

Evaluation of the Acoustic Environment in a Protestant Church Based on Measurements of Acoustic Descriptors

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Abstract

The new guidelines of the Catholic Church are in line with the guidelines adopted by Protestant churches since the Reformation, unifying appreciation for the liturgical practices of preaching and congregational singing. These guidelines require that the room, in this case the church, provides appropriate acoustic characteristics, which can be characterized by acoustic descriptors such as Reverberation Time (RT), Clarity (C80) and Definition (D50). In this article, we analyzed the acoustic quality of a protestant church whose design tried to follow these guidelines. Our findings revealed the poor quality of the acoustic environment in terms of both speech intelligibility and music. These findings emphasized the need to adopt not only Reverberation Time but also other acoustic descriptors such as Clarity and Definition in church design.

Keywords

Acoustic Quality, Church, Clarity, Definition, Reverberation Time

1. Introduction

Architectural acoustics has helped churches to achieve their liturgical goals [1]-[3]. The church became a center for the proclamation of the gospel whose acoustics should meet people's needs [1]. The Protestant Reformation introduced congregational singing, and Martin Luther (Germany) and John Calvin (the Netherlands and Switzerland) found in music a way to hear the word of God and to praise and thank Him [4] [5].

The acoustics of a church must be appropriate for its worship service program. Three types of activities should be considered: 1) Preaching of the word from the rostrum or altar by the preacher; 2) Congregational singing by the faithful in the nave of the

church; and 3) Musical performance by the church choir, organ or musical ensemble behind the altar or in the choir stalls [1]. These activities are often acoustically exclusive. However, to overcome these problems, Berardi [6] proposed the formulation of a parameter called “double synthetic index”. Also, according to Berardi [6], “A double synthetic index has been defined to synthesize the acoustical properties related to the music and to the speech separately”. Therefore, based on Berardi [6], one can probably find ways to manage the different acoustic requirements. A sanctuary optimized for speech intelligibility means sacrificing musical performances. The desired reverberation time (RT) of 2.5 to 3 s for a church with a pipe organ will reduce the intelligibility of the sermon [1]. The acoustics suitable for a choir is not the same as that for a preacher [1] [7] [8], but it will support and encourage the participation of the congregation [9]. Therefore, it is not acoustics that designs liturgical spaces; rather it is acoustics that must find ways to meet the liturgical requirements of the church [8]. The particularities of liturgies make churches acoustically complex environments that require responses and conditions that go beyond the solutions found for concert halls, opera houses and theatres [1] [10].

Assessments of the acoustic quality of a church involve two tasks: 1) Characterization of the acoustic space based on measurements of its acoustic properties, and 2) Comparison of the measured and optimal values for each liturgical event [7]. Because it is difficult to achieve such optimal values simultaneously, one condition must be prioritized at the expense of the others [1]. Three conditions for reverberant spaces are cited for Catholic churches, the most suitable one being the third condition: 1) Short reverberation time, which favors the speech intelligibility of the preacher; 2) Average reverberation time, which is useful for both music and speech intelligibility; and 3) A sufficiently long reverberation time to produce a resonant and glorious response of pipe organ music or choir singing [7] [8].

Jürgen Meyer [11], author of *Church Acoustics* (Kirchenakustik, in German), on pages 162 to 167, offers three suggestions to reduce the reverberation time in churches. According to Meyer, as is known, most churches have stone slab floors, whose absorption coefficient is usually low. Meyer’s [11] first suggestion is to: “Make a 10 cm deep hole under the chairs or pews and install a wooden floor in this cavity. The wooden floor must be flush with the stone floor”. **Table 1** shows the improvement in absorption coefficients for three types of floors, according to Meyer, page 163 [11]: 1) Smooth stone floor, 2) Wood floor set directly on the subfloor, and 3) Wooden floor set in the 10 cm deep cavity, flush with the level of the stone floor.

In his book *Kirchenakustik*, on page 167, Meyer’s [11] second suggestion is to: “Install sound absorption material underneath the pews”. The author recommends the use of mineral fiber or foam. His third suggestion is to upholster the pews. **Table 2** shows the absorption coefficient of pews with and without upholstery.

In evangelical churches, speech intelligibility should generally be prioritized by a shorter reverberation time. However, in some churches, due to the emphasis given to praise and worship, or the use of a pipe organ or choir, a longer reverberation time or

Table 1. Absorption coefficients of some types of floors, according to Meyer [11].

Flooring material	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Situation 1	0.01	0.01	0.02	0.02	0.03	0.03
Situation 2	0.04	0.04	0.05	0.06	0.06	0.06
Situation 3	0.15	0.12	0.10	0.07	0.06	0.06

Table 2. Absorption coefficients of church seats (mean values), according to Meyer [11].

Church Seats	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Non-upholstered	0.10	0.15	0.18	0.20	0.20	0.20
With 3 cm upholstery	0.10	0.20	0.60	0.75	0.85	0.85

values intermediate to the recommended ones should be adopted: 1) Readings and sermons require a reverberation time of less than 1 s; 2) Contemporary music requires a reverberation time of about 1.5 s; 3) Congregational singing requires a reverberation time of about 2 s; and 4) A pipe organ requires a reverberation time of about 3 s [1] [7].

Given the increasing importance of Evangelical Churches in Brazil, a country whose population is mostly Catholic, the aim of this work was to analyze the acoustic environment of a new Evangelical Church, which is in its final stage of completion. To this end, measurements of the following acoustic descriptors were undertaken: Reverberation Time (T30), Clarity (C80), and Definition (D50). The growth of the evangelical church in Brazil is shown by the following data: in 1991 the evangelical church represented 9% of the population, with 13.7 million followers; in 2000 it represented 15.4% of the population, with 26.1 million followers. Today it has over 43 million followers, representing more than 22% of the population.

2. Description of the Church under Analysis

The aforementioned acoustic parameters were measured in the Abba Christian Fellowship Church in the city Curitiba (southern Brazil). This church has 2800 individual upholstered seats, 4 mm carpeting, 12.5 mm perforated acoustic ceiling panels, textured painted walls and a rostrum with wooden flooring. The church has a 4-way front cluster sound system, which was not used during the acoustic measurements. **Figure 1** shows the external facade of the church, while **Figure 2** shows the floor plan of the nave, rostrum and detail of the columns of the mezzanine. **Figure 3** presents an overview of the nave seen from the mezzanine. **Table 3** describes the main dimensions of the church, whose total volume is about 16,200 m³.

