CHOIR REHEARSAL ROOM CONDITIONING

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This paper suggests modifications to be considered in order to improve the acoustic comfort of a choir rehearsal room. In addition, these modifications contemplate the acoustic coupling with a dressing room located next to it. Reverberation time measurements (EDT, T20 and T30) were carried out in situ and from the results obtained, the behavior of the room was simulated in EASE and COMSOL. In this way, the results obtained from the proposed modifications were also evaluated, achieving a reverberation time of 1.02 s for the choir rehearsal room, and 0.46 s for the dressing room. The results presented in this work also includes absorption and scattering coefficients of every surface material and SPL mapping of the rooms.
Keywords: choir rehearsal room, acoustic coupling, EASE, COMSOL.

1. Introduction

The choir rehearsal room treated in this work is located underneath the 'Soka Gakkai' auditorium in Buenos Aires. It has an adjoining dressing room, which is connected by an opening the size of a regular door and together they have a total volume of 227 cubic meters. Having different purposes, their required acoustic characteristics are different and the use of both rooms simultaneously can generate disturbances from one to the other. The purpose of this work is to bring the response of the rehearsal room to international standards, and to acoustically couple this room with the adjoining dressing room. In order to evaluate the acoustic performance of the rehearsal room, Nowegian Standard NS8178 is used. It provides an acoustical criteria for different halls, including small choir rehearsal rooms. It takes into account room volume and reverberation time to determine the suitability of the room for a specific purpose. In addition, ISO 23591 is also used as a guideline for the acoustic performance evaluation.

To support this work, the state of the art in choral acoustics is reviewed and the theoretical bases are developed, including in detail the international standards used. Then, an analysis of the measured reverberation time is carried out, followed by a study of the acoustics of the choir rehearsal room. Finally, an intervention is proposed that will result in an improvement of the acoustic coupling of the two rooms.

2. State of the Art

The history of choral music, from its beginnings in ancient times with tribal communities to its development by the Greeks and Romans, evidences an evolution that included adoption by the Christian Church in the 4th century and the emergence of polyphonic music in the Middle Ages. During the Renaissance, there was a revival of choral music with composers employing polyphony to enrich the meaning of sung lyrics [1].

Historical studies indicate that composers considered the acoustic characteristics of performance spaces. In the Renaissance, for example, inappropriate dissonances were avoided in churches with long reverberation times [2].

At the end of the Renaissance and the beginning of the Baroque, compositions for several choirs were prominent, such as the polyphonic school of Venice, where multiple choirs sang psalms alternately, taking advantage of the spatial layout of the churches [3].

Historical documents reveal that W.A. Mozart, when composing a mass for Salzburg Cathedral, considered not only the musical composition, but also the precise placement of musicians and singers, as Leopold Mozart indicated in the 'Technical Recommendations' [4].

The term 'choral acoustics', introduced by Professor Sten Ternstrom, addresses aspects such as voice, room acoustics and the psychoacoustic properties of the auditory system [5]. A key parameter is reverberation time, influencing the clarity of the choral sound. Prolonged reverberation has a negative effect, while short reverberation produces a 'dry' sound [6]. This impacts vocal perception, transmission and production. [7]

Performers adjust their techniques and volume to different acoustic environments, with rehearsal rooms being smaller and with fewer musicians than performance rooms [8].

Standards such as the Norwegian NS 8178 (2014) and ISO 23591 (2021) set physical and acoustic parameters for music rehearsal rooms, adapting to specific types of music, sizes and formations. These standards are crucial to ensure a match between the room and the music performed [9][10].

The acoustics of a hall can either enhance or detract from the musical experience, affecting volume, geometry and reverberation. An environment with poor acoustics poses challenges for performers and conductors, underscoring the importance of considering these characteristics in architectural planning. The evaluation of acoustics, while subjective, is supported by standards such as NS8178, providing objective criteria for assessing the acoustic suitability of venues and allowing a uniform approach for different musical ensembles.

3. Theoretical Framework

3.1 NS 8178

The Norwegian standard NS8178, entitled "Acoustical Criteria for Halls and Premises for Musical Performances," establishes the essential parameters for acoustic quality in venues designed for music performance.

This standard segments its criteria into three main categories of music, each of which has specific needs and requirements:

- Mild Acoustic Music: Includes performances by choirs, vocal ensembles, string orchestras, stringed instruments, and other similar acoustic instruments.
- Loud Acoustic Music: Includes performances by brass bands, wind ensembles, acoustic big bands, percussion, symphony orchestras, and other ensembles that generate high acoustic volume.

- Amplified Music: This category includes performances by bands, big bands with amplified instruments, and other groups using sound amplification equipment.

For each of these categories of music, NS8178 establishes specific guidelines that are adapted to the needs of each type of musical presentation.

The standard also classifies the types of music venues into five distinct groups:

- Single Hall - For audiences of 1-2 additional people.
- Small Ensemble Hall - Designed to accommodate 3 to 12 additional people.
- Medium Ensemble Room - Suitable to accommodate 12-20 additional people.
- Large Ensemble Room - Designed for more than 20 additional people, including the ability to accommodate full choirs, bands, or orchestras.

In addition, another category called "Concert Hall" is considered, which is subdivided into three subcategories, each tailored to one of the three types of music mentioned above.

The regulations establish reverberation time values for each room category as a function of room volume, as illustrated in Figure 1.

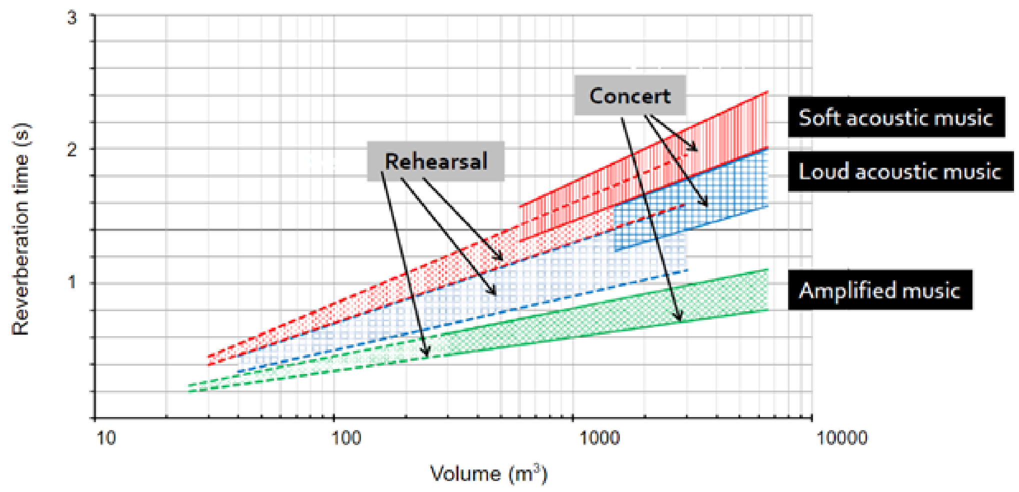


Figure 1: Relationship between reverberation time and room volume according to NS8178.

In addition, the Figure 2 shows the reverberation time values by frequency, according to the guidelines of the standards.

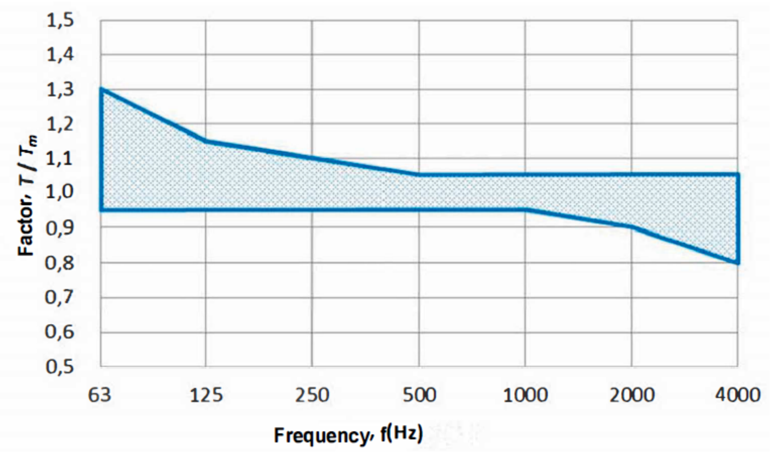


Figure 2: Reverb for Quiet Acoustic Music.

3.2 ISO 23591

ISO 23591, issued in September 2021 under the title "Acoustic Quality Criteria for Music Rehearsal Rooms," provides an international reference standard for the acoustic design of rehearsal rooms intended for musical practice. In situations where rooms lack adequate acoustic conditions, it is common to apply corrective measures related to variable sound absorption.

