech intelligibility.

MCB had the best overall STI value, this showed that smaller churches tended to achieve a better speech intelligibility compared to larger churches due to shorter distance between sound origin and recipients. According to STI Scale, all churches TCA, TCB, MCA and MCB fell under “good” category, with the average value between 0.63 to 0.73. MCA had the lowest minimum STI value among all churches, with a value of 0.54, which is under “fair” category. It explained why a modern wide hall lateral reflection for most listeners is weak (and late arriving) compared to frontal sound from the stage and ceiling [27].

Based on Fig. 6, both MCA2 and MCB2 had a higher average STI compared to MCA and MCB, which explained that the existing materials help to achieve a better speech intelligibility. In both churches, the maximum STI value was found in the front area which is closer to the sound source. The average STI values of all churches were higher than 0.6, which made both churches in a “good” category. The existing materials further increased the STI value of MCB from 0.73 to 0.76, making it fall under “excellent” category.

In addition, both MCA3 and MCB3 have a higher average STI value compared to MCA2 and MCB2, which illustrated that the loudspeakers help to achieve a better speech intelligibility in the churches. The loudspeaker in MCA3 helped the church to achieve the average STI value of 0.75, making it in "excellent" category. In the smaller church, the loudspeaker helped to increase the average STI value from 0.76 to 0.78. From the result, it was evidence that the loudspeaker is essential to improve the speech intelligibility in churches, which helped the audience to understand and enjoy the sermon and message delivered by the pastor. Apart from obtaining all scientific measurements of the acoustic characteristics, it is advised that the results be correlated to human perception of acoustic quality via surveys [28].

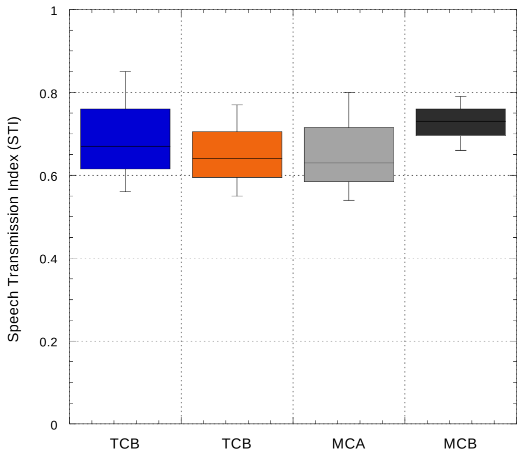


Fig. 5 - Speech Transmission Index, STI between churches with standardized materials (Sound source: BB93_Raised_Natural)

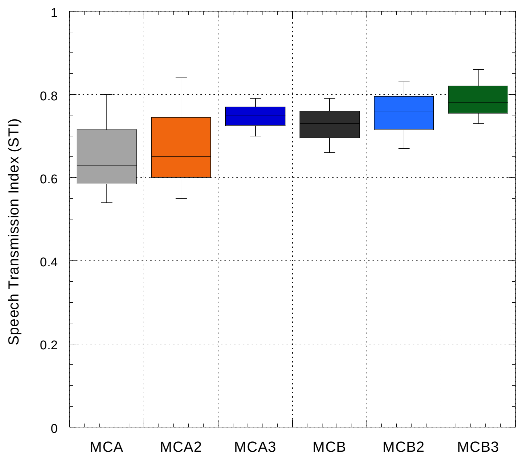


Fig. 6 - Speech Transmission Index, STI between modern churches with existing materials in BB93_Raised_Natural and Loudspeaker SLS_LS8800

4. Conclusion

In this study, various simulations were run to understand the relationship between the difference of both traditional and modern churches characteristics and the impact on their acoustical performance. Based on the results, smaller church scored better in STI thus it is better for speech driven worship service as while bigger church scored better in RT thus it is more ideal for musical worship. In addition, the existing materials found in modern churches improved the overall acoustical performance. Thus, the church acoustical performance is affected by factors like the volume, distance between the sound origin, receivers and the adjacent walls, total absorption area and types of surface material and its absorption coefficient.

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