

Acoustic analysis and adequacy design of the UFRJ Symphony Orchestra rehearsal room

Análise acústica e proposta de adequação da sala de ensaios da Orquestra Sinfônica da UFRJ

Abstract

Rehearsal rooms, especially those intended for orchestras, must have appropriate acoustic treatment so that musicians can work on tuning, sound perception, and tone production during rehearsals. This paper presents an analysis of the acoustic conditions of the rehearsal room of the Orchestra of the School of Music at UFRJ, which has been the subject of complaints such as excessive external noise and high reverberation. For the analysis, measurements of reverberation time and sound pressure level were carried out in the room. Based on this analysis, alternative acoustic intervention strategies are proposed to adapt the space to its intended use through acoustic simulations using the BRASS and Cype Acoubat software, which enable the evaluation of reverberation time and sound insulation performance. Reverberation time simulations were carried out for different occupancy configurations, ranging from small ensembles to a full symphony orchestra. The simulation results indicate that, through economically viable solutions, it is possible to transform the rehearsal room of the UFRJ School of Music Orchestra into a suitable environment, ensuring the required sound insulation and acoustic conditioning compatible with its function.

Keywords: Room acoustics. Sound insulation. Computer simulation. Acoustic design. UFRJ.

Resumo

As salas de ensaio, principalmente as de orquestras, devem ter tratamento acústico adequado, para que os músicos possam trabalhar a afinação, a percepção e a emissão sonora durante os ensaios. Neste trabalho é apresentada uma análise das condições acústicas da sala de ensaio da Orquestra da Escola de Música da UFRJ, sobre a qual há reclamações, tais como ruído externo excessivo e alta reverberação. Para a avaliação, foram realizadas medições de tempo de reverberação e de nível de pressão sonora na sala. Com base na análise, são propostas alternativas de intervenções acústicas para adequar a sala de ensaio ao seu uso, por meio de simulações acústicas, com os simuladores BRASS e Cype Acoubat, que possibilitam analisar o tempo de reverberação e nível de isolamento sonoro. As simulações de tempo de reverberação foram feitas para diferentes configurações, de pequenos grupos até uma orquestra sinfônica. Os resultados das simulações indicam que, por meio de soluções economicamente viáveis, é possível transformar a sala de ensaios da Orquestra da Escola de Música da UFRJ em um espaço adequado, garantindo o isolamento sonoro necessário e o condicionamento acústico compatível com sua função.

Palavras-chave: Condicionamento acústico. Isolamento acústico. Simulação computacional. Projeto acústico. UFRJ.

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1 Introduction

Among the most relevant acoustic aspects for musicians in a rehearsal room are the ability to hear themselves and to clearly perceive other performers, ensuring a proper balance between their own sound and that of the ensemble. Additionally, the conductor must be able to anticipate how the musical work will sound in the main concert hall. Other equally important aspects include preserving auditory health and providing sufficient space for comfortable positioning, avoiding excessive proximity to other musicians and reflective surfaces (Olsen, 2022). The acoustic behavior of unamplified music in a rehearsal space depends on several factors, including the type and number of instruments, their playing technique, the room volume, and its reverberation time (Rindel, 2014).

The rehearsal room of the Symphony Orchestra of the Federal University of Rio de Janeiro (OSUFRJ) is located on the 5th floor of Building 2 of the UFRJ School of Music, in the Lapa district of Rio de Janeiro. The building is listed as a municipal heritage site by the Municipality of Rio de Janeiro, which imposes restrictions on any modifications, particularly those affecting the facades (Rio de Janeiro, 1994, 2007). Currently, the room does not provide adequate acoustic conditions for its intended function. The musicians and conductors complain about excessive reverberation and external noise, as well as desired musical characteristics, such as intimacy and ability to hear clearly the other instruments. Therefore, for using such a room as an orchestral rehearsal space, it is essential that the environment presents proper acoustic treatment and sound insulation, as the quality of musical performance is directly related to the acoustic characteristics of the space where sound propagates.

The objective of this work is to design technical alternatives for sound insulation and for acoustic conditioning, to adequate the room to be used as an orchestral rehearsal space. To achieve this goal, firstly the existing acoustic characteristics of the room were evaluated through in situ measurements, according to international standards. Then, based on that analysis and how different the main parameters are from the ideal ones, alternatives of design tested using computational simulation¹.

2 Theoretical foundations

Reverberation Time (RT) is one of the primary parameters used to characterize the acoustic behavior of enclosed spaces. According to NBR 16313 (ABNT, 2025), RT is defined as the time, in seconds, required for the sound pressure level to decay by 60 dB after the sound source is interrupted. The same standard defines the Sound Pressure Level (SPL) as the mean sound energy at a given point in the environment over a specified time interval, referenced to the minimum audible sound pressure perceptible by the human ear.

In music rooms, the SPL during forte passages should not result in discomfort or risk of hearing damage. Recommended values range from 85 dB to 90 dB, with acceptable levels up to 97 dB under controlled exposure conditions. For rehearsal rooms, the reverberation time should generally be slightly shorter than that recommended for performance halls of similar volume (Rindel, 2014; Basso, 2024).

According to Brandão (2016), reverberation time was the first acoustic parameter to be systematically investigated in architectural acoustics and remains strongly correlated with several subjective aspects of auditory perception in enclosed environments. Sabine's classical formulation for RT is conceptually similar to Eyring's equation; however, the latter accounts for the progressive reduction in sound energy density at each surface reflection. As a result, for a given enclosure, the RT predicted by Sabine's model is typically slightly higher than that obtained using Eyring's formulation.

The NBR ISO 23591 (ABNT, 2025) establishes criteria for acoustic quality in rehearsal rooms, specifying minimum and maximum RT limits at mid frequencies (500 Hz), as a function of room use, volume, and normalized sound strength. For example, an orchestral rehearsal room with an approximate volume of 600 m³ should present a reverberation time between 0.8 s and 1.2 s, in accordance with the standard's recommendations.

Table 1 presents four examples of music rehearsal rooms, illustrating the relationship between room volume, reverberation time, and the target sound pressure level for adequate acoustic performance.

¹This initiative was carried out as an Extension activity, at no cost to the University, by members of the Research Groups Architecture and Sustainability (GPAS) and Project Management in Architecture (GEPARQ) - both affiliated with the Graduate Program in Architecture of the Faculty of Architecture and Urbanism at UFRJ (PROARQ/FAU/UFRJ) - in partnership with the Polytechnic School of UFRJ (POLI/UFRJ). In parallel, complementary projects for electrical and heating, ventilation, and air conditioning (HVAC) installations were developed by companies contracted by the School of Music of UFRJ (EMUFRJ), and these were coordinated with the architectural and acoustic design guidelines.

Table 1 - Relationship between type of musical ensemble, sound power level, gain factor, and ideal acoustic characteristics

Musical ensemble	Sound power level (dB)	Ideal gain factor (G) (dB)	Volume (m ³)	RT (s)
String quartet	95	21 – 26	30 – 200	0.4 – 1.1
Male choir (24 singers)	102	14 – 19	330 – 1,600	1.0 – 1.7
Brass quintet	110	6 – 11	2,000 – 10,000	1.0 – 1.9
Concert band (40 musicians)	116	0 – 5	≥ 8,000	1.3 – 2.0

Source: adapted from Rindel (2014).

Rindel (2021) investigated the influence of geometric proportions – length (L), width (W), and height (H) – on the distribution of modal frequencies in small rectangular rooms, such as studios, rehearsal rooms, and control rooms, aiming to achieve a more homogeneous low-frequency response. As an evaluation criterion, the study considered the relative variance in the distribution of the first 25 normal modes within the frequency range from 20 Hz to 200 Hz. The results indicated that the L/W ratio is significantly more critical to acoustic quality than the W/H ratio. For rooms with volumes up to approximately 300 m³, the author recommends that the L/W ratio be maintained between 1.15 and 1.45. Within this interval, the room height may be selected with greater flexibility, if W/H exceeds 1.1, without substantially compromising acoustic performance.

Orchestral rehearsal rooms require specific design criteria that extend beyond those typically adopted for concert halls, due to the need for adequate mutual hearing among musicians, controlled sound pressure levels, and appropriate room volume. Parameters such as the relationships between room volume, floor area, and total sound power relative to the number of musicians directly affect early support (ST_{early}) and, consequently, ensemble intelligibility and internal communication. Pompoli, Prodi and Farnetani (2012) demonstrated that, by defining a target value for ST_{early} (e.g., –12 dB), it is possible to estimate the reverberation time of the unoccupied room and, through graphical correlations, determine suitable combinations of room volume and number of musicians to ensure adequate acoustic quality. The authors emphasize that reducing reverberation time does not adequately address the specific requirements of rehearsal spaces, as room geometry, musician density, early reflections, and total volume must be considered jointly to achieve satisfactory acoustic conditions.

The optimal scenario for an orchestra would be to conduct rehearsals in the same venue used for performances. This arrangement is feasible in small cities or in facilities with low event turnover. However, in major cultural centers — where multiple events may occur weekly, and sometimes more than once per day in the main auditorium — this approach becomes impractical. With the publication of ISO 23591 (ISO, 2021), subsequently adopted in Brazil as NBR ISO 23591 (ABNT, 2025), designers gained access to minimum acoustic quality requirements for orchestral rehearsal rooms. These requirements include specifications for room volume, plan dimensions, ceiling height, reverberation time (RT), acoustic treatment characteristics, background noise levels, and the absence of perceptible echoes or resonances, among other criteria (Basso, 2024).

