Análisis acústico del auditorio Padre Werner en Unisinos
Acoustic analysis of the Padre Werner Unisinos auditorium

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Abstract

The acoustic quality in enclosed spaces is defined by the constructive characteristics of the environment, which must be designed to increase the propagation of the sound. Therefore, the sound message to be transmitted, whether spoken, song or by music instruments, can be intelligibly captured by the listeners. Among the main characteristics that influence the sound behavior in rooms are its dimensions, its geometric shape and the finishing materials applied on their internal surfaces. Each room has different acoustic requirements, directly related to the purpose for which it is intended. Therefore, the professional responsible for the design and construction of these environments should analyze and recognize the needs of each case. In this way, the present case study presents the evaluation of the acoustic quality of a multiple use auditorium, at Unisinos Campus, in São Leopoldo, southern Brazil. Acoustic measurements were performed to calculate the Reverberation Time (T30) and the Early Decay Time (EDT) of the room. Afterwards, the modelling of the auditorium in the acoustic simulation software CATT-Acoustics was carried out, allowing the estimation of other objective acoustic parameters such as the Speech Transmission Index (STI), Definition (D50) and Clarity (C80). The results obtained through measurements and acoustic simulations show that the auditorium has satisfactory acoustic quality for speech, but it is not so suitable for receiving musical presentations. The model generated in the software also made it possible to simulate constructive solutions aiming to improve the acoustic quality of the room.

Keywords: *Room Acoustics, auditorium, computational acoustic simulation, constructive solutions*

Resumen

La calidad acústica en espacios cerrados se define por las características constructivas del entorno, que deben diseñarse para aumentar la propagación del sonido. Por lo tanto, los oyentes pueden captar de forma inteligible el mensaje de sonido que se transmitirá, ya sea hablado, una canción o por instrumentos de música. Entre las principales características que influyen en el comportamiento del sonido en las habitaciones se encuentran sus dimensiones, su forma geométrica y los materiales de acabado aplicados en sus superficies internas. Cada habitación tiene diferentes requisitos acústicos, directamente relacionados con el propósito para el que está destinado. Por lo tanto, el profesional responsable del diseño y la construcción de estos entornos debe analizar y reconocer las necesidades de cada caso. De esta forma, el presente estudio de caso presenta la evaluación de la calidad acústica de un auditorio de uso múltiple, en el Campus de Unisinos, en São Leopoldo, sur de Brasil. Se realizaron mediciones acústicas para calcular el Tiempo de Reverberación (T30) y el Tiempo de Decaimiento Temprano (EDT) de la habitación. Posteriormente, se realizó el modelado del auditorio en el software de simulación acústica CATT-Acoustics, permitiendo la estimación de otros parámetros acústicos objetivos como el Índice de Transmisión del Habla (ITS), la Definición (D50) y la Claridad (C80). Los resultados obtenidos a través de mediciones y simulaciones acústicas muestran que el auditorio tiene una calidad acústica satisfactoria para el habla, pero no es tan adecuado para recibir presentaciones musicales. El modelo generado en el software también hizo posible simular soluciones constructivas con el objetivo de mejorar la calidad acústica de la sala.

Palabras clave: Acústica de habitaciones, auditorio, simulación acústica computacional, soluciones constructivas

1. Introduction

The target of the room acoustics analysis is to inspect the behavior of the sound field in enclosed rooms, aiming to show guidelines that help in the design of environments that meet the different acoustic requirements related to the purpose for which they are intended, which are quite variable and difficult to generalize (Rossing, 2007; Henrique, 2009).

In order for a room to have a satisfactory acoustic quality, it is essential that it meets certain performance requirements with regard to sound insulation, avoiding the transmission of noise both from outside, and inside the building itself and from the treatment of the sound in the interior of the room, aiming to adapt the constructive characteristics of enclosed spaces that demand satisfactory communication conditions, such as classrooms, theatres, concert halls, speech rooms and multipurpose auditoriums so that the distribution of sound inside the room reaches a satisfactory quality for its use (Long, 2006; Brandão, 2016; Ricciardi & Buratti, 2018).

Concerning the treatment of the sound inside the room, it is important to emphasize that rooms designed for speech need a higher level of intelligibility and short reverberation time. Therefore, its shape must be designed to minimize source-receiver distance, its volume must be small and absorption materials must be applied throughout the room, as well as geometric elements that direct the early reflections to the audience to support the direct sound. Concert halls must have a higher volume and a shape that provides strong lateral reflections, with rough, corrugated surfaces that give sound diffusion, distributing the sound evenly throughout the room and ensuring a denser reverberant field, making the audience feel surrounded by sound and valuing subjective aspects of musical sounds such as their texture and tonal quality (Long, 2006; Rossing, 2007; Barron, 2010).

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As the listening experience of the individuals in a room is subjective and is related to the taste and auditory training of each listener, it becomes necessary to use metrics that aim to quantify the subjective effects that the sound filed gives and these are expressed through objective acoustic parameters (Beranek, 2004; Brandão, 2016; Ricciardi and Buratti, 2018).

