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Evaluation and Optimization of Acoustic Parameters of a Concert Hall

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Abstract

This study deals with the acoustic assessment of the concert hall of the Elementary Art School, aiming to verify its suitability for chamber music performances and to propose optimal acoustic modifications. The assessment was carried out using a combination of theoretical analysis and numerical calculations based on wave, geometrical, and statistical acoustics in accordance with standards STN 73 0525:1964, STN 73 0527:2024, and ISO 3382-1:2009. The main parameters of room acoustics were evaluated-reverberation time, evenness of sound distribution, and diffusive behavior. The results showed that the original design exhibited an extended reverberation time, particularly in higher frequency bands. After implementing Fantoni Letwood 5L acoustic panels, the values stabilized within the optimal range of 1.25–1.30 s, and the sound uniformity improved to ±5 dB. The resulting design meets the requirements for chamber concert spaces and demonstrates the effectiveness of combining geometrical and material modifications in optimizing the acoustic environment.

Keywords: concert hall, spatial acoustics, reverberation time, evenness of sound

1 Introduction

The acoustic quality of concert halls is a decisive factor influencing both artistic performance and the perception of musical interpretation. A suitable acoustic environment ensures optimal reverberation time, diffusive distribution of sound energy, and even sound coverage without disturbing effects such as echoes or standing waves. The design and evaluation of such spaces are governed by room acoustics, which interconnects physical, architectural, and psychoacoustic aspects. Reverberation time, sound diffusion, and sound evenness belong to the main parameters of acoustic quality [1–3]. For chamber spaces, optimal reverberation times range between 1.2–1.5 s at mid frequencies [4]. Elementary art schools represent a specific category of smaller concert spaces that must meet the requirements for both music and speech without electroacoustic amplification. Their design requires a precise balance between absorption and reflection and the elimination of parallel walls [5].
This paper focuses on the acoustic evaluation of the concert hall of an Elementary Art School. The aim is to analyse its acoustic parameters, verify compliance with standards STN 73

0525:1964, STN 73 0527:2024, and ISO 3382, and propose adjustments to achieve an optimal acoustic environment [4,6,7].

2 Methods

The methodology for assessing the acoustic parameters of the concert hall was based on a combination of theoretical room acoustic analysis and numerical computation of acoustic quantities in accordance with applicable technical standards. The objective was to determine and optimize the reverberation time, sound uniformity, and diffusive properties of the space while considering the elimination of undesired phenomena such as standing waves and echoes.

The methodological framework consisted of the following steps:

- acquisition of geometric and material input data,
- determination of target acoustic parameters according to STN 73 0525:1964, ISO 3382, and recommendations for chamber halls,
- calculations based on wave, statistical, and geometrical acoustics,
- evaluation of results and proposal of surface modifications.

2.1 Geometric and volumetric parameters

The analysed space (Figure 1, Figure 2) has a total volume of 939.11 m³. The room aspect ratio was designed as 1 : 1.17 : 1.68, eliminating parallel surfaces and minimizing the risk of standing waves. The side walls are inclined by approximately 5°, the ceiling has a curved geometry, and the floor plan supports sound diffusion. The audience area provides 84 seats, and the stage accommodates up to 20 performers.

