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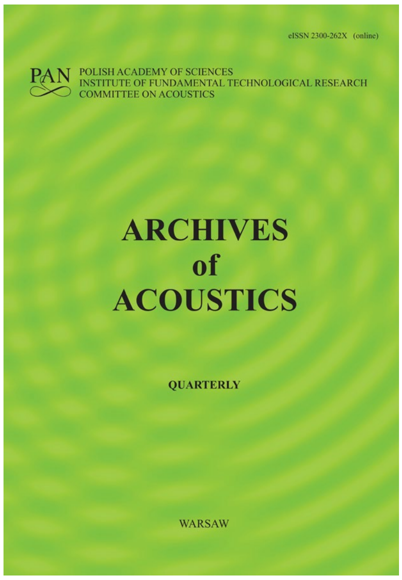

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Acoustical design of the multifunctional auditorium in Cultural Center at Podkarpacie

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Abstract

The article presents a room acoustics study conducted for a multi-purpose hall, which is currently in the design phase. The hall is part of the Cultural Center building, which will be constructed in Zagórz, a small town located in the southern part of Poland in the Podkarpacie region. The architectural design was developed by Studio Święciński Architekci, based in Krosno. The results of the acoustic prediction for the hall were obtained using the open-source software I-SIMPA. To perform the acoustic study, the multi-purpose hall was geometrically modeled as a 3D shape in acoustical scale; sound absorption and scattering coefficients for the internal surfaces were then assigned along with the sound source and receivers in the audience area. Several acoustic parameters ($T_{\_Sabine}$, $T_{\_Eyring}$, T_{30}, EDT, C_{80}, D_{50}, G, STI) were calculated in pre and post-treatment conditions, to simulate the acoustic efficiency of the conference hall in accordance with its future use.

Keywords: room acoustics, multi-functional hall, acoustical prediction, variable acoustics, I-Simpa

Acronyms: TCR - Classic Theory of Reverberation Time (*Théorie Classique de la*

Réverbération); SPPS - Sound Particles Propagation Prediction (*Simulation de la Propagation de Particules Sonores*); *STI* - Speech Transmission Index; T_{30} - Reverberation Time evaluated over a 30 dB decay range (from -5 to -35); *EDT* - Early Decay Time; D_{50} – Definition (at 50 ms); C_{80} – Clarity (at 80 ms); PN-B-02151-4:2015-06(PKN, 2015)- Polish standard for building acoustics (Acoustic comfort in school classrooms); IEC 60268-16 (IEC, 2020): International standard for the objective rating of speech intelligibility by the Speech Transmission Index

1. Introduction

The architectural project of a multi-purpose hall involves resolving numerous functional and aesthetic requirements. From an acoustic point of view it implies creating a comfortable environment which can meet different expectations within the audience. It's a frequent task in fact that different kind of sound messages are received, typically related to both speech and music. In these cases it is important to consider the possibility of varying the sound field conditions to improve the room's acoustics characteristics and/or avoid the necessity of correcting architectural mistakes related to unsatisfactory audience experience. However, subjective auditory impressions can vary significantly depending on a listener's position within a space, as well as between individual listeners (Weinzierl *et al*., 2018). To address these variations in human perception, some objective and quantifiable acoustic parameters have been developed. These indicators aim to support architects and acoustic consultants in designing spaces that meet specific functional and perceptual criteria (Cox *et al*., 1993; Bradley, 2011; Vorlander, 2013). The use of such parameters enables a systematic assessment of room acoustic quality; consequently, some of them will be used to evaluate the acoustical comfort of the multi-purpose hall considered in this paper. The hall is currently in the preliminary design phase; its internal acoustics was studied by means of computer-aided acoustic simulation, based on the architectural project. Virtual acoustics modeling, prediction and auralization, are topics of great interest among architects and designers who works on public halls for speech or music (Rindel, 1995; Polack *et al.*,1993). Since several software packages have become more accurate, user-friendly and more cost-effective than techniques based on physical scale models, these simulations allow for obtaining a preliminary acoustics estimation of a closed environment while still in the project phase. These tools allow for the evaluation of possible geometrical improvements, also in the form of acoustic flexibility, just to accommodate different types of events. Furthermore, even in the case of lost and destroyed contexts, virtual acoustic modeling can be useful to estimate the acoustic behavior of a room that no longer exists. Therefore, even if "it's not possible to describe precisely with a mathematical approach the complexity of acoustical behavior of a closed environment" (Ianniello, 2001), current room acoustics simulations are able to provide designers with fundamental indications that are non-negligible. The simplifying assumptions and limitations inherent in acoustic simulations can be generally accepted, provided it is understood that the primary acoustic goals of a room can be clarified in advance without significant errors. As it is well known among acousticians, the acoustic prediction begins with several preliminary settings, which are briefly summarized below.

1) 3D modeling: this stage is used to estimate the room volume and the total area of its internal surfaces. During this step, all boundaries and internal elements (coverings, seats, furniture, reflectors, etc.) are geometrically modeled to represent the surfaces hit by the sound waves.

2) Assignment of sound absorption and scattering properties to internal surfaces: Although this step could seem straightforward, it is often a source of significant errors in acoustics calculation as well as uncertainty in the final results (Peters, 2020).

3) Setting of sound source, as well as discrete and area receivers. This involves defining the characteristics and positions of the sound sources, along with establishing both individual receiver points and larger reception surfaces (grids) to map the sound field.

4) Calculation of objective acoustical parameters, used as *indicators* to qualify the internal perception of the room.

Various commercial room-acoustics software packages are currently available, primarily based on classical reverberation theory and ray tracing technique (Krokstad *et al*., 1968; Vorländer, 1989). In order to carry out the prediction of the main acoustic parameters within the conference hall, the open-source software I-SIMPA was used. The *STI* prediction was implemented as an Excel calculation based on the technical standard IEC 60268-16 (IEC, 2020). The aim of this study is to simulate the acoustic conditions of the multi-purpose hall located in the Cultural Center building in Zagórz, with a focus on evaluating the effectiveness of the proposed flexible acoustical treatment. Particular attention was paid to assessing its influence on perceptual attributes related to auditory comfort and satisfaction. This study is a first step in assessing acoustic comfort to identify and propose corrections for possible design defects. These findings are of particular relevance, since the architectural concept under evaluation is planned to be replicated in other locations.