The reverberation time is the main parameter due to its general relationship with the other room acoustic parameters and subjective experiences, besides the important influence of the concept of reverberation in the theory of room acoustics. It was developed a long time ago and therefore is the best-known parameter that has the most information about best values both in bibliographical references and in legislation (Beranek, 2004; Rossing, 2007; Vorländer, 2007).

However, it is important to analyze a set of parameters since each one aims to quantify one or more subjective experiences or dimensions. In addition, it is worth emphasizing that the recommended values for each parameter vary according to the use of the room, whether it is dedicated to speech, music, or multiple uses, and that should be considered in the project design (Barron, 2010; Brandão, 2016).

There are several studies about acoustic aspects on auditorium spaces, including field measurements (Rudno-Rudziński and Dziechciński, 2006; Kahle, 2013; Groendyke and Gipson, 2015; Jeon et al., 2015; Witew and Vorländer, 2016; Navvab and Heilmann, 2017; Ricciardi and Buratti, 2018), modelling or calculation (Garrido, et al., 2012; Mak and Wang, 2015; Wenmaekers et al., 2017), design or redesign (Ortega and Rivera, 2013; Brill et al., 2014; Coffeen, 2014; Szeląg and Flaga, 2015; Alam et al., 2016; Ortiz, 2016; Jambrošić et al., 2016; Jeon et al., 2016; Lu et al., 2016; Barron and Kissner, 2017; Guthrie et al., 2017; Mahalingam, 2017) history and concepts (Adelman-Larsen, 2014; Mourjopoulos, 2016)

The aim of this study is to presents the evaluation of the acoustic quality of a multiple use auditorium placed in a University Campus in São Leopoldo, southern Brazil.

2. Method

The method to evaluate the acoustic quality of the Padre Werner auditorium adopted in the present case study consisted firstly in the measurement of the reverberation time of the unoccupied room through the interrupted noise method, following the guidelines of ISO 3382-1:2009. The second step was to create a model of the room in the CATT-Acoustics to simulate the influence of the audience in the reverberation time of the room and to estimate other objective parameters, besides making it possible to propose constructive solutions to increase the acoustic quality of the room.

2.1 Characteristics of the object of study

The Padre Werner auditorium is placed in the Campus of the Universidade do Vale do Rio dos Sinos (Unisinos), in São Leopoldo, southern Brazil. It has a capacity for 703 people. The room is designed to receive cultural performances (orchestral music and theatre) and speech activities such as lectures, conferences, and other events. It characterizes the auditorium as a multiple use room. The layout of the building consists of a stage and two levels with seats for the audience (Figure 1).

The sidewalls are finished with cement, painted in the center, and have a smooth unpainted concrete finish in the back and front of the auditorium. The rear wall is covered with thin carpet over a solid surface. The seats are medium upholstered with cloth covering. The spacing between the groups of seats is 1.00m at the lower and 1.50m at the upper level of the room. The height of the seating rows is 10cm on the lower and 20cm on the upper level. The area of each seat is 0.495m² (0.90x0.55m). The floor is covered with carpet, except the stage that has wood flooring on a hard floor. The rear of the stage is closed with fabric curtains hung 1.00m from the wall. The access doors to the auditorium are made of wood. The ceiling. The ceiling has a metallic lining with a slope of 12.5% from the beginning of the stage to the rear wall of the room (Figure 1).

The room has a complex but symmetrical shape, with non-parallel sidewalls on both levels. Its plan area is 760.35m² (considering a single plan with both levels) and the average height of the room is 5.90m, resulting in a volume of 4,500m³. The area in the floor plan covers the inner area of the room and considers the two levels of the audience in a unified plan. The shaded area refers to the second level of the building (which can be seen at the bottom of the Figure 1).

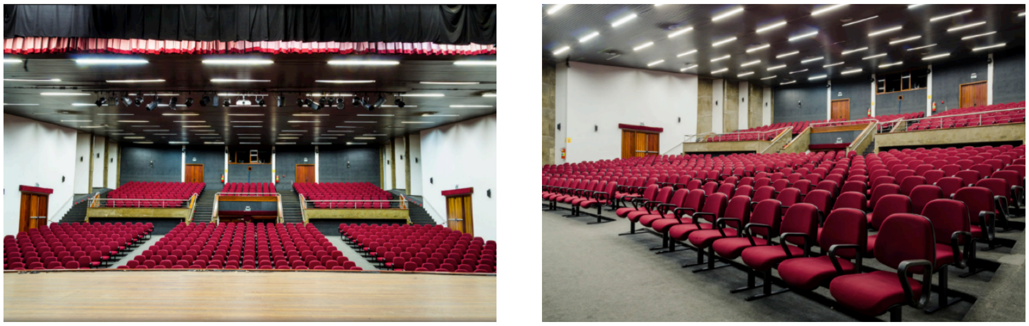


Figure 1. *Interior views of the Padre Werner auditorium*

2.2 Measurements procedure

Since the Padre Werner auditorium is used as a multiple use auditorium, it was decided to analyze its acoustic quality for both speech activities and musical performances. For this purpose, the data obtained with the sound source in position 1 were intended to analyze the room for speech activities, since a speaker tends to position himself closer to the audience and the data of the sound source in position 2 were used to evaluate the behavior of the sound for musical performances, considering that the musicians of an orchestra, for example, tend to position themselves more in the center of the stage. The floor plan (Figure 2) highlights the measurement scheme. The sound source position 1 is positioned at 1.70m from the front of the stage, while the position 2 is distant 5.10m from the stage front. The points numbered from 1 to 30 are related to sound source position 1, while the points from 31 to 60 refer to the measurements with the second positioning of the source.