Acoustic simulation enables the numerical prediction of sound propagation in enclosed or open environments using either geometrical acoustics algorithms — which represent sound propagation through ray-tracing approaches — or numerical solutions of the wave equation, such as the finite-difference method (FDM), the finite element method (FEM), and the boundary element method (BEM). Although wave-based methods offer higher physical fidelity by accounting for interference and diffraction phenomena, their computational cost generally restricts their application to low-frequency ranges and small spatial domains (Ihlenburg, 1998; Schenk, 1992; Solomons, 2001). Consequently, geometrical acoustics methods are more frequently employed in large spaces and at mid-to-high frequencies, despite neglecting certain wave effects.

These simulation approaches are widely applied in various contexts, including the acoustic reconstruction of historical buildings (Fagerlande; Niemeyer; Torres, 2020; Mu; Wang; Zhang, 2022), the design of concert halls (Brandão *et al.*, 2022; Jun; Yoon; Kim, 2025), classrooms (Mahl; Tenenbaum; Melo, 2024; Zhang; Tenpierik; Bluysen, 2021), transportation terminals (Bentes; Slama, 2011; Li; Zhao, 2025) and urban planning (Fallah-Shorshani *et al.*, 2022; Manyoky *et al.*, 2016). Virtual reality environments and gaming tools are widely used to investigate scenarios (Heck *et al.*, 2025; Pelzer; Masiero; Vorländer, 2014). Within this context, auralization has become an essential tool, allowing virtual auditory evaluation of simulated sound fields. Nevertheless, physical scale models may still provide advantages when investigating complex acoustic phenomena — such as diffraction effects and acoustically coupled volumes — which remain challenging to reproduce accurately using numerical simulation techniques (Brinkmann *et al.*, 2021).

Room acoustic simulations play a fundamental role in predicting acoustic parameters, optimizing sound system layouts, and analyzing modal behavior. Their effective use, however, requires a solid understanding of the underlying physical principles. Simulation methods can be broadly classified into wave-based approaches, which solve the full wave equation and are particularly suitable for low-frequency analysis, and geometrical acoustics approaches, which offer greater computational efficiency for high frequencies and large-scale environments. Within the latter group, energetic and phase-based methods can be distinguished, with the latter incorporating phase and incidence angle information to improve low-frequency accuracy. Among these, the ray tracing semiclassical (RTS) method, inspired by quantum mechanics, can reproduce the Green's function and accurately model the lowest modes of rectangular rooms while efficiently computing sound fields at multiple receiver positions. As a result, RTS has emerged as a promising alternative for low-frequency simulations, a domain traditionally dominated by wave-based methods (Prislan; Svenšek, 2018).

Şaher, Özgencil and Khoshkholghi (2025) evaluated the acoustic performance of four rehearsal rooms in Istanbul designed for individual practice of low-intensity instruments, following the criteria established in ISO 23591 (ISO, 2021). The study combined objective measurements, acoustic simulations, and musicians' subjective assessments. The results revealed dissatisfaction regarding room efficiency and spectral balance, particularly in the low-mid and high-mid frequency ranges. Measured reverberation times were, on average, outside the recommended limits, indicating challenges in achieving adequate acoustic balance. A total of 36 acoustic models were developed and computed based on different optimization strategies and subsequently evaluated by musicians through auralization procedures. The findings demonstrated a clear preference for models presenting average reverberation times within the recommended range, showing strong agreement between subjective perception and objective parameters and underscoring the importance of balanced low- and mid-frequency responses for perceived acoustic quality.

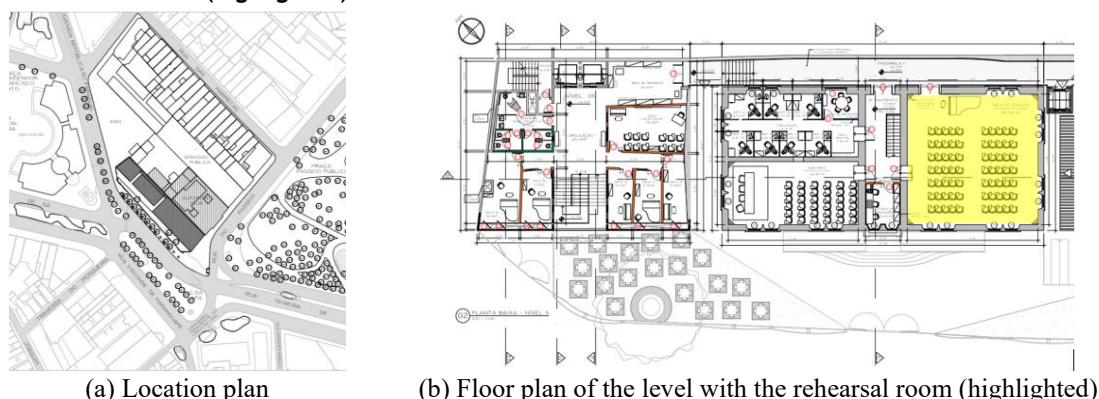
Vergara, Marros and Paul (2017) conducted an acoustic analysis of three individual practice rooms and three group classrooms in a university music department, combining objective measurements and musicians' subjective evaluations. The study found that users had difficulty articulating acoustic perceptions and distinguishing between conditioning and insulation concepts, describing the rooms mainly in terms of reverberation and instrument projection. Measurements confirmed the reported perceptions: rooms rated as "dry" presented RT values between 0.3 and 0.4 s, high clarity ($C_{80} = 1422$ dB) and definition ($D_{50} = 88-96\%$), while "reverberant" rooms exhibited RT around 1.5 s, $C_{80} \approx 1$ dB, and $D_{50} \approx 40\%$. Only two rooms were widely approved by musicians — one with low reverberation for individual practice and another reverberant for ensemble practice. The study demonstrates that the perception of acoustic quality results from the interaction between the room's physical characteristics (such as RT and volume), its intended use, and the musicians' subjective experience, also emphasizing the relevance of parameters such as C_{80} , D_{50} , and G for the perception of clarity and sound strength.

Lima and Vergara (2018) carried out acoustic simulations of different architectural configurations for a multipurpose room used for music education and practice. Initially, measurements were performed to obtain the main acoustic parameters of the room (RT, EDT – early decay time, C_{80} , D_{50} , and STI – speech transmission index). Subsequently, the environment was modeled in its existing state and with different design proposals. The developed model showed that multipurpose rooms can be adapted through simple yet well-considered interventions, provided they are guided by an appropriate acoustic study. Simulation made it possible to test multiple combinations of materials and devices, offering flexibility to adjust the room's response according to the intended use. The study thus highlights the potential of computational modeling as a tool to support the design and acoustic adaptation of variable-use environments, enabling practical and efficient transitions between optimal conditions for speech or music.

3 Methodology

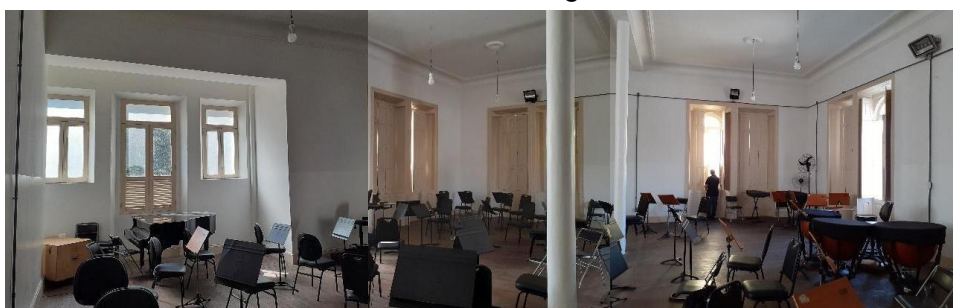
The rehearsal room of the Symphony Orchestra of the Federal University of Rio de Janeiro is depicted in Figures 1 and 2. Figure 1a shows the site plan of the School of Music, while Figure 1b presents the floor plan of the level containing the rehearsal room (highlighted). Figure 2 presents interior views of the rehearsal room in its current condition.

Figure 1 - Floor plans of the UFRJ School of Music: (a) location plan and (b) floor plan of the level with the rehearsal room (highlighted)



Source: adapted from University Technical Office (ETU) of UFRJ (2025).

Figure 2 - Interior views of the rehearsal room in its existing state



The architectural floor plan of the room was obtained from the University Technical Office as part of the expansion and restoration processes of the School of Music. The room has an area of 123.32 m², a ceiling height of 4.85 m, wooden windows with louvers and glass panes, a wooden door measuring 1.40 × 2.70 m, a smooth gypsum ceiling, and a wooden floor. The windows are distributed along three of the four walls: one wall faces Avenida República do Paraguai (the most exposed to external noise), another wall faces Building 1 of the UFRJ School of Music (where the Leopoldo Miguez Concert Hall is located), and the third one faces the School of Industrial Design of UERJ (Rio de Janeiro State University).

The following technical standards were adopted as references: NBR 10152 (ABNT, 2020b) for recommended indoor noise levels; NBR 10151 (ABNT, 2020a) for recommended outdoor noise levels; NBR 12179 (ABNT, 1992) for reverberation time (RT) calculations; NBR ISO 3382-1 (ABNT, 2017) for RT measurements in the existing room; NBR ISO 23591 (ABNT, 2025) for reference values of acoustic parameters in rehearsal rooms; and NBR ISO 12354-1 (ABNT, 2023) for estimation of the airborne sound insulation.

