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Acoustical Evaluation of the Itacuruçá Baptist Evangelical Church

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ABSTRACT

This paper presents the acoustical evaluation of a representative evangelical church in Rio de Janeiro, Brazil. The analysis, performed through measurements and simulations, has shown that the acoustic field needs to be more appropriate for the temple's actual use. The analysis measured the impulse responses at 14 positions from 2 source locations and calculated Reverberation Time and Clarity Factor acoustic parameters. According to the literature and the ISO standards, the Reverberation Time was considered higher than the optimum value for both speech or music. An acoustic model for the temple was developed using the BRASS simulator. The simulation results were compared to measured data to validate the acoustic model. Based on that and aiming to achieve optimum acoustic parameters, a new model was proposed to evaluate alternatives to adequate the acoustical characteristics of the temple. The strategy to develop the final model and to achieve the target Reverberation Time is presented and discussed. An acoustic intervention is then proposed and evaluated using simulated data. The results obtained with the proposed changes, which considered the inclusion of perforated panels and carpet in some walls, were adequate, providing Reverberation Time in accordance to the standards and significant improvement to Clarity for music and speech.

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1. Introduction

The greek and roman theaters had fundamental importance to the acoustic development of contemporaneous concert halls [1, 2]. They possessed critical acoustical characteristics, such as low residual noise, direct sound, and reinforcement. The low background noise was achieved by implementing them in areas far from city centers and due to the barrier effect promoted by the bleachers. The direct sound, reaching all the audience, was obtained with the circular arrangement and with the seats distributed on a slope [3]. Finally, the sound reinforcement was promoted from the sound reflection on the stage rigid floor and by diffusion by the columns.

The so-called Italian Opera Theater had its hegemony in Europe during the 18^{th} and 19^{th} centuries. Many 18^{th} century treatises published writings addressed issues related to the design and building of theatrical and operatic rooms. Although without scientific support, intuition and experience allowed a constant improvement in theatrical models, optimizing the visual and sound quality of the rooms. Over the centuries, such typologies were adapted to fit into buildings for theater purposes and to hold religious temples. Several old churches remain up to the present, keeping their original architecture and constituting crucial historical heritage. For example, the acoustical characteristics of Italian churches were widely studied [4, 5] to investigate the relationship between subjective ratings and acoustical parameters by listening tests.

However, some historical churches were altered along the time due to war, worship, or cultural changes. Several aspects might contribute to modifying the natural acoustic response: layout and material changes, such as chairs or bench materials; the addition of absorptive materials, such as curtains, cushions, and paintings; the sound source locations, such as choir position or the introduction of electro-acoustic systems. Furthermore, historical and new churches were built or adapted to serve as “multi-purpose” or “multifunctional” temples, sometimes serving different religions and doctrines [6-8]. This situation poses a difficult task to acousticians since they must design solutions that provide high intelligibility to the congregation to understand the spoken message clearly, but at the same time, create an environment with spaciousness, vivacity, and brightness for musical activities [9-11].

Several studies have been conducted dealing with acoustics in religious temples. Some interesting historical reviews about church acoustics are presented in [12,13]. More specific investigations, including systemic methodology to measure and evaluate the acoustics in different types of churches, can also be found in [14-16]. A global index to define the acoustic quality in churches was proposed by Kosala *et al*. [17-19], which mixed the acoustic parameters, such as Reverberation Time, Clarity Factor, Strength, Speech Transmission Index, and Equivalent Level, into a more generic and global indexes.

The music type in the church constitutes, by itself, another challenge since different solutions might be required for a Gregorian chant or Protestant worship music. The use of electronic instruments, such as electric guitars, basses and drums, countless different types of choirs or organ music also impose remarkable restrictions. The diversity of shapes of Christian temples also makes it challenging to define optimal parameters or specific indexes for the Church acoustics [20-22]. The seat occupancy rate also influences the acoustic characteristics and the perceived sound inside the church [23, 24].

Another recent challenge is the service and cult broadcast through social media, which imposes several restrictions, such as low background noise, high intelligibility, and proper microphone positioning to achieve "good spots” to capture the congregation's singing and responses. Based on such a comprehensive list of requirements, some guidelines assist in the church's acoustic design and adequacy [17, 25]. This paper deals with the analysis and the adequacy of an evangelic church with multi-purpose use, similar to the works developed in [26, 27].

2. The Itacuruçá Baptist Church

The Baptists emerged in the early 16^{th} century, in England, within the Puritan movement. An independent group of the Anglican Church emerged in 1609 and had to immigrate to Holland. They spread across Europe and the United States, from where the first missionaries came to Brazil. The first Baptist church in Brazil appeared in 1871, in Santa Bárbara do Oeste, São Paulo State, spreading throughout the country. According to the latest Brazilian census (2010), there are more than 3.1 million Baptists in Brazil.

Located in Rio de Janeiro city, in a residential neighborhood, the Itacuruçá Baptist Church was founded in 1936, by William Edison Allen (1892 - 1985), without a temple – the community gathered together in a neighborhood school. In 1952, after two years of construction, the actual temple was finished, presenting a typology as in a modern congress hall, as depicted in Fig. (**1**). It presents a semi-circular frontal stage and audience in an arc shape with two floors: the primary audience and the balcony, with space for about 400 seats. The average ceiling height is approximately 7 meters and the volume of 1700.

Fig. (**2**) presents two temple pictures showing the wall materials and furniture. The main surfaces are made of polished and painted concrete (all walls and ceiling), large glass windows, wood benches and parquet floors. Typical cults present musical performances of several types, such as choirs (from 15 to 50 singers) accompanied by electronic organ, piano, electronic drums, flute, strings and voice quartets, bands, and orchestras (including brass and percussion sets). In every cult, there are prayers and a preacher on the stage. Thus, well understanding spoken word is crucial for daily activities, requiring good Speech Intelligibility and Clarity, but, at the same time, Brightness and Reverberation for music appraisal. The diversity of uses in the same space, without acoustical configuration changes, poses an adverse task for musicians, preachers, and technical crew, to try to ensure, during the service, intelligibility, and spaciousness to the audience.

