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DESIGN OF A THEATER ROOM AND CINEMA ADAPTATION

ACOUSTICS AND ELECTROACOUSTICS

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Contents:

1. INTRODUCTION

This laboratory project aimed to apply the theoretical principles of room acoustics and electroacoustics to the practical design and evaluation of a multifunctional performance space. The work was divided into two sequential stages. In the first stage, we developed the complete acoustic design of a theatre, following specific geometric and architectural acoustic criteria. In the second stage, we adapted the theatre to operate as a cinema, integrating electroacoustic considerations and meeting the performance requirements typical of small cinema rooms.

The theatre design phase required the creation of a room geometry that satisfied seat capacity constraints, volumetric ratios, stage dimensions, and access pathways. Once the geometry was defined, materials with frequency-dependent absorption properties were selected from the EASE database to achieve a reverberation time within the prescribed range across the mid-frequency bands. Additional acoustic elements, such as reflector panels, were designed to ensure adequate early reflections, particularly for listeners in the rear seats. The resulting model was then evaluated through reverberation time calculations, echogram analysis, intelligibility mapping (STI), and auralization to assess the subjective quality of the hall.

After completing the theatre design, the second stage involved its adaptation as a cinema room. This included the configuration of a left/right loudspeaker system behind the screen, adjustment of source orientation, and calibration of sound pressure levels to meet cinema standards. The adapted room had to comply with the requirements of minimum wide-band SPL, coverage uniformity, and speech intelligibility. When needed, the acoustic response of the room could be improved with reversible treatments, such as curtains, so that the cinema adaptation would not compromise the original theatre function.

The following report describes the modelling process, design decisions, simulations, and acoustic evaluations carried out during both phases of the project.

2. THEATRE

2.1. ROOM DESIGN

We draw a geometry schematic of our theatre to make all the calculations and measures so it would be easier to design it using EASE. In the first place we placed the main walls as a pentagon, as we designed, and the ceiling respecting the height restrictions. Once we had the empty room, we established what space would occupy the audience, how it would be distributed and where would be the correspondent pathways. We kept empty the space that belongs to the mouth of the stage and installed a reflector panel once we calculated its position and direction.
For the seats, we opted for a design with three different sections. The two front sections, one on each side and both identical, increase in width as you approach the back rows. As for the back section, we liked the idea of curving the entire section evenly and, like the front section, increasing its width as you move away from the stage, mimicking a Roman theatre.

2.2. ROOM CHARACTERISTICS

2.2.1. NUMBER OF SEATS

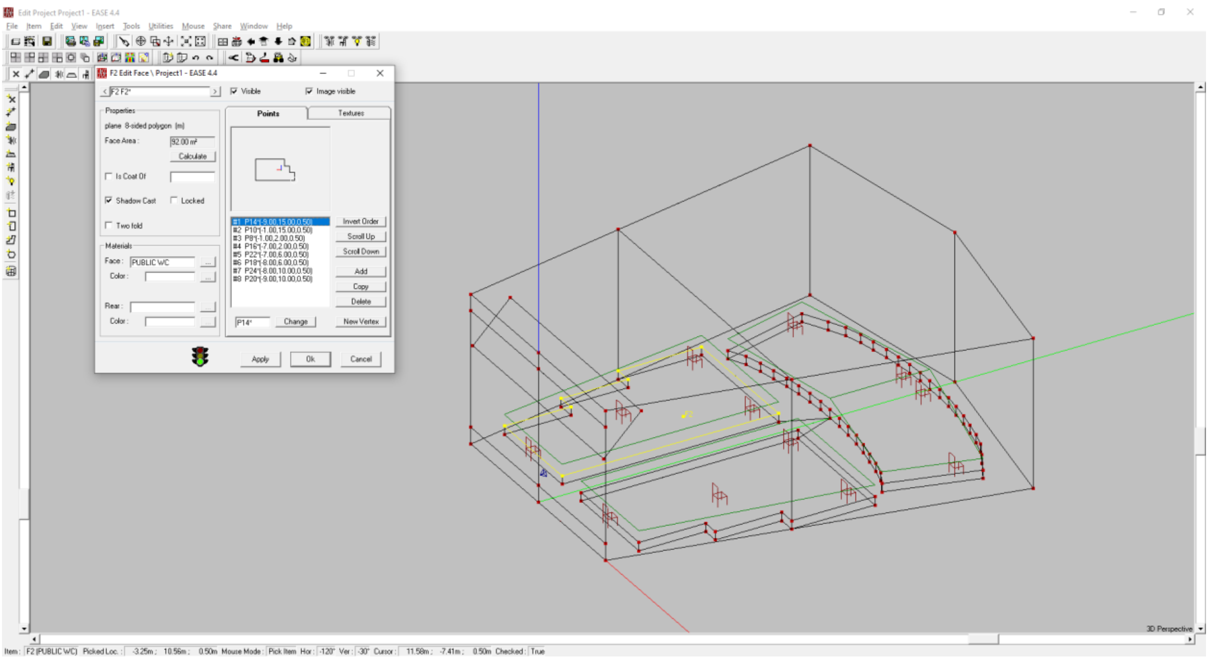


Figure 1: Front section seats area

This surface area is 92 m^2. Each seat takes 0,55m · 0,95m = 0,5225 m^2, so in this area we have 92 ÷ 0,5225 ≈ 176 seats. In total, for the front section, there's 352 seats.