3. Materials and Method

According to Cirillo and Martellotta [7], to qualify a space acoustically requires measuring its acoustic properties. In this study, the acoustic parameters of Reverberation time (T30), Clarity (C80) and Definition (D50) were measured according to the guidelines of

the standard ISO 3382-1:2009-Acoustics-Measurement of Reverberation Time-Part 1: Performance Spaces [12]. The measurements were taken using the following instruments: 1) Brüel & Kjaer 4296 omnidirectional sound source; 2) Lab. Gruppen Lab 300 power amplifier; 3) Brüel & Kjaer 2238 sound level meter; 4) DIRAC 3.1 software, using the sine sweep method; and 5) an RME Fireface 800 firewire audio interface circuit board. According to the ISO 3382-1: 2009 standard [12], these measurements require the use of one sound source in two different positions. Therefore, a sound source was placed in two different positions—F1 and F2—on the rostrum, symmetrical in relation to the center line of the church, as indicated in **Figure 4** and **Figure 5**.

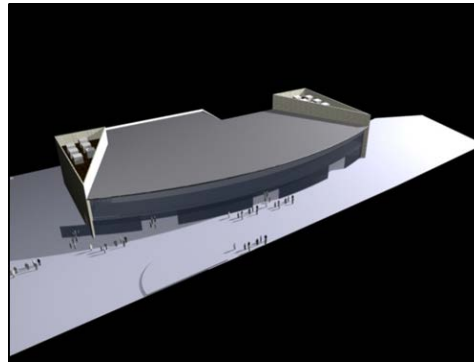


Figure 1. External view of the church.

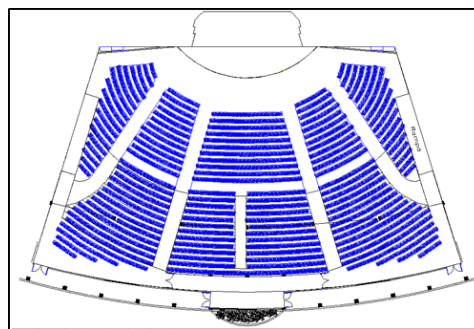


Figure 2. Floor plan of the nave and rostrum and detail of the columns supporting the mezzanine.



Figure 3. General view of the nave and rostrum.

Table 3. Key internal dimensions of the church (in meters).

Location in church	Internal dimensions (m)		
	Width	Average height	Depth
Rostrum	15	9	5
Frontofchurch	40	11	0
Middleofchurch	50	10	15
Front (Mezzanine)	52	3.2 - 8.7	18
Back (Mezzanine, church)	60	3.6 - 6.2	30

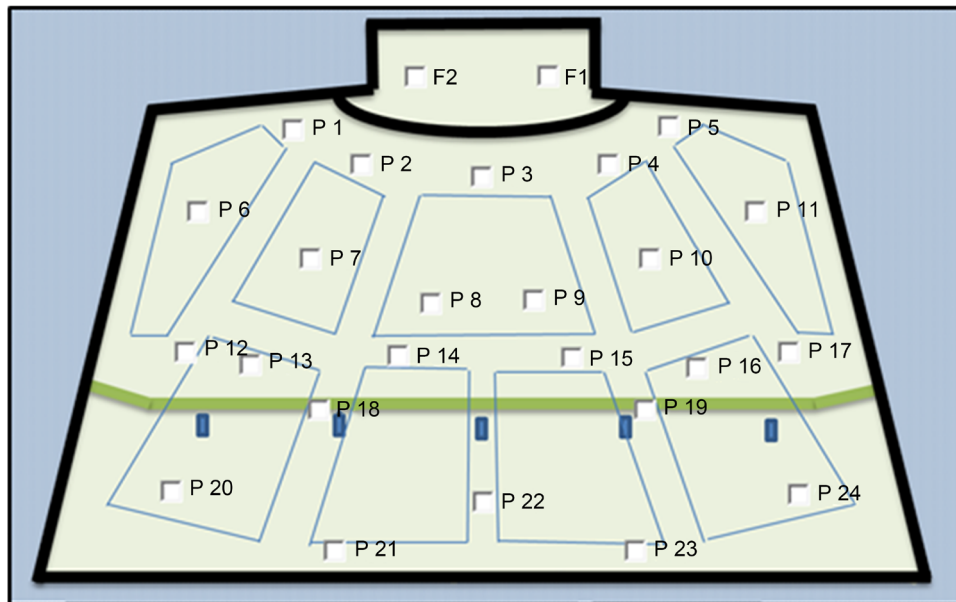


Figure 4. Location of the sound sources on the rostrum and receiver points on the ground floor.

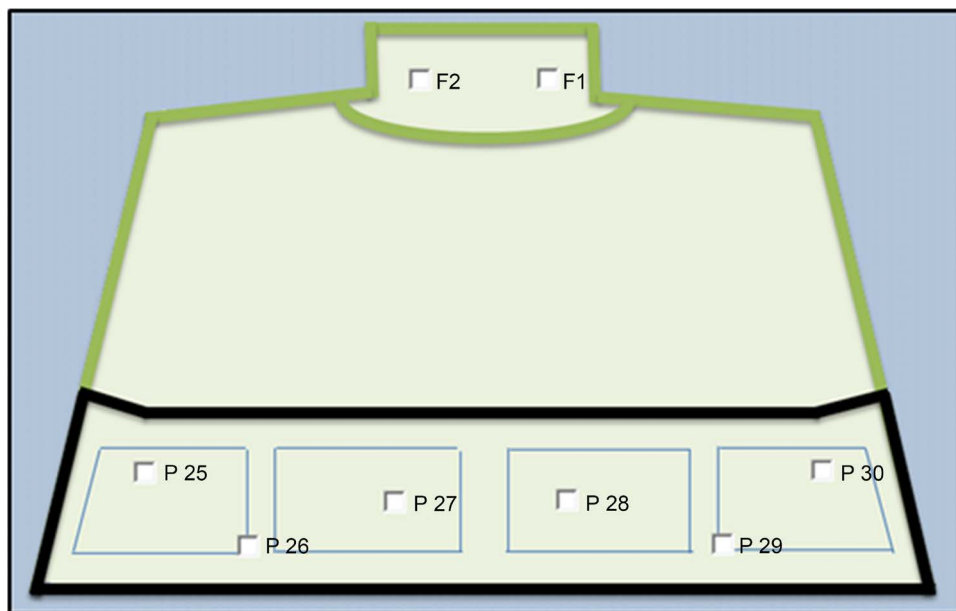


Figure 5. Location of the sound sources on the rostrum and receiver points on the mezzanine.