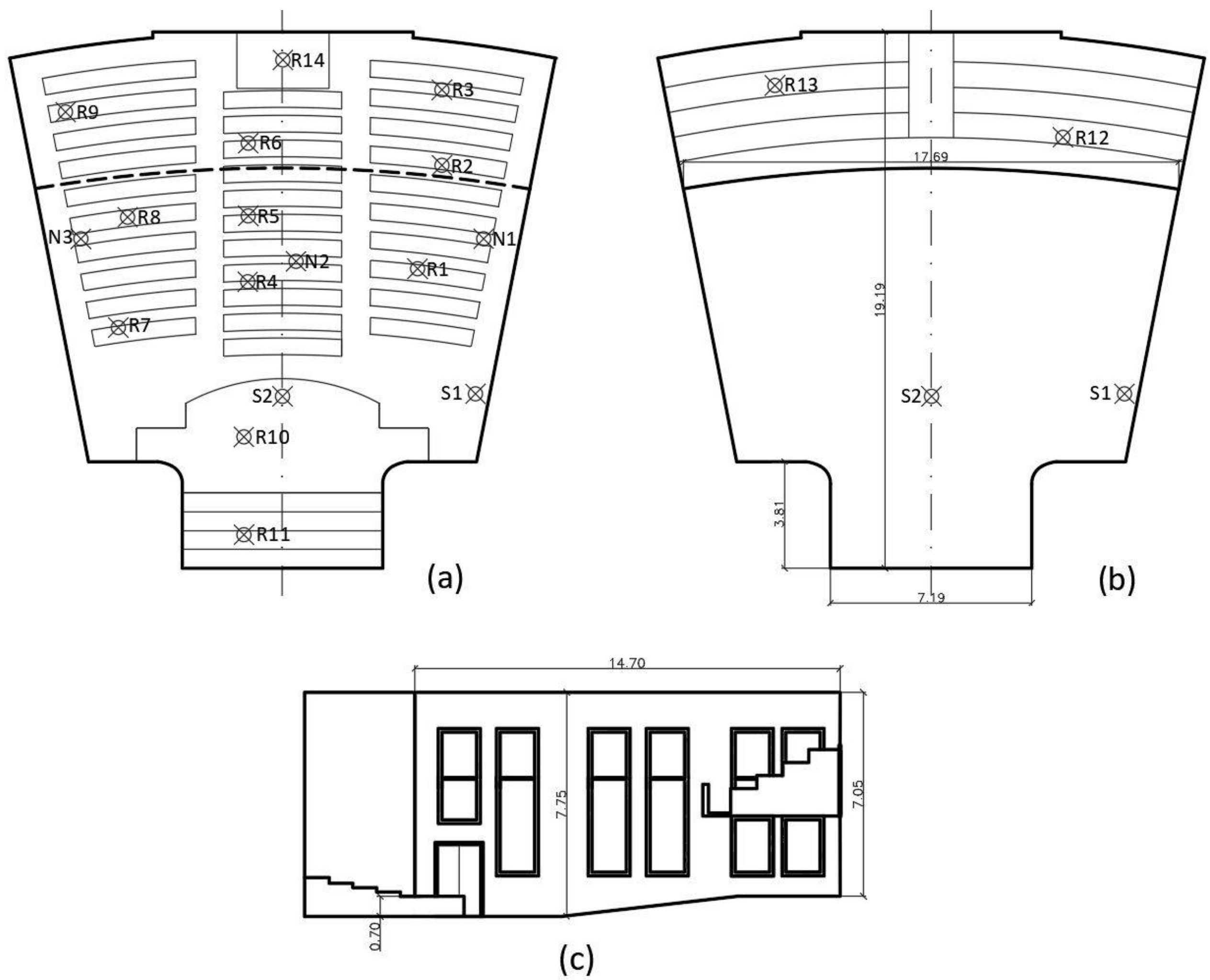


Figure 1: Itacuruçá Church drawings: (a) First floor and (b) Mezzanine top views and (c) cross-section. Source (S) and receiver (R) locations for measurements.

This paper presents the temple acoustical investigation based on impulse response measurements and simulations. The analysis consisted of evaluating the acoustical parameters and verifying if the values are in accordance to the international standards. An environment with different usages, ranging from intelligibility focus during the preacher's sermon to the vivacity of an orchestra, might not be appropriate for both, for one, or even for no one. According to the analysis, a refurbishment is proposed to adjust the acoustic parameters and optimize it for multi-purpose usage.

3. Acoustic Measurements and Analysis

This section presents the acoustical evaluation of the church by measurements. Impulse responses were measured by using REW software (https://www.roomeqwizard.com), omnidirectional microphones (Behringer ECM-8 model), and a pair of standard loudspeakers (model Yamaha DBR 15). One loudspeaker was already installed on the church wall, while the other was available. Before starting the measurements, the microphone was calibrated using a 1 kHz sine-wave signal at 94 dB (referenced to 20 μPa). During the measurement section, the air-conditioning machines were kept off.

3.1. Background Noise Evaluation

The background noise was evaluated at three positions (N1, N2, and N3), as shown in Fig. (**1a**), at 1.2 m above the audience floor. Point N2 was located at the temple central area. Points N1 and N3 were placed 1.5 m from the lateral wall in front of the closed windows. Point N1 was more affected by traffic noise since this church side connects to the street. N3 would be affected by school leisure noise due to the proximity to the Baptist school. The background noise for these three points is shown in Fig. (**3**). It can be observed that most of the noise is composed of low-frequency content, promoted by nearby air-conditioning machinery and street traffic noise. The sound pressure level, in the "A" scale, achieved 42 dB(A), while the peak measured approximately 60 dB(C), around 60 Hz.

Figure 2: Itacuruçá pictures. Top: Front view from first-floor back seat. Bottom: back view.

3.2. Impulse Response Measurements

According to the Brazilian version of ISO Standard 3382 part I [28], a minimum of 2 positions for the sound sources and 6 positions for the receivers are required since the church provides less than 500 seats. Therefore, two sound sources were used: one of the main loudspeakers (already installed on the side wall) and another loudspeaker (same model) placed at the stage, simulating a speaker (preacher) without using any electro-acoustic system. In order to provide a good description of the acoustics in the whole church, including audience and altar areas, there were selected 14 locations to measure the impulse responses, as depicted in Fig. (**1**). These source-receiver pairs provided 28 combinations. All the receivers were located 1.2 m above the floor level. Two points were selected at the stage area (R10 and R11), two were placed at the mezzanine (R12 and R13) and receiver R14 was located inside the sound control cabin. Source S1 was positioned at 3 meters from the lowest floor level, while source S2 as located 1.5 m above the stage floor (2.2 m from base floor).

