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EFFECTS OF STRUCTURAL OPENINGS ON ACOUSTIC PERFORMANCE IN CONTEMPORARY MALAYSIAN PROTESTANT CHURCHES ACROSS VARYING ENVIRONMENTAL CONTEXTS

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ABSTRACT

This study examines the influence of structural openings and the surrounding on the acoustic properties of contemporary Protestant churches in Malaysia. The lack of adequate natural lighting and ventilation in numerous modern Protestant churches can adversely impact the worship experience and the building's atmosphere. Poorly planned openings that lead to inadequate ventilation and insufficient natural light may adversely affect congregants' comfort and spiritual experience. This study aims to identify optimal openings and contextual elements for acoustic design in places of worship, balancing practical and aesthetic considerations. Churches with different sizes of openings and surrounding context which are soft landscape and glass facades were stimulated and analyzed. In general, the stimulation of church without surrounding context, the larger the openings, the lower the reverberation time. If the church opening is next to soft landscapes and the sound source is inside the building, larger opening will decrease the reverberation time and vice versa.

Keywords: Structural Openings, Surrounding Context, Sound Parameters, Church Acoustics, Sound Absorbing Materials

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1. INTRODUCTION

Wong, D., & Tien, N. I. (2014) indicated that the study of denominational church history and urban, middle-class, English-speaking congregations has predominated the scholarship on Christianity in Malaysia during the post-Independence era. Malaysian churches are designed in many architectural styles that reflect the nation's varied heritage. Gothic, Romanesque, and modernist architectural styles coexist, each posing distinct acoustic issues. Sound transmission in space is influenced by open floor plans, elevated ceilings, and the prevalent use of hard, reflective materials such as marble and glass. The architectural classification of places of worship is of considerable importance. The history, traditions, and culture of a nation and its populace are encapsulated within them (Domenighini et al., 2023).

Besides, churches and other sacred edifices are erected for architectural and religious purposes. They are influenced by governmental policies, local history, and design trends. It is uncommon for churches, or more broadly, other religious edifices, to be dismantled after their construction. Instead, these buildings are refurbished, expanded, and modified to align with the architectural style of a specific period (Bettarello et al, 2023). The architectural of churches significantly influences the faith of their congregants. Regularly renovating, remodeling, or redesigning a church building is a crucial method for transforming a community's religious lives. On the other hand, St. Paul's Church in Malacca was the first church constructed in Malaysia, established in 1521, and is recognized as the oldest church in Southeast Asia. The ecclesiastical system has evolved from 1521 to the present, accommodating either Catholic or Protestant denominations. In Protestant churches, the engagement between the congregation and the worship team during the praise and worship segment has become paramount throughout Sunday services. A segment of Protestant pastors will interact with the congregation throughout the sermon, while the congregation actively participates in worship inside the contemporary church (Robinson, G. 2020). Furthermore, the church sanctuary is designed to be increasingly enclosed and devoid of natural light, reflecting the growth of the service and reliance on artificial lighting and public address (PA) equipment. As light is a creation of God, churches ought to be architecturally structured to facilitate natural illumination during services, eliminating the need for artificial lighting. Nonetheless, the church's acoustic properties may be influenced by the utilization of reflective or open materials.

The architecture of Malaysian churches is progressing via the amalgamation of traditional and contemporary architectural components. Achieving equilibrium between aesthetic and aural considerations is arduous. Conventional materials such as wood and stone may have acoustic deficiencies despite their favorable appearance. Contemporary materials and technology provide solutions to these challenges; yet they must be seamlessly incorporated into the overall design. A primary research issue in ancient churches is establishing an appropriate acoustic environment due to their complex geometry (Tămaș-Gavrea et al., 2018). Historically, church windows have served as significant architectural features that provide both utilitarian and ornamental purposes. The church windows in medieval Famagusta, Cyprus, exhibited diversity in dimensions, shapes, and ornamentation (Babazadeh Asbagh, N., 2019). A church in Veseloye, Russia, constructed in the ninth and eleventh centuries, featured both colored and unpainted window glass produced using disk-blowing techniques (Armarchuk et al, 2024). The rose window, a hallmark of Gothic cathedrals in the Ile-de-France, functioned as a visual focal point on the church façade (Dow, 1957). Levantine I type soda-lime-silica glass was employed to fabricate the window glass of the Petra Church in Late Antique Jordan with glassblowing processes.

Additionally, Modern Protestant churches have increasingly ceased to incorporate structural openings for natural light and ventilation due to concerns that reflective materials, such as glass, may adversely impact the acoustic quality of their sound systems. Contemporary churches exhibit a more simplistic architectural design. There is a deficiency of research articles and studies regarding the impact of structural openings on the acoustic quality of Protestant churches. Furthermore, there is limited research on how the acoustic quality of a church is influenced by its surrounding setting when structural holes are present.

This research will enhance our comprehension of how structural openings affect the acoustics of churches, taking into account the surrounding context. The findings will guide optimal practices for acoustic design, ensuring that worship rooms are aesthetically appealing and acoustically appropriate for prayer, reflection, and the conduct of religious rites. By improving the acoustic environment, churches can foster a greater sense of connection among parishioners and with God, thereby enriching their spiritual experience.

2. LITERATURE REVIEW

2.1 History of Church Window

According to Reynolds, E. A. (2013), a prominent characteristic of Gothic churches is stained glass. The increasing popularity of stained glass, particularly in the mid-12th century, significantly transformed the public's understanding of religion. The visual depictions of biblical narratives in the window were potentially more impactful than the priest's verbal preaching. Tall, spear-shaped lancet windows and circular rose windows were the predominant stained-glass window styles utilized in Gothic churches. The phrase "rose window" was first employed in the 17th century due to the circular design of the windows, featuring tiered radiating panels that resembled an open rose. Abbot Suger of Saint Denis, known as the "Father of Stained Glass," initially conceptualized the use of stained-glass windows to produce a "heavenly light" regarded as the presence of God in the cathedral. Suger included the concept of heavenly light into his architectural plans and focused the design of the new cathedral on stained glass windows, as he believed Dionysius was the patron saint of Saint-Denis. This novel architectural style, characterized by luminosity, spaciousness, and increasing verticality, was initially exemplified by the Abbey Church of Saint Denis and subsequently developed into the Rayonnant style (Stokstad and Cothren 2011, 494-495). The windows and Gothic sculptures, esteemed as divine illumination, have been referred to be the "poor man's Bible" due to their role in conveying Biblical narratives to the uneducated, so endangering the bulk of the public (Reynolds, E. A., 2013).