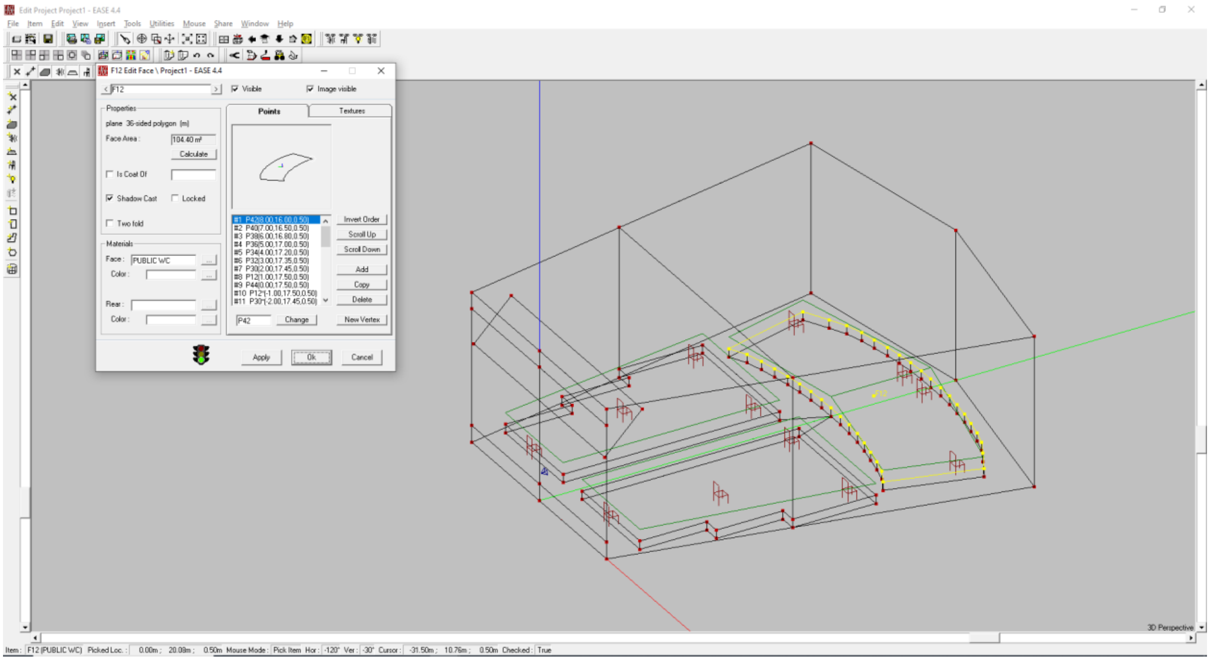


Figure 2: Back section seats area

This surface area is 104,4 m^2. In the back section we have 104,4 ÷ 0,5225 ≈ 200 seats

That makes a total of <u>552 seats</u>. That fits perfectly the number of seats required.

2.2.2. RATIO OF TOTAL VOLUME

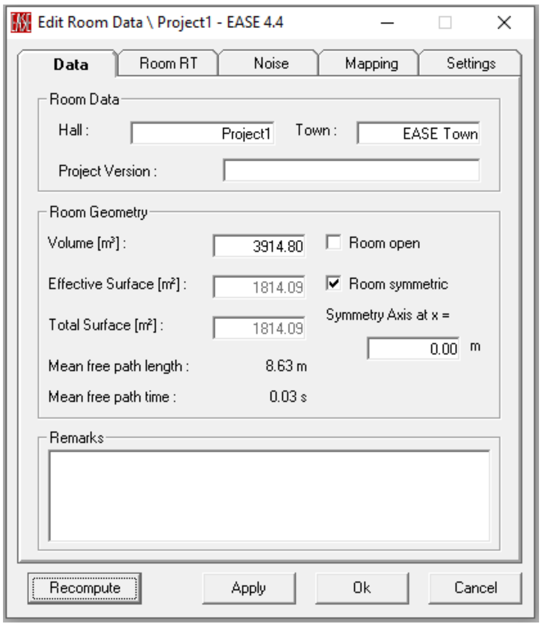


Figure 3: Room data

As we can see in the picture, the total volume of our theatre is 3914,8 m^3. Knowing that we have a total of … seats, we calculate the ratio of total volume:

$$Ratio\ of\ total\ volume = \frac{Total\ room\ volume}{Number\ of\ seats} = \frac{3914.8}{552} = 7{,}09$$

2.2.3. ROOM DIMENSIONS

When designing the room, we considered the dimensions imposed by the laboratory guide. To meet the requirements while respecting our design, we opted for the following room dimensions:

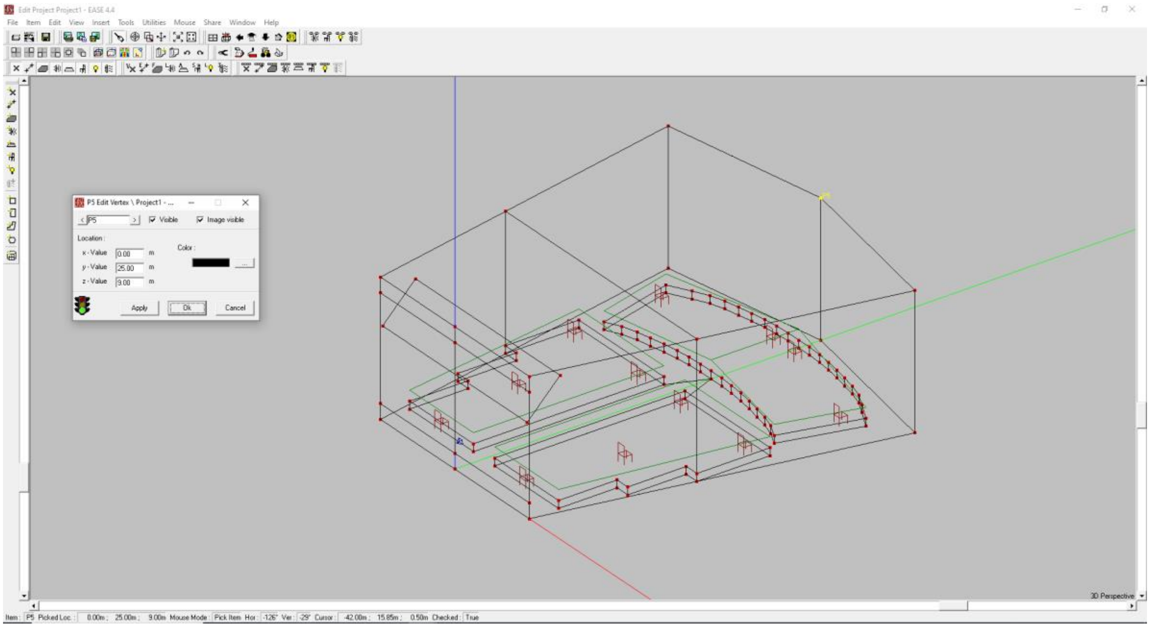


Figure 4: Room dimensions, length and height

As we can see in this figure, the total length of the room is 25 m, which is the maximum allowed in the laboratory guidelines. Furthermore, we can observe that the room will have a maximum height of 9 meters.

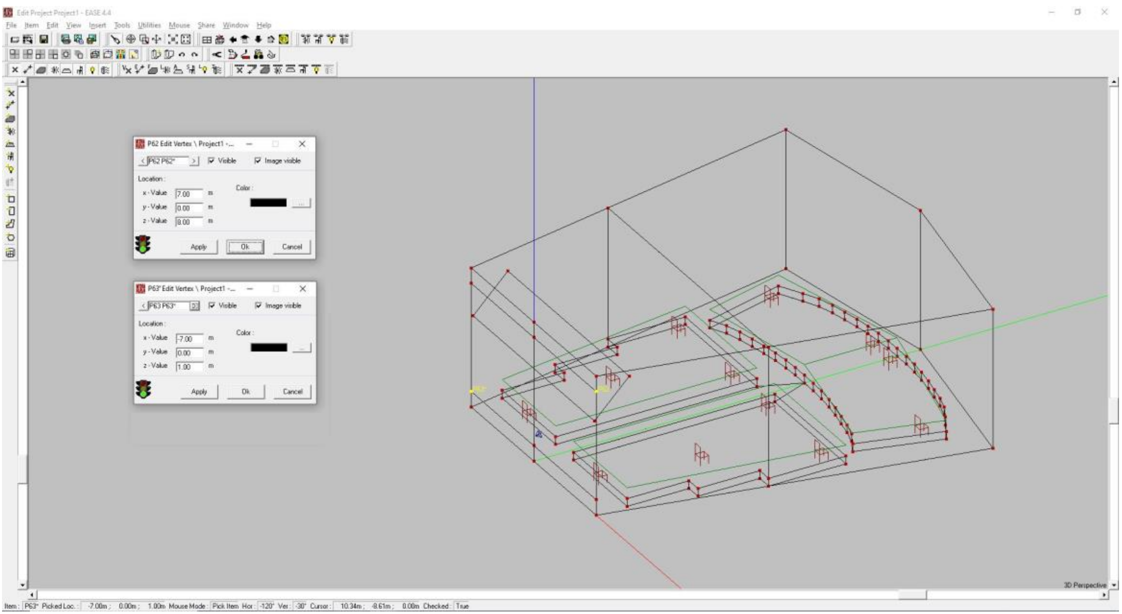


Figure 5: Room dimensions, mouth of the stage

As for the mouth of the stage, checking both corner points in the image, we observe that it has a height of 7 meters and a width of 14 meters. These two dimensions are the minimum required in the laboratory guide.