The content is organized as follows. A brief description of the space's architecture under study is provided in section 2; the results of the acoustic prediction before the implementation of flexible treatments are presented in section 3; a description of the proposed flexible acoustic treatment, as well as an analysis of its efficiency, is detailed in section 4; concluding remarks are presented in section 5.

2. Conference hall architecture

The acoustics prediction presented here refers to the a multi-functional conference hall included in the project for the new Public Library. The building will be constructed in Zagórz, a little town located in the Podkarpackie Voivodeship of Poland. The architectural project was developed by Świecinski Architects based in Krosno. The main features of the room's shape are illustrated in Fig.1.

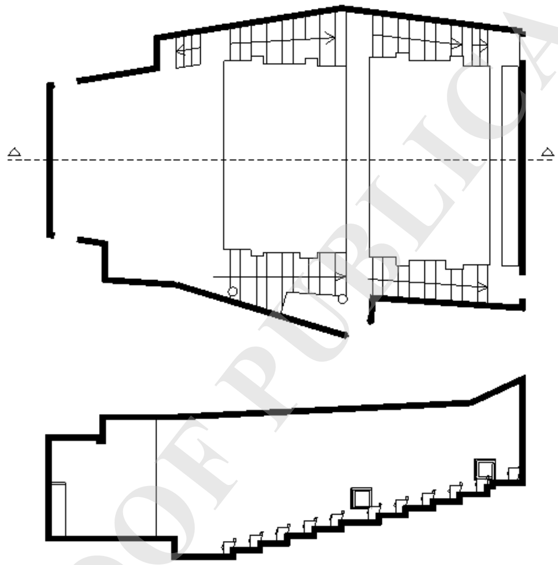


Fig. 1. Plan and longitudinal section of multifunctional conference hall

The hall is situated at the first floor of the entire building. Its volume measures approximately 740 m^3, the total hall's length of roughly 18.0 m. The width varies from 5.7 m at the stage to 12.4 m at the rear wall, while the height ranges from 3.5 m (rear) to 5.3 m (stage). The hall accommodates 175 seats, resulting in a volume-to-seat ratio of approximately 4.3 m^3/seat. From an architectural perspective, the floor plan forms an *asymmetric hexagonal diamond* shape, created by the overlap of two opposing *fan-shape* figures. The audience area covers a surface of ≈ 75 m^2, distributed continuously the two lateral walls. The seating is divided into two sectors, consisting of five main rows plus an additional row near the rear wall. Rows are spaced 1.0 m apart, with the number of chairs per row varying from 14 to 16. The audience area is sloped at approximately 16° relative to the lowest floor level near the stage, reaching an elevation of +2.64 m at the rear wall. In the floor plan, the lateral walls are not perpendicular to the seating rows. Following the diamond geometry, the left wall opens at the angle of ≈ 8° up to the central aisle. The right wall is roughly symmetrical in its first section, while its second section maintains the same orientation but with a shallower inclination. The stage area, measuring ≈ 35 m^2, is elevated 0.7 m above the lowest aisle level and is defined by asymmetric boundaries and a segmented front walls. The ceiling consists of a single inclined flat surface that meets the lateral walls at varying heights.

From an acoustical point of view, the architectural shape of the hall represents a geometric variation of a basic rectangular plan (Appleton, 2008). This kind of shape generally facilitates the perception of lateral sound reflections across the audience area; in this case the condition is further enhanced by the steep slope of the seating, an architectural feature that minimizes the grazing incidence (sound absorption effect) among the seats. At a first glance, the architectural design suggests favorable acoustic suitability for both speech (conference, lecture, etc.) or live music (chamber ensemble, choir, etc.). Given the limited room volume, relative to the large audience surface, it's expected a mean reverberation time (T_{60}) between 0.8 s and 1.4 s (Kosten, 1965). However, the multi-functional nature of the space - requiring high quality for both speech and music - suggests the need for variable acoustics. This would allow for the calibration of the sound field characteristics to suit each specific type of future event.

3. Acoustic prediction

Several commercial software packages are available, each one characterized by specific features (3D model geometry input, calculation algorithms, output results, etc.). For this conference hall, the primary acoustics prediction parameters ($T_{\_Sabine}$, $T_{\_Eyring}$, T_{30}, EDT, C_{80}, D_{50} and G) were obtained using I -SIMPA, the open source software developed by a research team at University of Paris (UMRAE, 2018). As mentioned above, the *STI* (Speech Transmission Index) parameter was instead calculated via excel, following the IEC 60268-16 technical standard (IEC, 2020). To perform the acoustical prediction, the following key parameters were defined: 1) the audience area was modeled as an extruded volume extending 0.8 m above the auditorium floor. This area was treated as a surface receiver; additionally, ten discrete omnidirectional receivers (n. 1 to n. 10) were placed within this volume and oriented toward the stage.

2) the sound source was positioned on the stage at a height of 1.5 m, with a sound power level (L_w) of 120 dB, a white noise spectrum and omnidirectional directivity.

3) Sound absorption coefficients (α) were assigned across six octave bands (from 125 Hz to 4 kHz). These values (Tab. 1) were sourced from the Physikalisch-Technische Bundesanstalt (PTB, 2020) or manufacturer specifications. The audience area was assumed to be at 50% occupancy; specific absorption coefficients have been calculated by interpolation. Atmospheric absorption was automatically accounted for by the software, while scattering coefficients were set based on the scale and depth of the architectural surface geometries.

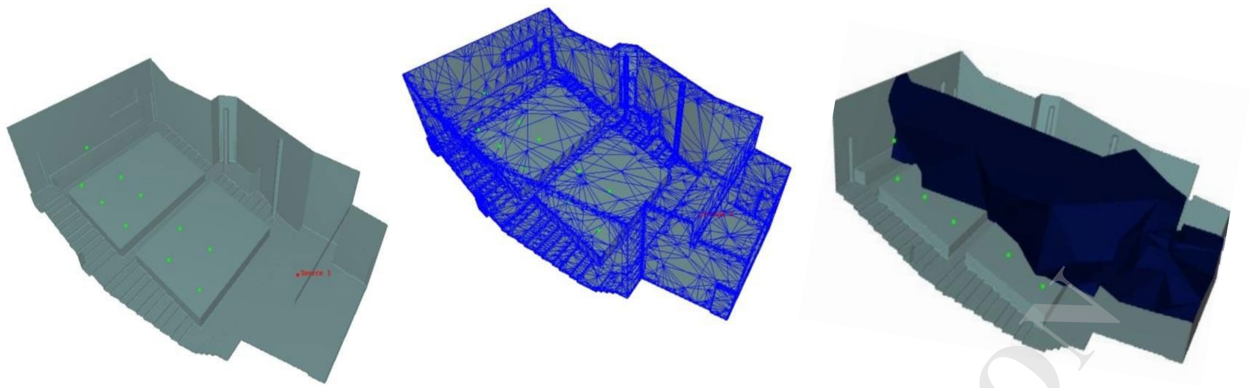
Table 1. The sound absorption and scattering coefficient values.