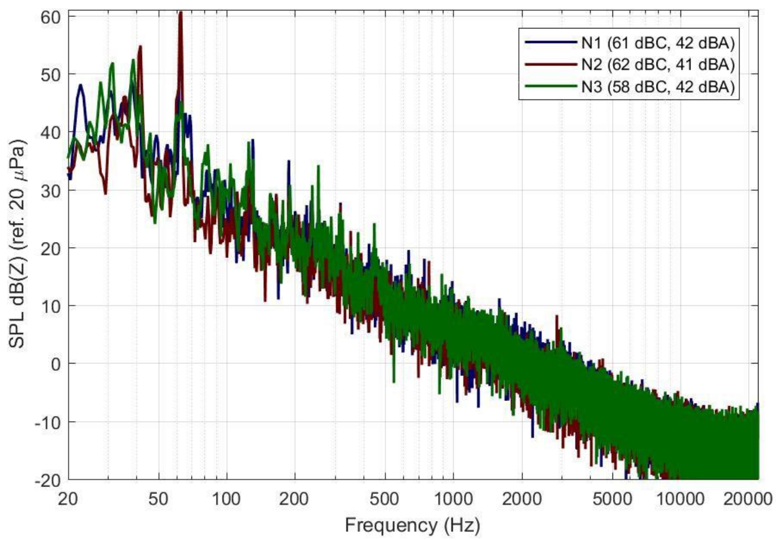


Figure 3: Background noise at 3 points: Left side, close to the street (N1), central temple area (N2), and right side, close to the school (N3). See Fig. (**1a**).

Recordings were done by placing the microphone at the defined locations and playing a logarithmic sweep-sine signal 6 seconds long through the loudspeakers separately. The loudspeaker output was set to provide a sound pressure level of 100 dB(Z) (referenced to 20 μPa), measured at 1.0 m on the acoustic center axis and using white noise before running the sweeps. The maximum SPL level for the loudspeaker is 132 dB, according to the Yamaha DB15 specifications. Therefore, a 100 dB SPL provided a 30 dB of safe margin not to produce distortions, which were not perceived during the measurements. Such source level was also defined to provide a signal-to-noise ratio of, at least 35 dB in accordance to the ISO 3382 part I. Therefore, the background noise level did not affect the measurements, as can be observed from the global decay curves shown in Fig. (**4**). from these plots, there is more than 40 dB until the decay curves reach the background level. Another reason the background noise does not interfere with the measurements is because the loudspeakers used were configured with a low-cut frequency filter starting at 100 Hz. Therefore, valid measurements were achieved only for frequencies between 100 Hz and 24 kHz (48 kHz sample rate frequency), while the main noise components were located below such frequency range (Fig. **3**).

A typical impulse response is presented in Fig. (**5**). On top, a typical reverberant energy decay can be seen, while, at the bottom, the zoom at the first 100 ms shows the direct sound followed by peaks, which correspond to the sound wave reflections on the walls and other surfaces (mainly benches).

Using Schroeder Backward Integration method [29, 30], implemented by the Matlab ToolBox provided by the IHTA Institute of Acoustics (https://www.ita-toolbox.org) [31], the full-band decay curves for all receivers and source S1 were calculated as well the averaged (using synchronized decay curves, as defined in ISO 3382-2 [32]), as shown in Fig. (**4**). From this Figure it is clear that the decay behavior is practically the same for the whole church area, without predominance of second decay modes. A headroom with more than 40 dB can also be observed, which provides a reasonable estimate of the Reverberation Time based on 30 dB without background noise interference. For both sources, the main left loudspeaker and the one at the altar the behavior remains the same, with slight slow decay and more extensive standard deviation for source S2.

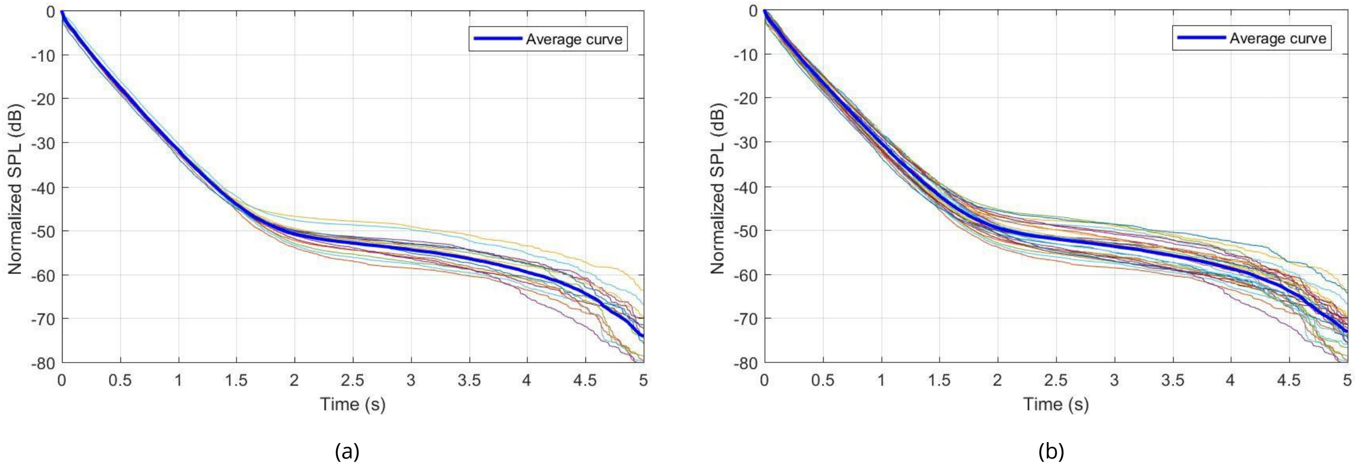


Figure 4: Decay curve analysis for sources (a) S1 and (b) S2 at all receivers. Bold lines are the average curve.

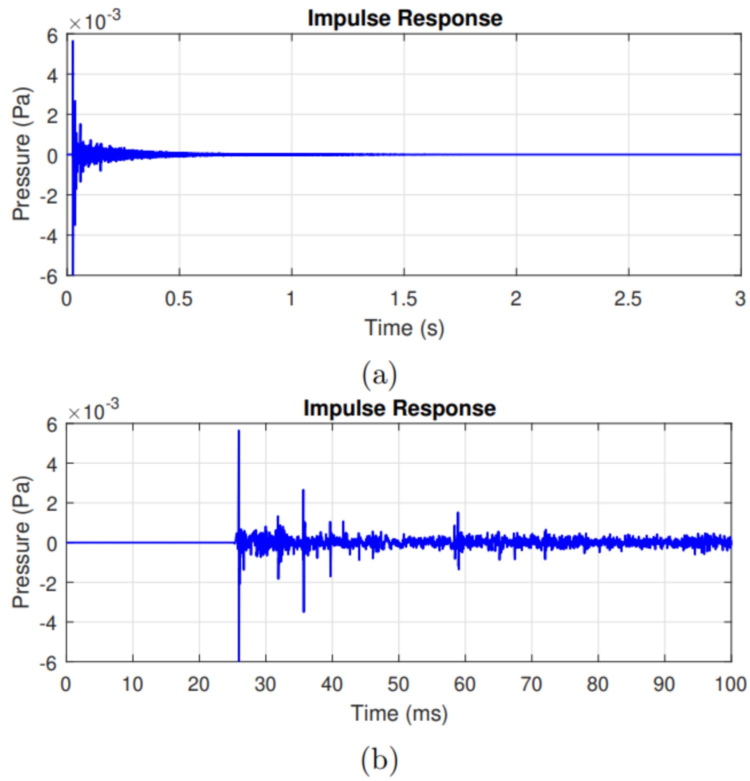


Figure 5: Typicall measured impulse response (source-receiver pair S1-R4): (a) Truncated at 3 seconds and (b) zoom view of the first 100 ms.