However, it is essential to emphasize that the first step is to thoroughly evaluate the room acoustics, which includes direct listening experience in the rehearsal room itself and awareness of the musicians in relation to this issue. ISO 23591 plays a crucial role in providing planning guidance and serving as a sound argumentative framework. This makes it possible to analyze the acoustics of the rehearsal room, develop proposed solutions, and, where possible, improve them, ultimately to the benefit of all musicians involved.

3.3 Reverberation Time

The Reverberation Time (RT) is defined as the period required for the sound intensity to decrease by 60 decibels (dB) after the interruption of the sound source. This measurement standard, which uses a 60 dB reduction as a reference, provides an objective metric for evaluating the acoustic characteristics of a room. The RT is essential for the characterization of room acoustics as it influences the sound quality in various applications such as concert halls, recording studios, and classrooms.

To obtain the Reverberation Time T_{30} and T_{20}, dynamic ranges less than 60 dB are considered and extrapolated from T_{60}. T_{30} is defined as the time it takes for the sound decay curve to drop from -5 dB to -35 dB below the initial level, while T_{20} is defined as the time it takes to drop from -5 dB to -25 dB.

3.4 Acoustic Coupling

Spaces exhibiting acoustically coupled volumes typically consist of a secondary room with high reverberation that is connected to a main room through an acoustically transparent opening. This geometric arrangement is particularly interesting because of its potential to generate temporally unequal sound decay rates in the main room. This type of decay, known as "non-exponential", is uncommon in single-volume spaces and can lead to unique acoustic conditions. Specifically, acoustically coupled volume systems can be designed to produce a non-exponential decay characterised by a pronounced initial decay followed by prolonged reverberation. It is assumed that this type of decay leads to high perceived levels of both clarity and reverberance, qualities that are often highly valued in performing arts environments.[11] The transition from a confined space acoustic environment to a double-decay acoustic environment occurs when openings open to 5% or less. Similarly, the transition from a dual-slope acoustic environment to a wide-space acoustic environment occurs when the apertures open to approximately 45-50%. Although the concept of dual slope has been widely documented as a phenomenon, its study as a tool has been limited.

In particular, the effect of a small opening on double slope decay is negligible. Therefore, to achieve double slope decay, the area of the coupling aperture must be substantially small compared to the total area of the coupling room. The coupling constant quantifies the double slope decay decay. The more dramatic the double-slope decay, i.e., the more it varies from a classical Sabine exponential decay, the higher the coupling constant. The coupling constant is calculated as:

$$Coupling\ constant = \frac{R_T}{T_{15}} \tag{1}$$

Where RT is the time required for the sound to decay by 60 decibels without extrapolating, measured from 0 dB to -60 dB, and T15 is the time required for the sound to decay by 15 decibels and extrapolate to produce a decay of 60 decibels, measured from 0 dB to -15 dB.

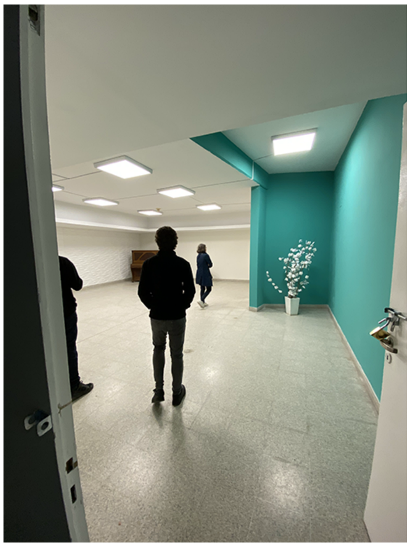
3.5 Absorbers and Diffusers

When a sound wave reaches a surface on its way, some of its energy is absorbed. Within the phenomenon of absorption two types can be described: a porous absorption and another reactive absorption [12]. Porous absorbers are materials where sound propagation occurs in a network of interconnected pores that generate tortuous paths for the acoustic wave. When passing through this type of material, the acoustic energy is dissipated as it has been transformed into thermal energy. Instead, reactive absorption is achieved by resonance phenomena (by membranes or cavities). In this way it is possible to obtain absorption at low and medium frequencies, where absorption is difficult to achieve with porous materials because, for reasons of the size of wavelengths at said frequencies, very large thicknesses and sizes of porous material would be needed. The absorption coefficient is represented by α and is measured at $0 < \alpha < 1$, with 1 being the maximum absorption. The scattering coefficient (s) of a surface is the ratio between reflected sound power in non-specular directions and the total reflected sound power [12]. This coefficient may take values between 0 and 1, where $s = 0$ means purely specular reflection and $s = 1$ means that all reflected power is scattered according to some kind of ideal diffusivity. Diffuse reflections can be simulated in computer models by statistical methods [13]. By comparison of computer simulations and measured reverberation times in some cases where the absorption coefficient is known, it has been found that the scattering coefficient should normally be set to around 0.1 for large plane surfaces and to around 0.7 for highly irregular surfaces. The correct simulation of the diffusion phenomenon and therefore the configuration of the diffusion coefficient in the modeling have an impact on the calculation time of the software as well as on the results of the acoustic parameters obtained.

4. Procedure

The owner of the room shown in figures 3(a) and 3(b) expressed his willingness to adapt the its acoustics specifically for use as a choral rehearsal space. Additional images of the hall can be found in Annex A.

(a) Room during the acoustic measurement.



(b) Room viewed from the door.

Figure 3: Choir rehearsal room.

4.1 Physical measurements of the room

The process of acoustic conditioning of the choir's rehearsal room began with physical measurements of the room, together with a thorough inspection of the materials used in its construction.

Various components were identified, such as painted bricks that act as a barrier between the room and the outside environment, as well as plaster walls that have been used both to hide air ducts and to delimit the dressing room spaces.

One of the walls of the room is lined with diffusers to counteract the acoustic phenomenon known as "flutter echo". These can be seen in Figure 4. These diffusers are approximately 2 cm thick, which means that their effective operation starts at a frequency of 8500 Hz. Consequently, their impact is most noticeable in controlling frequencies above this figure. The incorporation of these diffusers in the room is intended to mitigate the undesired effects of reflections that could generate a degradation in the acoustic quality of the room.

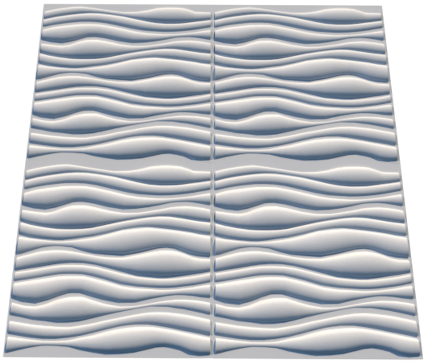


Figure 4: Diffusers used.

4.2 Room acoustic measurements

In addition to the physical measurements and inspection of materials, detailed acoustic measurements were carried out, from which the necessary data were extracted to assess the suitability of the hall for different musical ensembles.

In the process of measuring the reverberation time, the guidelines established by the international standard ISO 354 [14] have been followed. This standard prescribes that at least 12 measurements must be made, which can be obtained using a configuration of 1 source position and 12 microphone positions, or using 2 source positions and 6 microphones. For each microphone position, the minimum distance from the source is required to be at least 2 metres, 1,5 metres from other microphones, and 1 metre from any surface in the room.

Figure 5 illustrates the source position and microphone positions used, indicating their heights and the points of closest proximity between elements that might not meet the requirements of the regulations. It is important to note that, in general, all microphone positions comply with the suggested minimum distances, with the exception of one which is at a distance of 1.92 metres from the source, slightly below the threshold set by the standard.

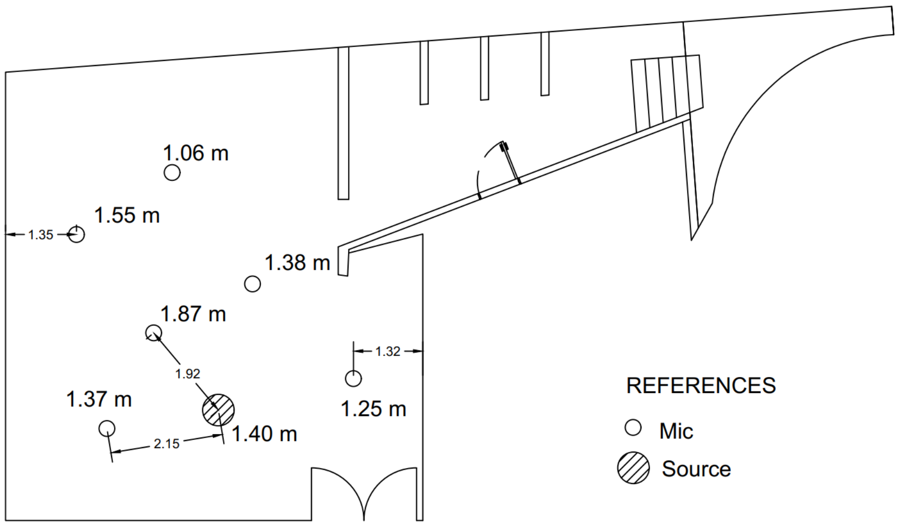


Figure 5: Reverberation time measurement.