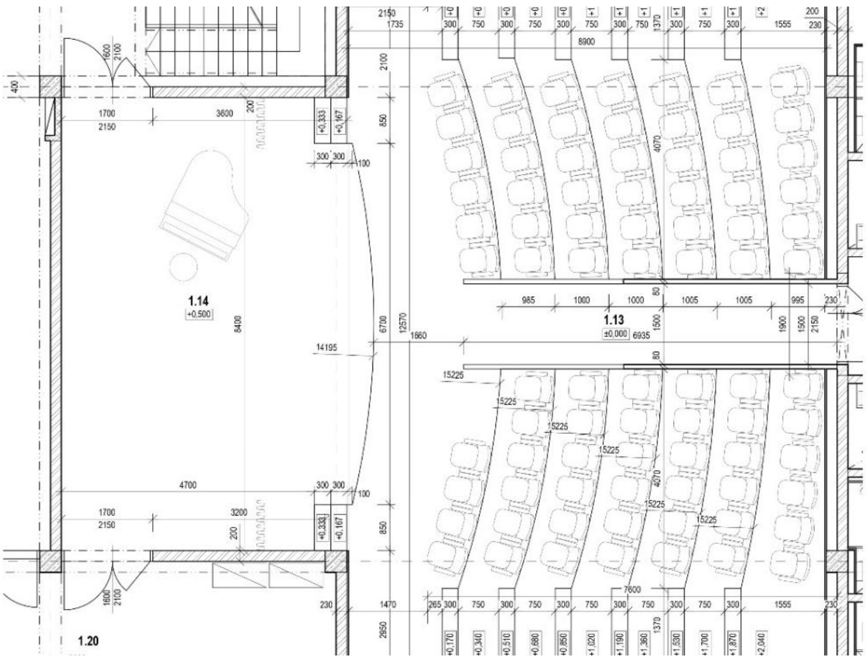

Figure 1: Floor plan of the concert hall with seating and stage layout

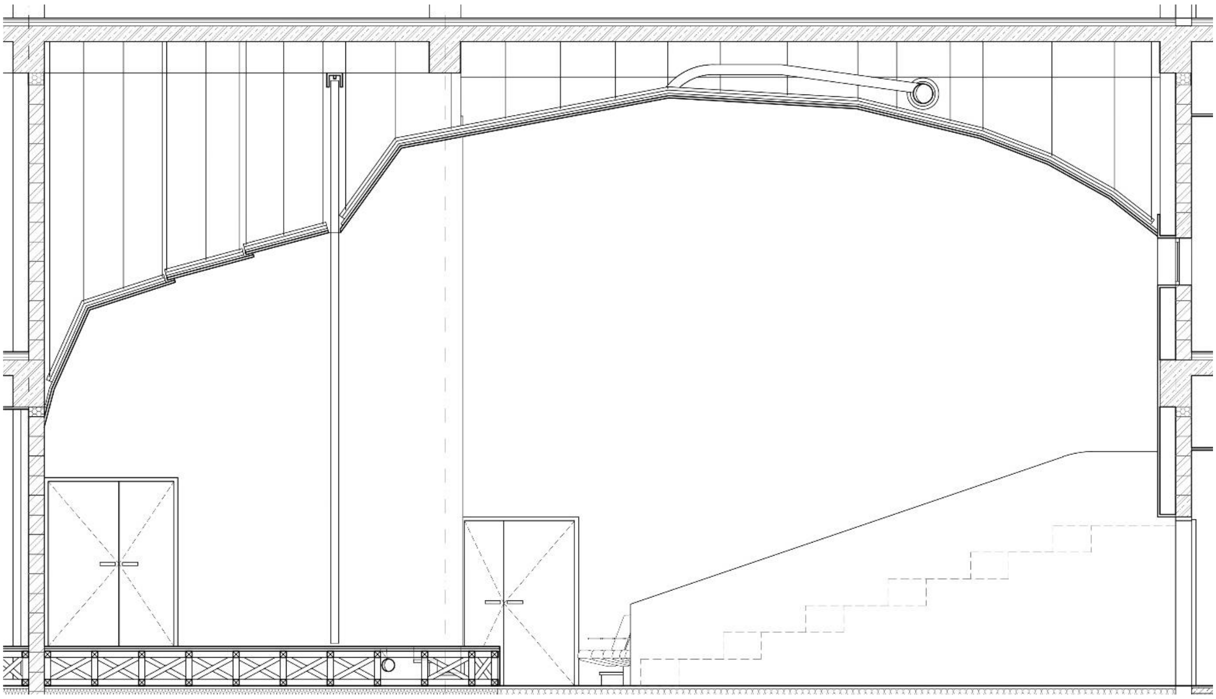

Figure 2: Section through the hall showing the curved ceiling

2.2 Wave acoustics - Schroeder frequency

To determine the transition between modal and diffuse sound behavior, Schroeder's frequency was calculated using equation (1):

$$f_s = 2000\sqrt{\frac{T}{V}} \tag{1}$$

where f_s is Schroeder frequency [Hz], T target reverberation time [s], and V is the room volume [m³].
For a volume of 939.11 m³ and target reverberation time T_0 = 1.28 s, was determined value $f_s =$ 160 Hz. Frequencies above 160 Hz behave diffusely in the room, which is ideal for concert venues.