Another critical analysis is about the curvature of the decay curves. According to the ISO NBR 3382 part II standard, the Curvature Factor (*C*) can be obtained from Eq. (1) and provides information about the presence or influence of secondary decay modes. A regular Curvature Factor must be below 5%, meaning that Reverberation Times T_{30} and T_{20} are very similar and the measurements are reliable.

$$C = 100 \times \left(\frac{T_{30}}{T_{20}} - 1 \right) \quad (1)$$

Fig. (**6**) compares T_{20} and T_{30} on for each receiver for source S1 and their corresponding Curvature Factor. The same profile was obtained for source S2, omitted here for a space-saving reason. The T_{30} as function of frequency, for all receivers, was calculated in 1 octave frequency band, as shown in Fig. (**7**), as well as the spatial average, calculated according to ISO 3382-1 (arithmetic average of individual parameters). The averaged T_{30} at 500 Hz frequency band is 2.4 seconds. Speech and Music Clarity Factors (C_{50} and C_{80}, respectively) are room acoustic quality descriptors whose objective is to measure clarity. They are expressed in dB and relate the early and the late reflections of the impulse response concerning a split time, usually 50 and 80 ms. Therefore, the clarity factor will be negative if there is more energy after such time. In this case, the reverberation may mask the first reflections and reduce the audience ability to distinguish the words clearly and to perceive the musical note changes.

The same analysis done for T_{30} provided for Music Clarity Factor C_{80}, as shown in Fig. (**8**). There are significant differences depending on the receiver location. The highest clarity values are obtained at the receivers positioned closer to the sound sources (as expected). The lowest values are located at the back and the balcony, far from the direct sound coming from the sources and more influenced by the reverberant field. Notice that Clarity Factor is highly correlated with the Reverberation Time: The higher the reverberation, the lower the clarity, as described by Barron [33]. Therefore, for text shortness and objectivity, this paper focuses only on the Reverberation Times, knowing that, in most cases, its reduction leads to Clarity Factor improvement.

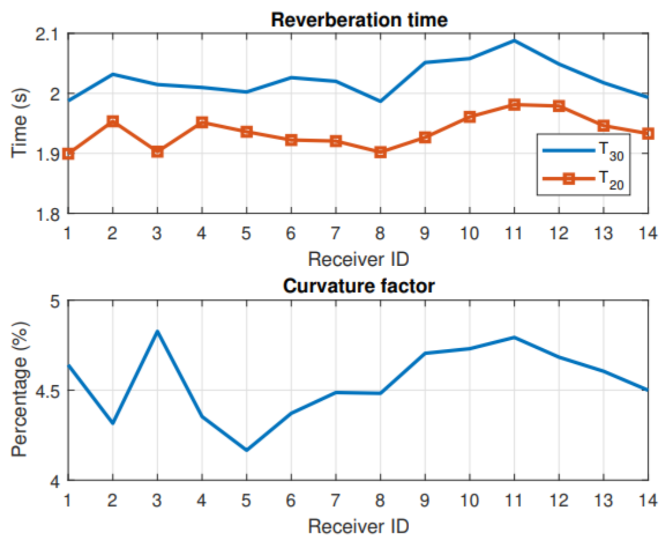


Figure 6: Comparison of measured Reverberation Times T_{20} and T_{30} each receiver (top) and their respective Curvature Factor for source S1 (bottom).

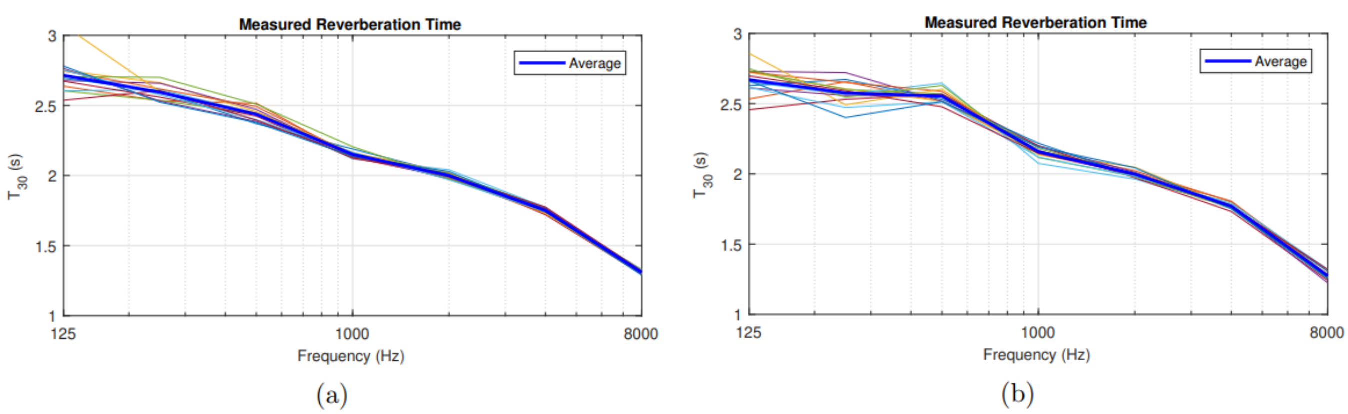
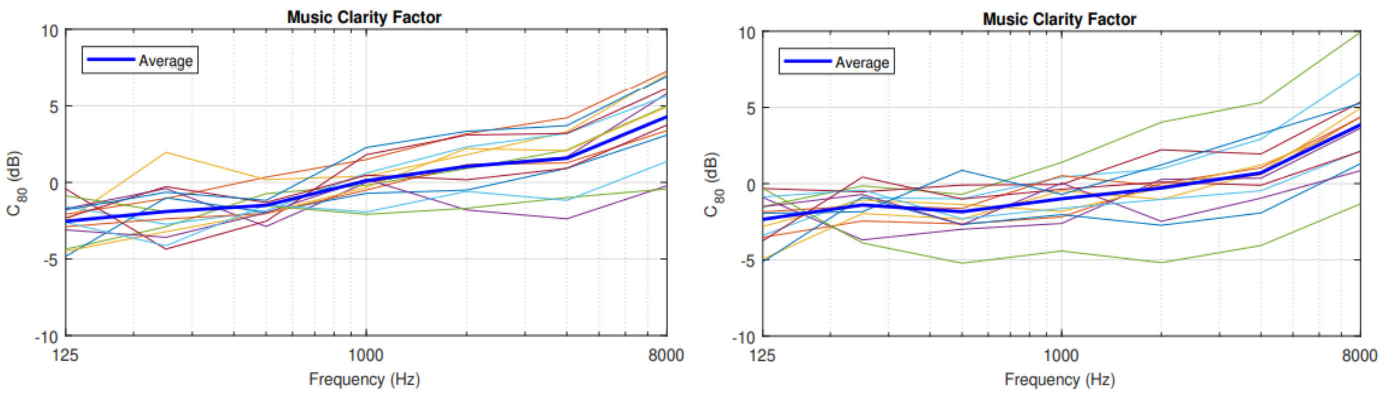