Table 4 describes the distance between the receiver points and the positions of the sound source on the rostrum—position F1 and position F2. Measurements were taken at 30 receiver points, where the microphones were positioned at points representing the seats in the nave, at a height of 1.2 m from the floor, distributed as illustrated in **Figure 6**. The measurements were taken in the empty church without using the church's sound system.

Table 4. Distance, in meters, between the receivers points and the sound source positions on the rostrum (position 1 = F1) – (position 2 = F2).

Measuring point (receivers)	Distance to the sound source in meters [m]	
	F1	F2
P1	17.73	8.04
P2	12.50	7.50
P3	9.43	9.43
P4	7.50	12.50
P5	8.04	17.73
P6	23.52	13.91
P7	18.87	11.66
P8	17.49	15.03
P9	15.03	17.49
P10	11.66	18.87
P11	13.91	23.52
P12	30.23	22.67
P13	29.73	23.32
P14	21.95	19.03
P15	19.03	21.95
P16	23.32	29.73
P17	22.67	30.23
P18	27.46	23.54
P19	23.54	27.46
P20	37.54	30.81
P21	32.65	24.43
P22	25.50	25.50
P23	24.43	32.65
P24	30.81	37.54
P25	36.43	29.11
P26	35.57	30.08
P27	27.38	24.28
P28	24.28	27.38
P29	30.08	35.57
P30	29.11	36.43

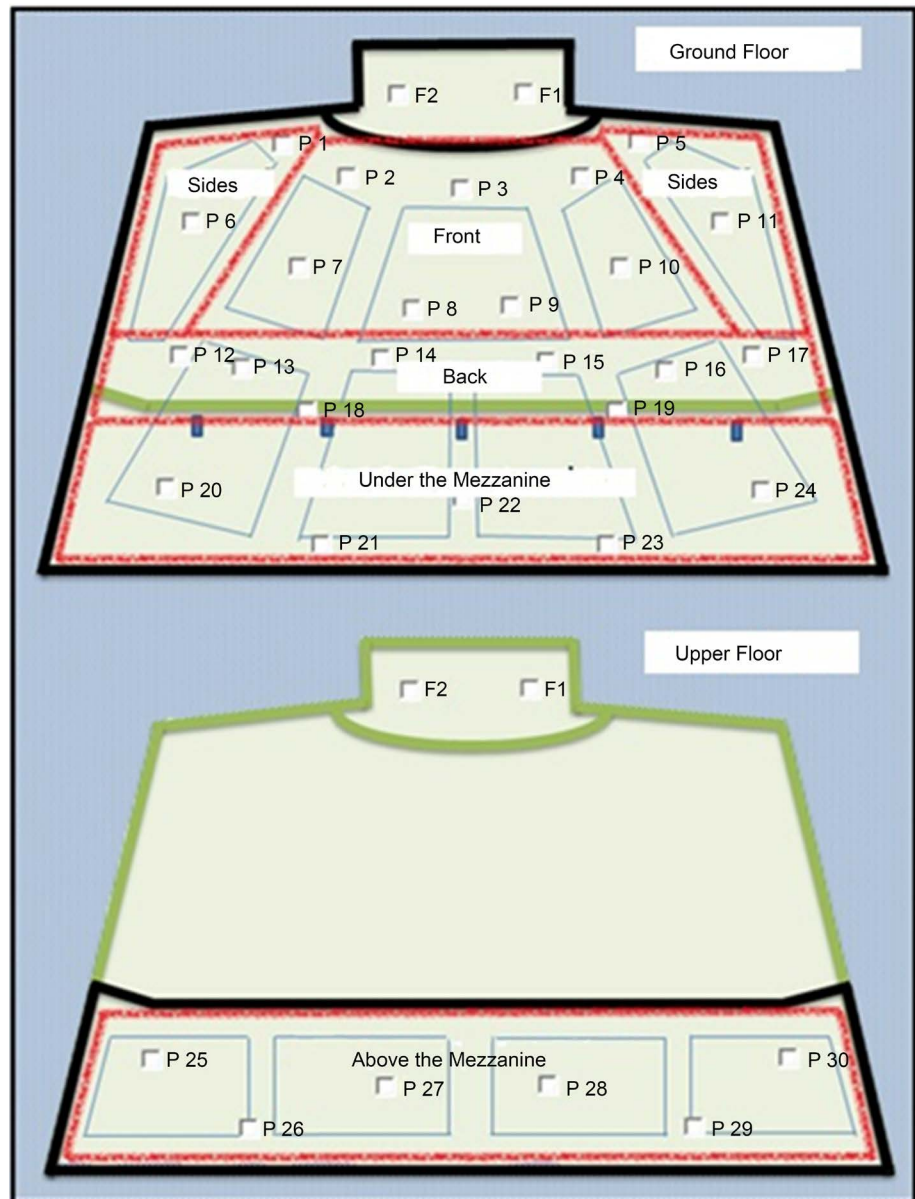


Figure 6. Division of the church's internal space into subareas-ground and upper floors.

The following parameters were investigated in this study: Reverberation Time (RT) according to Harris [13], and Clarity (C80) and Definition (D50) as described by Beranek [14] and Cirilo and Martellota [7]. The reference values for D50 and C80 used in this work are presented in Table 5 and Table 6, according to Marshall [15]. With regard to RT, the optimal time was obtained from the Brazilian standard NBR 12179: 1992-Acoustic Treatment in enclosed spaces [16]. For Protestant churches with a volume of 16,200 m³, this standard indicates an optimum RT of 1.8 s.

4. Results and Discussion

The values of the parameters for each receiver point were measured in octave bands

Table 5. Values for the parameter Clarity, C80, according to Marshall [15].

Clarity	C80 [dB]
Pop rock	7 to 18
Opera	3 to 7
Symphony	-2 to 3
Organ	-12 to -4

Table 6. Values for the parameter Definition, D50, according to Marshall [15].

Definition	D50 [%]
Excellent	0.86 to 1.0
Very good	0.67 to 0.86
Good	0.39 to 0.67
Bad	0.17 to 0.39
Terrible	0.06 to 0.17

and the mean value was calculated from the arithmetic mean of the frequencies of 500, 1000 and 2000 Hz for the values of T30 and of D50, as recommended by Marshall [16]. The average value of C80 was obtained by the logarithmic mean of the frequencies of 500, 1000 and 2000 Hz, as recommended by Marshall [15]. **Table 7** lists the mean values of parameters C80, D50 and T30 at each receiver point.