Additionally, Hort, G. M. (1916) mentioned that Durandus properly compares the stained-glass windows of a church to the purpose of Holy Scripture. “Just as windows allow sunlight to enter while blocking wind and rain, Scripture illuminates the soul with the light of the True Sun and shields off harmful elements.” The similarity was both real and symbolic; it served as examples of Scripture, imprinting scenes and characters from the Sacred Record into memory. Other than that, Hort, G. M. (1916) also outlined the function of Medieval Church Windows. Two principal theological concepts contributed to the creation of medieval church windows are mentioned which are the intention to provide a sacred ambiance and the pursuit of conveying a religious truth. The former idea was predominant in the East, while the latter prevailed in the West. In Eastern Christendom, the coloring of a church window was permitted to serve as an aim in itself. The "radiance darkly bright" coming from the window served as a catalyst for devotion, giving the worshipper with serenity and sacred reflections. Although a beautiful object, when properly perceived, inherently possesses significance, and each color carries its own sacred interpretation, Western Christendom disagreed with church windows only exhibiting a "sacred hue." They were also required to narrate a sacred story or portray a divine fact.

2.2 Sound Absorption by Tree Barks

Li et al., (2020) demonstrated that, alongside assessing several non-acoustical features, systematic tests were performed utilizing an impedance tube to measure the sound absorption coefficient at normal incidence for the barks of 13 different species. In the frequency range below 1.6 kHz, the absorption coefficients often remain below 0.1. Nonetheless, there exist statistically significant interspecies differences. *Conifers* typically exhibit superior sound absorption compared to broadleaved trees. The majority of species display a reasonably stable and low absorption coefficient below 1 kHz, succeeded by a marked increase with sound frequency. Moss markedly enhances low-frequency absorption.

Among all the tree species examined, *Larix kaempferi* exhibited the highest absorption coefficient. The absorption coefficient is associated with bark thickness, tree age, and two indices of bark roughness. The radial roughness index and tree age seem to be the most significant determinants (Li et al., 2020).

Watanabe et al,. (1996) mentioned that sound energy decreases by absorption as sound waves penetrate vegetation. Sound energy can be seen as scattered through friction with leaf surfaces and transformed into heat energy. The absorption coefficient of trees is theoretically independent of the overall leaf surface area. The transmission of the sound wave is likely obstructed by trees, resulting in non-uniform diffusion within the reverberation room; thus, the absorption coefficient varies according to the total leaf surface area present.

2.3 Sound Parameters

2.3.1 Reverberation

Churches are often huge and filled with materials that reflect sound, making them acoustically reverberant spaces (Iannace et al., 2019). In the church auditorium, reverberation, echo, sound diffusion, and background noise are some of the problems that are frequently observed. The configuration of the seats, the shape and design of the auditorium, and the type of material utilized all work together to improve the auditorium's sound quality. Most auditoriums have reverberation times longer than the permissible one (1) second, which is the amount of time it takes for a powerful sound to become inaudible after it leaves its source.

The sound frequency, form, and space volume all affect this. In many auditoriums, reverberation time is further influenced by the use of reflective materials such as glossy wall surfaces and floor tiles. Reverberation time can be decreased by using absorbing surface treatments like textile window blinds, perforated ceilings, and floor rugs (Alibaba, H. Z., & Itontei, E. E., 2016).

Within a small space, sound waves will continue to reverberate long after the source has stopped emitting energy (Din et al., 2016). The amount of time it takes for the sound level decrease by 60dB following the cessation of the sound source is known as the reverberation time (RT). Depending on the type of liturgy, RT of 1.2 to 2.6 seconds is advised for churches. The ideal RT for contemporary church worship (concert with sound system) is 1.2–1.6 seconds. Measurements can be taken between -5 and -35 dB or between -5 and -25 dB in accordance with ISO 3382. RT is also known as T20 and T30 (Gagliano et al., 2015). The reverberation time is calculated mathematically, assuming a fully linear decline. For speech intelligibility, a lower RT is required (Knudsen, V. O., 1929). Other than that, (Berardi, U., 2012) stated that the early decay time (EDT) value served as a representation of the church's resonance.

Sygulska, A. (2019) mentioned that a room can become lively and reverberant, enhancing music and liturgical involvement as well as authoritative speech, by carefully balancing the proportion of sound-absorbing and sound-reflective materials. Instead, an overabundance of draperies, carpeting, and other sound-absorbing elements can create a lifeless, boring atmosphere that hinders worship and detracts from the inspiration of speech and music. An effective acoustic setting requires a well-chosen ratio of sound-absorbing to sound-reflecting materials, which leads to a suitable RT.

Jones (2013) outlined that the sermon will be less understandable in a church with a pipe organ if the intended RT is set at 2.5 s to 3 s. On the other hand, Sygulska, A. (2023) established that for organ music, a much longer RT is typically anticipated than 3.5 s that is advised for churches with the highest internal loudness. The acoustics that work well for a choir are different from those that work well for a preacher (Cirillo et al.,2007 & Bettarello et al, 2023) but they will nonetheless encourage and support congregational participation (Grace, J, n.d.).

Consequently, acoustics must discover solutions to satisfy the church's liturgical requirements rather than designing liturgical settings (Fleisher, D.,2009). Because of the unique characteristics of religious ceremonies, churches are acoustically complicated spaces that ask for solutions and circumstances that go beyond those used in theaters, opera houses, and concert halls (Fasold, W., & Veres, E., 2016).

2.3.2 Intelligibility

To put it simply, intelligibility is the capacity to comprehend spoken language. It is important to distinguish between audibility and intelligence. It is important for everyone participating in church or sound system design to know how to maximize intelligibility, even though different worship styles will place varying degrees of weight on it. Au et al., 2021 outlined that different acoustic fields, such as linguistics (Mayo et al., 1997 & Lecumberri et al., 2010), building acoustics, and psychology of hearing (Miller & Licklider, 1950), have actively explored speech intelligibility in unfavorable situations. The adverse circumstance that is investigated the most is noise; speech masking is the detrimental effect of noise obscuring the target speech and making it difficult to understand (Brungart et al., 2006).