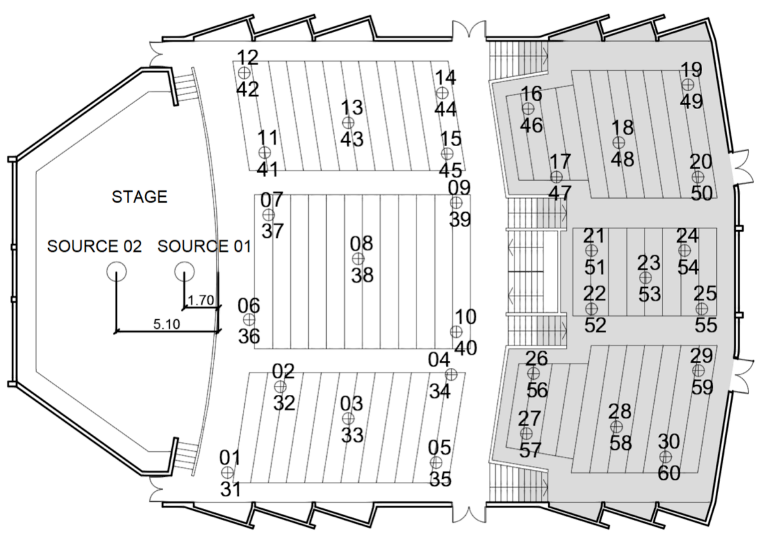


Figure 2. *Floor plan of the Padre Werner auditorium with sound source positions and the measuring points*

The measurements of reverberation time and equipment used to follow the guidelines instituted in the ISO 3382-1:2009 – Measurement of Room Acoustic Parameters – Part 1: Performance of Rooms. The equipment used in the measurements was:

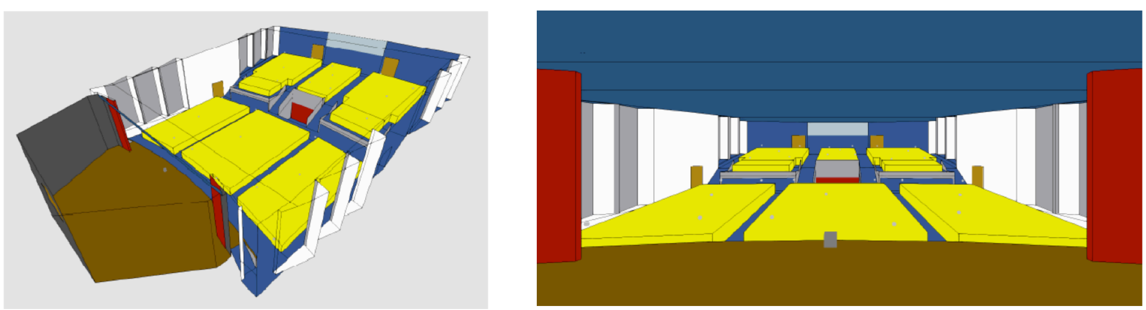
- Bruel&Kjaer Type 2270 Sound analyzer
- Bruel&Kjaer Omnipower 4292-L Omnidirectional sound source
- Bruel&Kjaer ZC-0032 Pre-amplifier model
- Bruel&Kjaer Type 4189 Microphone
- Bruel&Kjaer Type 4231 Sound calibrator
- Bruel&Kjaer Type 2734 Power amplifier
- Cable AQ-0673
- Calibrated metric line
- Instrutemp Model ITMP600 multifunctional meter, for temperature and humidity verification

Considering the random nature of the signal used in the measurement method could appear some variations in the results. So, the procedure was repeated three times for each measured point to increase the quality of data for the decay curve.

2.3 Acoustic Simulation

The computational simulations of the acoustic performance of the auditorium was developed with the CATT-Acoustics software. The simulation process consists on the implantation of a three-dimensional virtual model of the room in the program (Figure 3), assigning the surfaces (including walls, ceilings, floors, stage, doors, windows, audience, furniture, and others) and their forms. In sequence, are included the properties of the finishing materials applied on them, such as sound absorption and diffusion (through the absorption (α), and acoustic scattering (s) coefficients defined by frequency and in octave bands, respectively). These coefficients must be adjusted to obtain the results that are closer to reality, that is, comparing them with the values obtained through the measurements. The positions of the receivers and sound source in the room are also defined, attributing to it its characteristics of directionality, power, and the range of frequencies of the sound source.