The mean reverberation time was calculated to qualify the general environment of the church, as indicated in **Table 8**. As for the parameters of Clarity and Definition, it would not make sense to determine an average value for the general environment because these parameters are strongly dependent on the distance between the sound source and the receiver point [15]. However, for the analysis undertaken here, the space can be subdivided into areas that have the same acoustic or constructive characteristics, as illustrated in **Figure 6**. **Table 8** lists the mean values of C80, D50 and T30 in each subarea of the church and shows a mean of T30 for the entire church.

In the Abba Christian Fellowship Church evaluated here, the church's music program for meetings follows the "Pop Rock" genre. According to Marshall [15], the C80 for this music genre lies within the range of 7 to 18 dB.

Therefore, it should be clear in this part of this article that what is being studied here is C80 for an evangelical church that uses only the "Pop Rock" music genre.

Figure 7 illustrates the reverberation times, T30, as well as a logarithmic regression curve indicating the tendency of these values at each receiver point in relation to the distance from the sound source. Note that the points closest to the sound source present a slightly lower T30 than the more distant points, as indicated by the mean values listed in **Table 4**; the two points furthest from the regression line are located underneath the mezzanine. The mean reverberation time in this space is $T30 = 1.93$ s.

Table 7. Measured values of the acoustic descriptors C80, D50 and T30.

Measuring points (receivers)	Clarity C80 [dB]	Definiton D50 [%]	T30 [s]
P1	-0.79	0.34	1.87
P2	0.56	0.42	1.86
P3	1.42	0.51	1.84
P4	0.56	0.42	1.86
P5	-0.79	0.34	1.87
P6	-0.94	0.34	1.92
P7	0.00	0.35	1.89
P8	0.80	0.48	1.92
P9	0.80	0.48	1.92
P10	0.00	0.35	1.89
P11	-0.94	0.34	1.92
P12	-0.93	0.33	1.94
P13	-1.60	0.30	1.94
P14	-0.77	0.35	1.94
P15	-0.77	0.35	1.94
P16	-1.60	0.30	1.94
P17	-0.94	0.34	1.92
P18	-0.69	0.32	1.91
P19	-0.69	0.32	1.91
P20	-1.41	0.30	1.97
P21	-0.45	0.35	1.95
P22	-1.38	0.27	2.02
P23	-0.45	0.35	1.95
P24	-1.41	0.30	1.97
P25	-1.81	0.24	1.97
P26	-1.50	0.29	1.97
P27	-1.28	0.33	1.95
P28	-1.28	0.33	1.95
P29	-1.50	0.29	1.97
P30	-1.81	0.24	1.97

Table 8. Mean values of C80, D50 and T30 in each subarea of the church and mean T30 for the entire church.

Sub area	C80 [dB]	D50 [%]	RT30 [s]
Front	0.62	0.43	1.88
Sides	-0.87	0.34	1.89
Back	-0.98	0.33	1.90
Under the Mezzanine	-1.00	0.32	1.97
Above the Mezzanine	-1.53	0.28	1.96
Average Reverberation Time (General indoor environment)	-	-	1.93

Figure 8 shows the values of the parameter Definition D50, representing all the measured receiver points and a logarithmic regression line. As can be seen, the slightly downward inclination of the values of the farthest points on the regression curve indicates a tendency for lower speech intelligibility in the areas further away from the sound source.

With regard to the parameter Clarity, C80, for music, **Figure 9** shows the receiver points, along with the logarithmic regression curve. Despite the wide distribution of the receiver points on the logarithmic regression curve, note that this curve clearly shows a strong tendency for the values of C80 to decline with distance. **Figure 9** indicates that the mean values of C80 are much lower, than those required for the Pop Rock music genre used in the Abba Christian Fellowship Church. This is clearly indicated in **Table 5**, which shows that the lowest value of C80 for Pop Rock is 7 dB. The range of values found here would be adequate for symphonic music, see **Table 5**.

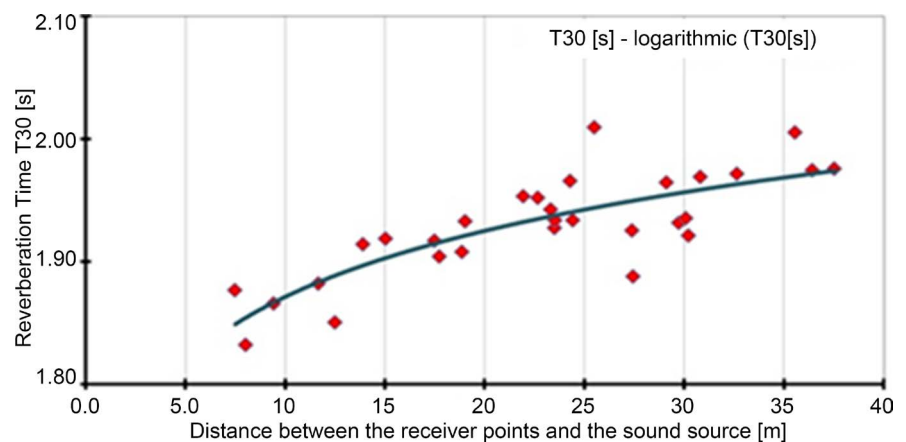


Figure 7. Reverberation Time T30 as a function of the distance [m] between the receiver points and the sound source.

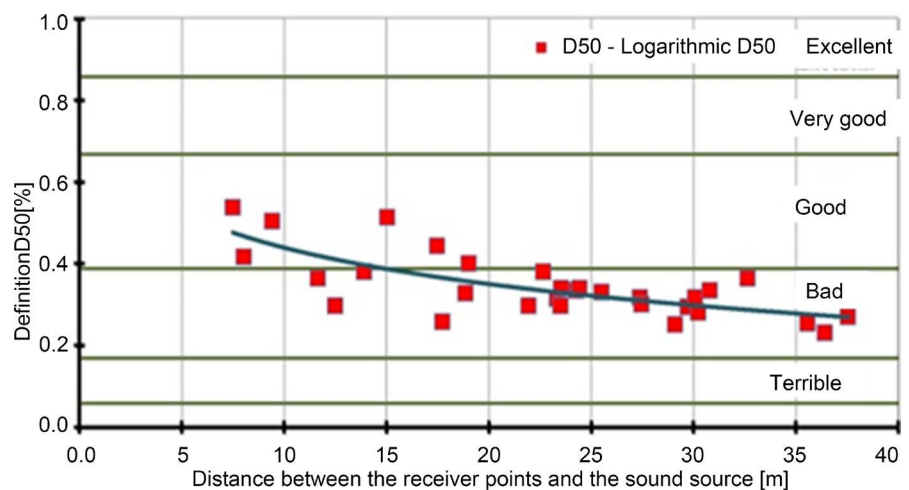


Figure 8. Distribution of the parameter Definition D50 [%] as a function of the distance [m] between the receiver points and the sound source. The graph also indicates the ranges proposed by Marshall [15].