For certain churches, particularly those that practice evangelical worship, intelligibility ranks as the project's most crucial architectural need. Preaching the Word is vital for the Evangelical church, as we have seen. The following verse from the book of Romans is regarded by many as the final word in the church. Romans 10:14 *How, then, can they call on the one they have not believed in? And how can they believe in the one of whom they have not heard? And how can they hear without someone preaching to them?*

Every week, most of what is spoken in the Evangelical church is brand-new. The Evangelical church anticipates that there may be someone attending a church service who has never heard the Gospel because it views converting non-Christians as its main goal. This person is probably not familiar with Church terminology, so in addition to lacking ritual to assist fill in the blanks, he or she also lacks linguistic background. Thus, it is imperative that technology, whether it be design or the sound system, not obstruct the message (Zarek, J.,1990). Three causes of poor intelligibility can be identified:

i. inadequate reverberation to support the speaker due to a weak voice, a far distance for the sound to travel, inadequate volume from the speaker due to a poor voice, or excessive background noise concealing the voice
ii. inadequate volume reaching the listener as a result of sound-interfering obstructions such big pillars or overhanging galleries
iii. too much reverberation, which distorts the speech, (Nowoświat et al., 2020) claims that a lower reverberation time makes speech easier to understand.

Referring to Brezina (2015), in every examined area, the measured STI values show a satisfactory degree of speech intelligibility. It is feasible to draw the conclusion that the level of clarity is not significantly impacted by the location of the sound source. According to the STI approach, speech intelligibility is also dependent on other factors such the source's direction, the strength of the speech signal, and the volume of background noise (Makrinenko et al., 1994).

2.3.3 Loudness of Sound

The usage of public address systems, which include microphones, loudspeakers, amplifiers, and other equipment, always amplifies the sound that was originally produced in the church auditorium. These kinds of devices should ideally not distort the sound that came from the original source. Certain instruments, like an organ, can be played loudly enough to be heard clearly without the need for additional support. Some, like finger-picked acoustic guitars, are naturally soft and might require amplification to be audible to the assembly (Eiche, 1990).

Fletcher and Munson (1933) defines that the loudness produced will be the same for the same intensity only if the listener is in the same psychological and physiological conditions as the source of the sound that is, if their level of fatigue, attention, alertness, etc. and if the sound's composition, or wave form, remains constant but their intensity varies at their ear. Therefore, the intensity of the sound, its physical makeup, the type of ear receiving it, and the listener's physiological and psychological characteristics must all be defined in order to establish the loudness created.

2.3.4 Noise

A popular definition of noise is an undesired sound that necessitates acoustic concerns in architecture design. Similar to any other enclosed public place, the church auditorium has a variety of noise types, including background, indoor, and exterior noise (Mahimairaj, et al. 2024). These kinds of noise make it difficult for the audience to hear the preacher's voice properly from the pulpit.

In Brazil, because of the high amount of noise exposure during services, priests are at risk for health problems. These noise levels include significant energy that might cause hearing loss due to noise. This setting is comparable to noisy industrial processes like those in metallurgy and mechanics (Felipe Silva, L., & Cabral, R., 2011).

(a) Background noise

Alibaba, H. Z., & Itontei, E. E. (2016) stated that church auditoriums frequently have this function. It comes from the surrounding environment and obstructs the preacher's voice since, with the exception of a few typical church buildings like the ecumenical center, it is typically not covered by reflectors or shading mechanisms.

(b) Outdoor Noise

This is typically a result of the activities that are taking place in the area around the church, such as foot traffic, mechanical equipment, children, and vehicles.

(c) Indoor Noises

This is caused by crowd conversions, which, if left uncontrolled, result in various speech patterns at variable frequencies and amplitudes that make the auditorium uncomfortable to listen to. Communication is hampered by this form of noise since one person's conversation may be interrupted by another, and so forth. Their proximity exacerbates this even more. Shoe noise, ceiling fans, electrical switches, air conditioners, and other appliances all add to the auditorium's noise pollution issue. It should be noted that these appliances can emit quite upsetting levels of noise. The church auditorium's door and window openings, furniture movement, and other factors all contribute to noise production.

3. METHODOLOGY

The selection of churches representing Malaysia's Protestant denominations was determined by their varying contextual environments and scale. Two churches in Kuala Lumpur, both situated within contrasting environments of soft landscapes with 111 m in radius at the eastern side from C1 building and high-rise skyscrapers within 100 m in radius at north, south, east and west direction from C2 building, have been selected. Measured drawings were conducted for both churches to acquire two-dimensional and three-dimensional representations. The seating capacities for the two churches are 200 and 1000 seats, respectively. The church's capacity and physical dimensions are summarized in Table 1 and 2.

Table 1: Main Physical Characteristics of the Churches in this study.

No.	Church	No. of Seats	Environment
1	C1	1000	Surrounding with Soft Landscapes
2	C2	200	Surrounding by Building with Glass Facades

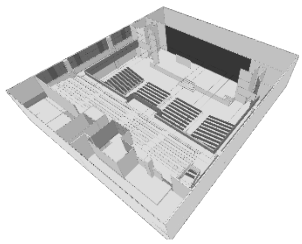
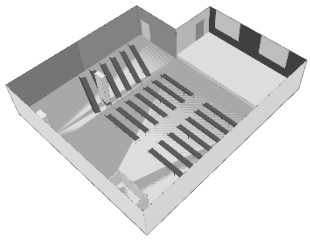
Table 2: Main Dimensions of the Churches in this study.

No.	Church	Dimension of Hall (m)			Volume (m3)
		L	W	H	
1	C1	37.8	33.9	7.7	9866.93
2	C2	19.1	16.5	3.6	1134.54

3.1 Current Church without Openings vs. Acoustic Performance

The first objective of this study was to identify and analyse the acoustical performance of the existing church configurations without any proposed structural openings. Both churches are located within multistorey buildings; therefore, for Simulation 1, the acoustic models were limited to the specific level and spatial area used exclusively for church services. Accordingly, both churches were modelled without openings, as presented in Table 3. In addition, identical material properties were assigned to both models as controlled variables to ensure a consistent basis for comparative analysis.