For the simulations of reverberation time in the project phase, the BRASS (Brazilian Room Acoustics Simulator) software, developed at the Polytechnic School of UFRJ, was used (Torres, 2018). Simulations of sound insulation between rooms and toward the exterior were performed using Cype Acoubat (CYPE Ingenieros S.A., 2024), based on the standards ISO 12354-1 (ISO, 2017a), ISO 12354-2 (ISO, 2017b), ISO 717-1 (ISO, 2020a) and ISO 717-2 (ISO, 2020b).

The methodology developed to adequate the room to be used as an orchestral rehearsal space consists in the following steps:

- (a) acoustic measurements of RT and background noise;
- (b) acoustic simulations of RT using the BRASS software (Torres, 2018) and of sound insulation using Cype Acoubat (Cype Ingenieros S.A., 2024);
- (c) model validation by comparing measured and simulated values for actual scenario;
- (d) definition of performance goals based on standards and design proposals;
- (e) acoustic simulations of the proposed interventions;

(f) comparison and analysis of simulated results with the target values for RT and sound insulation.

3.1 Acoustic measurements

The sound pressure measurements were performed using the following equipment: Behringer ECM-8000 omnidirectional microphone, ASIO M-Audio M-Track sound interface, Room EQ Wizard V5.20 software (REW, 2024), and a Behringer B212 loudspeaker (frequency range 65 Hz – 18 kHz). Due to the unavailability of an omnidirectional sound source, a directional source was used, and the system was calibrated with a 1 kHz, 94 dB signal (referenced to 20 μ Pa), measured at 1.0 m on the acoustic center axis using white noise.

Background noise measurements were conducted to determine the minimum sound pressure level for the loudspeaker system, used to obtain the Room Impulse Responses at each location. The A-weighted equivalent continuous sound pressure levels ($L_{Aeq,5min}$) were selected for the background noise characterization. A limited number of measurements were performed, as the objective was solely to verify compliance with signal-to-noise ratio requirements, rather than to provide a statistical characterization of background noise.

Two measurements per configuration were considered sufficient to estimate the order of magnitude and variability of the background noise levels under both open- and closed-window scenarios. Each measure had a duration of five minutes, in accordance with NBR 10152 (ABNT, 2020b).

The Reverberation Time (RT) based on a 30 dB decay (T_{30}) was obtained from the Impulse Response by applying the Schroeder Method of Reverse Integration (Schroeder, 1979). The impulse response measurements were carried out using a logarithmic sine sweep signal 6 seconds long, ranging from 20 Hz to 20 kHz, reproduced by the loudspeaker and recorded at different points in the room. The impulse response was obtained by deconvolution between the recorded and reference signals in REW software, eliminating harmonic distortions of the playback system. Based on the impulse response, acoustic parameters were calculated according to NBR ISO 3382-1 (ABNT, 2017), including T_{30} , clarity (C_{80}), definition (D_{50}), early decay time (EDT), and center time (CT), providing a precise characterization of the room's acoustic properties.

Seven measurements were taken with windows closed and five with windows open, providing sufficient spatial averaging for a room of approximately 600 m³. The acoustic design and simulation calibration were performed based on the closed-window configuration, which represents the reference design condition of the room. Accordingly, a larger number of receiver positions were adopted in this configuration to ensure robust spatial averaging and reliable validation of the numerical model. The open-window configuration was analyzed as a complementary scenario, in which sound energy leakage through the openings reduced the diffuseness of the sound field. In this case, five spatially distributed measurement positions were considered sufficient, as the spatially averaged T_{30} exhibited statistical stability.

Tables 2 and 3 present the measurement positions along the X and Y axes for the different combinations of sound sources ("F", loudspeaker) and receivers ("R", microphone), as well as the source orientation angles (0°, 90°, 180°, and 270°). The measurement configurations are identified by source–receiver pairs. Table 2 summarizes the measurements conducted with the windows closed, comprising the pairs (F1–R1, F1–R2, F1–R3, F2–R4, F2–R5, F3–R6, and F3–R7); in this condition, all measurements for a given source were performed with a fixed source orientation of 90°. Table 3 presents the measurements with the windows open, carried out at positions (F1–R1 and F1–R2), in which the source orientation was varied (0°, 90°, 180°, and 270°) to assess its influence on the room's acoustic response.

Table 2 - RT measurement points with closed windows

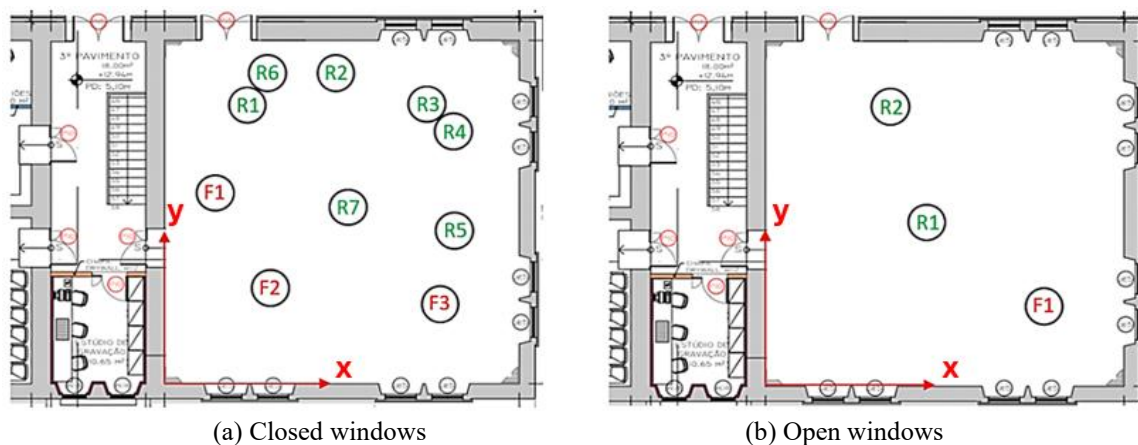
Measurement	X Source (m)	Y Source (m)	Source Angle	X Receiver (m)	Y Receiver (m)
1 (F1–R1)	1.40	5.60	90°	4.45	7.70
2 (F1–R2)	1.40	5.60	90°	5.76	10.41
3 (F1–R3)	1.40	5.60	90°	8.15	8.39
4 (F2–R4)	3.96	3.70	90°	8.15	8.39
5 (F2–R5)	3.96	3.70	90°	8.15	4.06
6 (F3–R6)	8.27	2.78	90°	2.73	9.57
7 (F3–R7)	8.27	2.78	90°	5.49	5.52

Table 3 - RT measurement points with open windows

Measurement	X Source (m)	Y Source (m)	Source Angle	X Receiver (m)	Y Receiver (m)
1 (F1-R1)	8.27	2.78	90°	5.49	5.52
2 (F1-R1)	8.27	2.78	0°	5.49	5.52
3 (F1-R1)	8.27	2.78	270°	5.49	5.52
4 (F1-R1)	8.27	2.78	180°	5.49	5.52
5 (F1-R2)	8.27	2.78	90°	4.38	8.36

Figure 3 shows the plan view with the positions of sound sources (red) and receivers (green) for both window conditions (a – closed and b – open), as well as the X and Y axes (in red).

Figure 3 - Location of the measurement points with (a) closed and (b) open windows



3.2 Simulations of acoustic treatment: current condition

For the simulation of the rehearsal room in both its current and design conditions, the BRASS software was used. BRASS is an acoustic simulator that employs the traditional ray tracing method combined with a clustering strategy, which groups rays belonging to the same wavefront into a single event. This approach allows for a more accurate representation of early reflections and the spatial distribution of sound energy. The combination of ray tracing and clustering enables BRASS to generate realistic impulse responses, balancing precision in early reflections with efficiency in the representation of the diffuse field (Torres, 2018, 2022).

The software can generate both monaural and binaural impulse responses, allowing for acoustic analysis and auralization through binaural audio. The calculated energy at each receiver depends on the number of rays captured, the room geometry, the source–receiver distance, and the acoustic properties of the surfaces (absorption, scattering, and transmission). The software supports both omnidirectional and directional sources, with power levels referenced to 1 meter on the main axis (Torres; Aspöck; Vorlander, 2018).

Initially, the current state of the room was simulated, and the acoustic parameters obtained were compared with the measured values to validate the generated model. The simulation procedure requires the development of a detailed geometrical and acoustic model of the room. All surfaces were initially modeled in a CAD environment capable of exporting DXF files, using 3DPolyline, 3DFace, or PolyFaceMesh entities. The geometry was then imported into the BRASS software, which assigns acoustic materials to the surfaces based on their corresponding CAD layers. For each material, random-incidence sound absorption coefficients were specified in nine octave bands, covering the frequency range from 63 Hz to 16 kHz. The positions of the sound source and receivers were also defined within the CAD model and imported into the simulation environment. A simulation of the existing condition was carried out using 20,000 rays emitted from the sound source, with omnidirectional monaural receivers and the sound absorption coefficients listed in Table 4. Scattering effects were not considered, as the software does not incorporate diffuse reflection models.