2.3 Statistical acoustics – reverberation time

Reverberation time T is one of the most important parameters of spatial acoustics. It represents the time it takes for the sound level in a space to decrease by 60 dB after the source is turned off. It is calculated according to Eyring's equation (2):

$$T = \frac{0{,}163 \times \mathrm{V}}{-\sum S_i \ln\,(1-\bar{\alpha}_i)} \tag{2}$$

where V is room volume [m³], S_i is the area of surfaces [m^2] a $\bar{\alpha}_i$ is sound absorption coefficient. The Eyring equation is more accurate than Sabin's because it takes into account the logarithmic attenuation of energy in spaces with higher absorptivity. The calculations were performed in the 125–4000 Hz range.

2.4 Geometrical acoustics – evenness of sound distribution

Sound distribution was determined using the inverse square law (3) and transformed into sound intensity levels (4):

$$I = \frac{P}{4\pi r^2} \tag{3}$$

where P is acoustic power of the source, r is distance from the source.

$$L_I = 10 \log_{10} \left(\frac{I}{I_0}\right) \tag{4}$$

where I_0 is the reference intensity with a value of 10^{-12} W/m^2. Differences in intensity levels within the audience area were evaluated according to the ±3 dB criterion.

2.4.1 Modified inverse square law

The real environment contains not only direct sound but also reflected sound. Therefore, equation (5) has been modified to take into account early reflections.

$$I_i = I_{ref} \left(\frac{r_{ref}}{r_{pi}}\right)^2 + \sum I_{ref}(1-a) \left(\frac{r_{ref}}{r_{oi}}\right)^2 \tag{5}$$

where I_i is intensity in point i, I_{ref} is reference intensity, r_{pi} a r_{oi} are the distance of direct and reflected rays, and a is sound absorption coefficient. The first part of the equation expresses direct sound, the second part expresses the increase in energy from reflected rays. Only the first reflection was considered, as subsequent reflections have a negligible effect.

2.5 Material design

The materials were selected to achieve uniform absorption across the frequency spectrum. The main surfaces consist of wooden cladding and plasterboard, ensuring adequate diffusion. The key element of the acoustic treatment was the Fantoni Letwood 5L panel, applied to the side walls, which significantly reduced reverberation time in the 500–4000 Hz range.
In Table 1 the absorption coefficients of the materials used, which were the basis for the Eyring calculation.

Table 1: Surface Materials and Absorption Coefficients

Surface	**Area [m^2]**	α					
		125 Hz	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Floor, concrete	37.98	0.04	0.04	0.07	0.06	0.06	0.07
Floor,	117.85	0.15	0.11	0.10	0.07	0.06	0.07
Plasterboard, curved ceiling	176.83	0.20	0.22	0.18	0.15	0.15	0.16
Paint	70.20	0.01	0.01	0.02	0.02	0.02	0.03
Wood cladding without cavity	111.10	0.05	0.05	0.05	0.05	0.05	0.05
Wood cladding with cavity	115.09	0.06	0.10	0.08	0.09	0.07	0.04

Doors	16.80	0.10	0.07	0.05	0.04	0.04	0.04
Windows	2.88	0.18	0.06	0.04	0.03	0.02	0.02
Curtain	9.964	0.05	0.12	0.35	0.48	0.38	0.36
Occupied sitting	84.00	0.10	0.15	0.20	0.25	0.25	0.25
Performers	20.00	0.22	0.30	0.38	0.42	0.45	0.45

3 Results

3.1 Assessment of space without the use of acoustic cladding

The assessment of reverberation time (Table 2) was performed in accordance with standards STN 73 0525:1964 and STN 73 0527:2024. The standard (STN 73 0525:1964) considers a tolerance deviation of ± 10% of the reverberation time in the space from the optimal reverberation time. However, the standard (STN 73 0527:2024) does not replace the previous standard, but adds a more benevolent tolerance range that takes into account the manner of expression in the space. In our case, this is a tolerance range for music and speech, where the ratio of the reverberation time in the space to the optimal reverberation time varies across frequencies and ranges from -35% to +45%.
The reverberation time is calculated using Eyring's equation mentioned above. The calculation did not take into account the influence of humidity in the space, as the volume of the room is not greater than 2000 m^3.