A detailed analysis of the parameters measured in each subarea indicates how the acoustic quality is distributed through environment. The subareas in question are identified as—FRONT, SIDES, BACK, UNDER THE MEZZANINE, and ABOVE THE MEZZANINE.

Figure 10 illustrates the distribution of D50 [%] in the subarea FRONT as a function of the distance [m] between the receiver point in the nave and the sound source on the rostrum. The more frontal points possess a “Good” speech intelligibility, which declines to “Bad” at the points farther from the rostrum.

Figure 11 shows the distribution of C80 [dB] as a function of the distance between

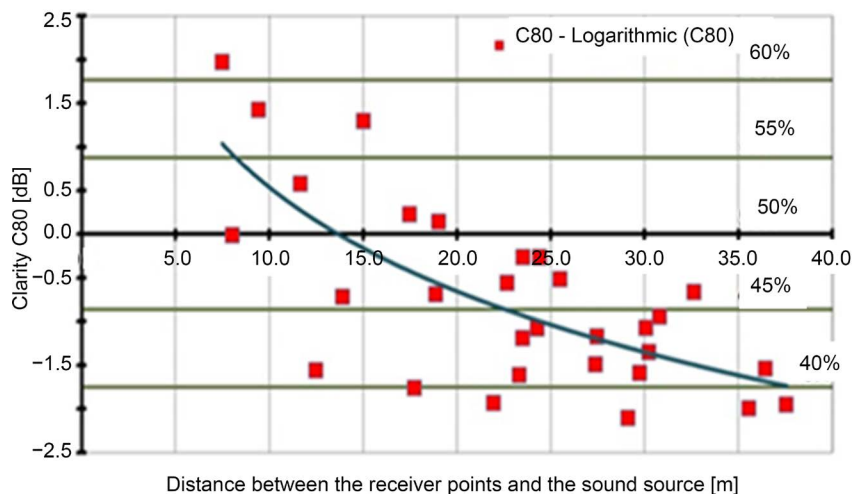


Figure 9. Distribution of the parameter Clarity C80 [dB] as a function of the distance [m] between the receiver points and the sound source.

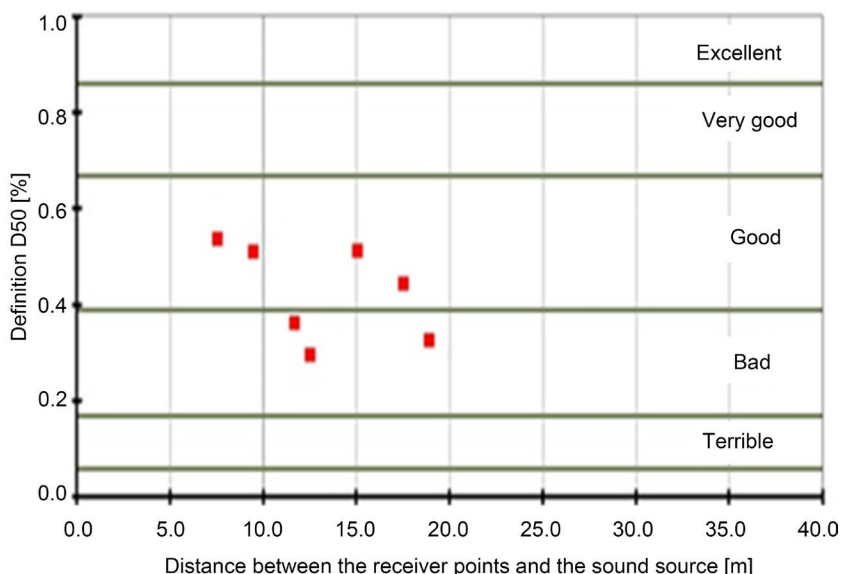


Figure 10. Distribution in the subarea FRONT of the parameter D50 [%] as a function of the distance [m] between the receiver points and the sound source. The graph indicates the range of values proposed by Marshall [15].

the receiver (listener) and the sound source on the rostrum. All the receiver points fall outside the range of values indicated for the church's music program, *i.e.*, Pop Rock. The range of values found would be ideal for the rendering of symphonic music, according to **Table 5**.

Figure 12 illustrates the values for D50 [%] for the subarea SIDES. Except for one measured point classified as "Good", all the other measured points lie within the range evaluated as "Bad". **Figure 13** shows that for the points of C80, the subarea SIDES has values ranging from 0 to -2 dB. These values for C80 do not meet any of the music genre presented in **Table 5**. **Figure 13** shows that for C80, the values of the points in the subarea SIDES lie within the range of 0 to -2dB. These C80 values do not satisfy any of the music genres listed in **Table 5**.

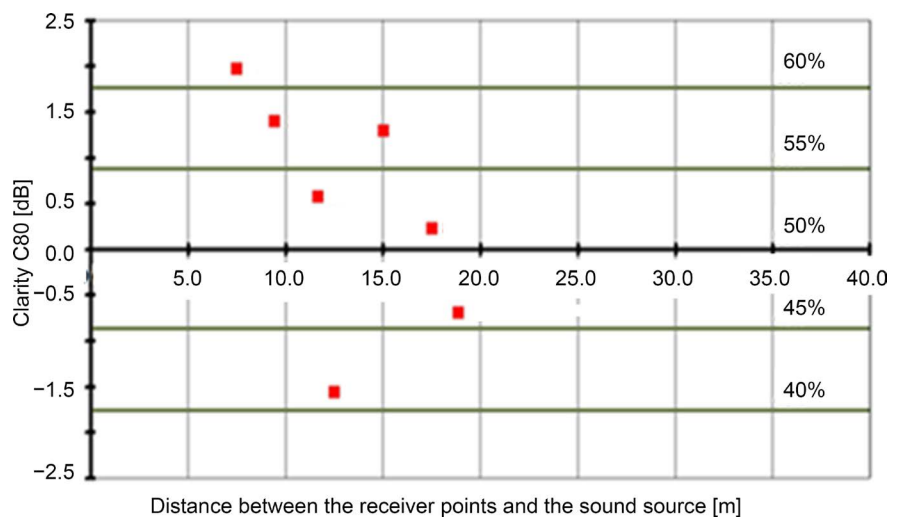


Figure 11. Distribution in the subarea FRONT of the parameter C80 [dB] as a functions of the distance between the receiver points and the sound source [m].