From this information, sound propagation is simulated by software using computational algorithms based on geometrical acoustics theory, estimating several numerical measures of parameters related to speech intelligibility and reverberation time, among other parameters that allow analyzing the acoustic quality of enclosed spaces. The results obtained for each acoustic parameter are presented by frequency in octave bands from 125Hz to 4kHz (with estimates for the bands of 8kHz and 16kHz).



(a) (b)

Figure 3. Models of the auditorium: (a) aerial view and (b) stage view

2.4 Choice of the parameters

2.4.1 Reverberation Time (T60, T20, T30)

Reverberation is defined as the persistence of sound energy in an enclosed space after the sound source has been switched off. Therefore, the reverberation time parameter shows how much time elapses before the sound pressure level emitted from the source undergoes a reduction of 60 dB after its shutdown, and can also be measured with the decay of 20 dB and/or 30 dB, extrapolating the results obtained mathematically, if the background noise in the room does not allow adequate measurement of 60 dB decay (Henrique, 2009; Barron, 2010). According to the standards and bibliographic references consulted, the best value of reverberation time for speech activities in a room with the study object volume is around 0.8s and 1.2s in the 500 Hz band and should still be flat in other frequencies. Already for music performances, especially the ones that do not count with a sound system reinforcement, the best value can vary a lot due to the diverse types of music, since each one has a specific and distinct demand. However, the best evaluated rooms for this purpose have reverberation times of around 1.8s and 2.0s in the 500 Hz band, and must still be flat in the mid and high frequencies above it and have a gradual increase in the low frequencies, valuing some subjective aspects of music such as the timbre of the instruments, the texture and fullness of tone of the musical sounds.

2.4.2 Early Decay Time (EDT)

The EDT is defined by the time, in seconds, necessary to occur a decrease of 10 dB in the sound level after ceasing the emission of the sound source, multiplied by a factor of 6 so that it is possible to make direct comparisons with the values of the reverberation time (Beranek, 2004). The EDT is related to the subjective impression of how the source signal is influenced by the reverberation and its best values follow the same criteria as the reverberation time (Barron, 2010).

2.4.3 Definition (D50)

The D50 is the parameter that shows the ratio of the sound energy that reaches the receiver to 5 ms after the direct sound and the total energy emitted. The sound reflections that reach the receiver within this period are considered beneficial because they enhance the direct sound. The D50 is used to evaluate speech intelligibility. Values greater than 0.5 (50%) are considered acceptable and show that the first reflections carry most of the energy contained in the impulse response (Brandão, 2016).

2.4.4 Clarity (C80)

It is a parameter like the D50, but considers the ratio between acoustic energy before, and after 80 ms. The C80 is very influential in rooms intended for music reproduction, as it shows the balance between the clarity with which the sound is received and the reverberation of the environment. The recommended values for this parameter depend especially on the type of music to which the room is intended, and the higher the value (in dB), the less reverberant the room is (Brandão, 2016). Optimum values for orchestral music should be between -2 dB and +2 dB (Barron, 2010).

2.4.5 Speech Transmission Index (STI)

The STI is an index that is directly linked to the intelligibility of speech. This parameter considers the influence of the background noise and the reverberation of the environment to evaluate how distorted the sound signal reaches the receiver in relation to the original signal, causing interference in the speech comprehension, where 1 is the ideal greatest value and the lower values show a reduction in intelligibility (Vorländer, 2007).

3. Results and discussion

A total of 30 measurements (5 for each group of seats) were performed for each position of the sound source (1 and 2), totaling 60 measurements (Figure 2). The measurements were performed by the interrupted noise method with the unoccupied room. The temperature inside the auditorium at the time measurements were taken was 27,6℃ and the relative humidity of the air was 61%. The flat spectrum signal (white noise) was emitted by the sound source until the room reached a steady state of operation and then the source was turned off and the microphone coupled to the analyzer measured the decay of the sound energy (Figure 4).

The collected data was transferred from the analyzer to the computer via Bruel & Kjaer software BZ-5503 and then transferred to the Reverberation Time software. Then they were calculated the parameters related to the reverberation time (T20, T30 and EDT).

The first parameter to be analyzed was the reverberation time (Figure 5). The results obtained through the measurements presented values of T30 slightly above of the recommended for speech activities, but lower that required for music in both positions of the sound source, with an average value of 1.22s in the 500Hz frequency band. However, after adjusting the absorption and scattering coefficients in the CATT-Acoustics software for the simulation results to approximate the measured values, the reverberation time of the room was estimated considering it occupied and values of 1s were obtained in the 500Hz band, which is within the range recommended for speech. However, it is worse for musical performances. The EDT values were higher than the T30 values throughout the measured frequency range, especially at lower frequencies, showing a stronger subjective impression of the reverberation, which is detrimental to speech intelligibility.