Table 4 - Absorption coefficients (α) of materials in the room for actual condition

Material	Location	Reference	Sound absorption coefficient α by frequency band					
			125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Wooden slats over concrete floor	Floor	Carvalho (2010)	0.15	0.11	0.10	0.07	0.06	0.07
Smooth plaster	Walls	NBR 12179 (ABNT, 1992)	0.02	0.02	0.02	0.02	0.03	0.06
Closed wooden doors	Door	NBR 12179 (ABNT, 1992)	0.14	0.10	0.06	0.08	0.10	0.10
Window glass	Glass	NBR 12179 (ABNT, 1992)	0.04	0.04	0.03	0.02	0.02	0.02
Open window	Open windows	NBR 12179 (ABNT, 1992)	1.00	1.00	1.00	1.00	1.00	1.00
Wooden slats with open space below	Closed windows	Carvalho (2010)	0.40	0.30	0.20	0.17	0.15	0.10
Wooden and leather seat chair	Leather chairs	Carvalho (2010)	0.09	0.13	0.15	0.15	0.11	0.07
Grand piano	Piano	Carvalho (2010)	0.20	0.52	0.60	0.57	0.52	0.43

3.3 Simulations of acoustic insulation: actual condition and proposed design

The acoustic insulation simulation process began with architectural modeling in the IFC Builder software (Cype Ingenieros S.A., 2026), including walls, doors, and windows, whose proper definition is essential for generating an accurate analytical model. After defining the spaces, it is crucial to ensure that their surfaces are coplanar with the partitions to avoid calculation errors in areas and volumes. The typologies assigned to elements and spaces facilitate the subsequent association of acoustic properties.

The architectural model is then imported into the AcouBAT software (Cype Ingenieros S.A., 2024), where calculation parameters, acoustic space typologies, and component properties are defined based on the CSTB database (CSTB, 2024), which contains thousands of constructive solutions with their respective sound reduction indices (R_w) in one-third-octave bands. Additionally, it is possible to insert new elements based on laboratory test data or simulations performed in other programs, such as Insul Acoustics (Marshall Day Acoustics, 2023), which calculates the airborne sound insulation (R_w – weighted sound reduction index) of building components. This integrated workflow enables the use of comprehensive architectural model data to perform consistent acoustic insulation analyses aligned with the standards NBR ISO 717-1 (ABNT, 2021) and NBR ISO 12354-1 (ABNT, 2023).

Table 5 presents each construction solution used in the models of the existing and proposed conditions, the constituent materials, the thickness, and the sound reduction index (R_w) adopted in the acoustic simulations performed in the Acoubat software (Cype Ingenieros S.A., 2024).

The thick external solid brick walls (60 cm and 50 cm) substantially enhance the overall airborne sound insulation of the enclosure. However, the presence of large window openings significantly reduces this benefit, compromising the global sound reduction performance. Figure 4a presents the geometric model developed in IFC Builder, whereas Figure 4b illustrates the corresponding acoustic model implemented in Acoubat. In both representations, the rehearsal room is highlighted in orange, and the room located directly below it — a library — is indicated in yellow.

Because the facades and window frames are protected by heritage regulations, new internal gypsum board walls were proposed to close the existing openings without altering the building's external appearance. These walls consist of two gypsum boards, a 90 mm metal stud frame filled with 64 kg/m³ rock wool, and two additional gypsum boards, with silicone sealing applied to the existing windows. Doors with R_w 50 dB sound insulation were also specified. For the ceiling, a 10 cm layer of 64 kg/m³ rock wool was proposed, and for the roof, a false ceiling incorporating 10 cm of rock wool beneath the tiles was added.

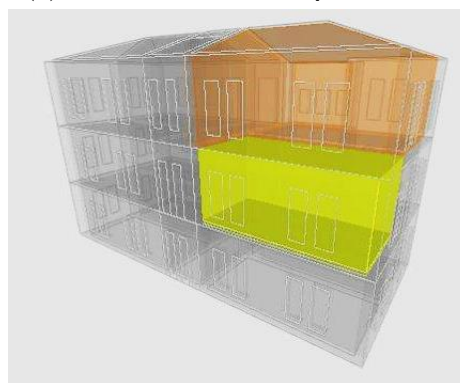
Table 5 - Building elements used in the acoustic insulation simulations in the Acoubat software, constituent materials, element thickness, and R_w values

Condition	Construction element	Material	Thickness (cm)	R_w (dB)
Actual condition	External wall 01	Solid brick	60	73
	External wall 02	Solid brick	50	70
	Internal wall 01	Solid brick	22	54
	Plasterboard wall	Two plasterboard sheets, 90 mm metal stud with 30 kg/m ³ rock wool, two plasterboard sheets	14	56
	Slab	Solid concrete	20	57
	Door	Wood	4	23
	Window	Wood and 4 mm glass	5	22
	Existing roof	Ceramic tiles	11	12
	Existing ceiling	One plasterboard sheet	1.25	5 (Δ)
Acoustic design	Acoustic door	Wood	10	50
	Roof with ceiling and insulation	Ceramic tiles with one plasterboard sheet and 30 kg/m ³ rock wool, 10 cm thick	22.25	43
	Ceiling with insulation	One plasterboard sheet and 30 kg/m ³ rock wool, 10 cm thick	11.25	12 (Δ)

Figure 4 - (a) Geometric model created in IFC Builder; and (b) acoustic model developed in Acoubat



(a)



(b)

4 Results

In this section the main and detailed results for each methodological step are presented.

4.1 Background noise levels

The background noise levels, measured using the A-weighted equivalent continuous sound pressure level index ($L_{Aeq,5min}$), showed 61 dB and 64 dB for the open-window condition, and 53 dB and 47 dB for the closed-window condition. All measured values were substantially higher than the reference sound pressure level (RL_{Aeq}) of 35 dB recommended for music education rooms. The noise levels observed are primarily attributed to traffic flow along República do Paraguai Avenue, Mem de Sá Avenue, and Teixeira de Freitas Street, which constitute major urban corridors with intense circulation of buses and heavy vehicles connecting the city center to the southern zone of Rio de Janeiro.

4.2 Reverberation time comparisons

The comparison between measured and simulated reverberation time for the actual room is presented in Figures 5 and 6. As there are several combinations of source-receivers, only some representative examples are shown in this work. Figure 5 shows the RT at closed windows configuration for two receivers (R2 and R5). Figure 6 shows two examples of RT for the open windows for receivers R1 and R2. These figures show the

agreement between simulated and measured values, with larger deviations observed at 125 Hz. This behavior is commonly reported in ray tracing based acoustic simulation software, as energy-based methods do not account for wave interference effects (Torres, 2018, 2022). For frequencies between 250 Hz and 4 kHz, the simulated T_{30} values were, in most cases, within $\pm 5\%$ of the just noticeable difference (JND), indicated by the dashed lines, relative to the measured reverberation time, as described in NBR ISO 3382-1 (ABNT, 2017). The measurement uncertainty remained within $\pm 10\%$ deviation, in accordance with NBR ISO 3382-1 (ABNT, 2017) at mid and high frequencies. At lower frequency bands the uncertainty was higher than for mid and high frequencies, particularly under the open-window condition. On this basis, the room model representing the existing conditions was considered valid.

The measured reverberation times for the room in its current state, at the frequency of 500 Hz, were 2.5 s and 1.8 s, for closed and opened windows, respectively. Figure 7 shows the graph of the recommended reverberation time, according to room volume and use. According to NBR 12179 (ABNT, 1992), the RT for a music studio of approximately 600 m³ should be 0.9 s. The red and green dashed lines indicate, respectively, the actual (opened and closed windows) and the ideal RT for the rehearsal room.

The existing reverberation time (RT) substantially exceeds the target values, thereby confirming the necessity of implementing an acoustic treatment project to reduce this parameter to appropriate levels.

Table 6 summarizes the recommended RT values (in seconds) for this music room at different frequency bands, according to Brandão (2016), Carvalho (2010), and Costa (2003). All three authors recommend higher RT values at low frequencies to preserve adequate bass support. Costa (2003) offers the highest values in this range, namely 1.80 s at 125 Hz and 1.26 s at 250 Hz.

Figure 5 - Reverberation time comparison between measured and simulated for closed windows; Receivers (a) R2 and (b) R5

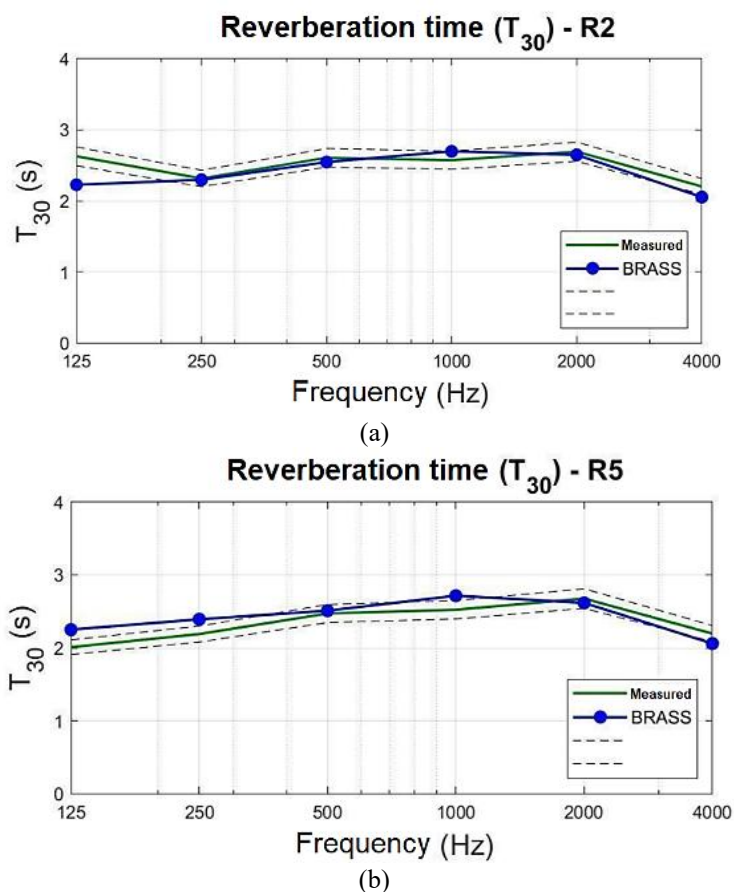


Figure 6 - Reverberation time comparison between measured and simulated for open windows; Receivers (a) R1 and (b) R2