Figure 7: Measured Reverberation Time (T_{30}) overlay for all locations and the spatial average for sources (a) S1 and (a) S2.

Based on the Brazilian Standard NBR 12179:1992 [34], the optimum Reverberation Time for the 500 Hz frequency band, considering a volume of 1700 m^3 was extracted and presented in Table **1**, according to the room type or activity. From Figs. (**7**) a-b, the average Reverberation Time is approximately 2.4 s. Comparing it with the optimum values of Table **1**, the Itacuruçá Church is presenting much higher Reverberation Time than the expected for a Protestant church.



(a) (b)

Figure 8: Measured Music Clarity Factor (C_{80}) overlay for all locations and the spatial average for sources (a) S1 and (b) S2.

Table 1: Optimum Reverberation Time for 500 Hz frequency band according to the room types and activities, considering a volume of 11700 m^3 [34].

Activity/Type	Reverb. Time (s)
Organ Music and Catholic Churches	1.6
Synagogues, Protestant Churches, and Concert Halls	1.2
Cinema and conference halls	0.9

Therefore, it is clear that this protestant temple is not appropriate for choir music, contemporary music, and neither spoken word, since reverberation, in all measured locations, is higher than that adopted by literature and international standards as optimal value. Another recent issue about such a long Reverberation Time is the audio quality of services transmitted online through streaming platforms and social media. In order to capture the audience participation – such as singing as a congregational choir or simply during loud voice reading, for example, a few hanging microphones are used. These microphones are hung approximately 2 meters above the audience and choir areas. They capture the reverberant field since they are located in the audience's central area. The same holds for those above the choir area. During the streaming, the sound from electronic instruments and hand microphones is mixed with such reverberant sound captured by the hanged microphones, creating low-quality sound with low clarity indexes. When these microphones are muted during the online mixing, an abrupt ambiance changes from reverberant to "dry."

Another issue observed is the presence of room modes. The Schroeder Frequency is given by 2000 $\sqrt{T_{30}/V}$, where V is the room volume. It represents the lower frequency threshold up to the natural room modes rules over the energy decay. For this church, with 1700 m^3 and T_{30} for low frequencies of about 2.7 s, the Schroeder Frequency is approximately 80 Hz. Therefore, above such frequency, room modes would not be relevant. However, as shown in Fig. (**9**), there are some resonance modes between frequency ranges from 100 to 400 Hz. Fig. (**9**) shows the low-frequency content of the magnitude spectrum for 2 receivers with both sources. The receiver R1 is closer to source S1 and with a higher direct sound level. Receiver R9 is located at the back and far from the sources.

In Fig. (**9**), a prominent peak for pair S1-R1 can be observed at frequency 228 Hz, approximately 8 dB above the remaining. The same resonance frequency is observed for the pairs S1-R9 and S2-R9. The pair S1-R9 in Fig. (**9**) also presents 3 resonant modes at frequencies 143 Hz (D3 note), 163 Hz (E3 note) and 192 Hz (≈G3 note). Another mode appears in pairs S2-R1 and S2-R9 for the frequency 116 Hz (A#2 note). Organ notes are typically pure tones that excite the natural room modes and amplify some frequencies, similar to acoustic feedback. It means that when the organ or any other instrument plays with enough power to excite those modes, a resonance occurs at several locations at the audience and stage, creating an unpleasant hearing sensation, depending on source and receiver locations.

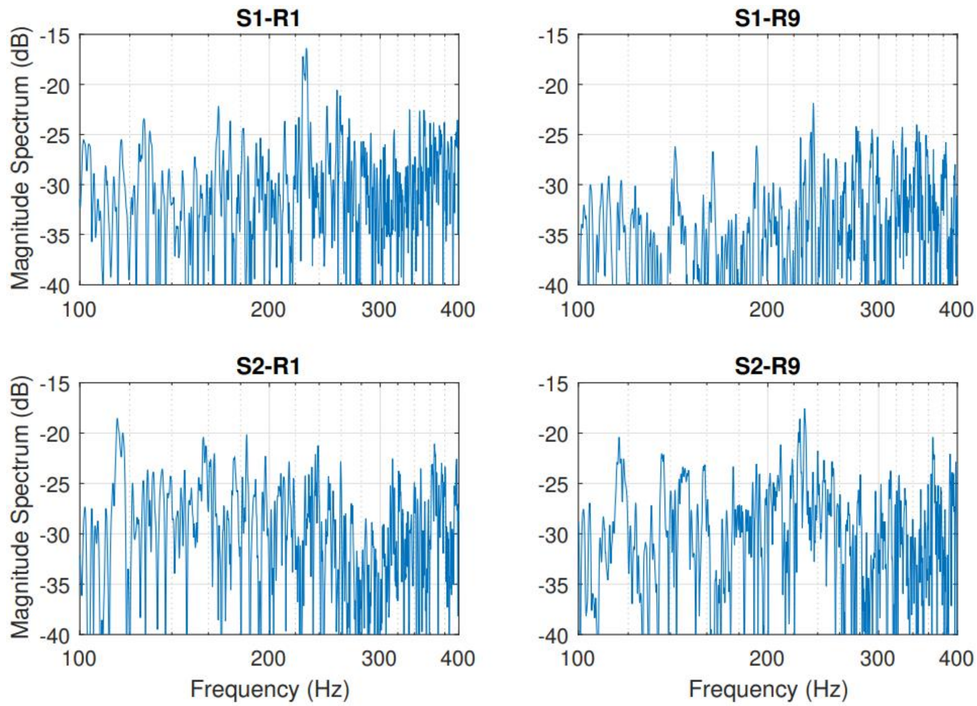


Figure 9: Frequency response magnitude at measured points R1 and R9 for sources S1 and S2 (Low-frequency range from 100 to 400 Hz).