Sound absorption coefficients versus frequency	Frequency (Hz)					
	125	*250*	*500*	*1k*	*2k*	*4k*
Doors (solid wooden doors; PTB n.396)	0.14	0.10	0.06	0.08	0.10	0.10
Glass (heavy plate glass; PTB n.194)	0.18	0.06	0.04	0.03	0.02	0.02
Absorbent (rear wall wood panel; Technical data sheet)	0.25	0.45	0.60	0.75	0.85	0.65

Audience floor (parquet on concrete; PTB n.394)	0.04	0.04	0.07	0.06	0.06	0.07
Stage floor (wood tiles on joists; PTB n.393)	0.15	0.11	0.10	0.07	0.06	0.07
Plaster board (2 frames, airspace with mineral wool; PTB n.276)	0.15	0.12	0.10	0.08	0.07	0.06
Plaster (gypsum or lime, smooth finish on lath; PTB n.351)	0.02	0.02	0.03	0.04	0.04	0.03
Seating (slight upholstered chairs, unoccupied; PTB n.549)	0.36	0.47	0.57	0.62	0.62	0.60
Seating (slight upholstered chairs, occupied) (PTB n.550)	0.51	0.64	0.75	0.80	0.82	0.83
Curtain (heavy velour; PTB n.129)	0.14	0.35	0.55	0.72	0.70	0.65
Sound scattering coefficients versus frequency	Frequency (Hz)					
	125	*250*	*500*	*1k*	*2k*	*4k*
Doors	0.10	0.10	0.10	0.10	0.20	0.20
Windows	0.10	0.10	0.10	0.10	0.10	0.10
Absorbent wood panel (rear wall)	0.10	0.20	0.30	0.40	0.50	0.60
Audience floor (parquet on concrete)	0.10	0.10	0.20	0.30	0.40	0.30
Stage floor (wood tiles on concrete)	0.10	0.10	0.10	0.10	0.20	0.20
Wall plaster board (2 frames, airspace with mineral wool)	0.10	0.10	0.10	0.10	0.20	0.20
Audience seats	0.30	0.40	0.50	0.60	0.70	0.80

3.1. Geometrical representation and calculation algorithms

Although I-SIMPA lacks internal CAD functionality, it allows to import 3D room models prepared externally and saved in standard formats (.3ds, .stl, etc.). The surfaces of the 3D model are tessellated into triangular mesh, which assists the user in defining the appropriate volume for acoustical prediction. I-SIMPA meshing function can then verify, along the three axes, that the model's volume is a closed geometry. It is important to underlined the I-SIMPA meshing function is innovative compared to traditional software that represent surfaces as simple boundaries. The meshing technique avoids the need to manually define coordinates for every corners of the architectural elements, allowing for a more fluid workflow with complex geometries. The resulting geometric model for the conference hall after importation is shown in Fig. 2.



(a) (b) (c)

Fig. 2. 3D model representation, (a) flat and (b) meshed surfaces, (c) mesh function along y axis)

Regarding the calculation approach, I-SIMPA utilizes two different algorithms, TCR and SPPS. The TCR algorithm provides a global evaluation of the room's T_{60} based on classical reverberation theory; the Sound Pressure Level (*SPL*), both for total energy and the direct sound component, is also provided. The SPPS code, however, allows for the calculation of a wider range of acoustic parameters $T_{\_Sabine}$, $T_{\_Eyring}$, T_{30}, *EDT*, C_{80}, D_{50}, *G*, LF_{80} in accordance with the ISO 3382-1 (ISO, 2009).The SPPS code operates within a 3D domain by tracking sound particles, each carrying a discrete amount of energy emitted by the source. Two different calculation engines are available: *Random* and *Energetic*. Following the recommendations in the user guide, the Random engine is suitable for preliminary predictions, while the Energetic engine is preferred for obtaining definitive results. Based on the variations observed when adjusting sound absorption inputs or switching calculation methods, the prediction uncertainty is estimated at approximately 10%.

The SPPS prediction settings used in this study are summarized in Tab. 2 below.

Tab. 2. I-SIMPA acoustical parameters (SPPS code)

Simulation mode	Energetic
Sound particles (n)	500 000
Receiver radius (m)	0.31
Simulation length (s)	2.0
Calculation sample time (ms)	10
Prediction uncertainty	10%

3.2. Acoustical prediction results

Among all acoustic results obtained, only a selection of the primary I-SIMPA outcomes is reported below.

- Audience area

T_{Sabine}, T_{Eyring}, SPL_{direct}, SPL_{global} (RTC code, Fig. 3,4)

T_{30}, EDT, D_{50}, C_{80} (SPPS code, Fig. 5)

- Punctual receivers (R1-R10, Fig. 7)

T_{30}, D_{50}, C_{80} (SPPS code, Fig. 6)