Table 3: Both Churches Without Openings.

Church	Original Design (Church Without Structural Opening)
C1	
C2	

3.2 Churches with Structural Openings and without Surrounding Context vs. Acoustical Performance

The purpose of this study was to evaluate the influence of structural opening dimensions on the acoustical performance of the church using a parametric simulation approach. A series of controlled simulation iterations were conducted for each church, in which the proportion of structural openings systematically varied at 5%, 10%, and 15%, as summarised in Table 4. Within this parametric framework, spatial volume and opening dimensions were treated as independent variables, while material properties, absorption coefficients, and overall geometric configuration were held constant. This approach enabled the isolation of opening-size effects on acoustic performance indicators, thereby ensuring consistency and comparability across simulation scenarios.

Table 4: Churches with Different Size of Openings

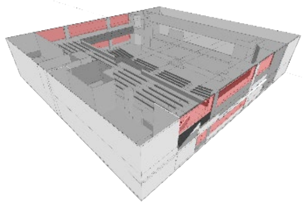
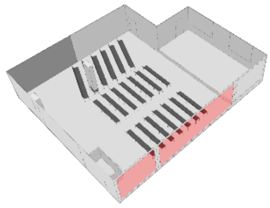
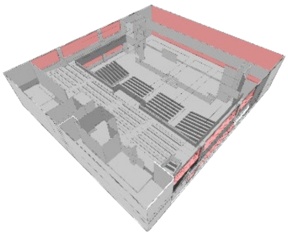
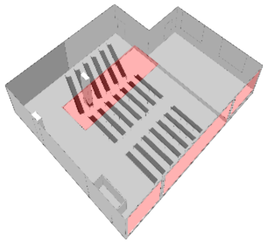
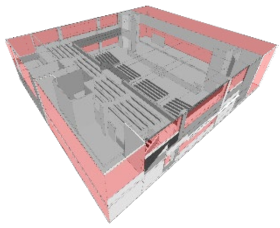
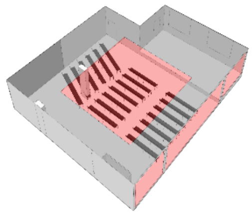
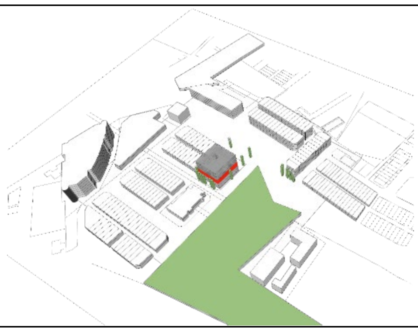
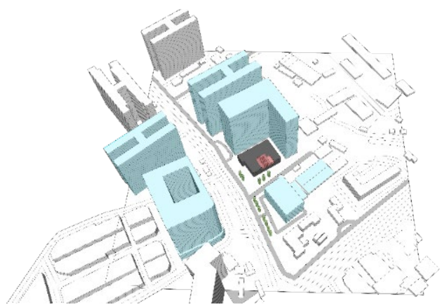
Church	C1	C2
5% Opening		
10% Opening		
15% Opening		

Table 5: Aerial View of Churches with Surrounding Context

	C1	C2
Environment Context		

Legends
Location of Church
Soft Landscapes: Trees
Glass Façades

Other than different sizes of openings, two churches also located at different surrounding contexts, which C1 is located next to the greenery area and C2 is located next to the glass facades buildings which shown in Table 5.

3.3 Simulation Procedure

The measurement drawings of two selected churches have been completed. The architectural designs of two churches have been rendered into three-dimensional models utilizing SketchUp Pro 2023. This software was selected due to its compatibility with Odeon 17.12 Industrial. ODEON proposed that the surfaces of the software's models be constructed with substantial dimensions of approximately 0.34 meters, deemed greater than one wavelength in the midfrequency range. Architectural elements such as railings, framings, and cornices were excluded from the 3D modeling process due to their lack of significant early reflections on the receivers or simulation outcomes (Abd Jalil et al., 2019 & Shyh-Qi et al, 2023). Nevertheless, it was discovered that many attributes pertaining to traditional church elements, such as doors and windows, remained consistent according to a previous study on modeling simplification for acoustic simulation in ODEON. ODEON was subsequently utilized to import the finalized models. This phase ensured the model was fully enclosed to produce simulations with accurate readings.

Table 6 presents the basic information of the simulation settings fixed in ODEON for the simulations. Table 7 and 8 illustrate the arrangement of sound sources and receivers for each church. In the absence of acoustical data and comprehensive information regarding the acoustic properties of materials provided by the church administration staff, the selected materials were employed using the most comparable absorption coefficient data that accurately represents the typical surfaces and materials of the churches, adapted from the software's material library database.

This study focused on the effects of structural openings and their contextual environment; hence, a uniform set of materials with similar acoustic absorption coefficients was employed to eliminate extraneous variables that might affect the simulation results. It is essential to emphasize that all simulated models presumed no occupancy as a constant variable representing the church's conditions without occupancy. This is apparent in the selection of materials for the seating. Table 9 displays the absorption coefficients of the materials included in the simulated models.

Table 6: Basic Information of the Simulation Settings Fixed in ODEON.

No. of sound sources	Interior sound source = 1 (set at 1.0m high from the floor) Exterior sound source = 1 (set at 1.0m high from the ground)
Sound source type	Omni.SO8
No. of multi-point responses	Grid Points (all set at 1.0m high) C1: 24 Points C2: 12 Points
Impulse response length	1900 ms
Temperature input	20 ◦C

The sound source is positioned at the center of the stage within the church, at a height of 1.0 meters. Conversely, when the sound source is external to the church, it is positioned 1.0 m above the ground to represent transportation noise. Despite the selection of modern churches constructed in the late 1900s, stimulation occurs without a contemporary audio system. The objective of this study is to examine the acoustic quality of churches, considering the variables of structural opening size and environmental context, in the absence of a modern audio system. The receivers were uniformly distributed across the church's main sanctuary at a height of 1.0 m, spanning the front, middle, and rear sections.