4. Temple Acoustical Adequacy

Considering that the temple of the Itacuruçá Church does not present the acoustical characteristics in accordance to the standards this section presents a project to adjust the Reverberation Time to a more appropriate value, aiming for multiple uses during the service.

In order to evaluate the effect of material changes and the inclusion of absorptive surfaces, the acoustic simulator BRASS (Brazilian Room Acoustic Simulator) was selected for the task [35-37]. BRASS is a simulation tool that generates impulse responses (pressure over time) based on the ray-tracing method [38]. The impulse responses vary according to the receiver type. If a microphone is defined, then a single channel output is provided, considering the directional pattern of the microphone, such as omni-directional, cardiod, hyper-cardioid, and eight-figure, among others. Human or dummy heads may also be simulated, using Head-Related Transfer Functions (HRTF) Databank [39, 40] in Directional Audio File Format (DAFF) [41]. In this case, binaural audio is generated for the impulse response, which can be convolved with an anechoic signal, to reproduce the 3D human spatial sound perception with auralization [42, 43].

The simulation requires a geometrical and acoustic model of the temple. The surfaces are, firstly, modeled in any CAD software able to export data in DXF file format using 3DPolyline, 3DFaces, or PoliFaceMesh entities. The BRASS software imports from the DXF file all the geometry entities and associates them with material according to the corresponding layer. For each material, random incidence absorption coefficients must be assigned in 9-octave bands, ranging from 63 Hz to 16 kHz. Source and receiver positions are also imported from the CAD model. Fig. (**10**) shows the BRASS model for the temple built when this paper was published, i.e., without acoustic treatment. The model contains 223 planes.

In acoustic simulations, it is a good practice to ensure that the model represents accurately the actual room, considering both geometrical and acoustical aspects, mainly absorption coefficients. Therefore, a simulation of the actual state was performed, considering 20,000 rays launched from each sound source, omni-directional monoaural receivers and the absorption and the coefficients shown in Table **2**. No scattering coefficient was used because the software did not include diffuse reflection models.

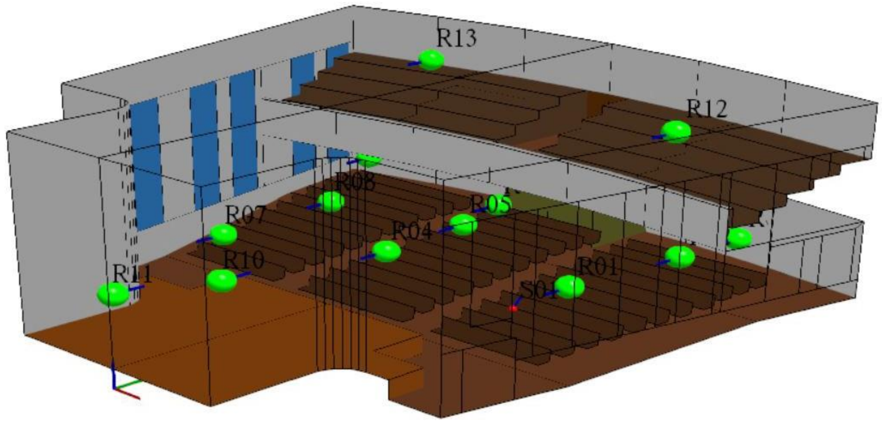


Figure 10: BRASS model for simulating the actual state of the temple (without any acoustic treatment).

Table 2: Random incidence absorption coefficients used for simulation (from Annex of [44]).

Material	Absorption / Frequency band (Hz)								
	63	125	250	500	1k	2k	4k	8k	16k
Glass window	0.35	0.35	0.25	0.18	0.12	0.08	0.06	0.04	0.04
Wood	0.15	0.14	0.10	0.08	0.10	0.11	0.10	0.10	0.10
Painted concrete	0.03	0.05	0.08	0.08	0.09	0.09	0.09	0.07	0.06
Parquet	0.06	0.06	0.06	0.08	0.12	0.12	0.16	0.16	0.16

It is known that geometric methods, such as Ray-tracing or Image Source, cannot deal with low frequencies due to interference wave phenomena. Therefore, only results above the 125 Hz octave band were investigated in this work, even using the lower bands in simulation. This is also in agreement with the frequency range used for the measurements.

Figure (**11a**) presents the comparison of the average T_{30} obtained from the measurements with the achieved from the simulation. The same comparison is provided in Fig. (**11b**) for parameter C_{80}. In both cases, the average was calculated over all the receivers and source S1. Very similar behavior was obtained for source S2. The simulation provided slight variation between the software output and the measured values, mainly for C_{80}. This is due to the hybrid simulation method adopted by BRASS, which clusters the first reflections and simulates the reverberant tail based on the rays which propagated up to the end of the impulse response time length. This method might provide some mismatch at the beginning of the impulse response, at the mixing area between the first and late reflections, even though the simulated and the measured might be in good agreement. Behaviors are compared, as shown in Fig. (**11**). Thus, it is considered that the model is representative of the current scenario, and changes made on some surfaces might also reflect the corresponding behavior.

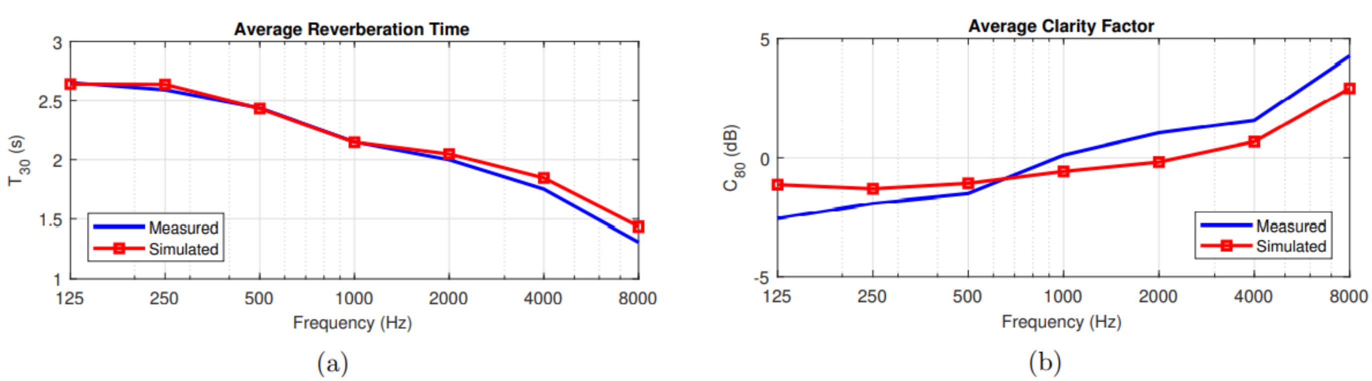


Figure 11: Comparison of measured and simulated averages for (a) Reverberation Time (T_{30}) and (b) Clarity Factor (C_{80}).