2.2.4. REFLECTOR PANEL

We performed the following calculations to find the axis of the reflector panel:

$$\begin{cases} \|\vec{v_A}\| = \sqrt{(-1{,}5)^2 + (-6)^2} \approx 6{,}18465 \\ \|\vec{v_S}\| = \sqrt{(21{,}5)^2 + (-6)^2} \approx 22{,}3215 \end{cases} \begin{cases} \hat{u}_A = \dfrac{\vec{v_A}}{\|\vec{v_A}\|} \approx (-0'2425\,,-0'9701) \\ \hat{u}_S = \dfrac{\vec{v_S}}{\|\vec{v_S}\|} \approx (-0'9634\,,-0'2687) \end{cases}$$

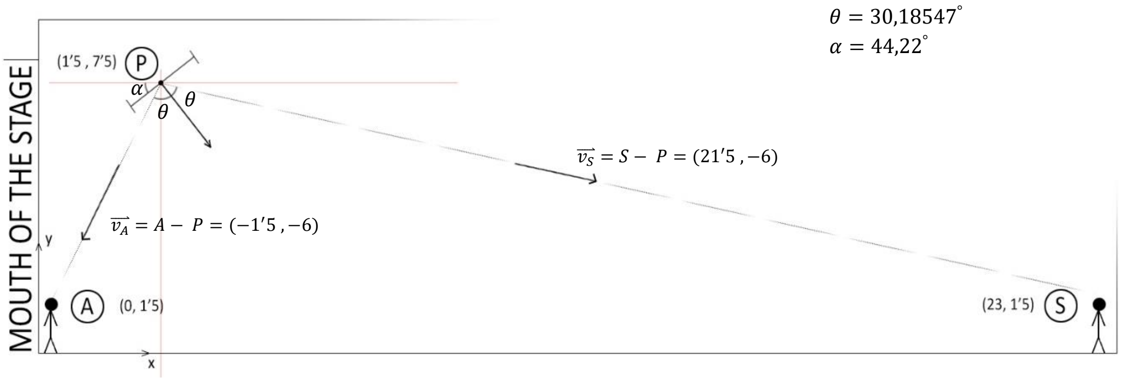


Figure 6: Reflector panel calculations

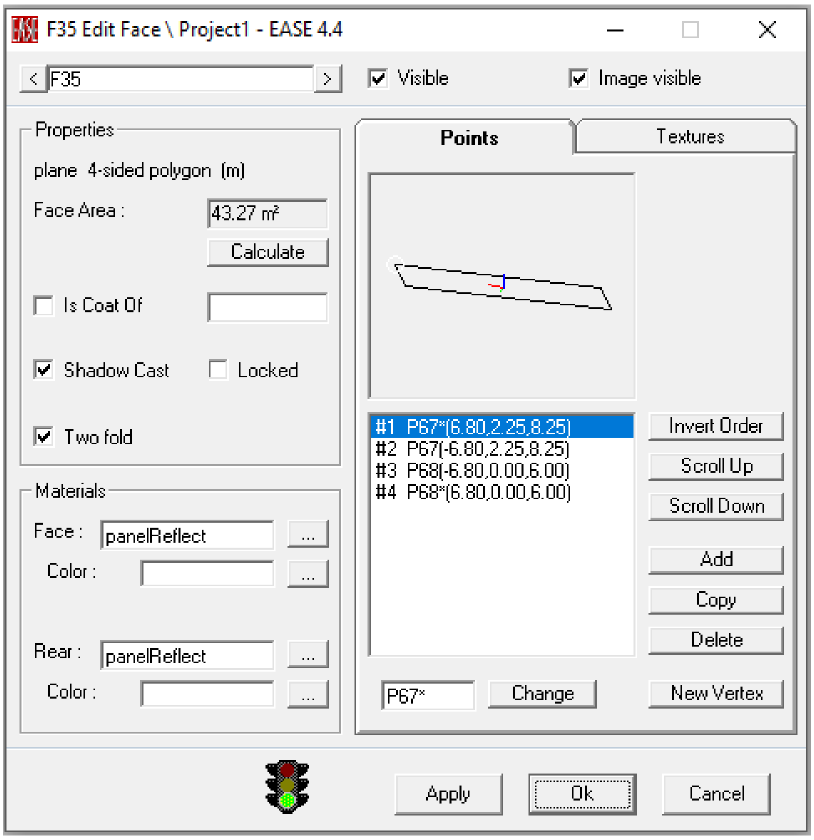


Figure 7: Reflector panel data

2.2.5. MATERIALS SELECTION

Since the room is symmetrical, we will explain the materials selected only for one side, as they are the same for the opposite side.

We observed that most of the sound paths that caused us echo problems due to the long propagation time had one thing in common: they bounced off the first half of the side walls or ceiling before reaching the viewer.
The echoes problem has two solutions: reduce the propagation time so the human brain detects the original sound and its delayed version as the same sound, or to significantly reduce the decibels at which the echo reaches the viewer so that it is almost imperceptible and drowned out by the sound arriving via the direct path. The first option implies a redesign of the room's geometry, so we opted for the second one and divided the side walls and ceiling in two.