Only 6 positions were recorded, which is half the minimum number required by the standard. The stimulus signal used consisted of a logarithmic sinusoidal sweep between 30 and 16000 Hz, with a duration of 40 seconds. The source used was an Outline dodecahedron+sub, as an omnidirectional source, and the microphones used were Earthworks M50. The recording equipment consisted of an RME interface connected to a MacBook.

It is crucial to note that, during the reverberation time measurement, approximately 12 individuals occupied the room, a factor that has a significant impact on the high frequencies and that must be carefully considered in the analysis of the results obtained. The presence of people in the measurement process may provide a more realistic approximation of the standard of room use during choral rehearsals. Additionally, it is pertinent to note that, in the room simulation, the software takes into account absorption parameters at the measurement points. This implies that it is feasible to obtain simulation values that are comparatively close to those obtained through experimental measurement.

4.3 Room modelling and simulation

Based on the physical measurements taken in the rehearsal room, a detailed plan of the test room was drawn up using AutoCAD. This plan was essential as a starting point for the subsequent creation of a 3D model of the room using SketchUp. The main purpose of this 3D modelling was to enable its application in specialised tools such as Ease and Comsol Multiphysics, in order to carry out simulations of the various acoustic parameters present in the environment.

In the process of simulating the room, it was decided to maintain the original position of the sound source used during the in situ measurements. This choice was based on the need to facilitate an effective comparison between the simulation results and the data obtained at the same measurement points.

To carry out the simulation of the room using the ray-tracing method, the software EASE [15] was used. In a first step, a 3D model of the room was generated in SketchUp and subsequently exported in .skp format to EASE (see Figure 6).

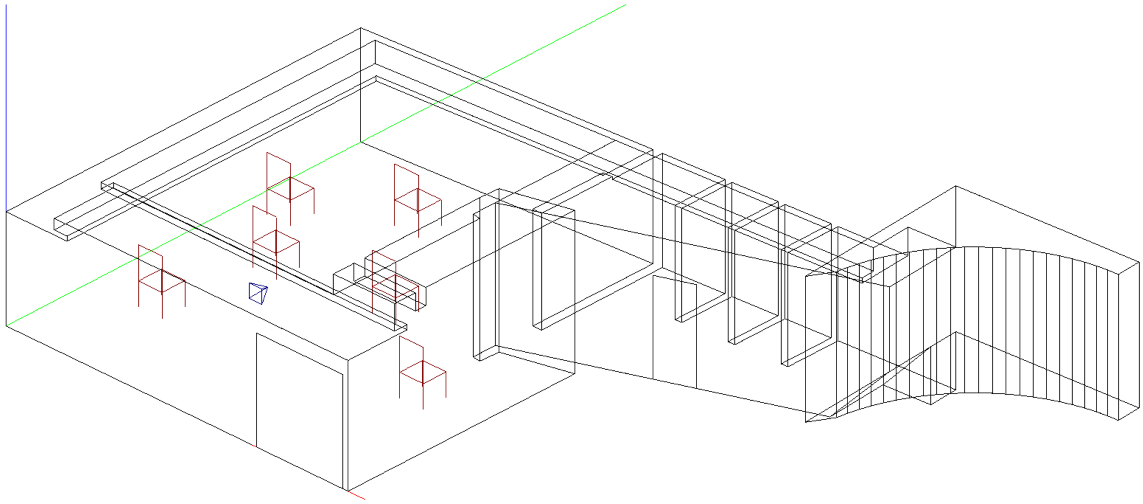


Figure 6: Rehearsal room geometry imported in EASE software with source and mic positions.

From the observations made in the room, it is possible to distinguish seven surfaces that make up the enclosure. These include the sheet metal doors, the granite floor, the plaster diffuser wall, the exterior brick walls with painted finish, the interior plasterboard walls, the ceiling incorporating an air chamber at the top, and a small concrete beam above the entrance door. Each of these surfaces requires the assignment of absorption and dispersion values per third of an octave.

As a starting point, approximate absorption and scattering coefficients for each surface were extracted from the literature. Subsequently, the 'Find Impacts' function in the EASE software was used to obtain a reflectogram of a single microphone position. At this stage, a number of rays per source of 200,000 and an order equal to 15 was set. With this configuration, an impact probability of 88% was achieved, meeting the minimum recommended according to the EASE manual. Figure 7 presents the complete configuration used for ray tracing.

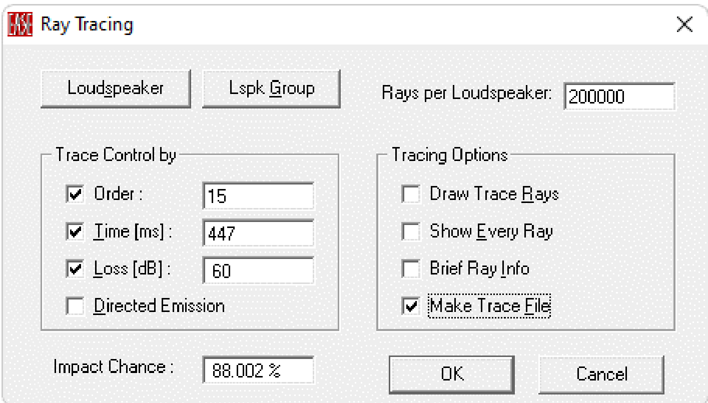


Figure 7: Configuration for the ray tracing processing.

At the end of the simulation, a statistical tail is incorporated in order to complete the reflectogram. The start time of the statistical queue is adjusted according to the calculation made by the EASE software. The amplitude of the added Gaussian noise and the gain are adjusted to a value of 10 dB, and the amplitude gain is modified by visual inspection of the reflectogram. The obtained results are exported in impulse response format (.wav) for further processing with the EASERA software.

Subsequently, after analysing the results of the acoustic parameters such as EDT, T20 and T30 derived from the simulation, adjustments were made to the coefficients assigned to the surfaces. These adjustments were made incrementally until the simulated reverberation time values matched those measured in situ. The absorption and scattering coefficients obtained are shown in Table 1.

Table 1: Absorption and scattering coefficient of each surface material.

	125 Hz		250 Hz		500 Hz		1 kHz		2 kHz		4 kHz	
Material	Abs	Scat	Abs	Scat	Abs	Scat	Abs	Scat	Abs	Scat	Abs	Scat
Brick wall painted	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01
Plasterboard Walls	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.03	0.01
Ceiling	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.03	0.01
Concrete painted	0.09	0.01	0.07	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Sheet metal	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Granite floor	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Plaster diffuser	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.03	0.01

4.4 Proposals for room fittings

In order to reduce the sound emission levels from the rehearsal room to the dressing rooms, it is proposed to implement an acoustic coupling between both spaces, involving the creation of an area with a high acoustic absorption coefficient. In this context, it is suggested to replace the existing opening in the original plaster wall to establish a new entrance to the dressing room. This new entrance is conceived as an acoustic labyrinth designed to operate as an interface between the two rooms, allowing an efficient control of sound propagation.

It is relevant to note that the modified plaster wall will extend to the ceiling, a feature that differs from its original configuration. This extension of the wall to the ceiling is essential to ensure continuity in the acoustic separation between the main hall and the dressing room, thus avoiding the transmission of unwanted sounds. The modification made is illustrated in Figure 8. In turn, Figure 9 provides a comparison between the current geometry and the proposed modification.

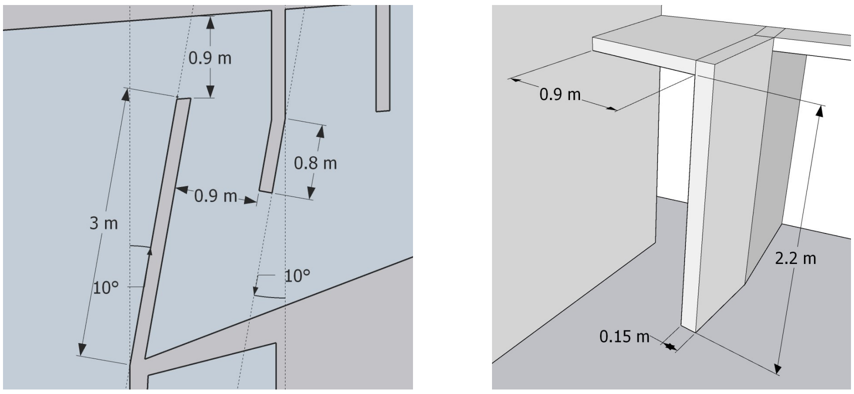
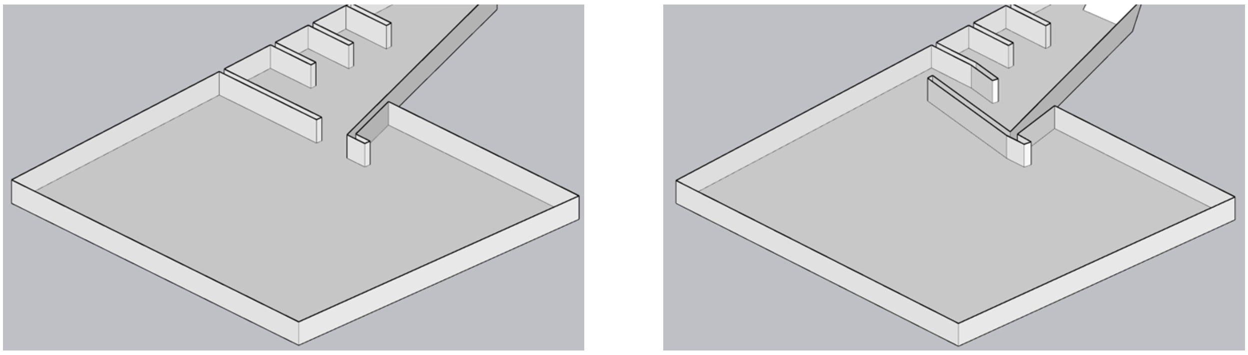


Figure 8: Proposed acoustic coupling.