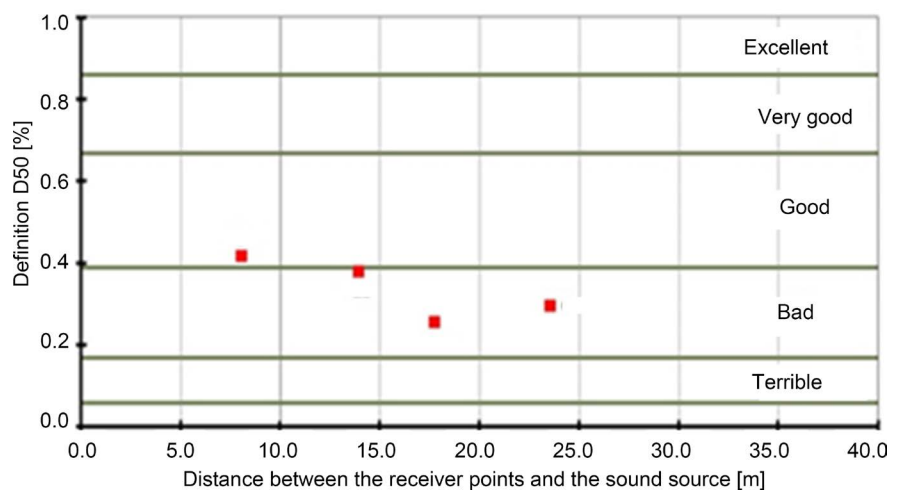


Figure 12. Distribution in the subarea SIDES of the parameter D50 [%] as a function of the distance [m] between the receiver points and the sound source. The graph indicates the range of values proposed by Marshall [15].

Figure 14 illustrates the values of D50 and Figure 15 those for the C80 for the sub-area BACK. Most of the receiver points lie within the “Bad” area for speech intelligibility, and also within intervals inadequate for the church’s musical program.

Figure 16 illustrates the values of D50 and Figure 17 those of C80 for the subarea UNDER THE MEZZANINE. At the BACK of the church, the values of D50 all fall

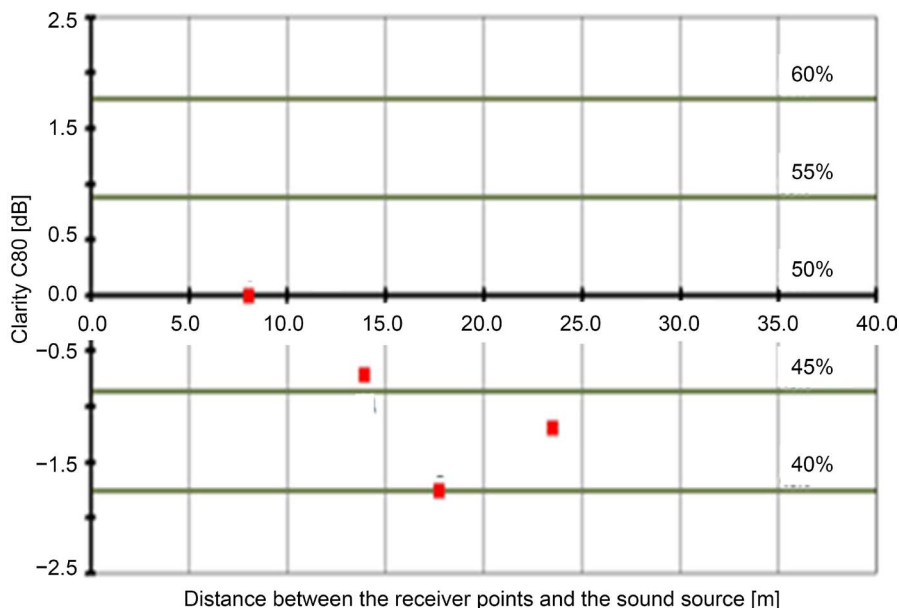


Figure 13. Distribution in the subarea SIDES of the parameter C80asa function of the distance between [m] the receiver points and the sound source.

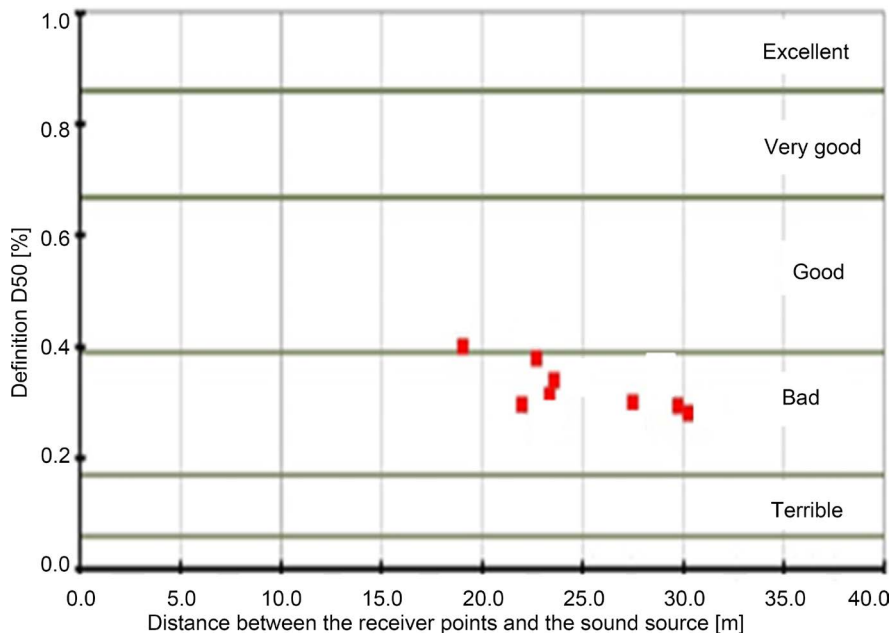


Figure 14. Distribution in the subarea BACK of the parameter D50 [%] as a function of the distance [m] between the receiver points and the sound source. The graph indicates the range of values proposed by Marshall [15].