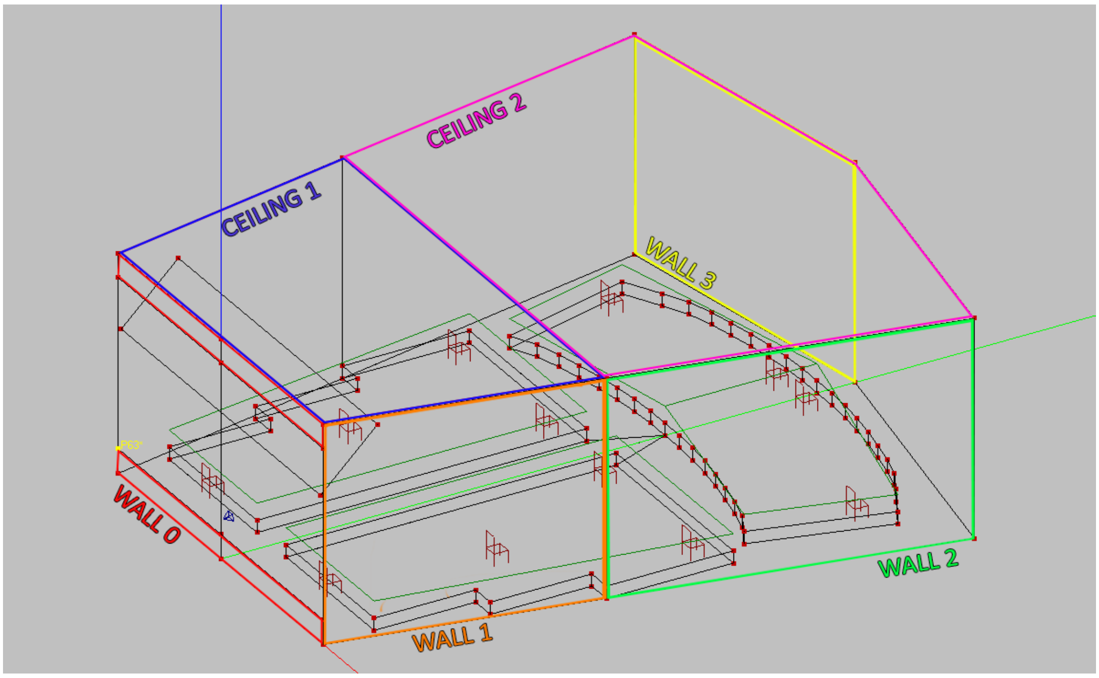


Figure 8: Walls and ceilings labels

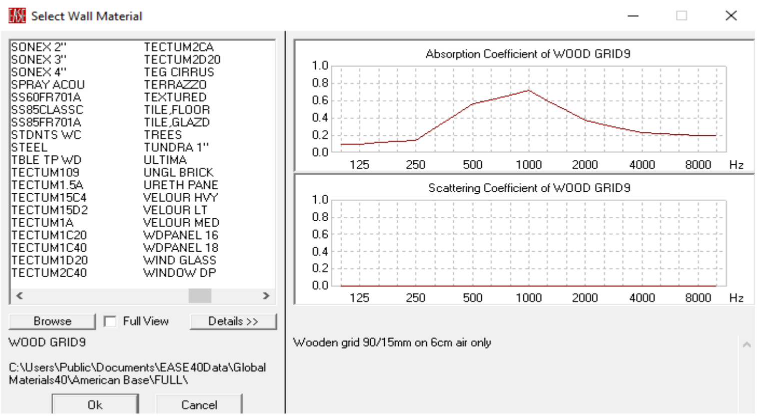


Figure 9: Wall 0 material

For wall zero, we used the material *"good grid 9"* to absorb medium frequencies. This wall is the less important since is located below and above the stage mouth.

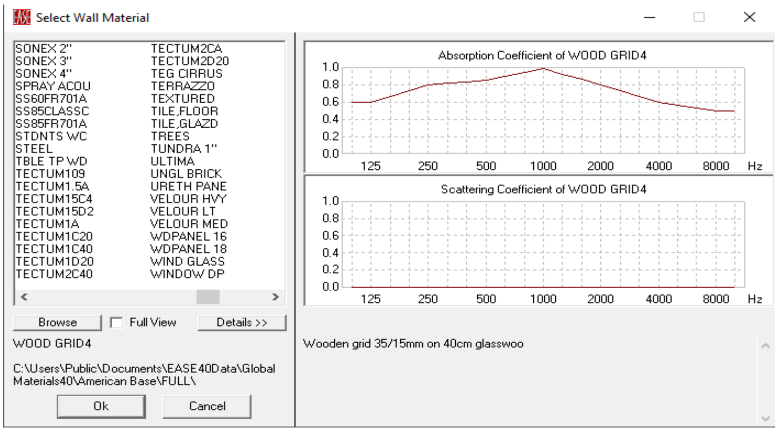


Figure 10: Wall 1 material

For wall one we needed a very absorbent material for the reason we explained earlier, when we mentioned that we divided the side walls into two. We believed that *"wood grid 4"* was the best option.