(a) Original room. (b) Proposed modification.

Figure 9: Section plane comparison.

Regarding the acoustic conditioning of the rehearsal room, in order to reduce the reverberation time, the decision was taken to incorporate absorbent materials in the floor and to place glass wool panels in the designated cavities. The installation of carpeting on the floor is suggested, in addition to the incorporation of absorbent material at the interface between the room and the changing rooms. The absorption coefficients for the proposed materials are detailed in Table 2.

Table 2: Absorption coefficient of the added surface materials.

Material	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Carpet	0.11	0.14	0.37	0.43	0.45	0.33
Walls	0.08	0.24	0.57	0.69	0.71	0.73

The proposed modifications have been implemented in the software to carry out a new simulation, in order to obtain the updated and optimised acoustic parameters for the choral rehearsal activity.

5. Analysis and Results

5.1 Room acoustics measurements

5.1.1 Reverberation time

According to ISO 354, measurements were carried out in the choir's rehearsal room. The results are shown in the figure 10.

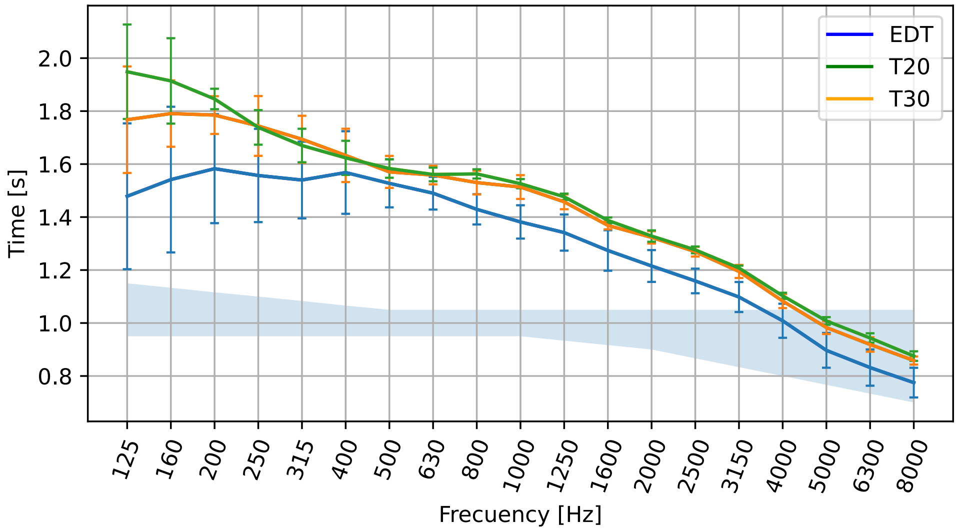


Figure 10: EDT, T20 and T30 measured.

In the curves in the figure 10, it can be seen that at low frequencies there is a longer reverberation time (around 1.8 s for 125 Hz), which decreases as the frequency increases. Furthermore, the EDT curve follows the reverberation time curve due to the fact that the room is one of the so-called "Sabine Room", which are characterised by similar reflecting surfaces.

The light blue shaded area corresponds to the suggested limits of reverberation time asociated with softh acoustic music in a rehearsal room, as stated in standard NS8178 [9]. It can be seen that the results obtained from the conducted measurements exceed the recommendations below 4 kHz. For this reason, the proposed acoustic treatment is aimed to obtain TR values that fall inside the shaded area.

5.1.2 Room acoustics and isolation

In relation to the acoustics of the room, a pronounced presence of low-frequency information has been observed, which could have significant implications on the quality and clarity of the sound generated during the rehearsal sessions. In addition, it is important to note that the walls and ceilings of the room are constructed with plaster and lack appropriate acoustic treatments, with the exception of one wall which has diffusers, the description of which is provided in the section 4.1.

The acoustic insulation in the room is deficient, allowing the entrance of external sounds and generating discomfort during rehearsal sessions. It has been observed that sound from outside and conversations in the dressing room affect the choir's concentration and performance in their musical practice. This lack of isolation also extends to the presence of the machine room in the dressing room, whose noises are audible inside the rehearsal room, generating unwanted interference in the acoustic environment.

Additionally, modal problems have been identified, as described in the Section 5.2.1. These modal problems can contribute to irregularities in frequency response and affect the perception of sound within the rehearsal room, compromising the musical experience of the choir.

5.2 Room modeling and simulation

In order to establish a starting point for the proposed acoustic conditioning of the rehearsal room, a simulation was carried out in EASE software. The measurements conducted in situ were used to validate the simulation, and the results obtained are presented in figure 11.

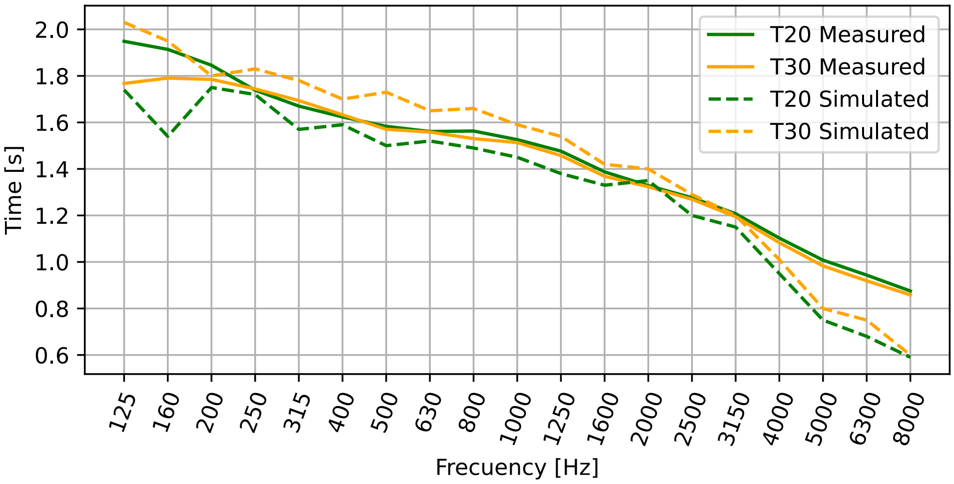


Figure 11: Measured and simulated T20 and T30 values of the rehearsal room.

The Figure 11 shows the reverberation time curves of the rehearsal room measured (solid lines) and compares them with the simulated results (dashed lines). The results obtained throught the software EASE show sligthy different T20 and T30 curves, while the curves corresponding to the in situ measurements show a higher similarity. Above 5 kHz the simulation shows significantly lower TR values.

5.2.1 Modal analysis of the enclosure

In this analysis of the test room enclosure, the computational tool Comsol Multiphysics has been used to evaluate the modal problems present in this space. The Schroeder frequency, determined at 128 Hz, has served as a crucial reference point for the detailed study of the acoustic characteristics of the room.

At the 30 Hz frequency, there is a significant concentration of sound pressure level in the dressing room and back wall, contrasting with the entrance to the rehearsal room where this tendency is not manifested. This pattern persists at 39 Hz, where the rehearsal room entrance and dressing room exhibit higher sound pressure levels compared to the back wall. The 59 Hz frequency reveals specific zones in the rehearsal room, particularly in the corners, with higher sound pressure levels, while other areas experience a reduction in sound pressure levels. At 100 Hz, a non-uniform distribution of the sound pressure level is observed, with a prominent increase in the ceiling at the back of the dressing room. In the analysis at 118 Hz, the observation of a non-uniform distribution of the sound pressure level is repeated, underlining the modal complexity of the enclosure. These variations in the sound pressure distribution at different frequencies indicate the presence of modal problems that need to be addressed to optimize the acoustic quality of the space when used as a rehearsal room.