Table 2: Reverberation time without acoustic cladding

Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**	**4000**
Reverberation time T [s]	1.7315	1.5510	1.5694	1.6063	1.6845	1.6767
Optimal reverberation time T_{opt} [s]	1.27826					
Δ T [%]	35.45	21.34	22.77	25.66	31.78	31.17
Assessment T = ±10% (STN 73 0525:1964)	Not compliant	Not compliant	Not compliant	Not compliant	Not compliant	Not compliant
T/T_0 [-]	1.35	1.21	1.23	1.26	1.32	1.31
Assessment (STN 73 0527:2024)	Compliant	Not compliant	Not compliant	Not compliant	Not compliant	Not compliant

When using only standard surface finishes, the design is insufficient at high frequencies when assessed according to STN 73 0527:2024, and completely unsatisfactory in terms of STN 73 0525:1964.

3.2 Design and assessment of optimal surface finishes in the space

The reverberation time values exceed the recommended value, so they need to be reduced and absorbent materials added to the space. Based on the previous results, it is possible to design the required properties of the newly designed acoustic cladding. Acoustic cladding from Fantoni, product Letwood 5L, which is designed for cladding ceilings and walls, was considered. The position of this cladding was considered on three walls of the auditorium, in the form of a 1 m wide strip, which will also replace the original wooden cladding. In the calculation, this will reduce the area of the wooden cladding and add acoustic cladding. Table 3 shows the results using this design.

Table 3: Reverberation time with acoustic cladding

Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**	**4000**
Reverberation time T [s]	1.3889	1.1946	1.2369	1.3416	1.4034	1.3782
Optimal reverberation time T_{opt} [s]	1.27826					
Δ T [%]	8.65	6.54	3.24	4.96	9.79	7.81
Assessment T = ±10% (STN 73 0525:1964)	Compliant	Compliant	Compliant	Compliant	Compliant	Compliant
T/T_0 [-]	1.09	0.93	0.97	1.05	1.10	1.08
Assessment (STN 73 0527:2024)	Compliant	Compliant	Compliant	Compliant	Compliant	Compliant

After applying the proposed sound-absorbing cladding, the space was assessed as satisfactory in terms of acoustic parameters, in accordance with the requirements of both relevant standards.

3.3 Sound evenness

Sound evenness were analysed in 15 point. An adjusted form of the inverse square law, which includes the effect of reflected rays, was used for the calculation. The difference between the highest and lowest intensity levels was 4 dB, which falls within the recommended ±5 dB range. This sound field was found to be uniform and stable, with slight psychoacoustical imperceptible variations between front and rear seating. The curved ceiling redistributed energy effectively and improved overall intelligibility. Figure 3 shows the results 500 Hz frequency.