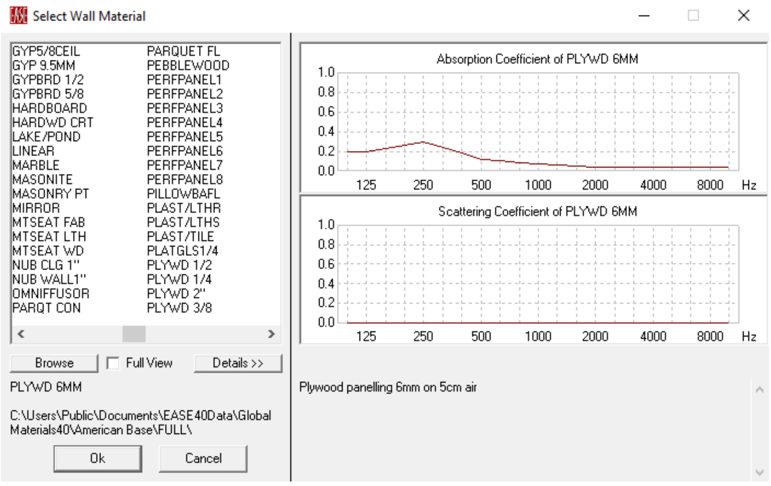


Figure 11: Wall 2 material

For wall two we used "plywood panelling", a material with low absorbency. We opted for a low absorption material sacrificing the few paths that bounced off it, compared to the many that bounced off wall 1.

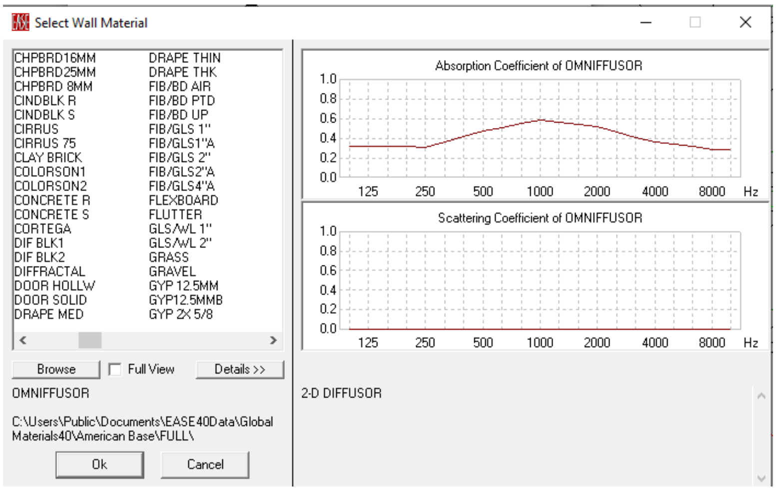


Figure 12: Wall 3 material

Wall three is made of a material with a low/medium absorption coefficient for all frequencies, with a slight increase for mid frequencies. *"omnifussor".*

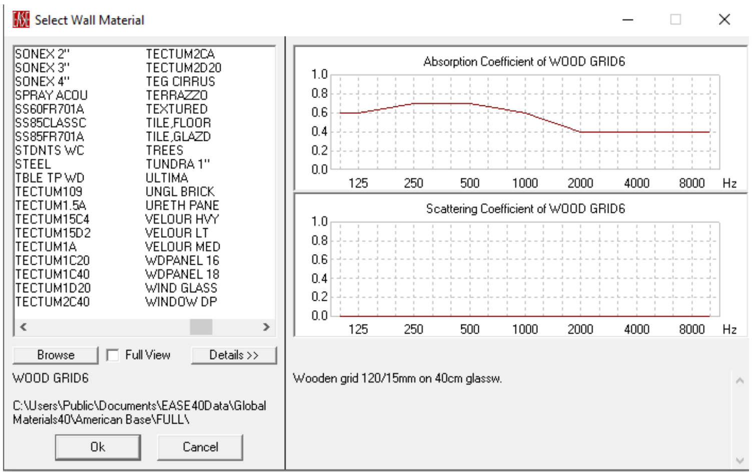


Figure 13: Ceiling 1 material

For ceiling one and two we have implemented the same strategy as for walls one and two. For the ceiling one we used *"wood grid 6"*.

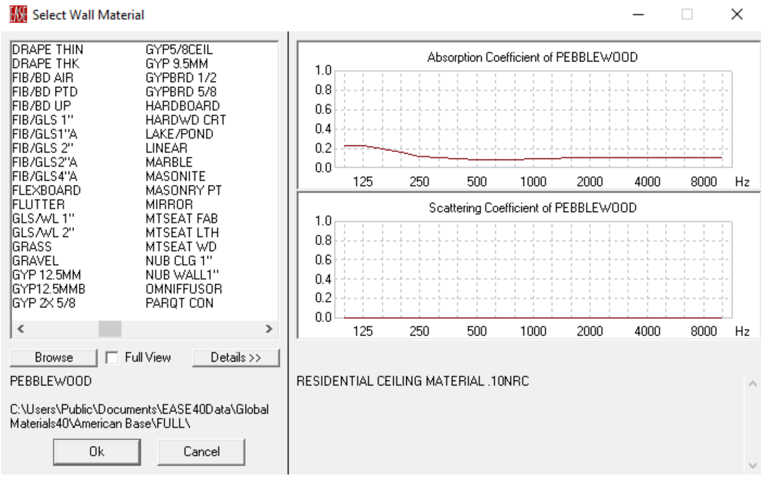


Figure 14: Ceiling 2 material

Ceiling two is made of *"pebble wood"*.