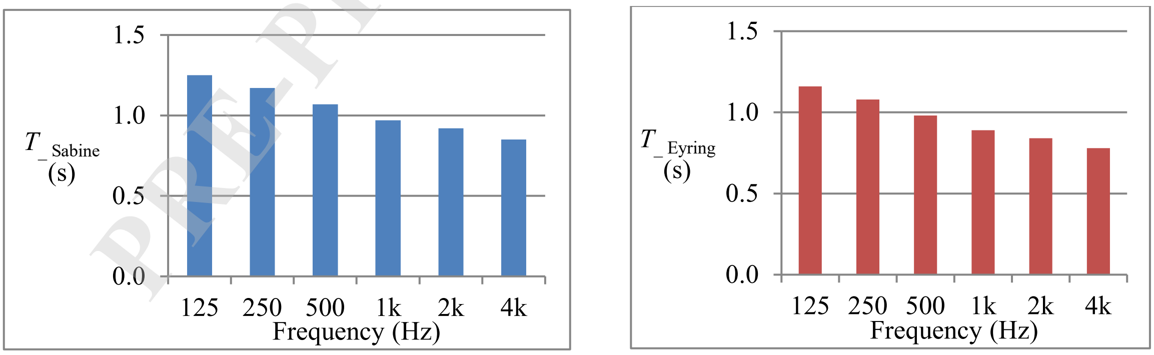
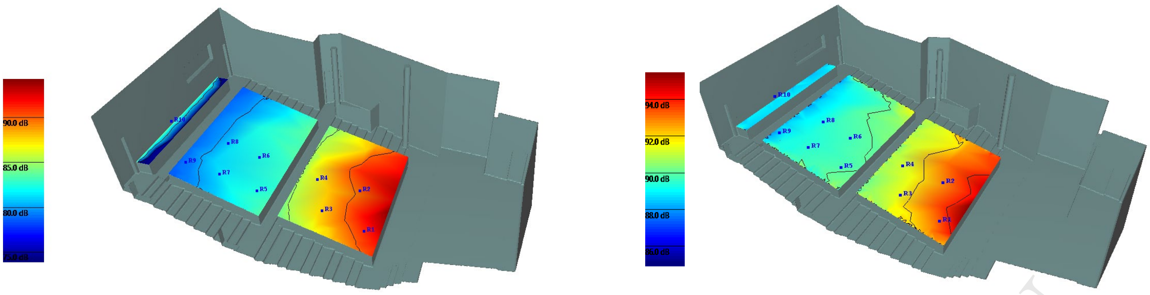


Fig. 3. Audience area, T_{Sabine} and T_{Eyring} (RTC code)



(a) (b)

Fig. 4. Audience area, SPL_{direct} (a) and SPL_{global} (b) (RTC code)

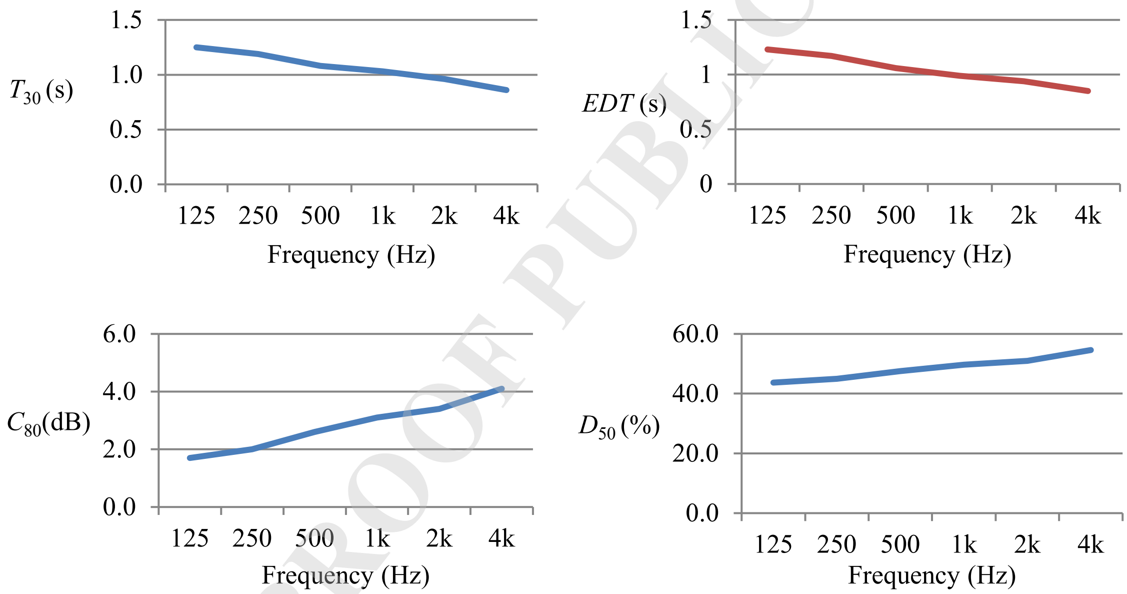
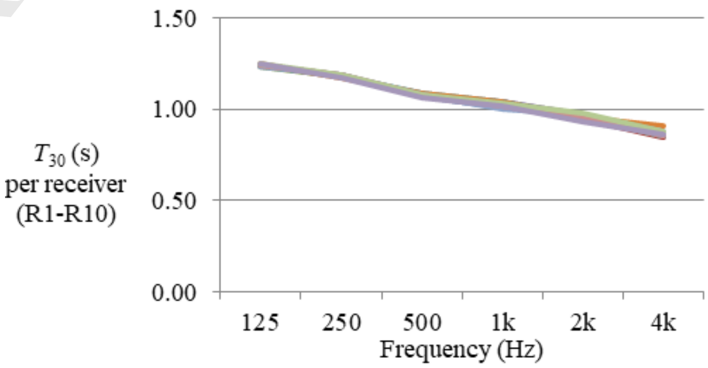


Fig. 5. Audience area, T_{30}, *EDT*, C_{80}, D_{50} (SPPS code)



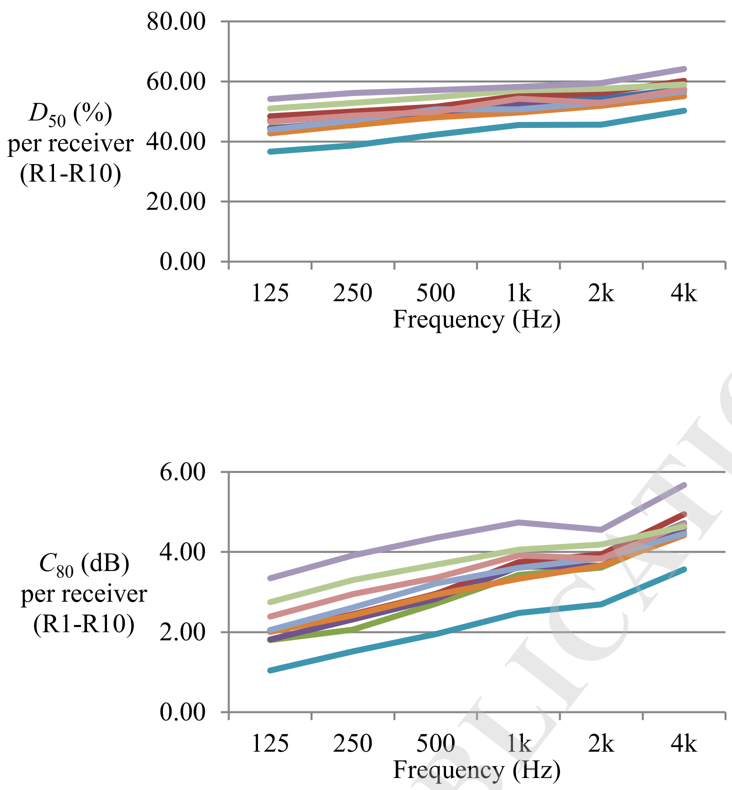


Fig. 6. T_{30}, D_{50}, C_{80} (SPPS code)