Figure 4. *Measurement procedure example: Omnipower on Source 1 and Sound analyzer on measuring position 9 (See Figure 2)*

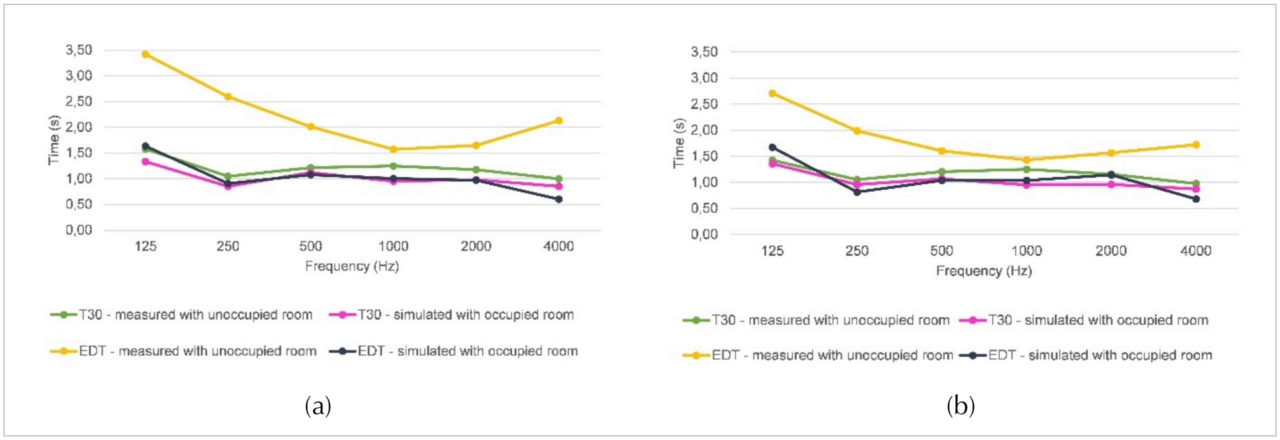


Figure 5. *T30 and EDT: (a) Source 1 and (b) Source 2*

The analysis of the parameters related to speech intelligibility (D50 and STI) shows best results for the first rows of seats and for some positions near the reflective surfaces and presents satisfactory results for the other seating areas at the lower level of the auditorium (Figure 6). At the upper level values fluctuate widely, while are still below satisfactory acoustic behavior for speech intelligibility. This difference occurs because the seats at the upper level are quite far from the stage, making the sound coming from the reflections of the inner surfaces of the room travel longer ways to reach the listener, compromising the intelligibility.

The mapping of parameter C80, used in the evaluation of rooms for music performance, presented high values and not homogeneous throughout the room (Figure 6). For a good qualification of a room that wishes to receive presentations of musical orchestras, it is important that all the seats present satisfactory conditions. Therefore, the C80 values should be lower than those obtained, and the reverberation time of the room should be higher, giving the room a denser reverberant field and an improvement in subjective aspects such as texture, timbre, and tonal quality of the musical sound.