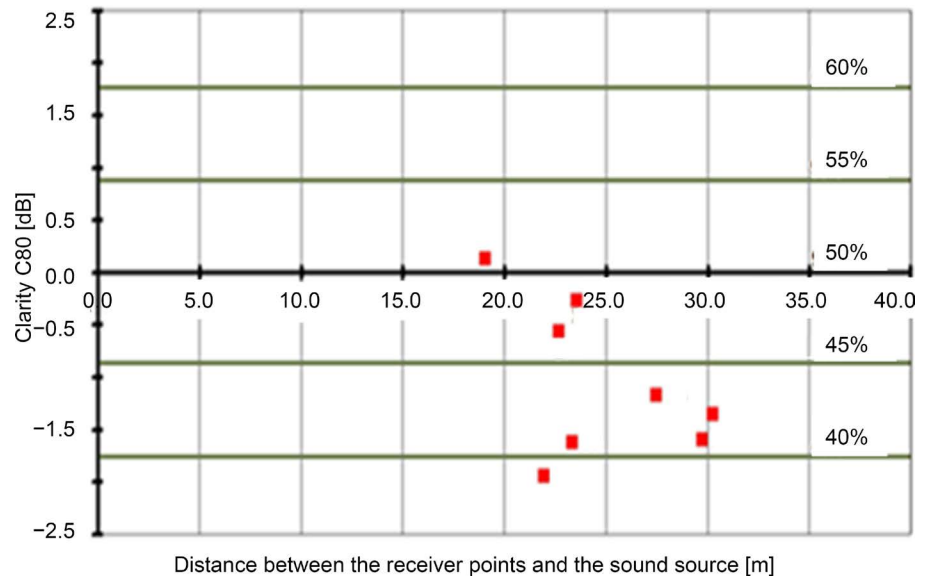


Figure 15. Distribution in the subarea BACK of the parameter C80 [dB] as a function of the distance [m] between the receiver points and the sound source.

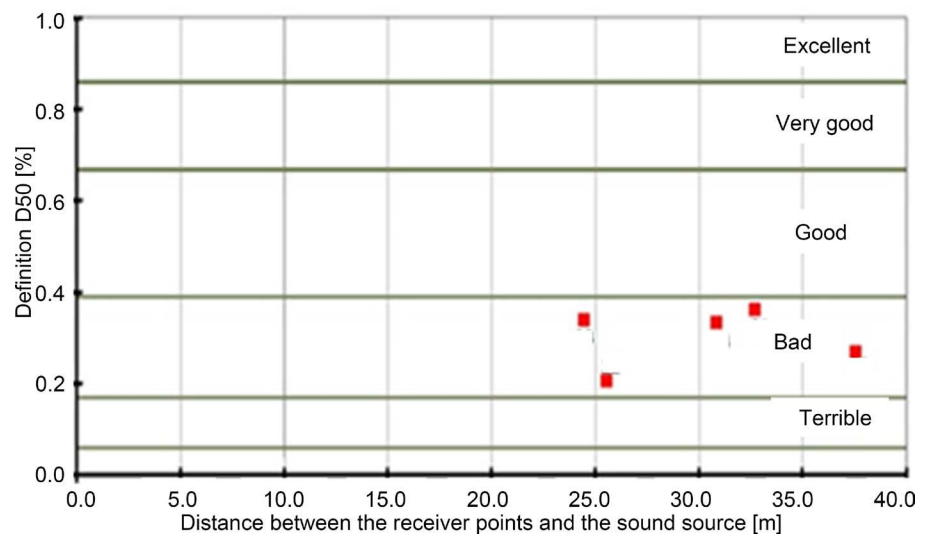


Figure 16. Distribution in the subarea UNDER THE MEZZANINE of the parameter D50 [%] as a function of the distance [m] between the receiver points and the sound source. The graph indicates the range of values proposed by Marshall [15].

within the classification “Bad”. The values of C80 range from 0 to -2.5 dB, and also do not satisfy the condition for the Pop Rock genre.

The subarea ABOVE THE MEZZANINE showed the worst values of Clarity (Figure 18), *i.e.*, -1 to -1.5 dB, thus presenting undesirable values for C80, according to Table 5. All the values for Definition fall within the range of 0.2 to 0.4 dB, *i.e.*, within the range classified as “Bad,” since all the points show values unacceptable for speech intelligibility (Figure 19).

Silva and Cabral’s study [17] about sound pressure levels in Protestant churches in

Brazil showed that these churches are very noisy, with sound systems reaching noise levels ranging from 96.5 to 99.5 dB (A). Noisy environments, contribute significantly to decay of speech intelligibility, which is characterized by the acoustic descriptor Definition D50 [%], and by decay in the quality of musical performances, characterized by the acoustic parameter of Clarity, C80 [dB].

For Protestant churches and for the volume considered here, the Brazilian standard NBR 12,179 [16] recommends an optimal RT of 1.8 s for $V = 16,200 \text{ m}^3$.

The average measured reverberation time was 1.93 s. The analysis performed here indicates that although the RT designed for the church is adequate, in view of the

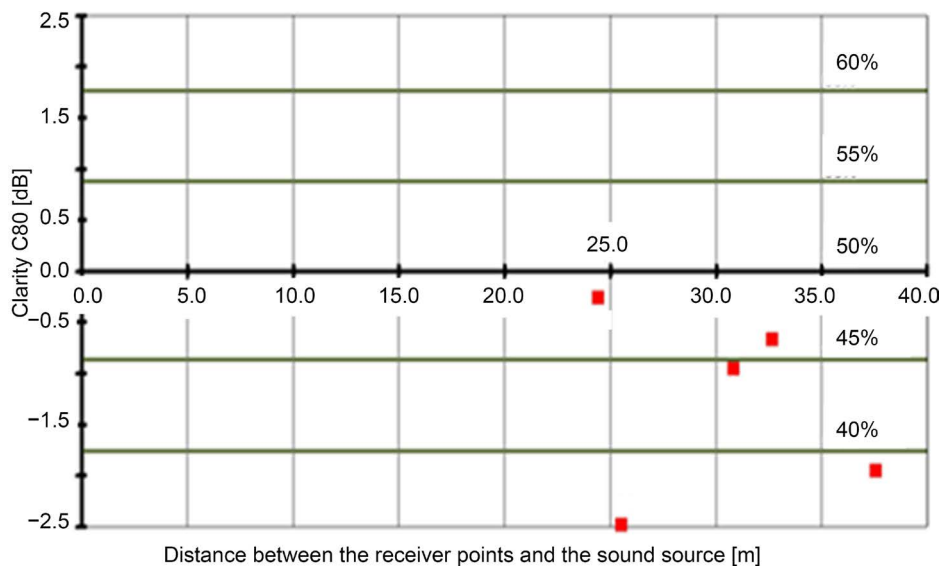


Figure 17. Distribution in the subarea UNDER THE MEZZANINE of the parameter C80 [dB] as a function of the distance [m] between the receiver points and the sound source.