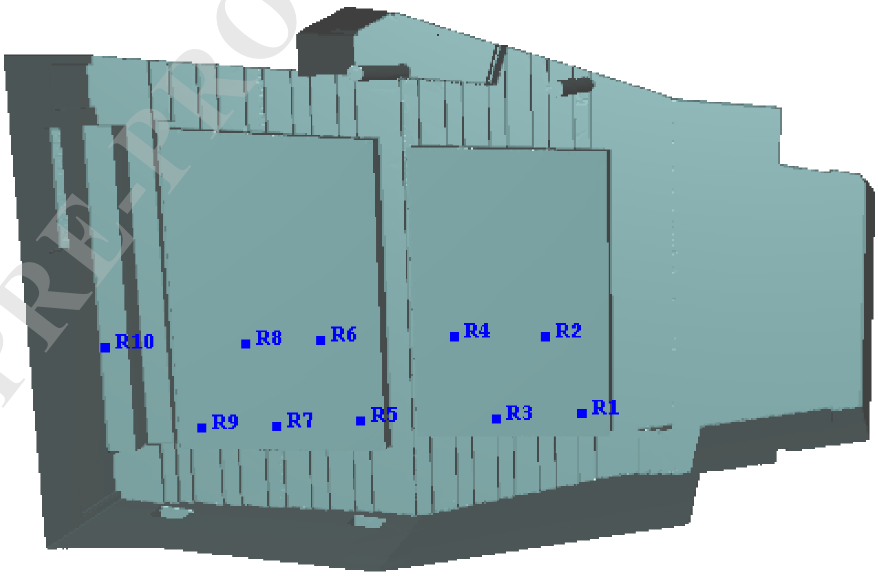


Fig. 7. Punctual receivers position (R1-R10)

4. Acoustical flexible treatment

The principal aim of the present work is to demonstrate the effectiveness of acoustic enhancements in a multi-functional hall to accommodate its different future use (Cairoli *et al*., 2024; Holden, 2016). This is a common requirement for small community spaces, particularly those located in smaller towns, such as the one discussed in the present work. In these cases, different sound field requirements are often needed, depending on the type of events (e.g. conferences, musical performances, live theater event, etc.). This versatility necessitates improving the user's acoustic experience, a goal that is strictly linked to the ability to vary the internal sound field conditions. While it is beyond the scope of this study to list every type of flexible acoustical treatments, we can briefly outline some of the most effective means of achieving acoustic improvements for the audience:

1) Calibrate optimal reverberation quality, tailored to the primary intended use of the hall;

2) Promoting a diffuse sound field, through the design of appropriate internal surface geometries or a uniform distribution of sound absorption;

3) Increasing the density of early reflections by optimizing the room's shape or incorporating additional architectural elements (such as reflectors);

4) Enhancing sound source levels and/or modifying the room's reverberant quality, through the use of electro-acoustic enhancement systems.

It's our opinion that a significant innovation in room acoustics design lies in the ability to manage these features through architectural *flexibility*. In this context the term *flexibility* refers to the capability to implement quick adjustments without complex pre-settings, even during a live event. For the conference hall presented here, the acoustic flexibility is primarily achieved by reducing or increasing the reverberation time of the room. Such variation effectively supports the two main types of sound messages the architectural project aims to accommodate, speech and music. Among the various options available, only one specific solution is proposed; it concerns the possibility of covering a portion of room's internal surfaces with additional absorbent material. This setup utilizes modular equipment to deploy heavy acoustic curtains, which can be extended from top to bottom along the lateral and the rear stage wall. Although a detailed design of this system can't be developed in this article, some basic specifications are provided below:

1) tissue weight > 600 g/m^2

2) distance from the solid wall ≥ 0.10 m

3) sound absorption $\alpha_w \geq 0.7$

4) global wall surface treated 135 m^2

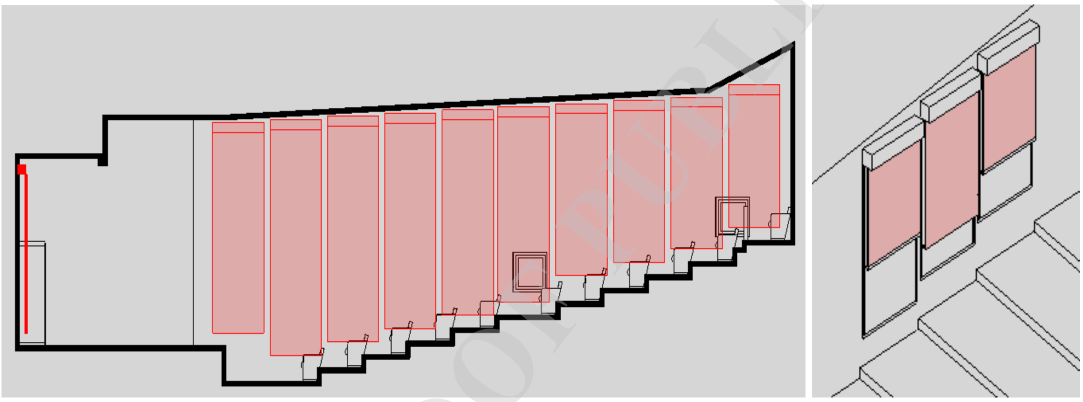


Fig. 8. Movable Acoustical Treatment Equipment (outline)