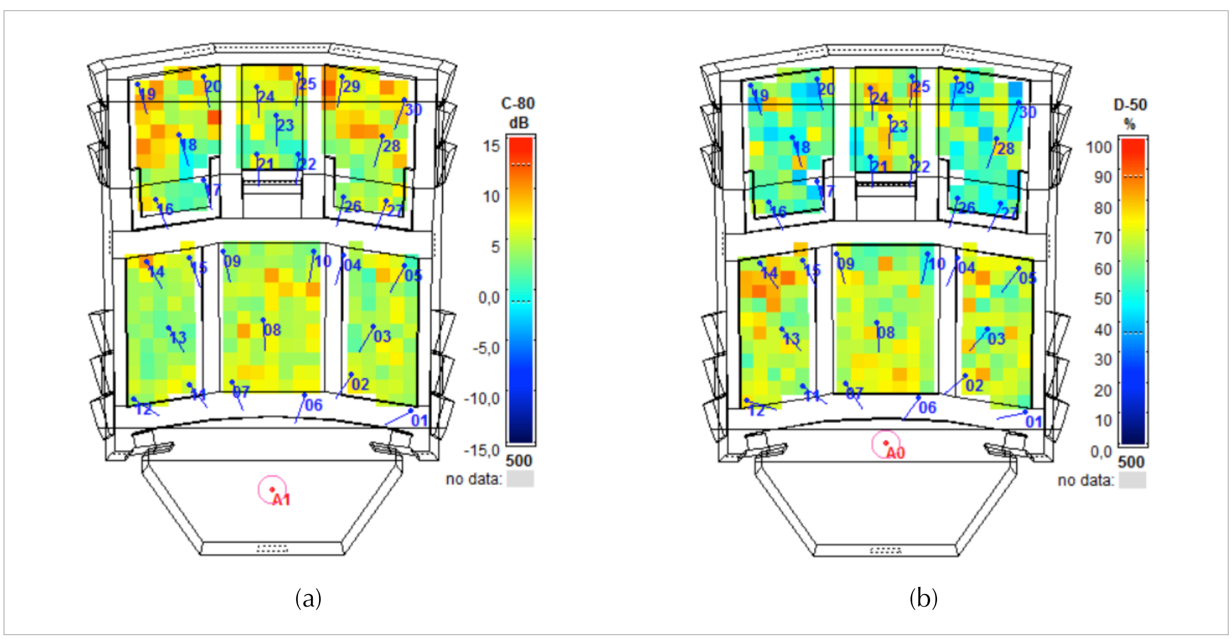


Figure 6. *Acoustic mapping: (a) C80 and (b) D50*

Since the Padre Werner auditorium does not presented a satisfactory acoustic behavior for music performances, the application of constructive solutions aiming to improve its quality was simulated through the software CATT-Acoustics. To reach a higher reverberation time in the room, an elevation of 80cm of the main lining was proposed, increasing the volume of the room, and reducing the absorption at the low frequencies promoted by the air gap between the liner and the ceiling. This elevation also intended to cut the fall of the T30 in the band of 250Hz, because the air gap above the liner causes it to work as a resonant absorber. The rear wall covering was changed from carpet to QRD type diffusers in wood, reducing the absorption of this surface and giving diffuse reflections, which help in preventing echoes and strengthening the reverberant field. Above the doors found on the sidewalls in the center of the room, it was proposed the installation of QRD wooden diffuser panels, to improve the distribution of the sound inside the room.

On stage, the proscenium arch could be eliminated, and an acoustic shell be installed, removing the closing curtains, and increasing the area of exposure of the stage, directing the sound more broadly to the audience (Figure 7). To compose the shell, it was proposed the installation of convex wooden diffuser panels mounted on aluminum frames on the sidewalls and the rear of the stage and the installation of flat suspended panels of wood forming a convex surface in the stage lining.

However, since the auditorium is used for different purposes, it is necessary to attribute to its elements that increase the sound absorption and direct the first reflections to the audience, thus reducing the reverberation time and increasing the definition of the sound, to adjust the acoustic behavior of the room for speech activities.

As in auditoriums for speech the reflections from the sidewalls are not a priority, as they may interfere with the location of the sound source, it was proposed the installation of motorized two-layer curtains (one layer of wool and one of the quilt) in front of the sidewall indentations, reducing the reverberation time. To give support for direct sound and increase sound definition, three series of 4x3m (four times the wavelength for the 500Hz frequency), fixed on the ceiling were modelled. As the present case study aims to evaluate the acoustic quality of the object of study for natural sound sources without the use of sound system reinforcement and since the seats found in the upper level are at a distance above the recommended for this purpose, the panels were modelled for direct the early reflections to the seats of the lower level. Figure 8 (a) shows the solutions applied to improve quality for musical performances and Figure 8 (b) the moving elements used to adapt the room for speech activities.