Throughout, the evaluation using Comsol Multiphysics has provided detailed information about the modal problems in the test room enclosure. Understanding the variations in sound pressure level at different frequencies is essential for implementing corrective measures and improving the acoustic quality of the space. This can be seen in the Figure in Annex A5.

5.3 Proposals for room fittings

Then, the modification of the test room is proposed in order to comply with the NS 8178 standard and a new simulation is carried out. The results are shown in the figure 12.

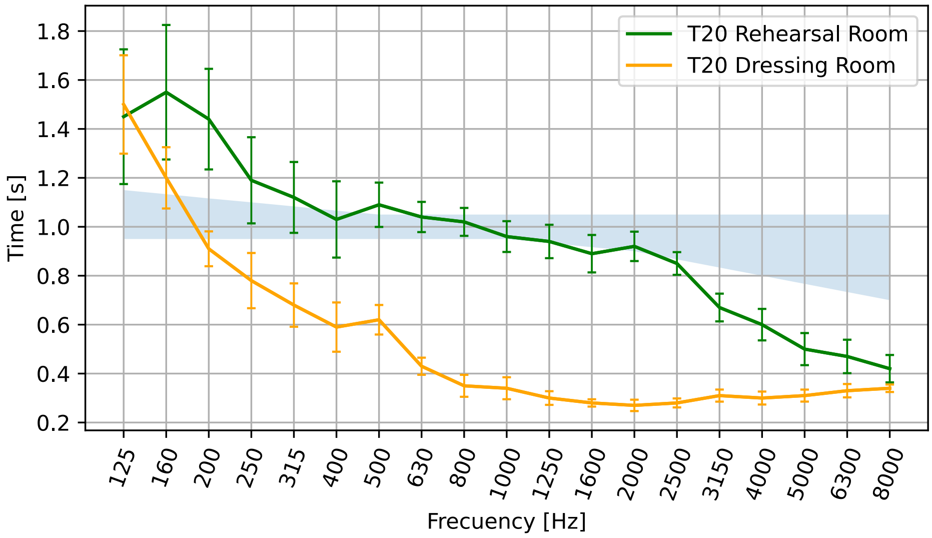


Figure 12: Reverberation time at room and dressing room simulated in EASE with modifications.

The curves in figure 12 show the simulated reverberation time of the rehearsal room and the dressing room with the proposed modifications. It can be seen that the reverberation time shows a decay as the frequency increases, although, the times are now more in line with the standard. Between 315 Hz and 2500 Hz the reverberation time inside the choir rehearsal room follows the suggestions expressed in standard NS8178. However, in the low frequency zone, the time exceeds the recommendations, while in the high frequency zone, shorter times were obtained.

Thus, it can be said that the proposed modification comes close to the standard, but does not strictly comply with it.

Regarding the dressing room, there is no target curve to achieve, it is only necessary to obtain a low enough TR curve in order to achieve a better coupling of the rooms.

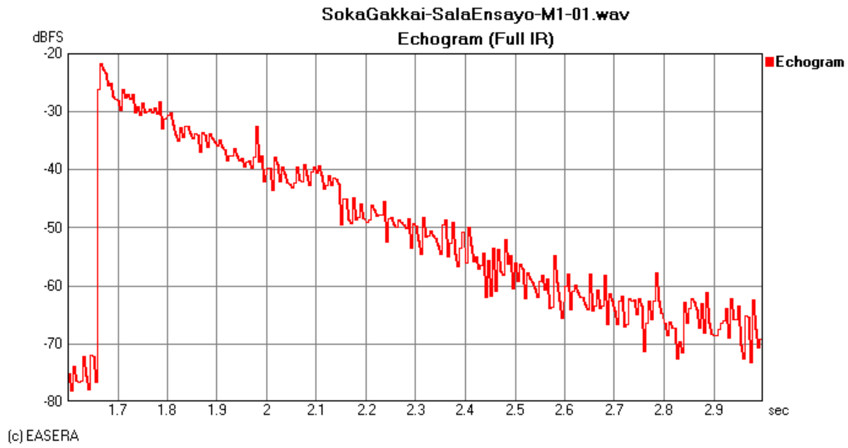
Finally, a TR mid of 1.02 s and 0.46 s were obtained for the rehearsal and dressing room, respectively.

5.3.1 Acoustic Coupling

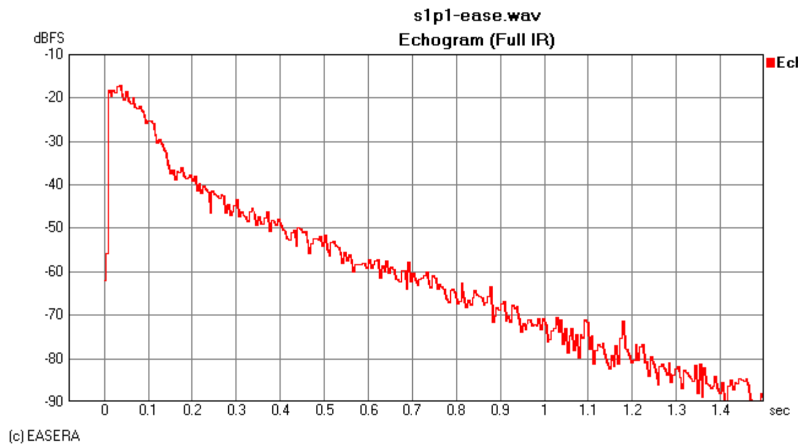
Figure A2 in the Appendix shows the coupling constant per third octave band with the proposed modification compared to the existing coupling constant of the rooms.

For the existing rehearsal and dressing rooms, the acoustic coupling value is expected to be close to 1 due to the fact that being a Sabine room, the energy decay is evenly distributed and the EDT, T10, T20 and T30 tend to be similar. By adding different absorbing materials and changing the geometry of the connection between rooms, the acoustic coupling constant increases.

This phenomenon can be explained looking at Figure 13(b), where from 160 ms the decay slope is different from the first 160 ms. In comparison, Figure 13(a) shows the measured energy decay of the room as it is, and a constant slope can be distinguished.



(a) Measured Energy Decay in the mic position n°1.



(b) Simulated Energy Decay in the mic position n°1 with the suggested acoustic coupling.

Figure 13: Energy decay with and without the proposed intervention .

5.3.2 SPL mapping

Sound pressure level distributed around the room with the proposed acoustic coupling was simulated using COMSOL Multiphysics. Figure 14 graphically represents the spatial distribution of the direct SPL at a height of 1.70 metres from the floor, emulating the position of a standing person, in response to the emission of a sound level of 94 dBSPL from a loudspeaker. This simulation allows to analyse how energy is distributed in space and to evaluate the acoustic impact at the specific location of interest [16]. It is important to note that the position of the sound source used in the simulation corresponds to the same position used in the in-situ measurements. The simulated model can be seen in Annex A4.

The graph reveals the differences in sound pressure levels in decibel (dB) in different areas of the room, highlighting the impact of the implemented acoustic coupling. It is noticeable that there is a disparity of more than 10 dB in sound pressure level between the rehearsal room and the dressing room. This discrepancy reflects the presence of an interface zone with a high acoustic absorption capacity, which leads to a rapid decrease in sound pressure level.

As a result of this configuration, in situations where sound activity is recorded in the dressing room, any discomfort experienced by the personnel in the rehearsal room is considerably minimised. The high absorption in the interface zone significantly reduces sound transmission between the two areas, thus ensuring a conducive acoustic environment in the rehearsal room and preventing the noise generated in the dressing room from interfering with activities in the main hall.

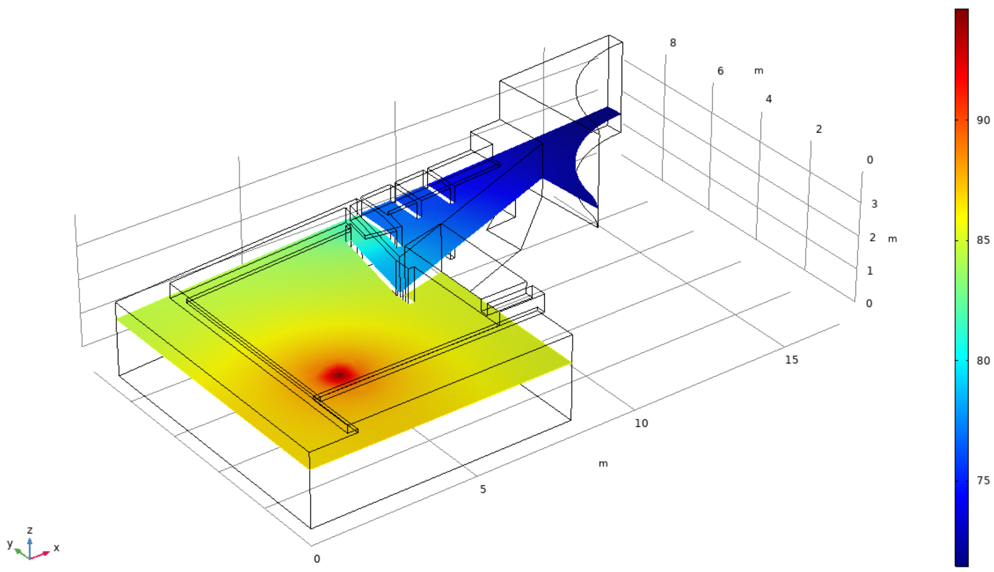


Figure 14: Sound pressure level [dB] distribution in the modified hall.