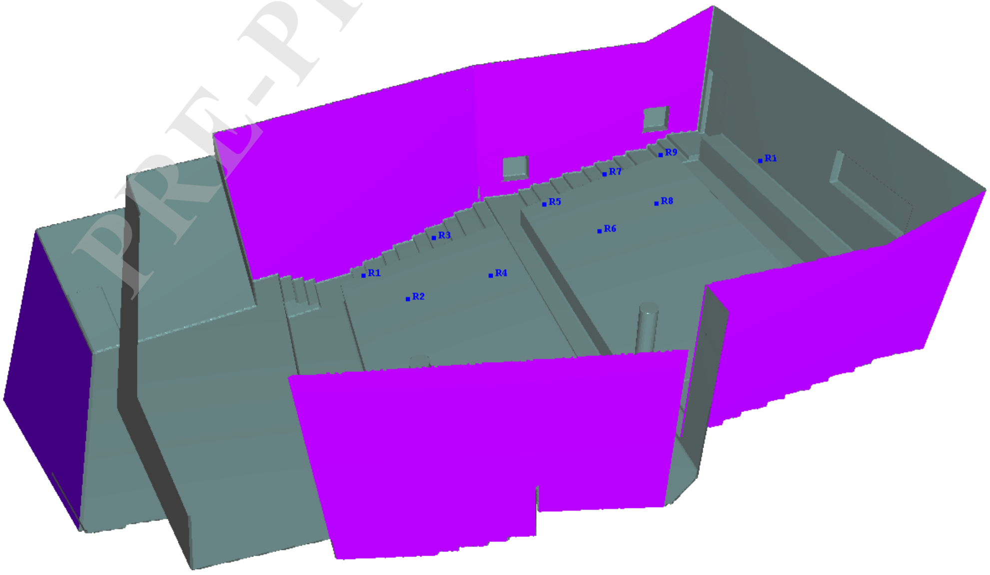


Fig. 9. Potential treatable surfaces (highlighted in color)

The effects of the proposed intervention are detailed below. Fig. 10–13 present a comparison of some acoustical parameters T_{30}, D_{50}, C_{80}, G, before and after treatment at receiver positions R3, R6, R10.

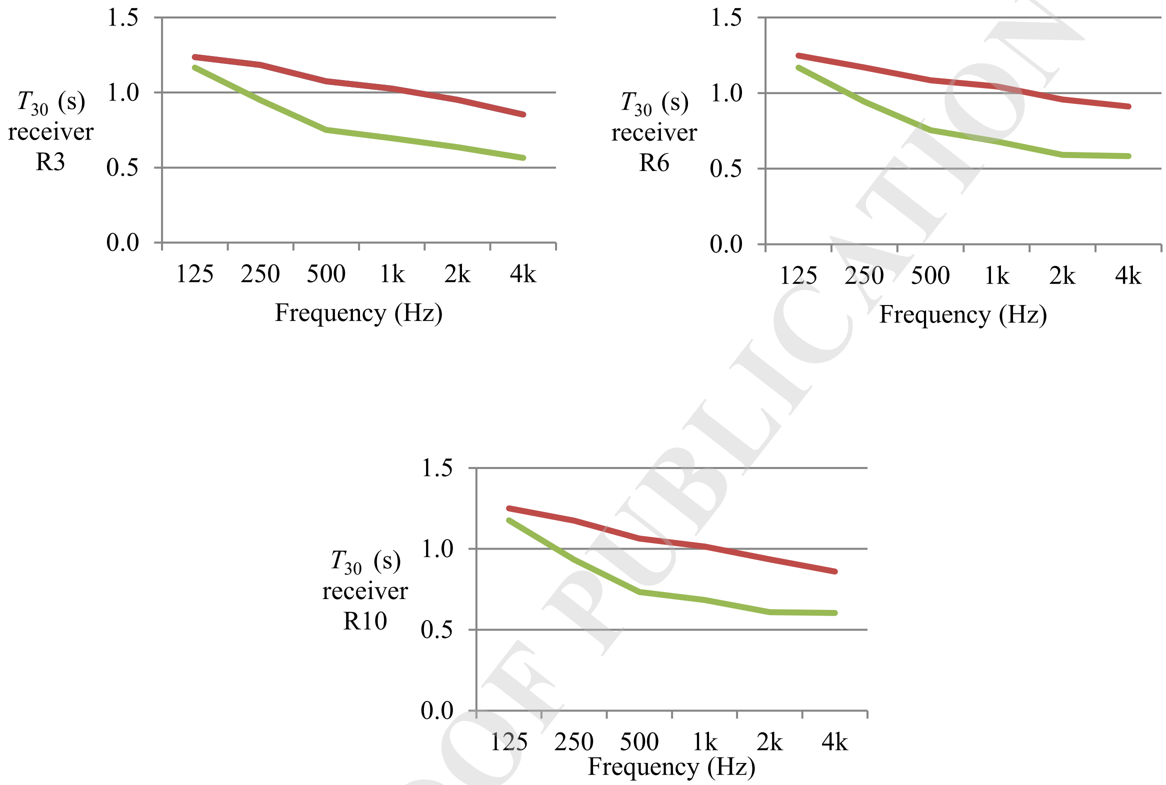
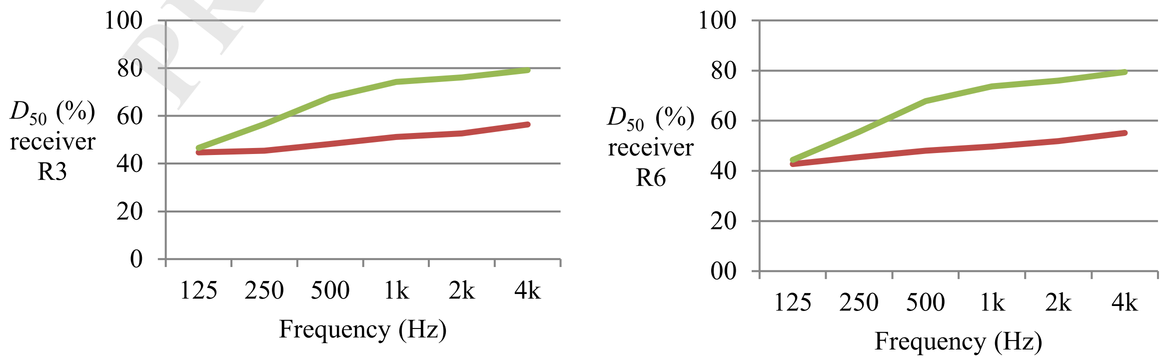


Fig. 10. Punctual receiver R3,R6,R10, T_{30} values before (red curve) and after (green curve) treatment (SPPS code)



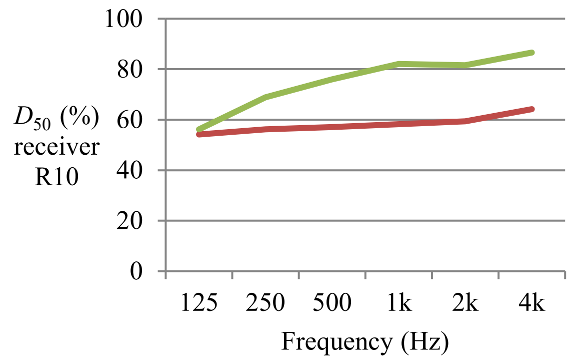


Fig. 11. Punctual receiver R3,R6,R10, D_{50} values before (red curve) and after (green curve) treatment (SPPS code)