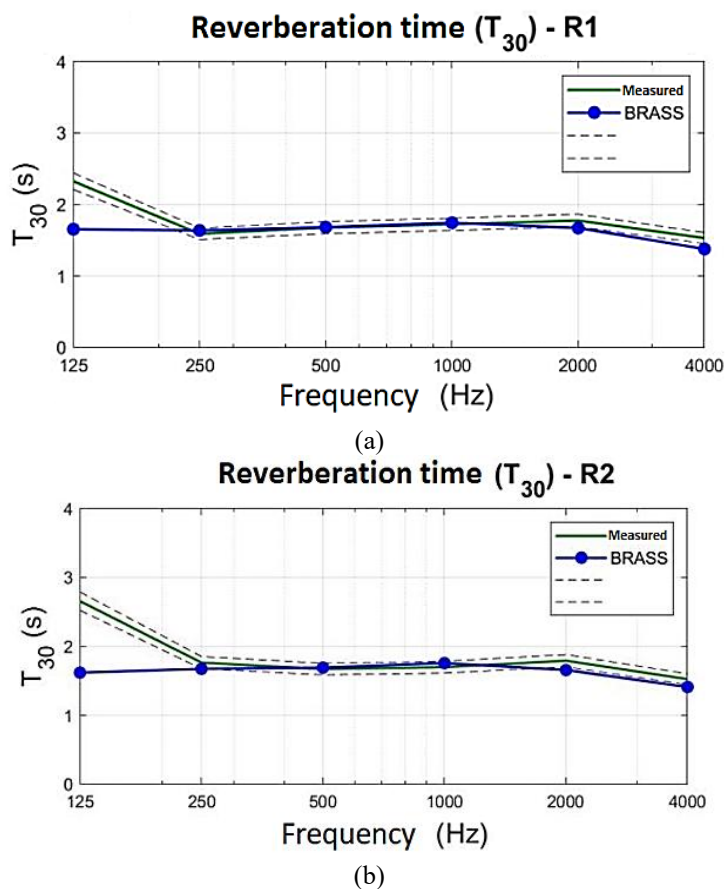
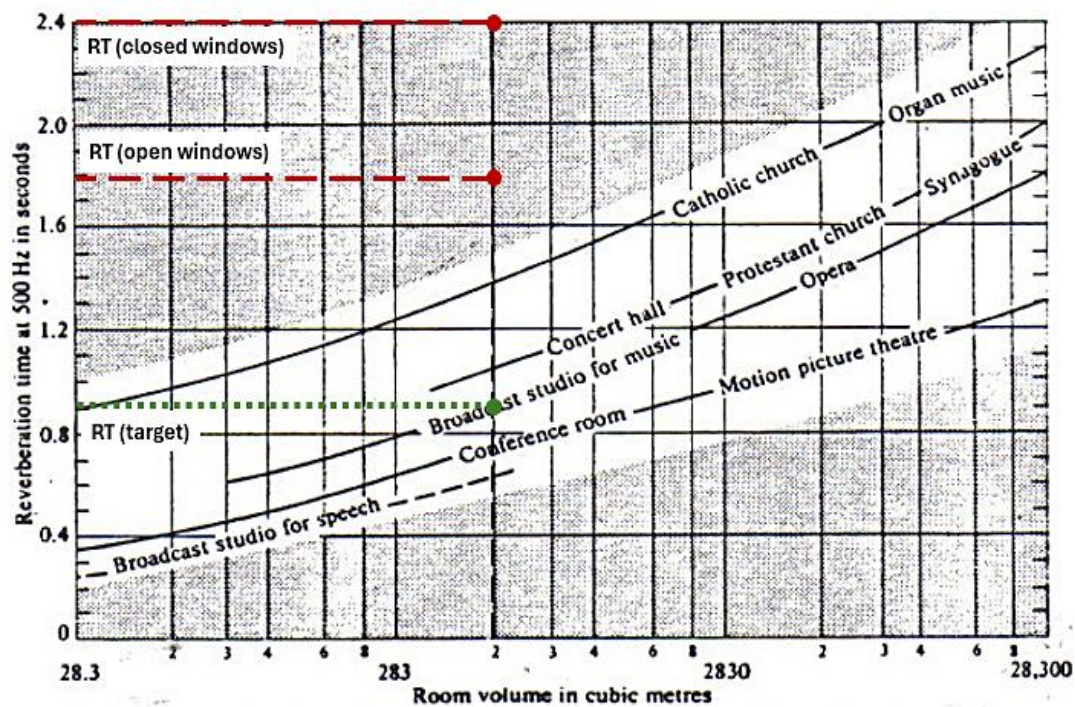


Figure 7 - Actual and ideal reverberation times at 500 Hz



Source: adapted from Beranek (1962).

Table 6 - Ideal reverberation times according to different authors

Author	RT 125Hz (s)	RT 250Hz (s)	RT 500Hz (s)	RT 1kHz (s)	RT 2kHz (s)	RT 4kHz (s)
Brandão (2016)	1.17	1.04	0.90	0.86	0.86	0.86
Carvalho (2010)	1.32	1.05	0.90	0.90	0.90	0.90
Costa (2003)	1.80	1.26	0.90	0.99	1.08	1.35

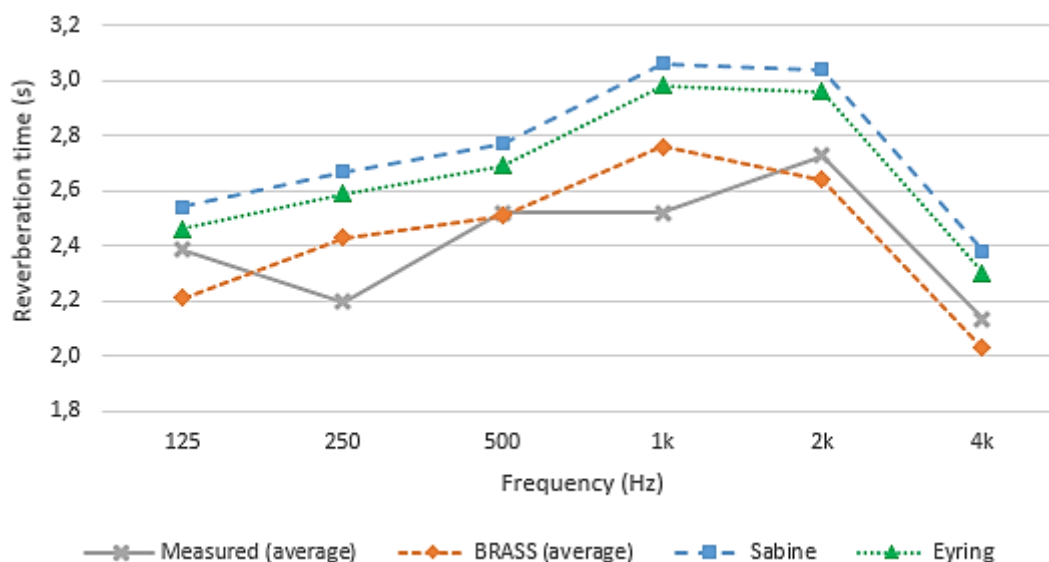
At higher frequencies, the recommendations diverge. Carvalho (2010) suggests maintaining the same RT value adopted at 500 Hz across the higher bands. Brandão (2016) recommends a reduction to approximately 0.86 s between 1 kHz and 4 kHz. In contrast, Costa (2003) proposes increasing RT at high frequencies, with values of 0.99 s at 1 kHz, 1.08 s at 2 kHz, and 1.35 s at 4 kHz.

The reverberation time values proposed by Brandão (2016) were adopted as the reference criteria for the present study, as they define a balanced and frequency-controlled target curve specifically suited to music rehearsal spaces. Unlike recommendations primarily developed for large concert halls, Brandão's criteria reflect acoustic conditions more consistent with medium-sized rooms intended for ensemble practice, where clarity, articulation, and effective mutual hearing among musicians are critical.

The proposed RT curve provides moderate low-frequency support while maintaining relatively stable values from 500 Hz to 4 kHz, thereby avoiding excessive high-frequency reverberation that could impair definition and temporal precision. This frequency distribution is consistent with contemporary acoustic design principles for rehearsal rooms, in which controlled reverberation enhances ensemble blend without compromising clarity. Accordingly, Brandão's criteria were considered technically appropriate and acoustically coherent with the functional objectives of the orchestral rehearsal room analyzed in this study.

Figure 8 presents a comparison between the computational simulation and the traditional reverberation time calculation methods (Sabine and Eyring). The graph includes the RT from the average of the measurements, the calculated ones using Sabine and Eyring methods and the average RT obtained from the BRASS simulations, considering the room with the windows closed.