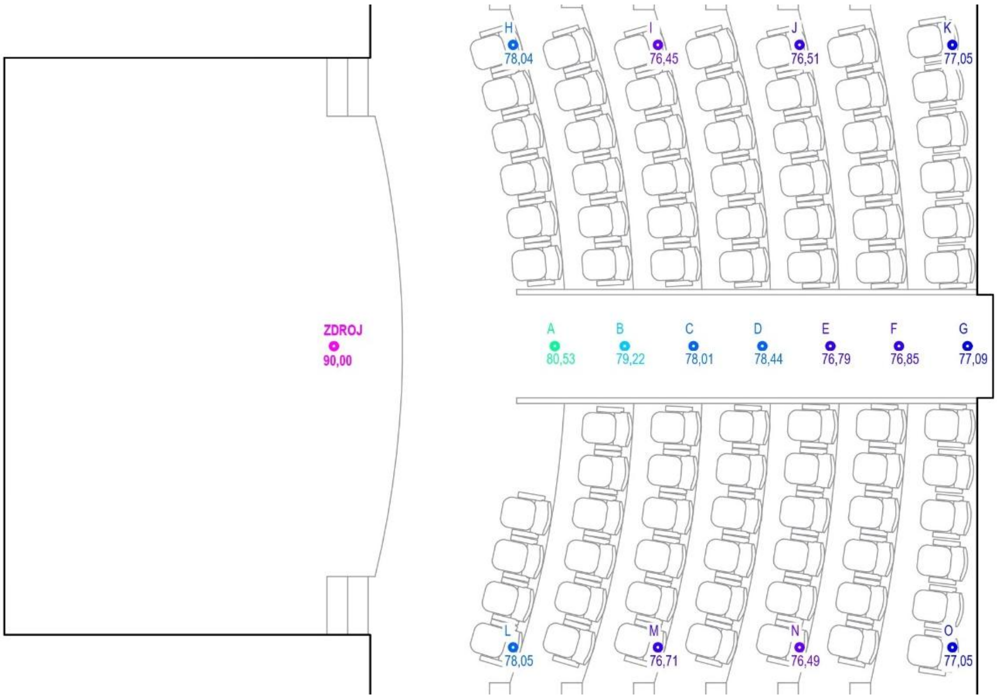

Figure 3: Sound evenness at 500 Hz

4 Discussion

The analysis confirmed that before treatment, the hall exhibited an excessive reverberation time, especially above 1000 Hz, caused by reflective materials such as wood and glass. After the implementation of Fantoni Letwood 5L panels, reverberation time stabilized around 1.25–1.30 s in mid frequencies, aligning with STN 73 0525:1964 and ISO 3382-1:2009 recommendations. The modifications reduced the reverberation time by about 20% and smoothed its frequency curve, improving both speech intelligibility and musical clarity. The evenness of sound distribution (±4 dB) confirmed good spatial balance, consistent with psychoacoustic thresholds defined by the Weber–Fechner law.

Geometrical shaping specifically the curved ceiling and angled walls, proved effective in minimizing standing waves and echoes, producing a homogeneous acoustic response.

Although the calculations did not include humidity or temperature variations, such factors have only minor influence ±0.1 s and do not affect the overall assessment.

Overall, the proposed acoustic design fulfils the requirements for small concert spaces, offering an optimal balance between musical richness and speech clarity.

5 Conclusion

This study focused on the acoustic evaluation and optimization of a concert hall designed for an Elementary Art School. By combining wave, geometrical, and statistical acoustic analyses, the research provided a comprehensive understanding of the hall's behaviour regarding reverberation and sound evenness.

The results confirmed that the original hall exhibited excessive reverberation at higher frequencies, which was effectively mitigated through the use of Fantoni Letwood 5L panels. The optimized design achieved balanced reverberation and sufficient diffusion without electroacoustic reinforcement.
Future research should include on-site experimental measurements and ray-tracing simulations to verify the computational model and better understand the effects of material distribution and audience presence on sound diffusion. Such an approach would further improve the accuracy of acoustic design in small to medium-sized concert halls.

Acknowledgments

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References

[1] Barron, M. (2009). Auditorium Acoustics and Architectural Design, Second Edition. In *Auditorium Acoustics and Architectural Design, Second Edition*. https://doi.org/10.4324/9780203874226.

[2] Cairoli, M. (2021). The architectural acoustic design for a multipurpose auditorium: Le Serre hall in the Villa Erba Convention Center. *Applied Acoustics*, *173*. https://doi.org/10.1016/j.apacoust.2020.107695.

[3] Cairoli, M. (2018). Architectural customized design for variable acoustics in a Multipurpose Auditorium. *Applied Acoustics*, *140*. https://doi.org/10.1016/j.apacoust.2018.05.026.

[4] EN ISO 3382-1:2009 Acoustics – Measurement of room acoustic parameters – Part 1: Performance spaces.

[5] Everest, F. A., & Shaw, N. A. (2001). Master Handbook of Acoustics, Fourth Edition. *The Journal of the Acoustical Society of America*, *110*(4). https://doi.org/10.1121/1.1398048.

[6] STN 73 0525:1964 Design in the field of room acoustics. General principles.

[7] STN 73 0527:2024 Acoustics. Design in the field of spatial acoustics. Spaces for cultural and educational purposes. Spaces for public purposes. Administrative offices.