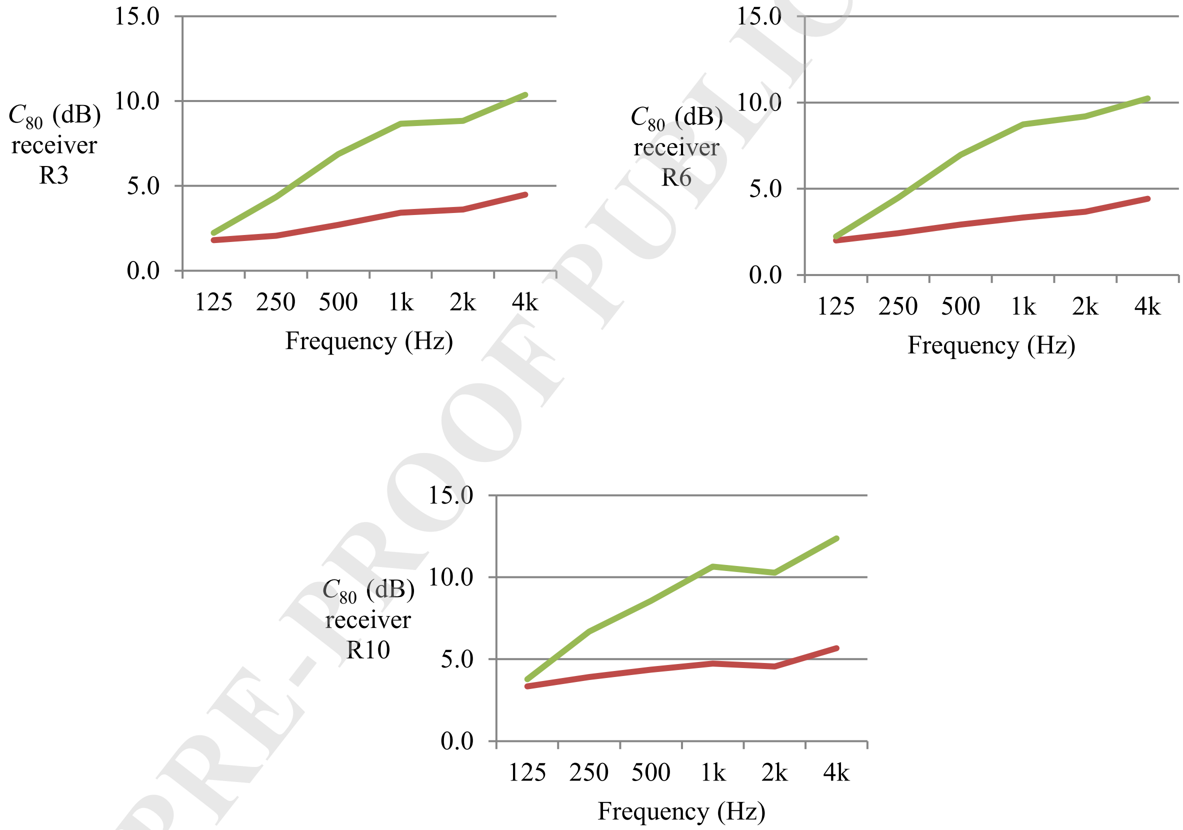


Fig. 12. Punctual receiver R3,R6,R10, C_{80} values before (red curve) and after (green curve) treatment (SPPS code)

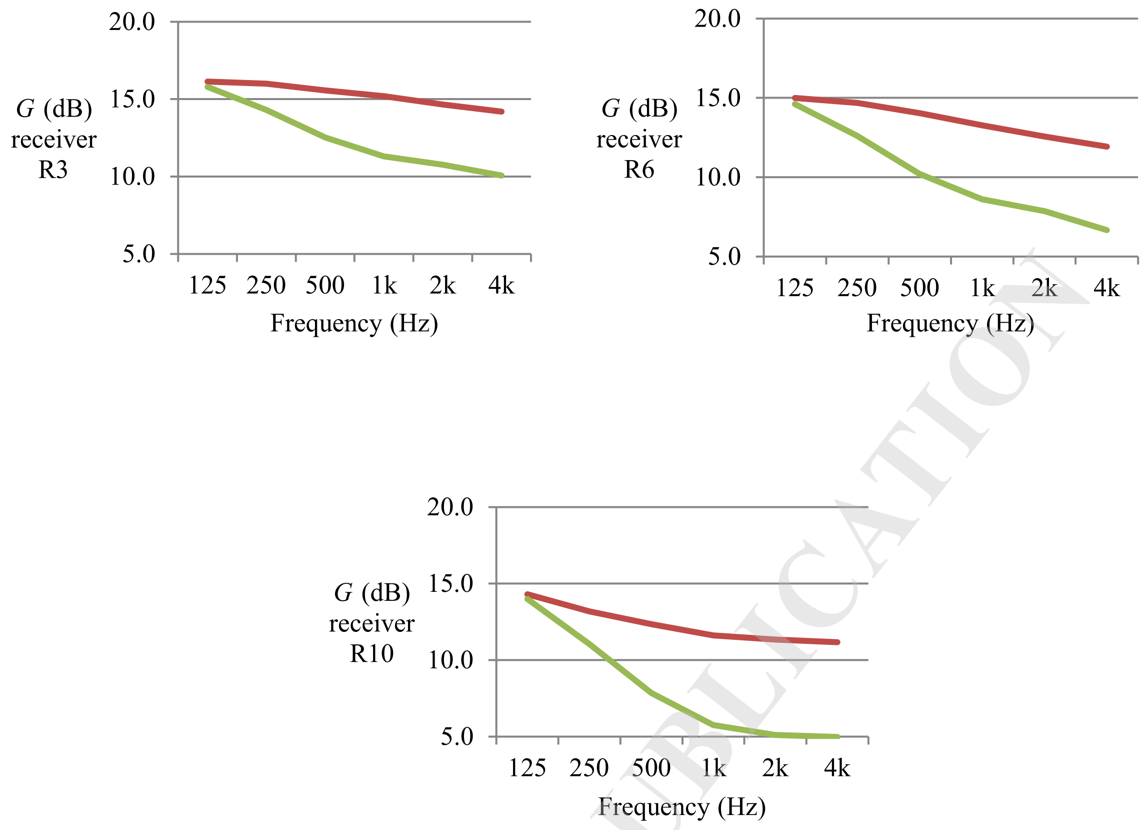


Fig. 13. Punctual receiver R3,R6,R10, *G* values before (red curve) and after (green curve) treatment (SPPS code)

As previously noted, I-SIMPA does not support any *STI* (Speech Transmission Index) calculation. Therefore, this task was performed using an Excel output based on the latest version of the technical standard IEC 60268-16 (IEC, 2020) (Houtgast et al., 1985; Nowicka, 2020). To carry out the calculation, more additional acoustic data were defined as follows.