The Figure 14 shows a homogeneous distribution of the sound pressure level in the simulated test room. This indicates that there are no major differences in sound levels in different areas of the room. In other words, the sound distribution is uniform, suggesting that people in different locations within the room will experience similar sound levels.

This uniformity in sound pressure level distribution is a positive aspect for the acoustic quality of the room, as it means that there will not be significant variations in the auditory perception of the people present. Consequently, the rehearsal room will provide a balanced and comfortable acoustic environment, which is essential for activities such as choir rehearsals.

Furthermore, a simulation of the "early decay time" of the rehearsal room in which the acoustic coupling between the main room and the dressing room has been implemented is carried out, as shown in Figure 15. This acoustic parameter is essential to understand the acoustic response of the room and how the sound waves behave after the sound source has stopped emitting sound. The early decay time is an important indicator of the acoustic quality of the space, as it reflects how quickly the sound decays after the source has been silenced, which can affect the reverberation and clarity of the sound in the room.

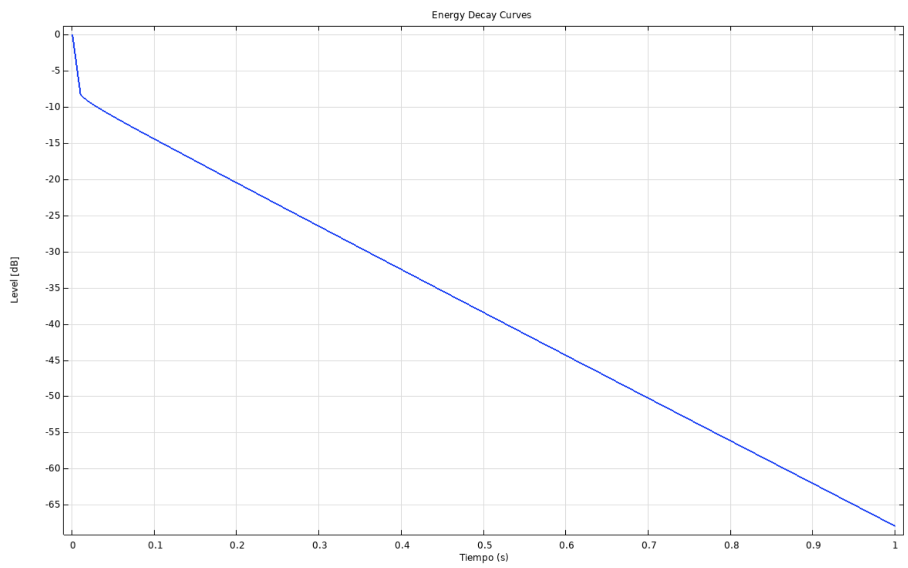


Figure 15: Energy decay curve inside the rehearsal room with the proposed acoustic treatment and coupling, simulated in COMSOL.

5.3.3 Room insulation

An Acuflex double contact door has been included in the enclosure configuration. The door is noted for its ability to provide efficient sound insulation, with a range varying between 40 and 45 decibels (dB). This level of insulation ensures effective reduction of external noise, which is especially valuable in environments where acoustic privacy is sought. The door incorporates an insulation system using rock wool with a density ranging from 145 to 180 kg/m3. This material provides outstanding thermal and acoustic insulation, which helps to maintain adequate acoustic conditions in the room. The central locking mechanism is of the refrigerator type, known as "Anti-panic," allowing quick and safe opening in emergency situations. For more specific details about the door and its design, it is recommended to refer to Annex A3, where a detailed and visual description of this door can be found. [17].

The introduction of glass wool between the ceiling and the roof is a measure aimed at reducing the transmission of sound waves and mitigating the formation of acoustic modes in this specific area of the room. This intervention seeks to optimize the modal response, contributing to the homogeneity of sound distribution throughout the rehearsal room.

Likewise, the inclusion of glass wool between the plaster walls and the partitions of the dressing room has the main objective of minimizing the resonances and acoustic modes present in these specific areas. By intervening at these key points, it is intended to reduce the interference of modes that could affect the vocal range of individuals during choir rehearsal sessions.

A specific strategy has been adopted to improve the acoustic insulation in the enclosure under study. A system proposed by the ISOVER [18] company has been used, which implements a mass-spring system that has proven to be effective in attenuating sound transmission. This solution consists of the use of a plate composed of two sheets of gypsum, between which is located a layer of glass wool with a thickness of 70 mm, from the same company.

The fundamental principle behind this mass-spring system is to take advantage of the glass wool's ability to absorb and dissipate sound energy, acting as an elastic material or spring in the structure. The arrangement of the two gypsum boards, flanking the glass wool layer, creates a mass effect, thus contributing to the improvement of the acoustic insulation of the enclosure.

This configuration provides a more effective physical and acoustic barrier against sound propagation, significantly reducing noise levels transmitted through the walls. According to tests and specifications provided by ISOVER, this system is able to achieve an acoustic insulation of around 53 dB, which is essential to minimize external sound interference and ensure a quiet environment suitable for its intended use. This can be seen in Figure A6 in the annex.

6. Conclusion

While more drastic measures could have been proposed to separate the environments discussed in this report, it is felt that a compromise solution was reached that can improve the user experience without affecting the comfort of users in the room. The acoustic coupling between the rehearsal room and the dressing room makes it difficult to perceive direct sound from one environment to the other. In addition, it was possible to obtain a reverberation time for each room that will increase the acoustic comfort of the users of each space, obtaining 1.02 s for the rehearsal room and 0.46 s for the dressing room. On the other hand, a systematic error that may have influenced the results and decision making is the methodology used for the measurement of reverberation time in the rehearsal room, since it was not performed with the room empty.

Based on the parameters established by NS 8178, it is concluded that this hall is suitable to function as a space for medium-sized ensembles, specifically for choirs. The main hall complies with the stipulated requirements in terms of volume and reverberation time, as established by NS8178.

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Annex

A. Images

(a) Photo of the dressing room.

(b) Photo inside the dressing room.

Figure A 1: Additional photos of the rehearsal room.

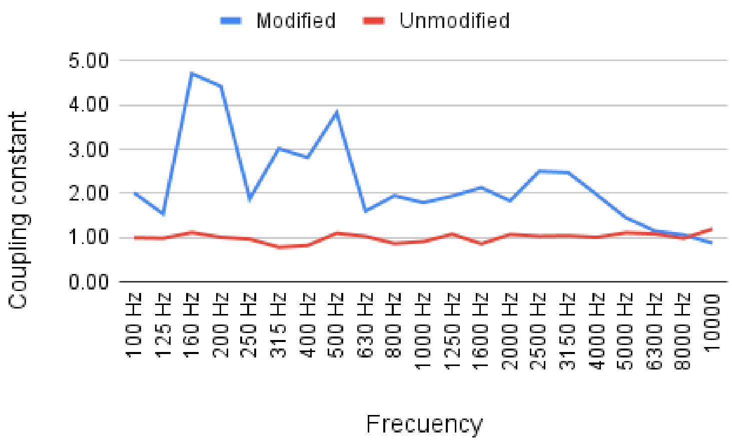


Figure A 2: Coupling constant per third octave band.

Finishes

- Thermosetting epoxy powder coated sheet metal.
- 100 micron paint coating on the sheet, 120 micron on the frame.
- Standard colour grey.
- White colour at no extra cost.

Insulation table

Calculated sound insulation (dBA)				
250 Hz	500 Hz	1000 Hz	2000 Hz	RW
37	54	60	63	40 / 45

Figure A 3: Double contact door specification.