Table 7: Location of the Interior Sound Sources and Receiver (red: source; blue: receiver)

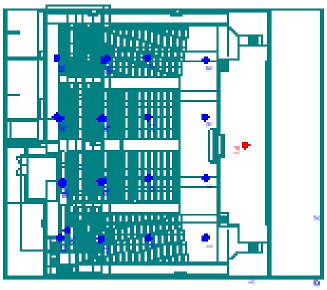
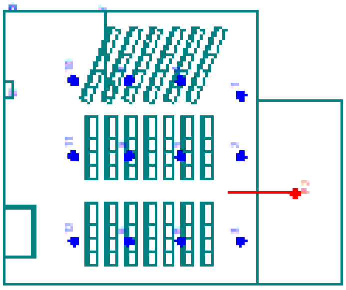
Church	Source and Receivers' Location
C1	
C2	

Table 8: Location of the Exterior Sound Sources and Receiver (red: source; blue: receiver)

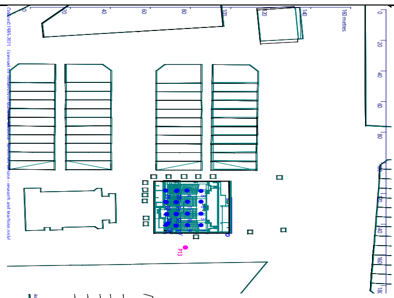
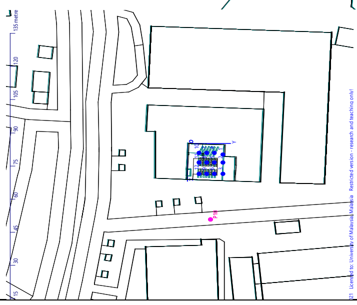
Church	Source and Receivers' Location
C1	
C2	

Table 9: Sound Absorption Coefficient of the Materials Used in the Simulated C1 and C2 Models

No.	**Component**	**Material/ Description**	**Frequency**			
			250	**500**	**1000**	**2000**
1	Floor	3mm wood veneer on 50mm studs	0.14	0.09	0.06	0.06
2	Walls	Smooth Painted Concrete	0.01	0.01	0.02	0.02
3	Ceiling	Gypsum	0.10	0.10	0.05	0.05
4	Column	Smooth Painted Concrete	0.01	0.01	0.02	0.02
5	Seating	Empty chairs, upholstered with cloth cover	0.60	0.77	0.89	0.82
6	Window	Single Panel of Glass	0.04	0.03	0.03	0.02
7	Projector Screen	Vinyl	0.02	0.03	0.04	0.04
8	Panel	Wood Fibre	0.20	0.20	0.10	0.05
9	Green Area	Trees	0.35	0.28	0.85	0.90

3.4 Acoustical Parameter

The acoustic parameters used to evaluate the acoustic efficacy of the selected churches in this study were (i) speech transmission index (STI) and (ii) reverberation time (RT). Paschakis (2023) noted the STI is a quantitative indicator that assesses the influence of the transmission medium on the intelligibility of messages communicated from speaker to listener. The STI serves as a robust method for assessing PA systems, as it excludes the speaker and listener, focusing exclusively on the influence of the transmission channel on speech intelligibility. The calculation is based on the modulation variation of a test signal, producing a result ranging from 0 to 1, with 1 signifying greatest intelligibility and 0 signifying minimum intelligibility. The STI Range for contemporary churches is 0.58-0.62, as seen in Figure 1 below:

Band	STI Range	Examples of typical uses
A+	> 0.76	Recording studios
A	0.74- 0.76	Theatres, speech auditoria, parliaments, courts
B	0.70 - 0.74	Theatres, speech auditoria, parliaments, courts
C	0.66 - 0.70	Teleconference, theatres
D	0.62 - 0.66	Classrooms, concert halls
E	0.58 - 0.62	Concert halls, modern churches
F	0.54 - 0.58	PA in shopping malls, public offices, cathedrals
G	0.50- 0.54	PA in shopping malls, public offices
H	0.46 - 0.50	PA in difficult acoustic environments
I	0.42- 0.46	PA in very difficult spaces
J	0.38 - 0.42	Not suitable for PA systems
U	< 0.36	Not suitable for PA systems

Figure 1: Speech Transmission Index (STI) of Typical Uses Area
(Source: Paschakis, 2023)

As all churches included in this study are contemporary, the suggested reverberation time (RT) is established as follows: for Churches and Worship Centers, fellowship halls should have a reverberation time of less than 1.2 seconds. Churches with classical music may prefer extended reverb, although contemporary services typically require 1.5 seconds or less. For the stimulation of this research as depicted in Figure 2, the main worship space should be within the range 1.3 seconds – 2.5 seconds (Eguez, 2017).

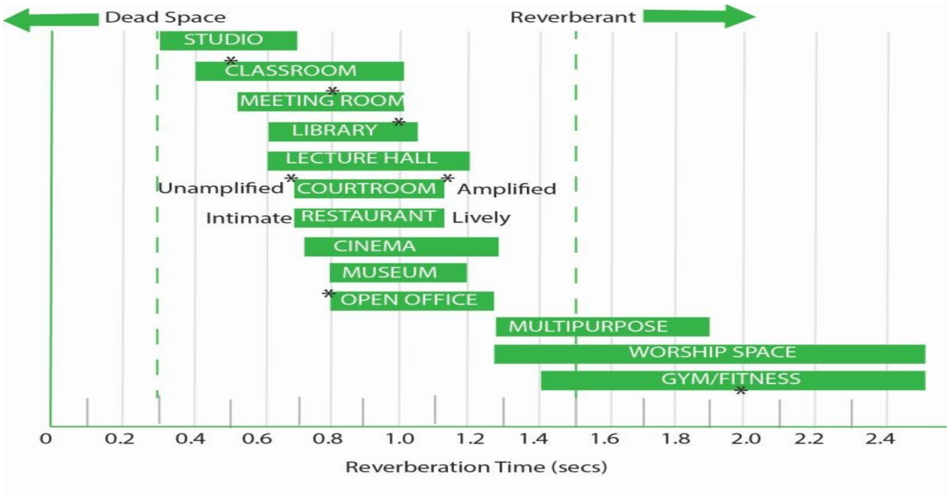


Figure 2: Reverberation Time for Different Places
(Source: Eguez, 2017)

4. RESULTS AND DISCUSSION

As depicted in Table 10 and Figure 3, reverberation time generally increases with room volume. Given that C1 has a larger volume than C2, it would therefore be expected to exhibit a longer reverberation time. However, at the 250 Hz and 500 Hz frequency bands, C1 demonstrates shorter reverberation times than C2. This deviation from the expected volume–reverberation relationship suggests the influence of material-based absorption characteristics, whereby C1 incorporates surface materials with higher absorption coefficients at low-to-mid frequencies, thereby reducing reverberation time within these bands.