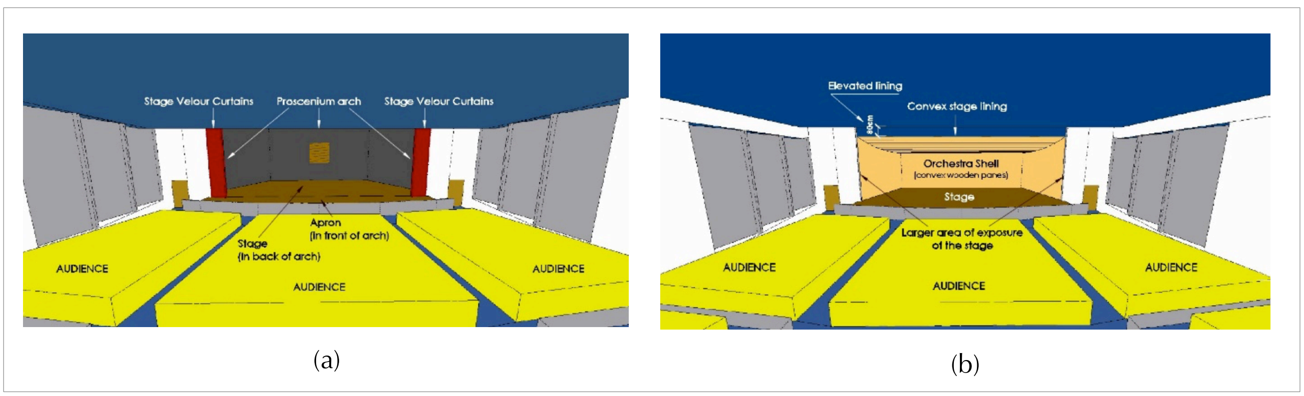


***Figure 7.** Stage schemes: (a) original and (b) new configuration*

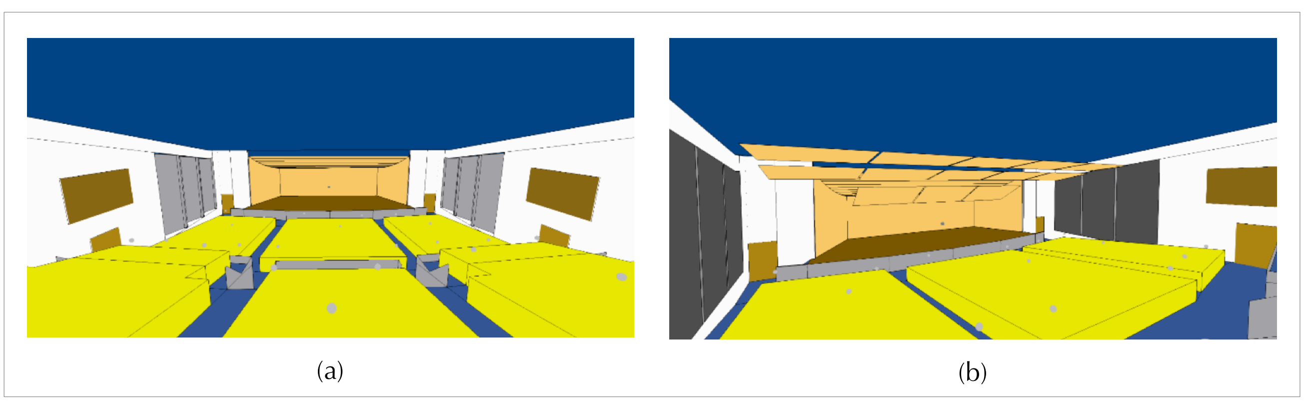


***Figure 8.** Proposed constructive solutions: (a) for musical and (b) for speech activities*

After the simulation of acoustic behavior of the auditorium including the proposed solutions, it is possible to see that the reverberation time could to have a considerable increase in the mid and low frequencies, reaching 1.5s in the 500Hz band (Figure 9). The behavior of the curve as a function of the frequencies also improved with a gradual increase in the low frequencies and cutting the decrease in the 250Hz band caused by the air gap over the main liner.

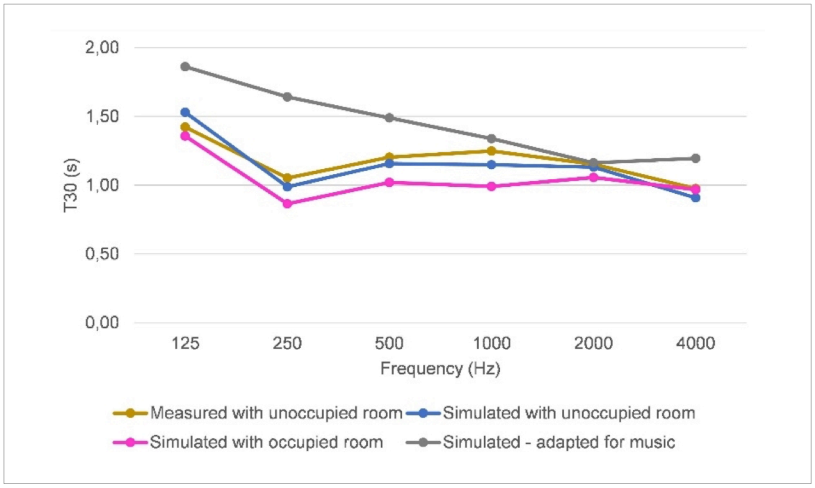


Figure 9. *Reverberation time in the situations analyzed with sound source 2*

Analyzing the C80 mapping before and after the application of the constructive solutions, shown in Figures 6 and 10, it can be verified that the values are closer to the ideal due to the reduction of reverberation time. In addition to this factor, the modifications also promoted a more even distribution of the sound along the room due to the application of the diffusion devices, presenting similar acoustic conditions for all the seats. These data show that the proposed solutions presented improvements in the acoustic quality of the room for music performance.

Focusing on the acoustic quality of the room for speech, the comparison of Figures 6 and 10 shown an increase in the values of D50 for the seats of the lower level with the simulation of the constructive solutions, for the first rows of seats. This increase is associated with the installation of the reflective panels on the sound source, which directs the first reflections to the audience in a brief period and with enough energy, promoting direct sound support and increasing speech intelligibility. These results suggest that it is possible to assign to the room constructive solutions that allow adapting the reverberation time to different activities, considering that the solutions proposed for speech were implanted in the same model that promoted improvements in the acoustic quality of the room for music performance.

It is verified by the Figure 11 that the reverberation time fits the best values in the mid and high frequencies. The similarity between values obtained for the octave bands between 250Hz and 4kHz indicates that the absorption of the room is well distributed for this purpose. It is possible to verify that the T30 curve after the application of the constructive solutions behaved in an analogous way to the original room, and in the 500Hz band, there was even a reduction to 0.9s.