Figure 8 - Reverberation time of the room in its existing condition: average of measurements, Sabine and Eyring calculation, and average of BRASS simulations



In general, all curves exhibit higher values at 1 kHz and 2 kHz and lower values at 125 Hz and 4 kHz. The curve derived from the computational simulations showed the closest agreement with the measured values, even though the same material absorption coefficients were adopted in the Sabine and Eyring calculations. This result indicates greater reliability of the BRASS simulator in representing the actual acoustic behavior of the room.

4.3 Acoustic treatment proposal

Considering that the ideal RT values were defined, the following materials were specified for the room acoustical conditioning: a 5 mm carpet applied to selected wall surfaces and sixteen perforated and grooved acoustic panels, each measuring 1.35 m × 1.35 m, backed with 50 mm thick rock wool (32 kg/m³) and suspended from the ceiling. These materials were selected by availability and according to their absorption coefficient, aiming to achieve the ideal RT values, described in Table 7.

To improve window sealing and reduce external noise transmission, double-layer gypsum board walls were proposed, installed with a 5° inclination relative to the existing walls to avoid parallel surfaces. This geometric modification contributes to a more uniform spatial distribution of sound energy and mitigates the formation of strong axial modes and flutter echoes.

The proposed configuration was simulated using the same computational parameters adopted for the untreated model — including the number of rays and termination criteria — differing only in the inclusion of the new surfaces and their respective frequency-dependent absorption coefficients. Table 7 presents the sound absorption coefficients of the materials specified in the proposed design.

Table 7 - Sound absorption coefficients (α) of the materials used in the proposed design

Material	Location	Reference	Sound absorption coefficient α by frequency band					
			125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
5 mm carpet	Walls	NBR 12179 (ABNT, 1992)	0.04	0.04	0.15	0.29	0.52	0.59
Double gypsum board, 48 mm stud with mineral wool	New walls	Acoustic Project Bureau (2025)	0.15	0.10	0.06	0.04	0.04	0.05
Ambi Brasil 16.1 panels	Ceiling	Ambi Brasil (2025)	0.65	0.95	0.99	1.00	0.78	0.74

Figure 9a illustrates the room floor plan, indicating the sound source positions (FA and FB) and the receiver locations (R1 to R10) employed in the BRASS simulations. Figure 9b shows the three-dimensional model developed in SketchUp (Trimble Inc., 2021), incorporating the proposed acoustic interventions.

In the simulations, three occupancy scenarios were considered:

- (a) quintet with piano, totaling six musicians;
- (b) small orchestra with 36 musicians, piano, and conductor, totaling 38 occupants; and
- (c) full orchestra with 63 musicians, piano, and conductor, totaling 65 occupants.

These configurations were defined in consultation with the musicians, as they represent typical ensemble arrangements encountered in both classical and popular music contexts.

Figures 10 and 11 present the results of the simulated reverberation time (RT) at receivers 1, 5, 6, and 8. Figure 10 shows results with the sound source located at position FA, and Figure 11 with the source at position FB. These four receiver positions were chosen for being well distributed throughout the room, thus representing a more homogeneous simulation scenario.

In Figures 10 and 11, a decrease in reverberation time from low to high frequencies can be observed, which is advantageous for musical performance according to the recommended values presented in Table 6. In addition, the RT values are close to those proposed by Brandão (2016), with variations depending on the room occupancy, due to the sound absorption effect of the human body.

Figure 9 - Proposed acoustic adaptations: (a) Floor plan, showing the sound sources and receivers used in the simulations and (b) three-dimensional model

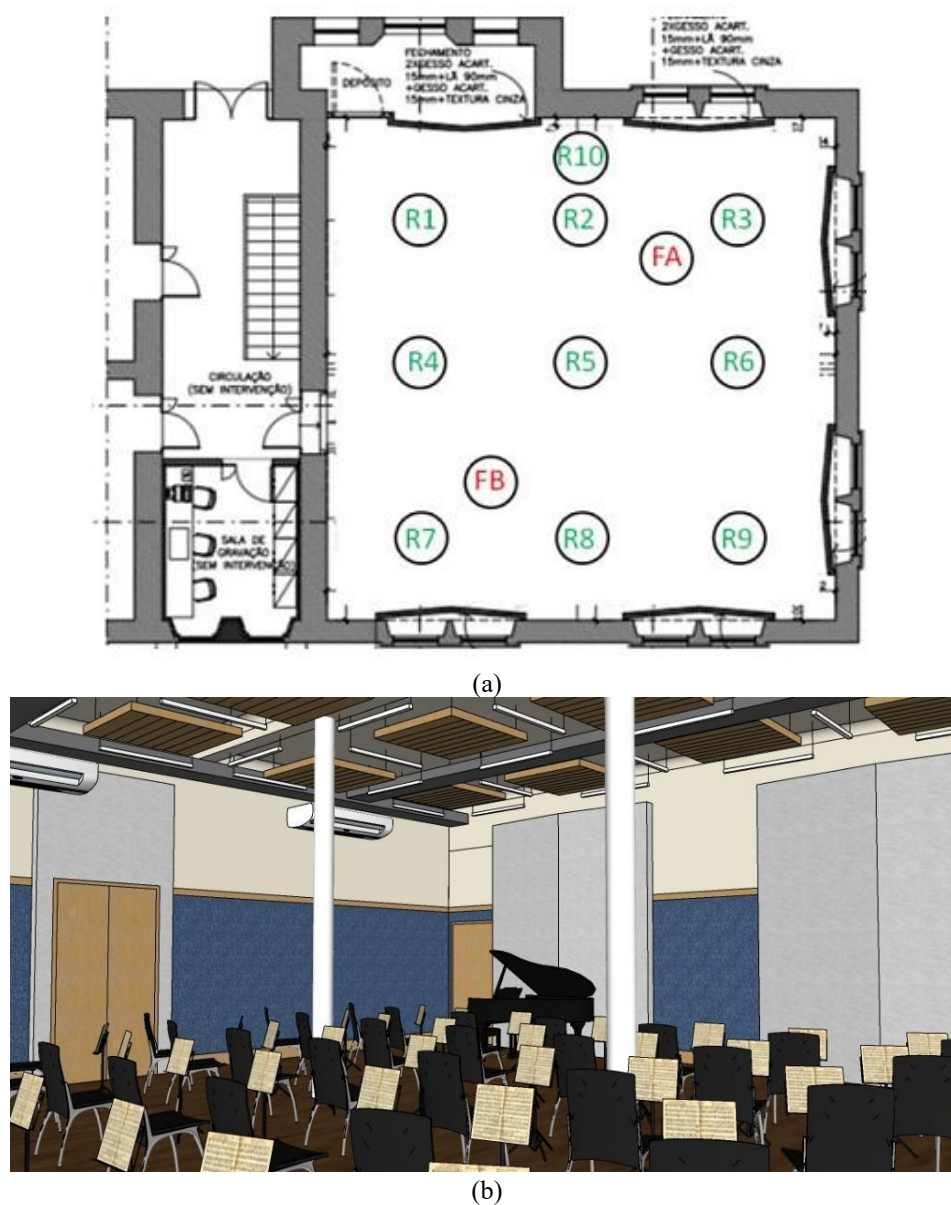


Figure 10 - Results of the simulated RT at receivers 1 (a), 5 (b), 6 (c), and 8 (d) for the three scenarios, with the sound source at position FA