Table 10: Reverberation Time of Churches Stimulation without Openings

Church	**Average T30(s)** Frequency			
	250	500	1000	2000
C1	1.44	1.27	1.48	1.34
C2	1.63	1.59	1.30	1.11

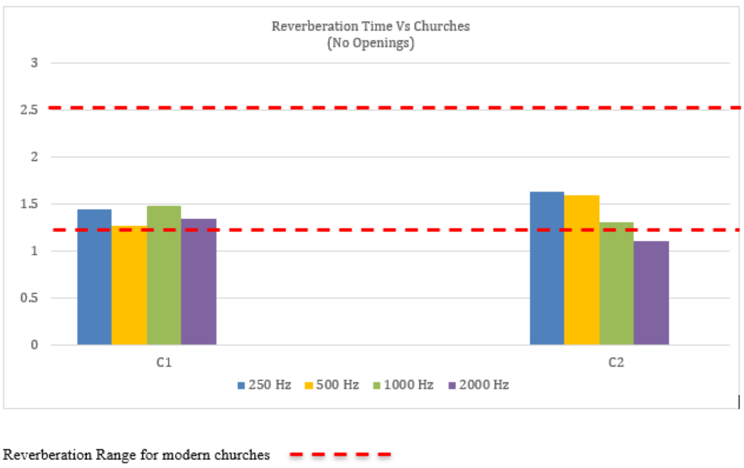


Figure 3: Reverberation Time of Churches without Openings

Table 11: Speech Transmission Index (STI) of Churches Stimulation without Openings

Church	**STI**		
	Min	**Max**	**Ave**
C1	0.54	0.68	0.62
C2	0.62	0.71	0.66

Figure 4: Speech Transmission Index (STI) of Churches without Openings

As illustrated in Table 11 and Figure 4, the STI of C2 is higher than that of C1, which can be attributed to its smaller spatial volume. From an architectural acoustics perspective, the reduced volume results in a shorter reverberation time, thereby limiting temporal masking and improving the modulation transfer of speech signals. This acoustic condition enhances speech intelligibility and is reflected in the higher STI values observed for C2.

4.1 Sound Source from Building Inside with and without Surrounding Context vs. Acoustical Performance

Overall, the larger church, C1, exhibits a longer reverberation time compared to C2. (The Physics of Music PHY103 Lab Manual Lab #6 - Room Acoustics, n.d.) indicates that a larger volume space will have a longer reverberation time than a smaller volume space, as sound takes longer to travel between reflections in a larger room. In church construction devoid of contextual factors, larger openings correlate with less reverberation time. (The Physics of Music PHY103 Lab Manual Lab #6 - Room Acoustics, n.d.) states that reflective surfaces extend reverberation time, while absorptive surfaces reduce it. In the absence of surrounding context, it is presumed that sound particles are absorbed as they are transported to the surrounding environment. Consequently, bigger structural openings result in less reverberation time.

Table 12: Reverberation Time of Churches Stimulation with Openings (Sound Source Inside)

	Sound source from building inside							
Reverberation T30								
	Model Without Surrounding Context				Model With Surrounding Context			
	250	500	1000	2000	250	500	1000	2000
C1 (Area 1200 sqm)								
5% Opening	2.76	1.57	1.42	1.34	1.41	1.37	1.39	1.28
10% Opening	1.10	0.95	1.14	1.06	1.48	1.34	1.56	1.36
15% Opening	0.95	0.78	0.83	0.77	1.30	1.07	1.09	1.04
C2 (Area 284 sqm)								
5% Opening	1.11	0.94	1.09	0.91	0.96	0.85	0.77	0.70
10% Opening	0.69	0.59	0.75	0.63	1.01	0.85	0.87	0.77
15% Opening	0.66	0.58	0.65	0.57	0.97	0.89	0.92	0.80