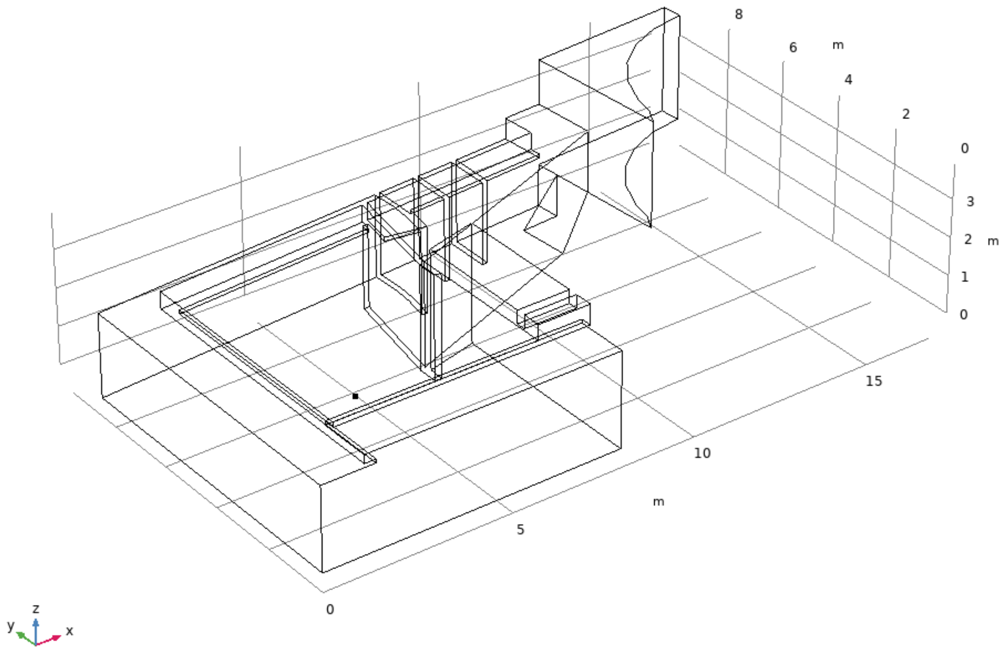
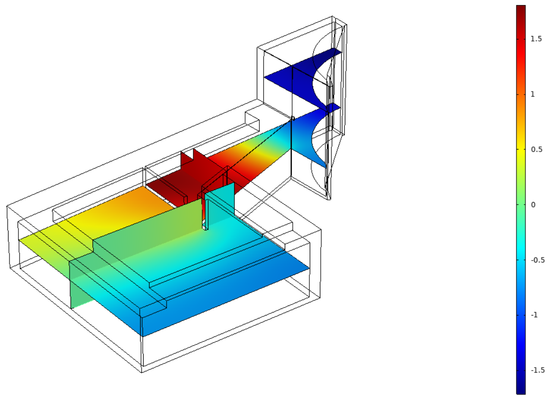
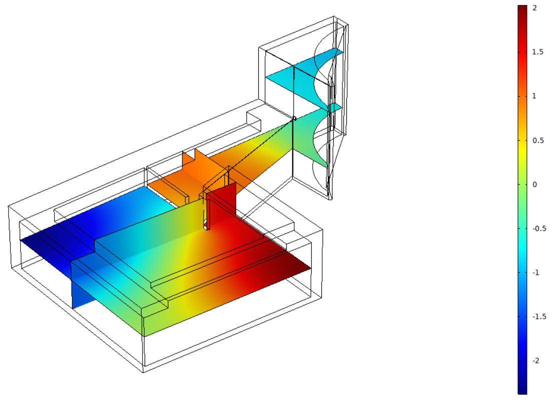


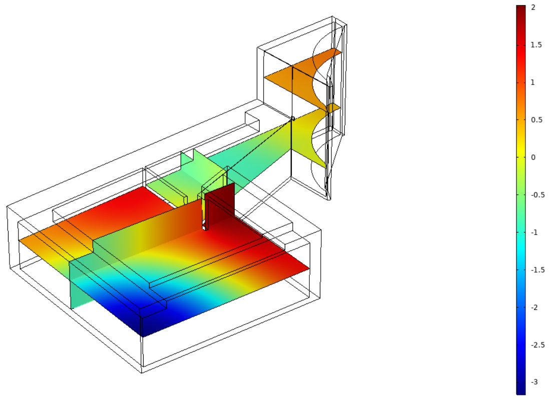
Figure A 4: Test room model simulated in Comsol Multiphysic.



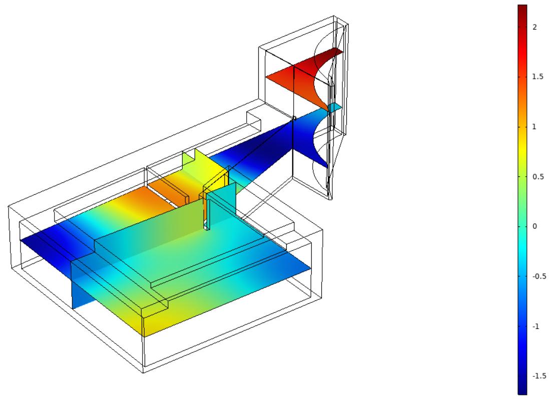
(a) 30 Hz.



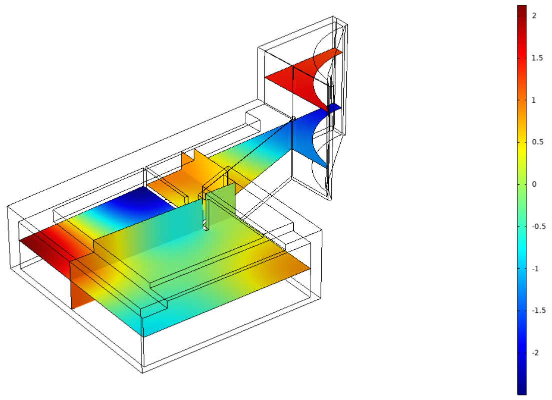
(b) 39 Hz.



(c) 59 Hz.



(d) 100 Hz.



(e) 118 Hz.

Figure A 5: Room resonance modes simulated in COMSOL Multiphysics.