5. Acoustic Treatment

This section presents the acoustic proposition to adequate the temple to reduce the reverberation and improve clarity. The actual surface areas, with their respective materials, provide the averaged absorption coefficients shown in Table **3**. Such coefficients can be calculated by Sabine's formula in Eq. (2), where S is the total surface area (in this case approximately 1200 m^2), α is the absorption coefficient (frequency dependency was avoided for simplicity), and RT is the Reverberation Time (or T_{30}). Table **3** shows that the average (combined) absorption provided by the wood benches, parquet floor, glass windows, and painted concrete walls, among a few other materials, promotes about 10% of absorption.

$$RT = 0.16 \frac{V}{S\alpha} \tag{2}$$

Table 3: Equivalent absorption coefficients from actual measurements.

	Frequency band (Hz)						
	125	250	500	1k	2k	4k	8k
Measured T_{30}	2.6	2.5	2.5	2.1	2.0	1.7	1.3
Average absorption	0.09	0.09	0.9	0.11	0.11	0.13	0.17

According to NBR 12179, the optimal T_{30} for a Protestant church with approximately 1700 m^3 would be 1.2 seconds at 500 Hz (Table **1**). A more conservative approach to prioritize organ music would be to define the reverberation goal to 1.5 seconds with an empty church. When the church audience is occupied by more than 70%, the Reverberation Time will decrease due to the higher absorption promoted by people. Therefore, the final RT, at 500 Hz, is expected to be between the optimum 1.2 s (protestant services) and the maximum 1.5 s (organ music).

Neither the Brazilian nor the ISO standards define optimum value per frequency band. Along the time, a few different approaches were proposed to define such values for music and speech activities in rooms. According to [45], for music, a desirable Reverberation Time at lower frequencies (from 100 to 500 Hz) should be 1.5 times longer than the value at 500 Hz. Figure (**12**) presents proposed optimum values for RT according to [45-48].

Assuming that the Itacuruçá temple is a multi-purpose church, which presents organ music, choir performances, contemporary music with bands, and speech sermons, it was adopted as a goal for the Reverberation Time the profile shown in the black bold solid line of Fig. (**12**). It was based on the average of the other propositions and setting the RT at 500 Hz to 1.2 s as reference. Therefore, the goal of RT for the church, after including or substituting surface area with materials with more absorptive characteristics, is the solid black curve ("proposed").

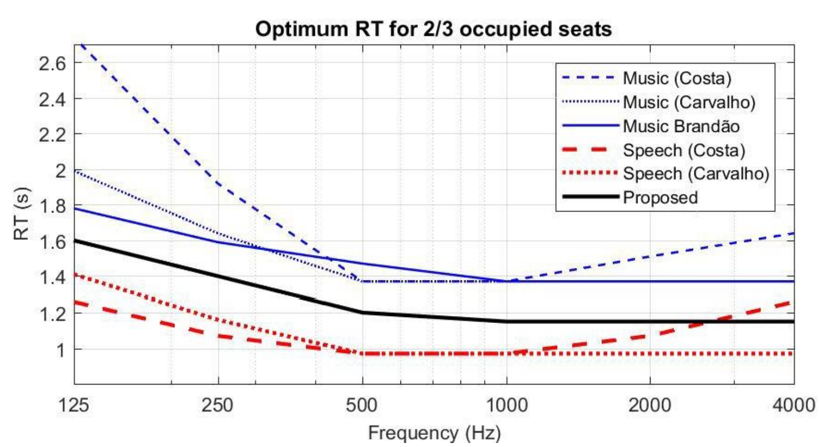


Figure 12: Optimum Reverberation Time for music and speech according to [46-48].

The church architecture does not present many options to substitute material on the side walls since almost half of the area (43%) is composed of glass windows and doors. The ceiling is flat, horizontal, and made of concrete. However, it has several lighting holes, which could only be changed with a new lighting-specific project. Therefore, only part of the lateral, back, and front walls are available for acoustic treatment.

In order to achieve the target profile defined in Fig. (**12**) and considering the architectural restrictions mentioned before, it was agreed with the church administration that more absorptive materials could be applied at the front and back walls. Besides that, the upper part of the windows and some areas of the lateral walls could be covered with acoustic panels. The total area available to receive acoustic treatment is approximately 129 m^2. Using Eq. (3), which is a variation of Eq. (2), the new average absorption α_T can be calculated for each frequency band by knowing the new acoustic treated area (S_T), the total surface area (S = 1200 m^2) and the target RT (for shortness and simplicity, the frequency dependency was omitted in the equation).

$$RT = 0.16 \frac{V}{(S - S_T)\alpha + S_T \alpha_T} \tag{3}$$

Based on that, several combinations of materials and areas were tried in order to lead to the desired absorption coefficients provided by Eq. (3). The following adequacy was proposed:

- To include perforated wooden absorptive panels, over rock wood panels, in the front wall;
- To create absorptive panels made with thin linen over rock wool;
- To cover the back wall (first floor and balcony) with a carpet;
- To cover the upper windows and the central portion of the lateral wall with the same type of wooden panels for the front wall.

Figure (**13**) illustrates the acoustic treatment for the church walls. The corresponding area and absorption coefficients can be observed in Table **4**. There were included 129 m^2 of materials with higher absorption coefficients. The equivalent absorption coefficients of the new materials are present in the last line of Table **4**. The materials and their respective area were adjusted to fit the desired Reverberation Time indexes per frequency band, as shown in Fig. (**12**).

Table 4: Proposed materials and absorption coefficients for Reverberation Time adjustment.

Material	Area (m^2)	Frequency band (Hz)								
		63	125	250	500	1k	2k	4k	8k	16k
Wooden panels	89	0.2	0.2	0.6	0.8	0.8	0,7	0,7	0,55	0.55
Cloth over rock wool	8	0.6	0.6	0.6	0.6	0.6	0.7	0.6	0.55	0.55
Carpet [44]	32	0.02	0.02	0.04	0.08	0.20	0.35	0.4	0.40	0.40
Combined influence	**129**	**0.19**	**0.19**	**0.40**	**0.58**	**0.70**	**0.74**	**0.74**	**0.68**	**0.68**

The wooden panels, cloth, and carpet to be added or applied to the surfaces must be chosen in the market according to the absorption coefficients defined in Table **4**. There is a variety of manufacturers and models that may adapt to such coefficients. The proposed values were already adjusted considering some products available in the Brazilian acoustic market.