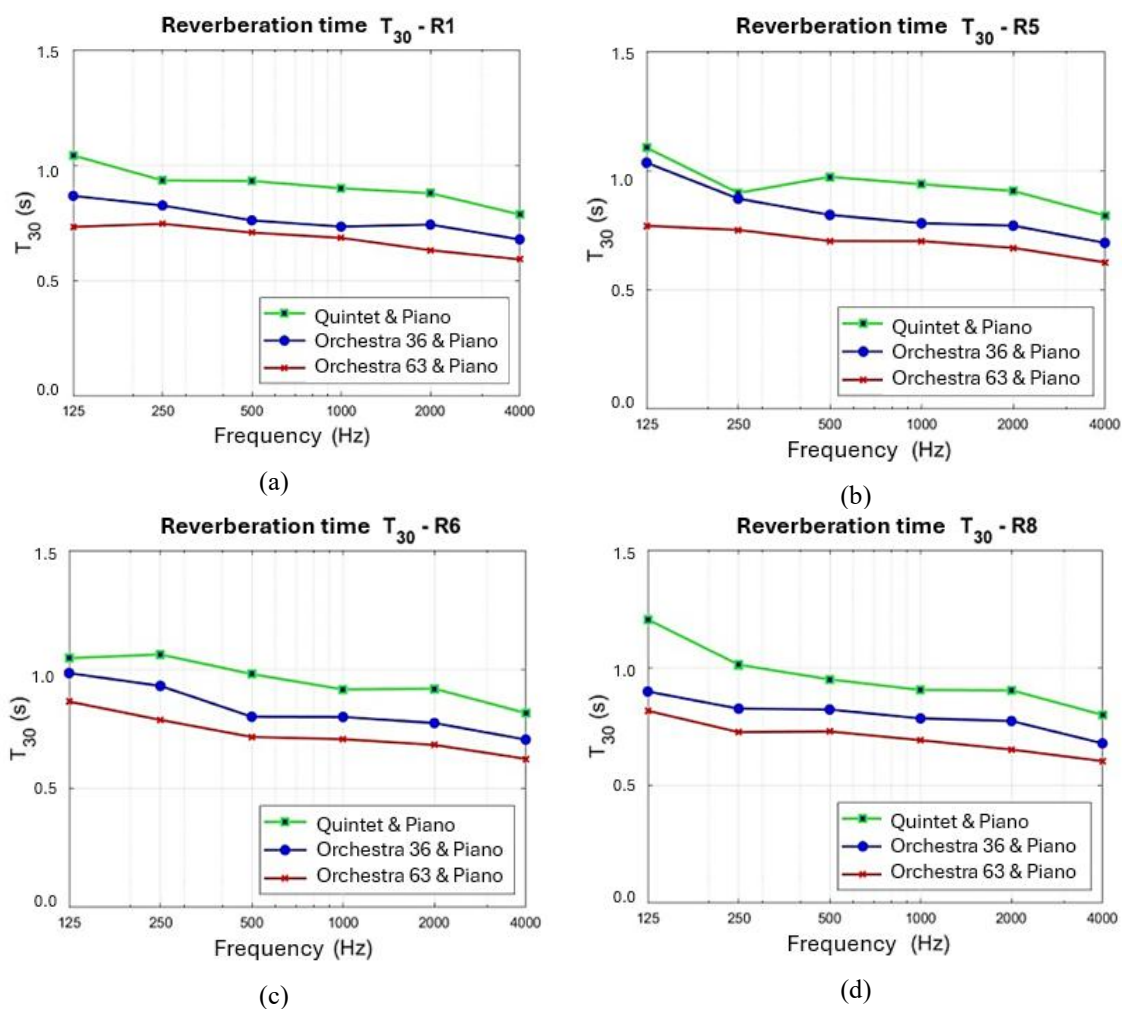
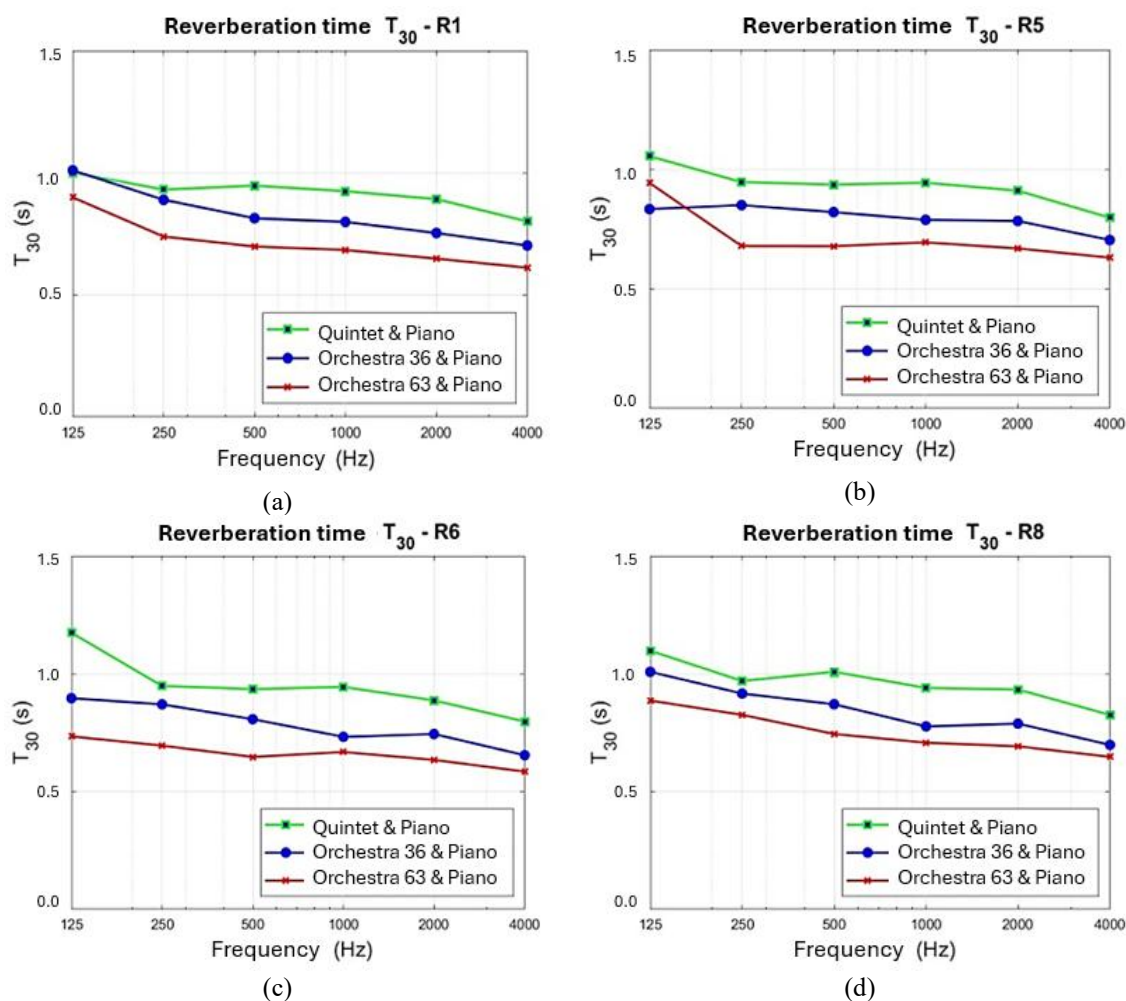


Figure 11 - Results of the simulated reverberation time (RT) at receivers 1 (a), 5 (b), 6 (c), and 8 (d) for the three scenarios, with the sound source at position FB

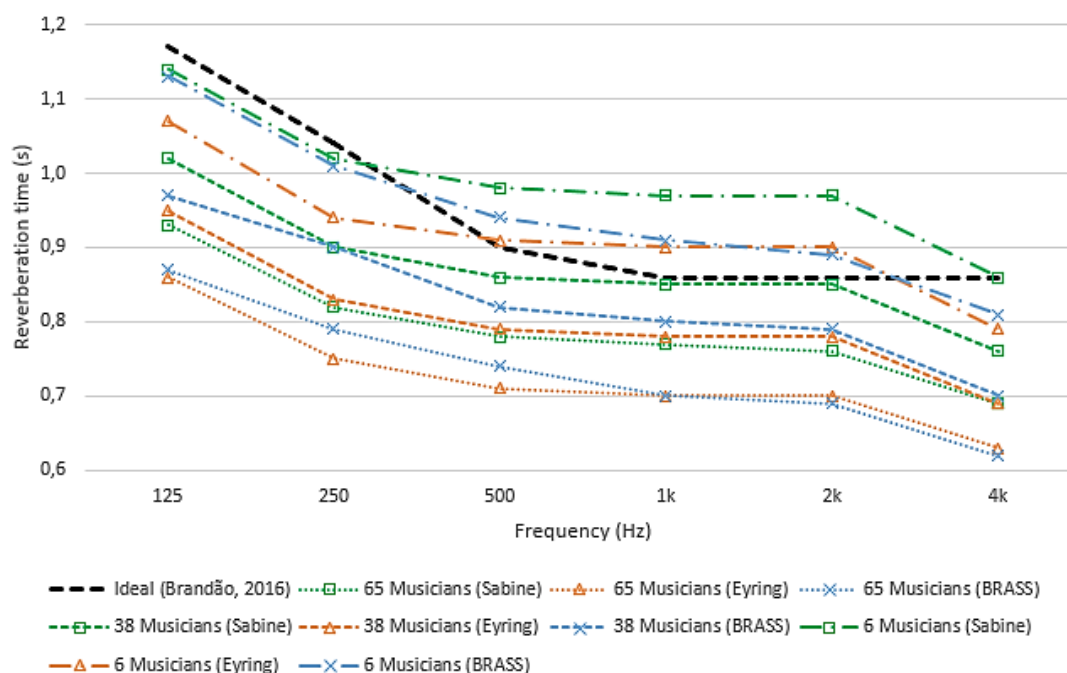


It is observed that RT decreases as room occupancy increases, ranging from 1.1 s at low frequencies and 0.85 s at high frequencies for the quintet with piano, to 0.8 s and 0.65 s, respectively, for the full orchestra. These results demonstrate the significant influence of the number of musicians on sound absorption, bringing the average RT values closer to normative recommendations for rehearsal and concert rooms. Thus, the observed behavior confirms the acoustic adequacy of the environment for different musical configurations, combining reverberation control and auditory comfort.

The RT values calculated using the Sabine and Eyring methods were compared with the ideal values recommended by NBR 12179 (ABNT, 1992) and Brandão (2016). Figure 12 presents the RT values calculated by these methods for the three occupancy scenarios in the proposed intervention, compared to the average results obtained from the BRASS simulations.

The comparative analysis of the reverberation times obtained using the Sabine, Eyring, and BRASS methods — considering room occupancies of 6, 38, and 65 musicians — demonstrates the significant influence of room occupancy and calculation methodology on the acoustic performance of the environment. In all proposed scenarios, there was a notable reduction in reverberation times compared to those of the existing room conditions.

Figure 12 - Ideal reverberation time, Sabine, Eyring, and BRASS results



All curves exhibit higher RT values at low frequencies and lower values at high frequencies, which is typical of music performance rooms, where low frequencies are emphasized due to the reduced auditory sensitivity of the human ear in this range. Overall, the BRASS simulation results for the three configurations were intermediate between the Sabine and Eyring calculations, with Sabine producing slightly higher RTs and Eyring slightly lower ones. It was also observed that at low frequencies (125 and 250 Hz), the BRASS simulations more closely matched the Sabine results, while at higher frequencies (1 k, 2 k, and 4 kHz) they showed greater agreement with Eyring's predictions. These findings reinforce the validity of simulation-based methods as complementary tools to classical analytical approaches in predicting the acoustic performance of rehearsal rooms.