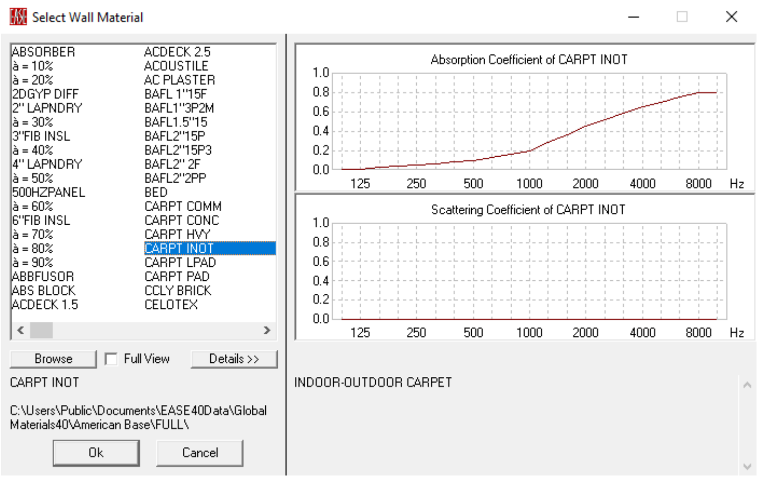


Figure 15: Floor material

The flooring was the material that allowed us the least flexibility, as all flooring materials are very similar. We opted for a *"indoor-outdoor carpet"*, since it gave us the best results.

2.3. ACOUSTIC CRITERIA

2.3.1. REVERBERATION TIME

As the lab guide says, “The finished room should have an RT according to Sabine in the range of 0,8s to 1,2s for all the frequency bands from 125Hz to 4 KHz.” We accomplished it with a maximum error of -0,04s.

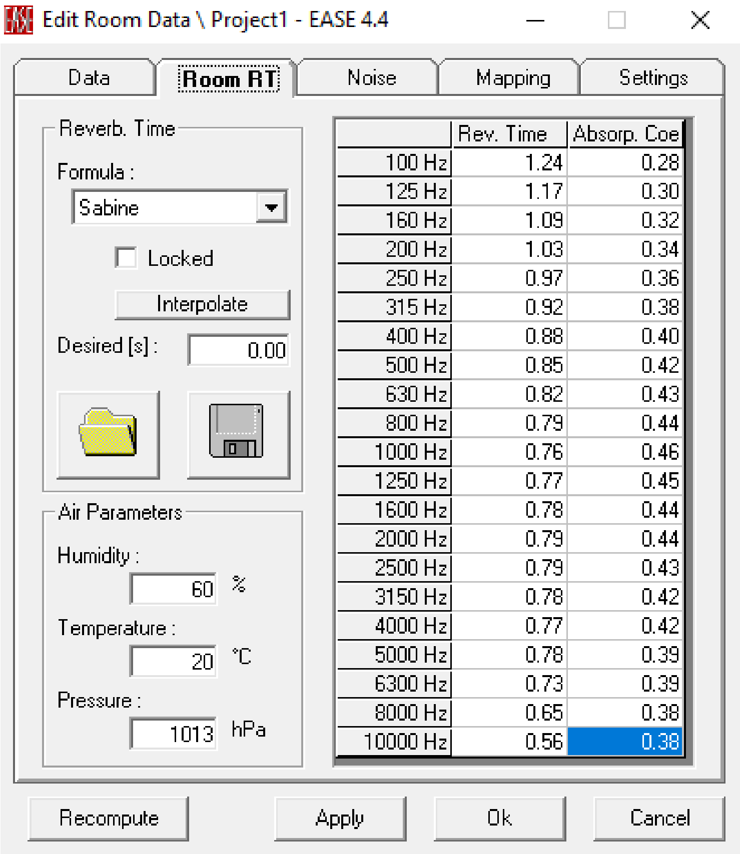


Figure 16: Room reverberation time

To calculate the room’s reverberation time, we had to choose a material for all those surfaces to which we hadn't assigned one:

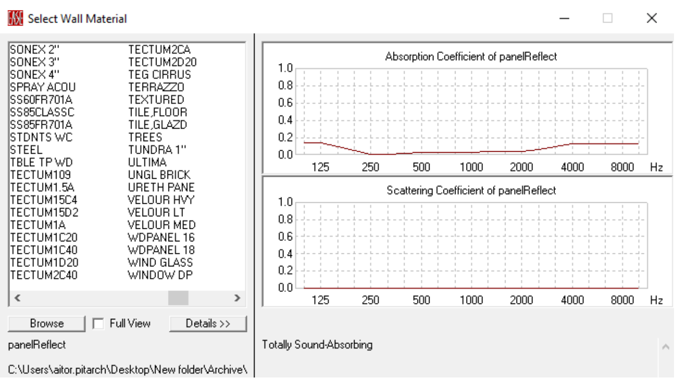


Figure 17: Reflector panel material

For the reflector panel we’ve used a material that was given to us in the project folder, *“panelReflect”.*