Highest Value
Lowest Value

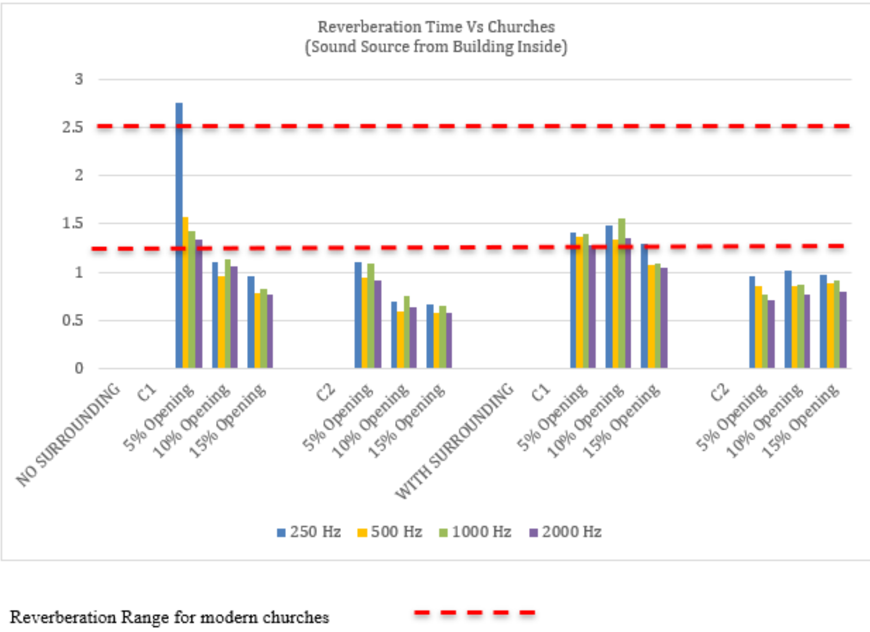
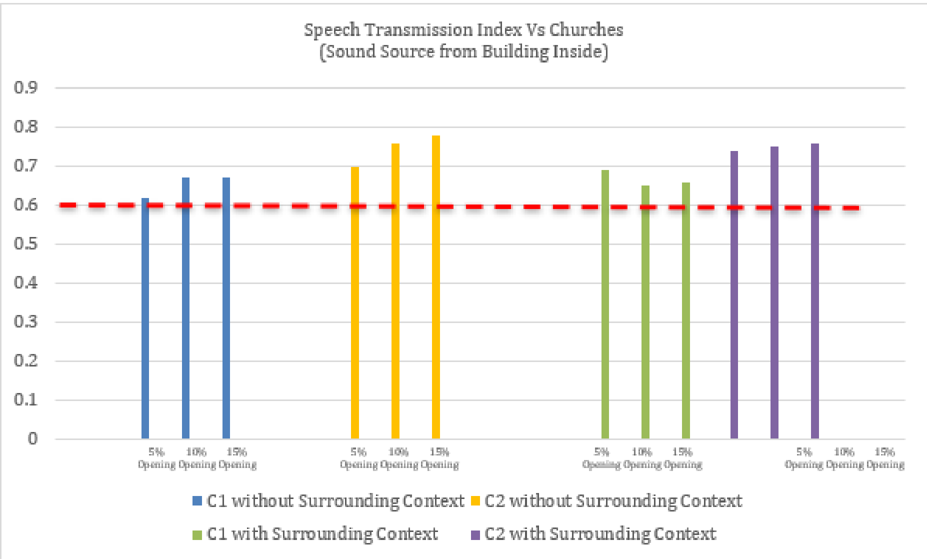


Figure 5: Reverberation Time of Churches with Openings (Sound Source Inside)

Table 13: Speech Transmission Index (STI) of Churches Stimulation with Openings (Sound Source Inside)

	Sound source from building inside					
Speech Transmission Index						
	Model without Surrounding Context			Model with Surrounding Context		
	Min	Max	Average	Min	Max	Average
C1 (Area 1200 sqm)						
5% Opening	0.57	0.69	0.62	0.61	0.76	0.69
10% Opening	0.59	0.85	0.67	0.59	0.74	0.65
15% Opening	0.62	0.75	0.67	0.55	0.77	0.66
C2 (Area 284 sqm)						
5% Opening	0.68	0.73	0.70	0.71	0.79	0.74
10% Opening	0.74	0.79	0.76	0.70	0.80	0.75
15% Opening	0.76	0.81	0.78	0.72	0.80	0.76
Highest Value	(yellow)					
Lowest Value	(green)					



Average STI for modern churches - - - - -

Figure 6: Speech Transmission Index (STI) of Churches with Openings (Sound Source Inside)

Other than that, the surrounding environment will feature both reflective and absorptive surfaces that respond to varying sound frequencies. The surrounding materials influence the duration of reverberation time. As shown in Table 12 and Figure 5 at varying frequencies, C2 is situated near to reflecting buildings with glass facades that can reflect sound; hence, a smaller opening result in a reduced reverberation time. Conversely, C1 is adjacent to an expansive green space that can absorb sound; hence the bigger structural openings will contribute to a reduction in reverberation time.

On the other hand, with C2 and C1, the STI from the interior sound source, in conjunction with the surrounding context, does not adhere to the notion that STI increases as RT decreases as shown in Table 13 and Figure 6. According to (Sascha Riedling, 2024) and (Basics of STI measurement., n.d.), the STI is influenced by ambient noise and the position of the sound source. Additionally, sound particles will be influenced by absorptive and reflecting materials at varying frequencies.

4.2 Sound Source from Building Outside with and without Surrounding Context vs Acoustical Performance

Table 14: Reverberation Time of Churches with Openings (Sound Source Outside)

	Sound source from building outside							
Reverberation T30								
	Model without Surrounding Context				Model with Surrounding Context			
	250	500	1000	2000	250	500	1000	2000
C1 (Area 1200 sqm)								
5% Opening	1.91	1.39	2.36	1.43	0.82	0.83	0.59	0.52
10% Opening	1.29	1.44	0.75	1.08	1.49	1.56	1.46	1.46
15% Opening	0.70	0.58	0.44	0.55	1.86	1.94	2.17	2.03
C2 (Area 284 sqm)								
5% Opening	0.71	0.62	0.65	0.62	2.72	2.45	2.60	2.40
10% Opening	0.41	0.38	0.38	0.37	2.10	2.09	2.03	1.90
15% Opening	0.29	0.29	0.26	0.26	2.35	2.34	2.01	1.82
Highest Value								
Lowest Value								