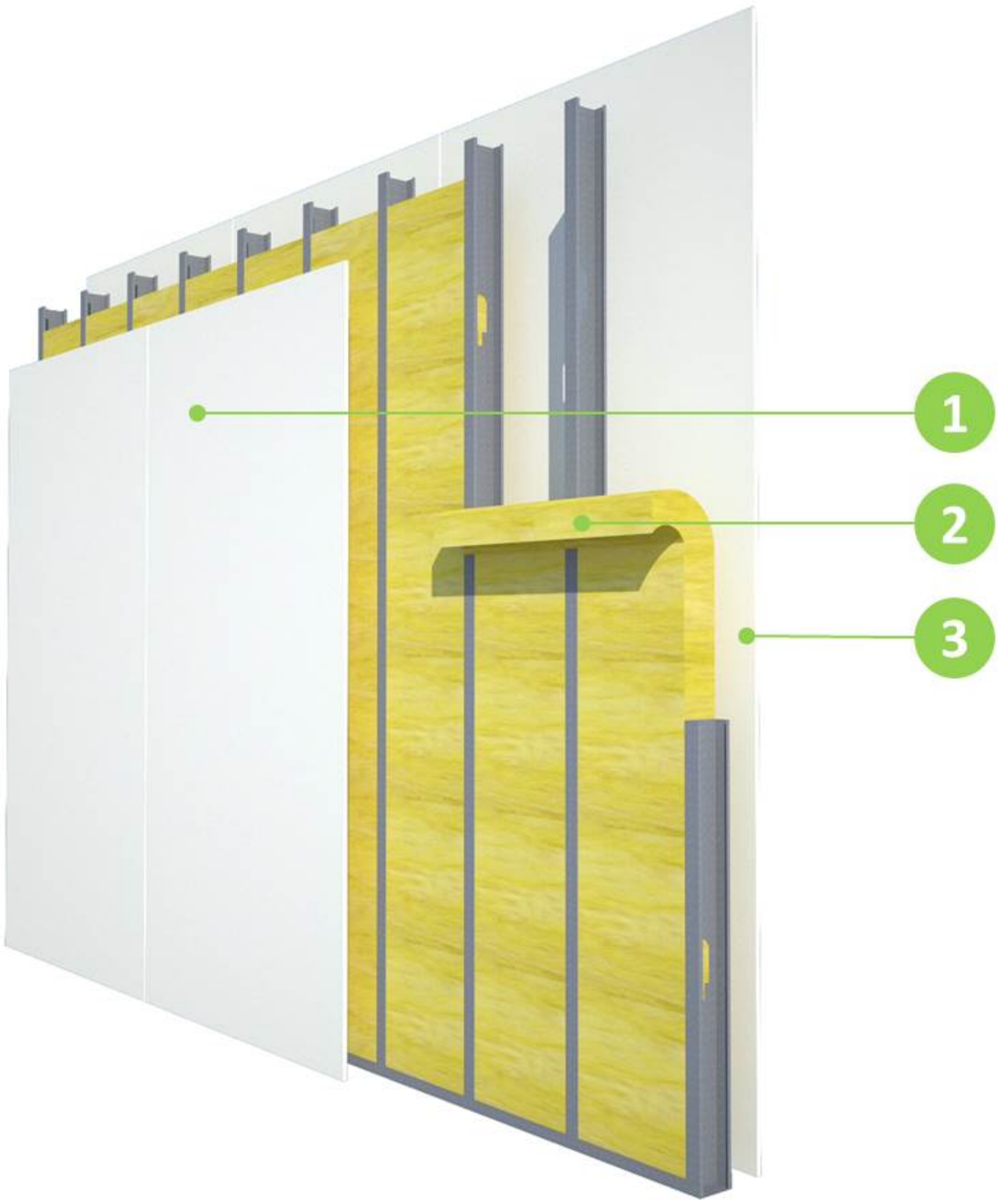
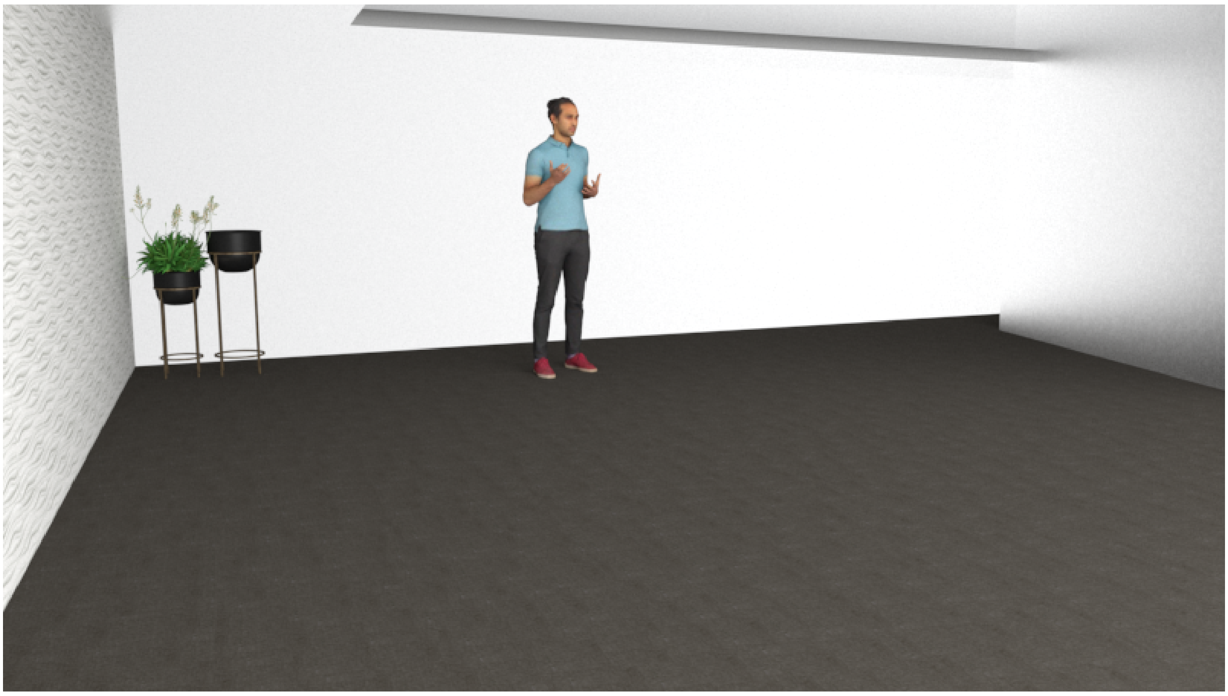
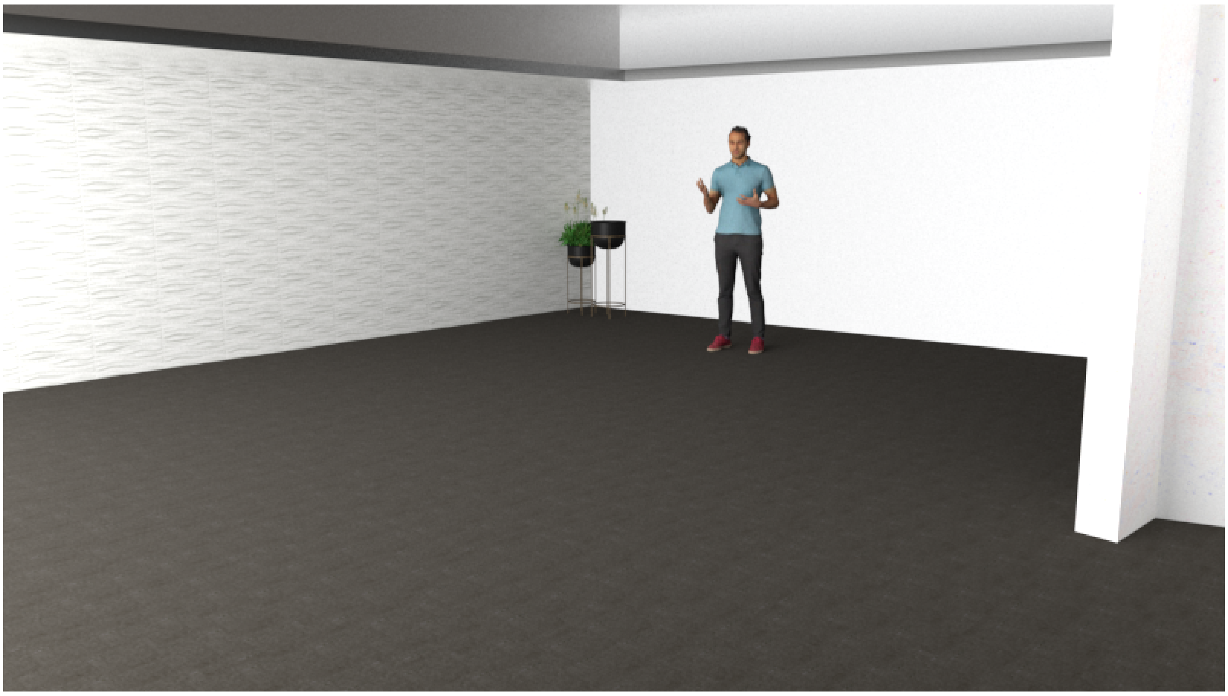


Figure A 6: Acoustic solution proposed by ISOVER.



(a)



(b)

Figure A 7: Render of the modified choir rehearsal room.

B. Tables

Tabla B 1: Measured acoustic parameters of rehearsal room.

	125 Hz	**160 Hz**	**200 Hz**	**250 Hz**	**315 Hz**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**
EDT [s]	1.48	1.54	1.58	1.56	1.54	1.57	1.53	1.49	1.43	1.38
T20 [s]	1.77	1.79	1.79	1.74	1.69	1.63	1.57	1.56	1.53	1.51
T30 [s]	1.95	1.91	1.85	1.74	1.67	1.62	1.58	1.56	1.56	1.53

	1300 Hz	**1600 Hz**	**2000 Hz**	**2500 Hz**	**3200 Hz**	**4000 Hz**	**5000 Hz**	**6300 Hz**	**8000 Hz**
EDT [s]	1.34	1.27	1.22	1.16	1.10	1.01	0.90	0.83	0.78
T20 [s]	1.46	1.37	1.32	1.27	1.19	1.08	0.98	0.92	0.86
T30 [s]	1.48	1.39	1.33	1.28	1.21	1.10	1.01	0.94	0.88

Tabla B 2: Simulated acoustic parameters of rehearsal room.

	125 Hz	**160 Hz**	**200 Hz**	**250 Hz**	**315 Hz**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**
T20 [s]	1.74	1.54	1.75	1.72	1.57	1.59	1.5	1.52	1.49	1.45
T30 [s]	2.03	1.95	1.8	1.83	1.78	1.7	1.73	1.65	1.66	1.59

	1300 Hz	**1600 Hz**	**2000 Hz**	**2500 Hz**	**3200 Hz**	**4000 Hz**	**5000 Hz**	**6300 Hz**	**8000 Hz**
T20 [s]	1.38	1.33	1.35	1.2	1.15	0.95	0.75	0.68	0.59
T30 [s]	1.54	1.42	1.4	1.29	1.2	1.01	0.8	0.75	0.6

Tabla B 3: Simulated acoustic parameters of modified rooms.

	125 Hz	**160 Hz**	**200 Hz**	**250 Hz**	**315 Hz**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**
T20 [s] Dressing R.	1.45	1.55	1.44	1.19	1.12	1.03	1.09	1.04	1.02	0.96
T20 [s] Rehearsal R.	1.5	1.2	0.91	0.78	0.68	0.59	0.62	0.43	0.35	0.34
	1300 Hz	**1600 Hz**	**2000 Hz**	**2500 Hz**	**3200 Hz**	**4000 Hz**	**5000 Hz**	**6300 Hz**	**8000 Hz**	
T20 [s] Dressing R.	0.94	0.89	0.92	0.85	0.67	0.6	0.5	0.47	0.42	
T20 [s] Rehearsal R.	0.3	0.28	0.27	0.28	0.31	0.3	0.31	0.33	0.34	