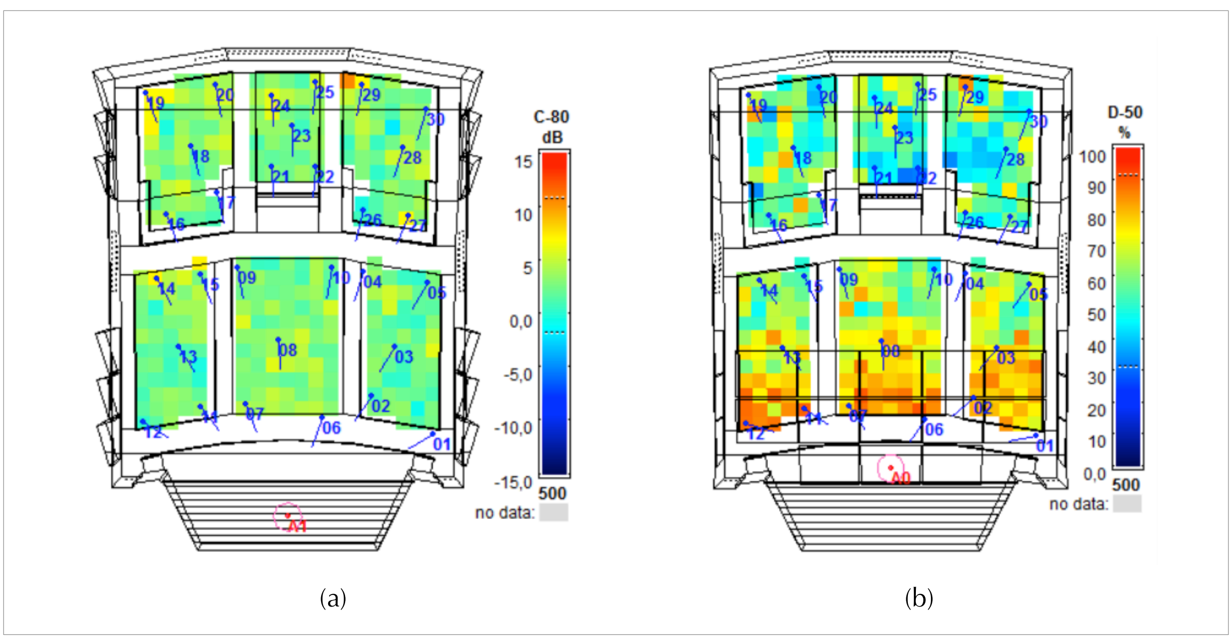


Figure 10. *Mapping after the simulation of the constructive solutions (a) C80 and (b) D50*

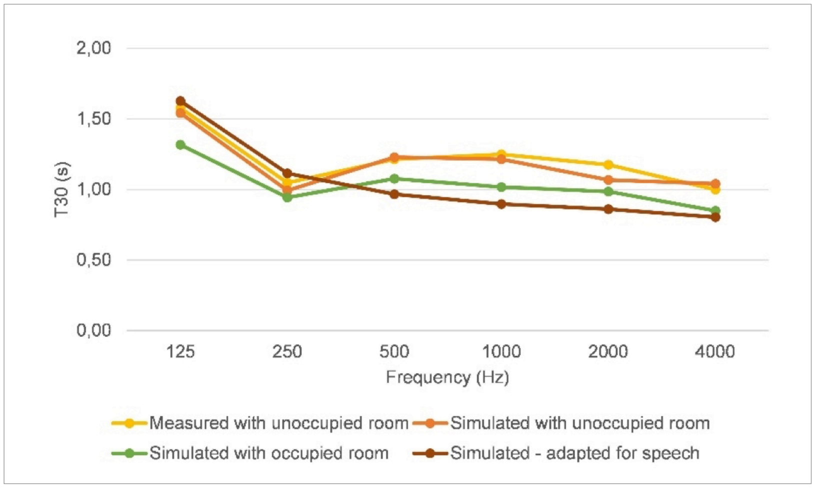


Figure 11. *Reverberation time in the situations analyzed with sound source 1*

5. Conclusions

The analysis of the acoustic quality of the Padre Werner auditorium presented a complexity associated with the fact that this environment receives several activities, both musical and speech. Since each of these activities demands a different acoustic treatment within the enclosure, a specific evaluation of the object of study for the different purposes became necessary.

From the analysis of the results obtained through the measurements and the computational simulations carried out from the software CATT-Acoustics, it was verified that the reverberation time of the unoccupied room presents higher values than expected for speech and well below the recommended for music performance, according to the references consulted for this study. Considering the absorption provided by the presence of the audience, the values of reverberation time would suffer a significant reduction, falling within the range of values recommended for speech rooms and further disfavoring the acoustic environment for music performances.

The estimated values for the D50 and STI parameters show good speech intelligibility for a substantial part of the seats. However, due to the dimensions of the room, it was concluded that the best acoustic conditions for speech without considering sound system reinforcement are obtained with the occupation of the room limited to the lower level seats, since the long distances between the speaker and the upper-level seats make the sound attenuated to the listeners, compromising the transmission of the sound message.

Because of the low values of reverberation time, the C80 mapping presented values well above the recommended for orchestral music rooms, in addition to presenting large variations in the results along the seats. Since in concert halls it is desired that the reverberation time is higher and the clarity (C80) is reduced, it is concluded that the Padre Werner auditorium does not have a satisfactory acoustic quality for this purpose.

From the results obtained in the simulation of the constructive solutions proposed in the software CATT-Acoustics, it was verified that the application of the proposed solutions would allow a considerable improvement in the objective parameters used to evaluate the acoustic quality of the room for music performances, although not achieve the desired results for this purpose. However, the mobile elements used in this same model to adapt it to speech activities gave a reverberation time that fits the recommendations, besides giving good speech intelligibility showed by the high values estimated for the parameters D50 and STI. It is concluded, therefore, that the Padre Werner auditorium has a better acoustic quality for use in speech activities than for music performance, although it is used for both purposes.

6. Acknowledgements

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