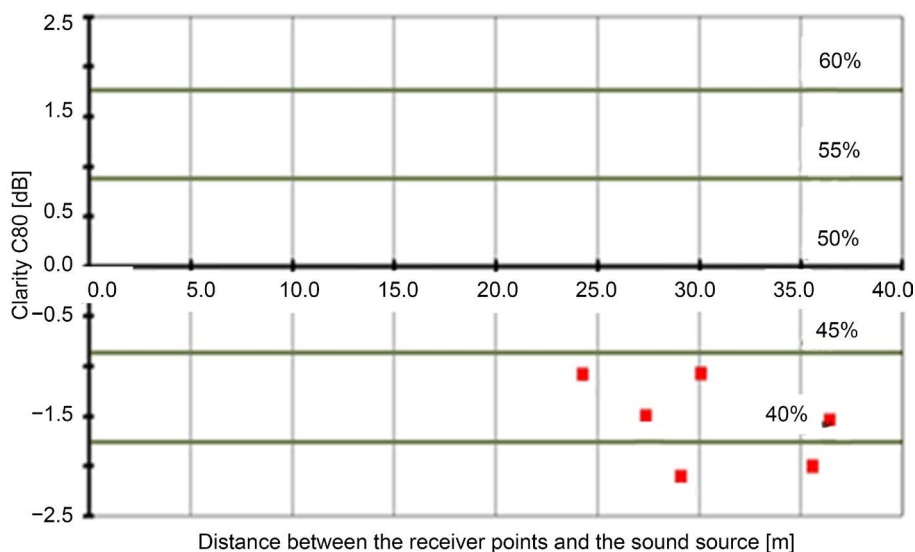


Figure 18. Distribution in the subarea ABOVE THE MEZZANINE of the parameter C80 [dB] as a function of the distance [m] between the receiver points and the sound source.

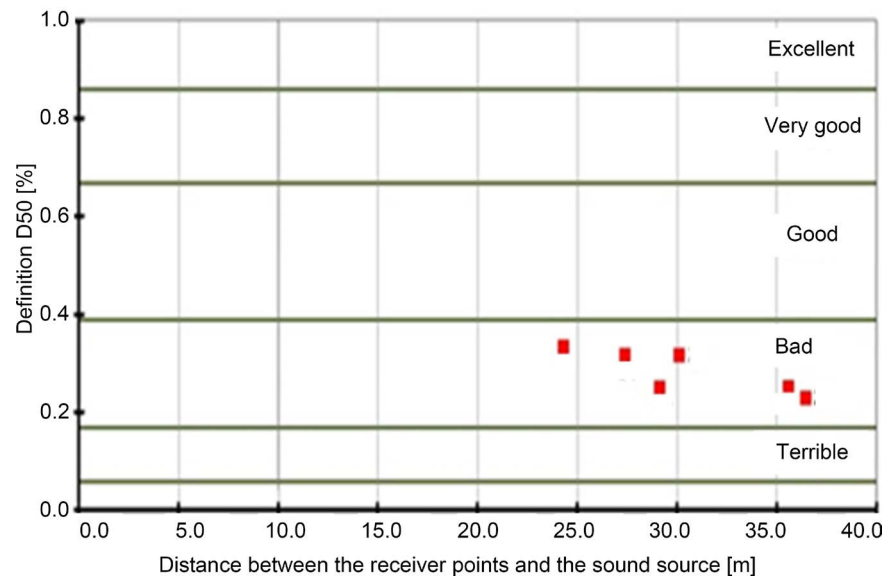


Figure 19. Distribution in the subarea ABOVE THE MEZZANINE of the parameter D50 [%] as a function of the distance [m] between the receiver points and the sound source. The graph indicates the range of values proposed by Marshall [15].

minor difference between the measured value and the optimal value recommended by the Brazilian standard NBR 12,179 [16], the church presents low acoustic quality in terms of speech intelligibility and quality of music reproduction.

The values measured for Definition, D50, indicate that most of the analyzed points show values classified as “Bad”, according to Marshall [15], for speech intelligibility, which is translated by difficulty in understanding the rendition of sermons. As for the quality of the environment for music performances the profile of the program used in the church—*Pop Rock*—proved to be even more inadequate, with values of Clarity, C80, never reaching the lowest value recommended by Marshall, *i.e.*, $C80 = 7$ dB, keeping in mind what was stated earlier in this article, *i.e.*, that this evangelical church uses only the “**Pop Rock**” music genre.

5. Conclusions

From the acoustic/ergonomic point of view, this creates a deleterious working environment for priests and pastors, as well as an environment lacking in speech intelligibility for the listeners. In the specific case of priests/pastors, an environment with low acoustic quality in terms of speech intelligibility will force them to speak louder, which may lead to vocal fatigue.

This paper demonstrates that although the measured reverberation time and the recommended optimum value are almost the same, *i.e.*, measured: 1.93 s and recommended: 1.8 s, the other parameters analyzed here, D50 and C80, are completely outside the recommendations indicated in the literature used as reference, *i.e.*, Marshall’s paper [15]. Therefore, these acoustic descriptors should be included in the design of environments such as that of the church valued here. It should be kept in mind that

only the Pop Rock music genre is performed in this church, which, according to Marshall, should have C80 values ranging from 7 to 18 dB. The measured values lie far outside of this range. The same applies to Definition, D50, most of whose measured values are classified as “Bad”, *i.e.*, between 0.17 and 0.39 dB, according to **Table 6**.

These churches should review the music genre they use in order to improve their overall acoustic conditions.

Acknowledgements

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