5.1. Simulation Results

The proposed modifications were evaluated using only simulation since the acoustic project was not implemented until this work publication. Therefore, comparing the simulated results with actual measurements was impossible. However, it is assumed that, due to the excellent agreement of the acoustic model used for the temple analysis and the software confidence from late works, the results will also be in accordance with the expected results.

A new model for the BRASS simulator was built, substituting the areas shown in Fig. (**13**) with the corresponding absorption coefficients of Table **4** and keeping the remaining ones. The simulation model is presented in Fig. (**14**).

(a) Front wall.

(b) Lateral walls.

(c) First floor back wall.

(d) Balcony back wall.

Figure 13: Proposed acoustic treatment for (a) front wall, (b) lateral walls, (c) first floor back wall, and (d) balcony back wall.

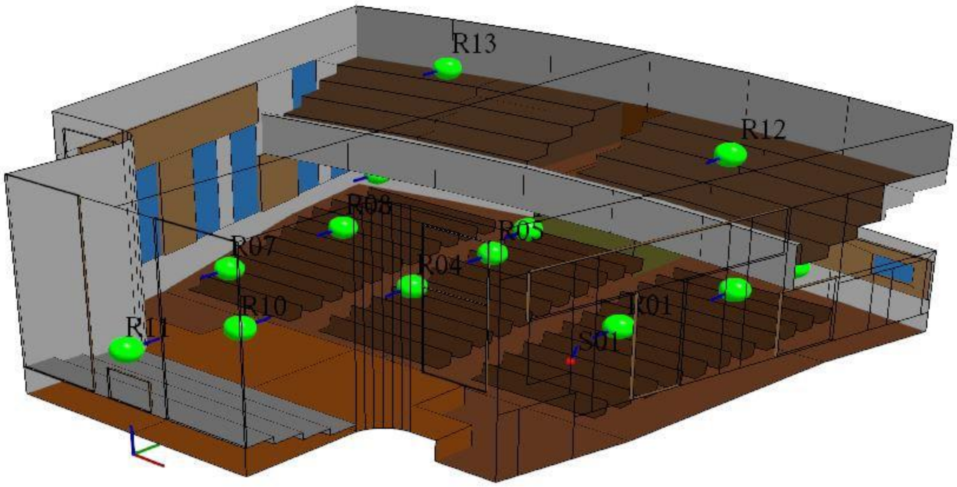


Figure 14: BRASS model for simulating the proposed acoustic treatment.

The proposed model was simulated using the same configuration (number of rays, stop criteria, etc.) as the untreated model, except for including the new surfaces and respective absorption coefficients. The Reverberation Time and the Clarity Factor for all receivers and their respective averages are shown in Fig. (**15**) for source S1. From this figure, it can be observed that the goals were achieved: an RT profile in good agreement with the proposed in Fig. (**12**) and a significant improvement in Clarity Factor, which will allow better speech intelligibility without compromising music programs. Similar behavior was obtained for source S2.

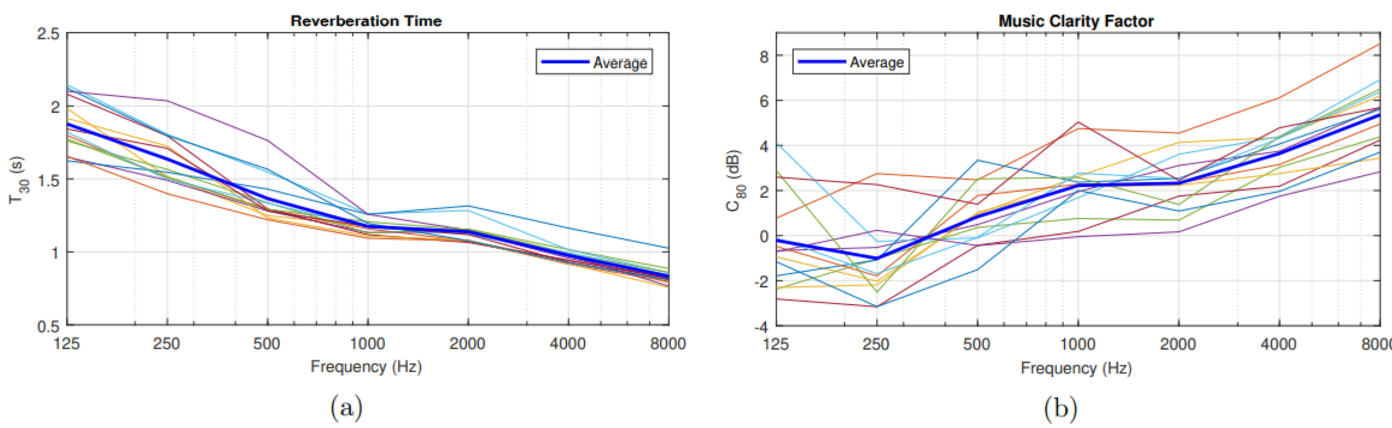


Figure 15: Results for the proposed acoustic treatment: (a) Reverberation Time and (b) Clarity Factor for source S1, all receivers. The bold lines correspond to the parameter average.

6. Conclusion

This paper presented an acoustic case study of the Itacuruçá Baptist evangelic church. The acoustic characteristics were obtained from measurements, showing that the RT for all locations was inadequate for the actual types of use. The mean value of RT was considered too high (2.4 s), even for organ music. Such long reverberation time would be appropriate only for a temple with almost 10 times the church volume. The acoustic model for simulation was built using BRASS software and calibrated using standard absorption coefficients, whose results presented an excellent agreement with the measurements. Based on that model, surface covering and perforated acoustic panels were introduced to adequate the parameters to the established RT targets. The new simulation was performed to evaluate such adequacy, demonstrating RT adjustment to 1.2 seconds at 500 Hz and improved clarity factor, varying from -2 to 4 dB, on average. The proposed acoustic treatment was not yet implemented in the church, so it was impossible to investigate if the simulated results matched the measurements. If the project is implemented in the future, the materials should be selected in order to have absorption coefficients closer to the proposed, and a new measurement set should be performed to evaluate and provide a fine-tuning of the temple acoustics. However, since the absorption coefficients were chosen according to the well-established reverberation theory and the BRASS simulator has proven to be accurate in several studies, the results presented for the proposed adequacy model might be considered reliable.

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