- the sound source was modeled based on a raised male voice (Sundberg, 1987)

- the background noise was assumed to have sound pressure levels in each octave band corresponding to the maximum values of the NC-30 curve (ANSI/ASA S12.2-2019)

Table 3. Environmental conditions set for STI calculation

Frequency	(Hz)	*125*	*250*	*500*	*1k*	*2k*	*4k*	*8k*
Lw sound source (male raised voice)	(dB)	65.0	72.0	75.0	77.0	68.0	62.0	59.0
Q sound directivity	(n)	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Background noise	(dB)	48.0	41.0	35.0	31.0	29.0	28.0	27.0

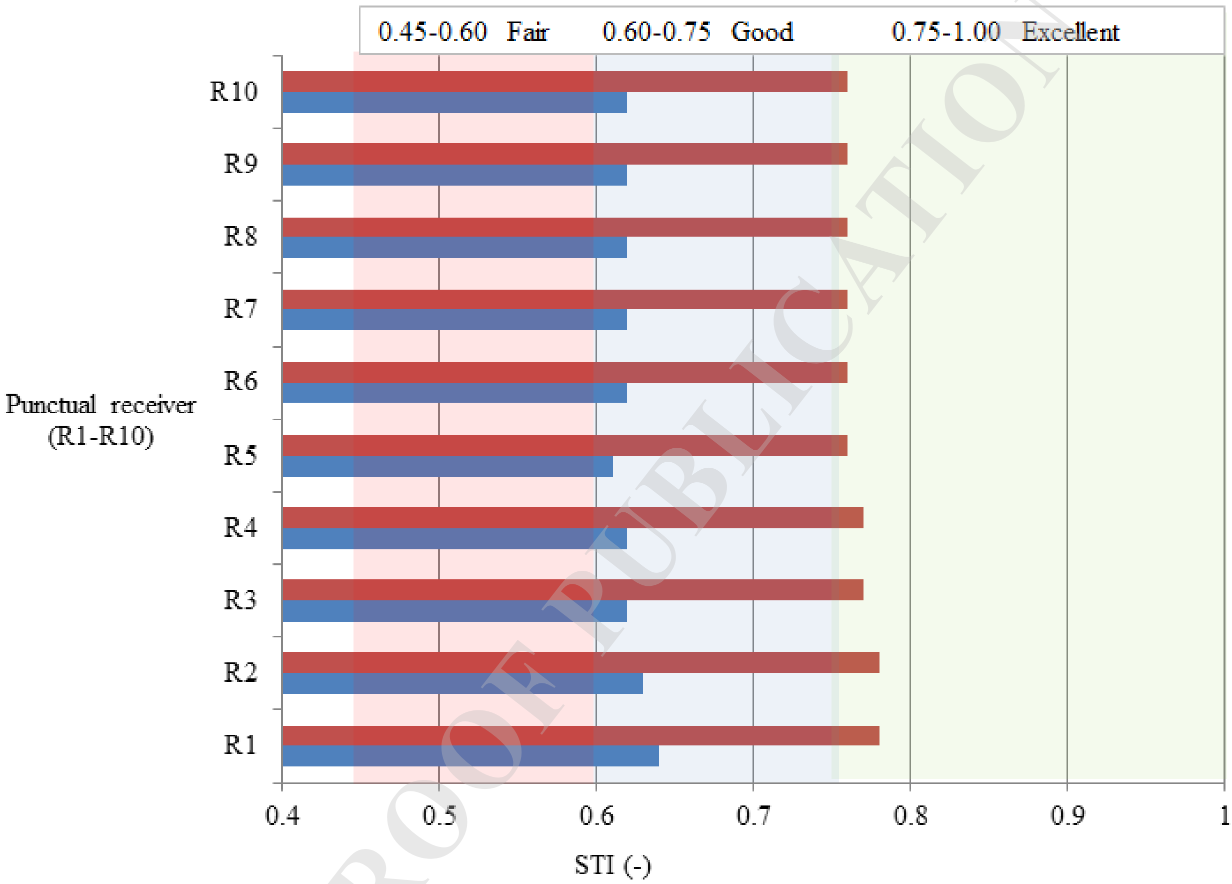


Fig. 14. (a) Speech Transmission Index (*STI*) values at discrete receivers (R1-R10) before treatment (blue bars) and after treatment (red bars).

5. Conclusions

Acoustical flexibility in multi-functional rooms can be a crucial strategy that significantly enhances sound appreciation in the place. While noise reduction remains an essential target, optimizing the sound field for different events is an equally important goal. This purpose can be easily integrated into any architectural design, often with minimal financial impact. By addressing these needs during the design phase, it is possible to avoid the supplementary costs of future acoustic retrofitting. This work, centered on a new conference hall project, proposes a practical solution for acoustic flexibility through movable equipment designed to modify the internal sound field. The effectiveness of this approach was demonstrate using computer-aided simulations with I-SIMPA software. Evaluating the primary parameters (T, T_{30}, D_{50}, C_{80}), it is evident that the proposed changing significantly improves acoustic suitability, particularly for speech intelligibility. Conversely, the system allows the hall to retain its original, more reverberant characteristics when required for musical performances. Not less important, the results confirm that the proposed acoustical treatment ensures compliance with the PN-B-02151-4:2015-06 (PKN, 2015) for reverberation time, while simultaneously achieving significant improvements in speech-related parameters, such as C_{50} and *STI*.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORS' CONTRIBUTION

Giovanni La Porta, conceptualized the study, performed data analysis and wrote the original draft.

Lucyna Leniowska, conceptualized the study, contributed to data interpretation, wrote integration to the original draft.

Michał Szarecki, performed data analysis

All authors reviewed and approved the final manuscript.

DATA AVAILABILITY STATEMENT

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

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