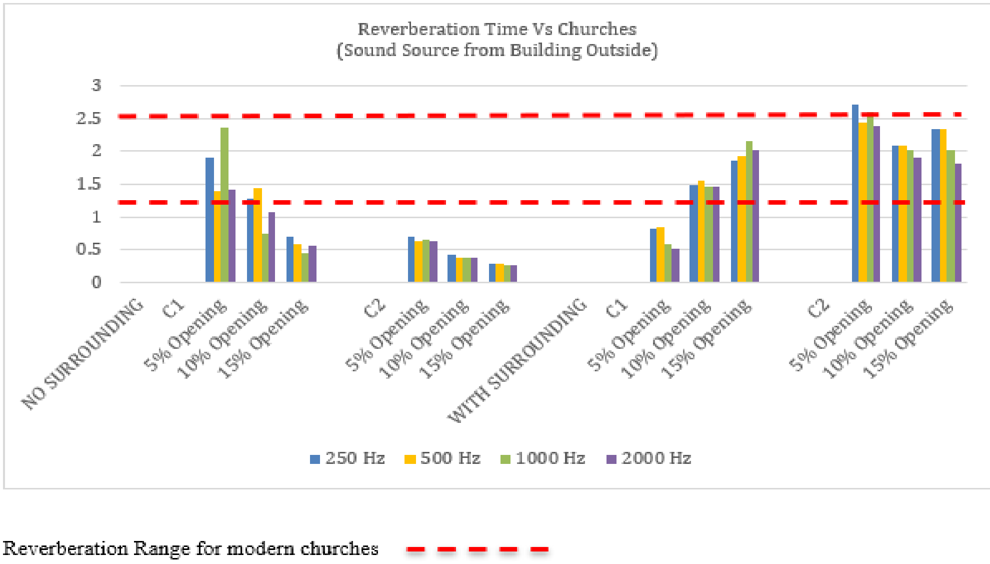
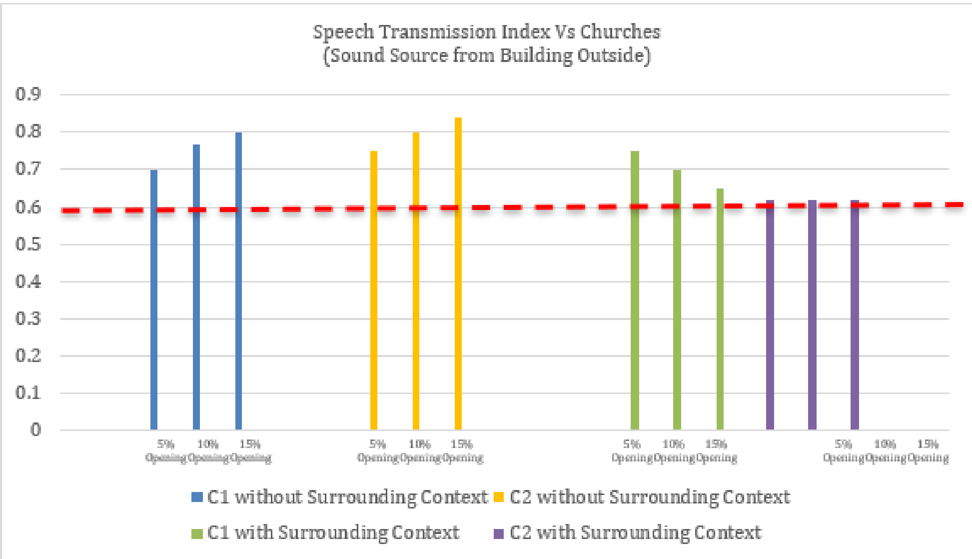


Figure 7: Reverberation Time of Churches with Openings (Sound Source Outside)

Table 15: Speech Transmission Index of Churches with Openings (Sound Source Outside)

Speech Transmission Index	Sound source from building outside					
	Model without Surrounding Context			Model with Surrounding Context		
	Min	Max	Average	Min	Max	Average
C1 (Area 1200 sqm)						
5% Opening	0.55	0.97	0.70	0.61	0.92	0.75
10% Opening	0.60	0.98	0.77	0.57	0.86	0.70
15% Opening	0.69	0.94	0.80	0.49	0.83	0.65
C2 (Area 284 sqm)						
5% Opening	0.58	0.83	0.75	0.56	0.69	0.62
10% Opening	0.69	0.95	0.80	0.55	0.68	0.62
15% Opening	0.72	0.96	0.84	0.54	0.75	0.62
Highest Value	(yellow)					
Lowest Value	(green)					



Average STI for modern churches

Figure 8: Speech Transmission Index of Churches with Openings (Sound Source Outside)

In general, the smaller-scale church C2 has the longest reverberation when the sound source originates from outside the building. This may be attributable to the extensive surface area of reflecting materials on the exterior of the buildings.

In the case of church construction devoid of external factors, a larger church opening correlates with a reduced reverberation period. However, there is one particular case: C1 500 Hz. This may be attributed to the fact that a bigger hole facilitates the rapid absorption of external sound particles by the absorbent material in the church, as there are no surrounding materials to influence the reverberation period.

In both church models with adjacent building context, the reverberation time for C2 is not consistently changed based on the percentage of opening. The surrounding environment will possess both reflecting and absorptive surfaces that respond to varying sound frequencies. The surrounding materials influence the duration of reverberation time. At varying frequencies, C2 is situated near to reflective glass structures that can reflect sound; consequently, smaller openings result in increased reverberation time, since sound waves are reflected outside the building before they can penetrate it as shown in Figure 7 and Table 14.

Conversely, C1 is adjacent to an expansive green space that can attenuate sound, hence facilitating the absorption of external sound waves. Smaller structural openings result in a reduced reverberation duration, as sound is absorbed before being reflected into the building. According to (Kang et al, 2023), an extended reverberation time (RT) diminishes speech intelligibility, as the voice signal in reverberant settings is obscured by numerous reflections, leading to a smoothed waveform profile. The voice transmission index of C2 and C1 for external sound sources, both with and without surrounding context, exemplifies this principle as shown in Figure 8 and Table 15.

The forthcoming study direction involves structural openings in more complicated environments. The two selected churches currently exhibit simpler environmental contexts; C2 is encircled by glass-facade business buildings and retail establishments, whilst C1 is adjacent to greenery. Consequently, the subsequent research on churches could involve a more complicated environmental setting. For instance, varying tree heights, diverse topography, and identifying environmental contexts adjacent to MRT or LRT stations. Future studies may investigate the acoustic properties of different church geometries with varying structural openings.

5. CONCLUSION

The research on the influence of structural openings and surrounding context on acoustic properties in contemporary Malaysian Protestant churches offers significant insights for the design and enhancement of worship spaces. It underscores the significance of structural apertures in achieving a balance among ventilation, natural illumination, and acoustic performance. The findings also indicate modern materials and technologies provide solutions to these issues, although they must be appropriately integrated to maintain the church's spiritual ambiance. Generally, in the stimulation of a church without surroundings, larger openings apply with reduced reverberation time. If the church opening is adjacent to soft landscape and the sound source is within the building, a larger opening will reduce the reverberation time, and conversely. The study underscores the importance of designing church interiors that fulfill both functional and aesthetic criteria. Churches can enhance the auditory and sensory experiences of their congregants by strategically configuring structural apertures and optimizing the use of sound-absorbing and reflective materials.

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