The occupancy with six musicians produced an RT curve closest to the ideal one proposed by Brandão (2016), with the BRASS simulations yielding results more consistent with the recommended values than those obtained by Sabine or Eyring. In this configuration, the Sabine method approximated the ideal curve at low and high frequencies but diverged at mid frequencies, whereas the Eyring method aligned better at mid and high frequencies and diverged at low ones.

For the configuration with 38 musicians, the Sabine RT curve approached the ideal curve more closely at mid and high frequencies (500 Hz to 4 kHz), while the Eyring and BRASS curves deviated further from it. The fact that the fully occupied room exhibited RT values below 0.9 s at mid and high frequencies should not be considered problematic, given that the sound pressure level produced by a full orchestra is very high (often exceeding 100 dB) for a room of this size. Furthermore, according to Rindel (2014) and Basso (2024), for rehearsal rooms, the reverberation time should be slightly shorter than that of performance halls of similar size.

The simulation results obtained with BRASS for the 600 m³ rehearsal room show a consistent reduction in reverberation time (RT) with increasing occupancy, reflecting the expected contribution of audience absorption. For 6 occupants, the RT ranges from 1.1 s to 0.8 s; for 37 occupants, from 0.9 s to 0.75 s; and for 64 occupants, from 0.8 s to 0.65 s. When compared with the criteria presented in Table 1 (adapted from Rindel (2014)), these values fall within or close to the recommended range for small ensembles such as a string quartet (0.4–1.1 s), particularly under lower occupancy conditions. For medium-size ensembles, such as a male choir, the simulated RT values are slightly below the suggested range (1.0–1.7 s), indicating a somewhat drier acoustic environment. Considering the relatively moderate room volume (600 m³) compared to the larger volumes recommended for brass quintets and concert bands, the simulated results are coherent with the intended scale of the space and suggest acoustic conditions suitable for rehearsal activities, especially for small to medium-sized groups, with increased clarity and definition as occupancy rises.

Although the differences between the Sabine, Eyring, and BRASS results were small, the BRASS simulations tended to yield slightly lower values than Sabine's, indicating greater consistency with a diffuse-field model and accounting for multiple absorption losses. As the number of musicians decreased, the RT increased slightly, reflecting the reduced absorption caused by occupancy, yet it remained within an acceptable range for satisfactory acoustic performance.

These results demonstrate good agreement between the empirical methods and the simulation model, validating the use of the BRASS software as a reliable tool for estimating reverberation time in music environments with varying occupancy levels.

4.4 Acoustic insulation

According to the methodology described previously, the geometric model was updated in IFC Builder (Cype Ingenieros S.A., 2026) to incorporate the adopted architectural and acoustic design premises. The revised model was then exported to CYPE Acoubat (Cype Ingenieros S.A., 2024), where the acoustic insulation properties of the proposed materials were assigned based on data from the CSTB database (CSTB, 2024), manufacturers' technical catalogues, or simulations performed using Insul Acoustics (Marshall Day Acoustics, 2023).

Table 8 summarizes the results obtained for sound insulation (weighted standardized level difference – $D_{nT,w}$ – or weighted standardized level difference at 2 meters – $D_{2m,nT,w}$ – in dB) and A-weighted equivalent continuous sound level (L_{Aeq} , in dB) calculated for the rooms and facades adjacent to the rehearsal room, both in the existing condition and after implementation of the acoustic project. The table presents: a) the room or facade adjacent to the rehearsal room; b) simulated sound insulation ($D_{nT,w}$ in dB) in the existing condition; c) simulated sound insulation ($D_{nT,w}$ in dB) with the proposed design; d) calculated equivalent sound level (L_{Aeq} in dB) for the adjacent room/facade originating from the rehearsal room in the existing condition; e) calculated equivalent sound level (L_{Aeq} in dB) for the same, after the acoustic project; f) measured background noise level (L_{Aeq} in dB); and g) the normative limit values (RL_{Aeq}) established by NBR 10151 (ABNT, 2020a) for external environments and NBR 10152 (ABNT, 2020b) for indoor environments, both for the daytime period (7 a.m.–10 p.m.). The calculations of sound levels were based on the A-weighted equivalent continuous sound pressure levels (L_{Aeq}) of a brass section of an orchestra (Rodrigues *et al.*, 2014) and the simulated $D_{nT,w}$ values. In the existing condition, the sound insulation between the rehearsal room and adjacent facades was insufficient, with $D_{nT,w}$ values between 36 and 39 dB and calculated external sound levels above 60 dB, exceeding the limits set by both standards for the daytime period.

With the proposed design, the simulated $D_{nT,w}$ values increase significantly. The facades facing Lapa, the Leopoldo Miguez Hall, and ESDI fully comply with NBR 10151 (ABNT, 2020a), showing calculated external noise levels L_{Aeq} of 40 dB, below the 50 dB limit, and even lower than the measured background noise levels (61 and 64 dB). The only exception is the roof, which, despite achieving $D_{2m,nT,w} = 52$ dB, still presents a calculated external level L_{Aeq} of 58 dB, above the standard limit. However, this result is acceptable, as the noise from the rehearsal room remains below the background noise level, therefore causing no perceptible impact on the outdoor environment.

Table 8 - Results of sound insulation between adjacent rooms/facades and corresponding sound levels

Adjacent Room / Facade	$D_{nT,w} / D_{2m,nT,w}$ Existing (dB)	$D_{nT,w} / D_{2m,nT,w}$ Project (dB)	Sound Level Existing L_{Aeq} (dB)	Sound Level Project L_{Aeq} (dB)	Background Noise Level L_{Aeq} (dB)	Reference Limit RL_{Aeq} (dB)
Lapa Facade	36	64	63	40	60.9 / 63.7	50 *
Leopoldo Miguez Hall Facade	36	64	63	40	60.9 / 63.7	50 *
ESDI Facade	39	64	60	40	60.9 / 63.7	50 *
Roof	27	52	70	58	60.9 / 63.7	50 *
Lower Library	65	–	39	–	–	40 **
Music Classroom	–	77	–	23	–	35 **
Circulation Area	–	64	–	38	–	50 **

Note: *according to NBR 10151 (ABNT, 2020a) - outdoor environments, daytime period (7 a.m.-10 p.m.). **according to NBR 10152 (ABNT, 2020b) - indoor environments, daytime period (7 a.m.-10 p.m.).

In adjacent indoor rooms – such as the library below, classroom, and circulation areas – the projected levels also comply with NBR 10152 (ABNT, 2020b), ensuring acoustic comfort and functional compatibility between uses. In particular, the music classroom adjacent to the rehearsal room achieved $D_{nT,w} = 77$ dB, and an internal sound level L_{Aeq} of 23 dB, well below the normative limit RL_{Aeq} of 35 dB, thus providing highly effective sound insulation, essential to avoid interference between simultaneous activities. In summary, the analysis demonstrates that the proposed project yields substantial improvements in sound insulation and noise control, ensuring compliance with Brazilian standards and providing adequate acoustic protection for both the urban surroundings and the building's internal spaces.

5 Conclusions

This paper presented an acoustic assessment of the OSUFRJ orchestral rehearsal room in its original condition, revealing inadequate acoustic performance for musical activities. The measured results indicated insufficient airborne sound insulation between adjacent spaces, elevated background noise levels, and reverberation times exceeding the values recommended by standards and specialized literature for orchestral rehearsal rooms. These deficiencies negatively affected musical intelligibility, auditory comfort, and ensemble precision during rehearsals.

Acoustic simulation models were developed to evaluate both room acoustics and sound insulation performance. BRASS software was employed to assess the reverberation characteristics of space and to predict the effects of architectural and acoustic interventions on parameters such as reverberation time. In parallel, the CYPE Acoubat software was used to estimate airborne sound insulation indices, allowing a systematic evaluation of the transmission paths between rooms. The combination of in situ measurements and predictive modeling proved to be an efficient and reliable approach to support design decisions.

Based on the calibrated models, architectural and acoustic solutions compatible with the preservation constraints of the historic building were proposed. The simulation results indicated a significant reduction in reverberation time and a substantial improvement in airborne sound insulation indices, bringing the rehearsal room into compliance with the acoustic criteria recommended for orchestral use. The study highlights the importance of integrating measurements with complementary simulation tools addressing both room acoustics and building acoustics, particularly in heritage contexts where intervention options are limited. Therefore, the case analyzed may serve as a reference for future acoustic retrofit projects in historic buildings intended for musical practice.

Future work may include post-intervention acoustic measurements to validate the predicted improvements in reverberation time, background noise levels, and airborne sound insulation, enabling a direct comparison between simulated and measured results and further calibration of the acoustic models. Additional studies could focus on low-frequency behavior and flanking transmission paths, which are not fully captured by geometrical acoustics simulations, as well as on the evaluation of alternative construction assemblies and materials. The analysis may also be extended to other acoustic quality parameters relevant to orchestral rehearsal spaces and complemented by subjective assessments involving musicians. Finally, the proposed methodology could be applied to other rehearsal rooms and heritage buildings, contributing to the development of guidelines for acoustic retrofitting under preservation constraints.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare no conflicts of interest.

Authors' Contribution

Guilherme Fagerlande: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Julio C. B. Torres**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Writing - original draft, Writing - review & editing. **Maria L. A. de Niemeyer**: Conceptualization, Funding acquisition, Investigation, Methodology, Supervision.

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