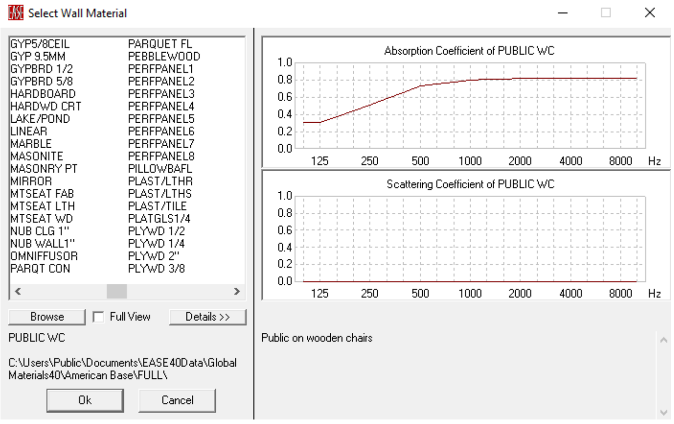


Figure 18: Public and their seats

The blocks representing the seats (with public) are covered with one of the materials from the EASE database, named *"publicwc".*

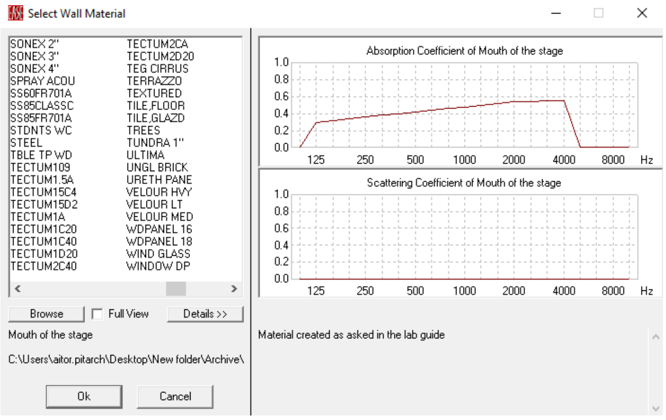
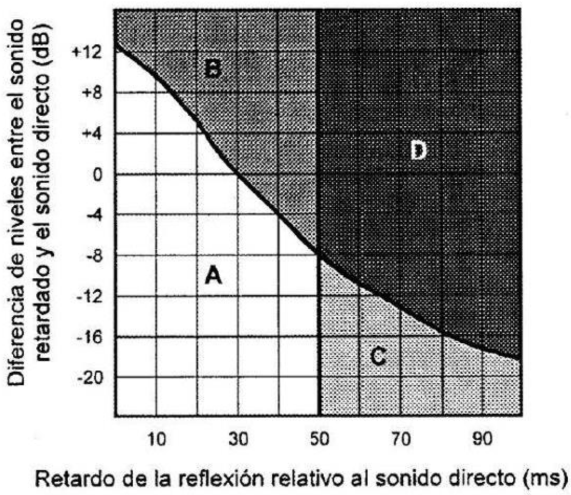


Figure 19: Mouth of the stage material

The surface representing the mouth of the stage is covered with a self-defined material with linearly growing absorption coefficients from 0,3 at 125Hz to 0,55 at 4 kHz.

2.3.2. ECHOGRAMS

To evaluate the behaviour of early reflections in our theatre design, we generated echograms for four selected seats at 500 Hz, 1 kHz and 2 kHz. These echograms allowed us to observe the arrival times and energy levels of reflections relative to the direct sound. Following the criteria in the lab guide, we compared our results with the Haas diagram, which indicates whether a reflection falls into acceptable regions or into region *D*, where late and strong reflections can negatively affect clarity and speech perception. According to the guide, any reflection appearing in region *D* would require modifying the room to suppress it, without excessively compromising the reverberation time (RT). By reviewing the echograms for each seat and frequency, we verified whether any problematic reflections were present and assessed whether our current design meets the recommended acoustic behaviour.



(To check the position of any of the seats mentioned below, refer to Figure 33: Seats Map.)

Seat 2:

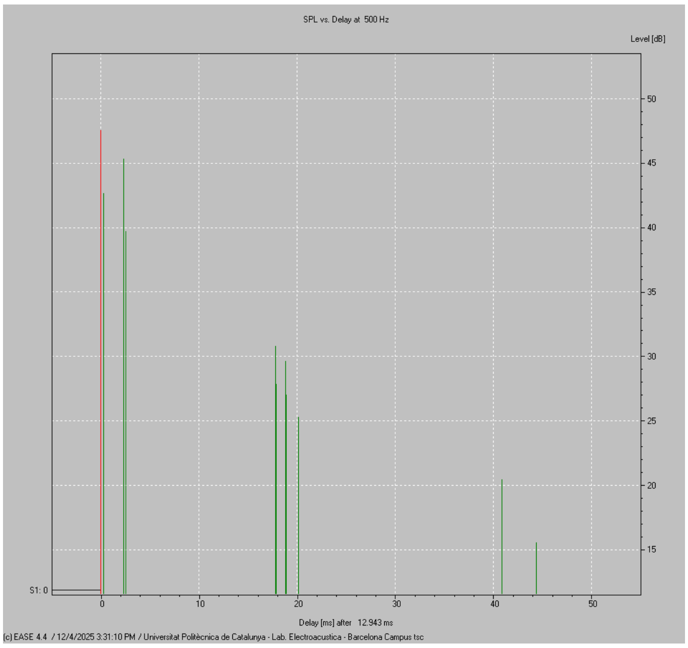


Figure 20: Echogram [Seat 2, 500Hz]

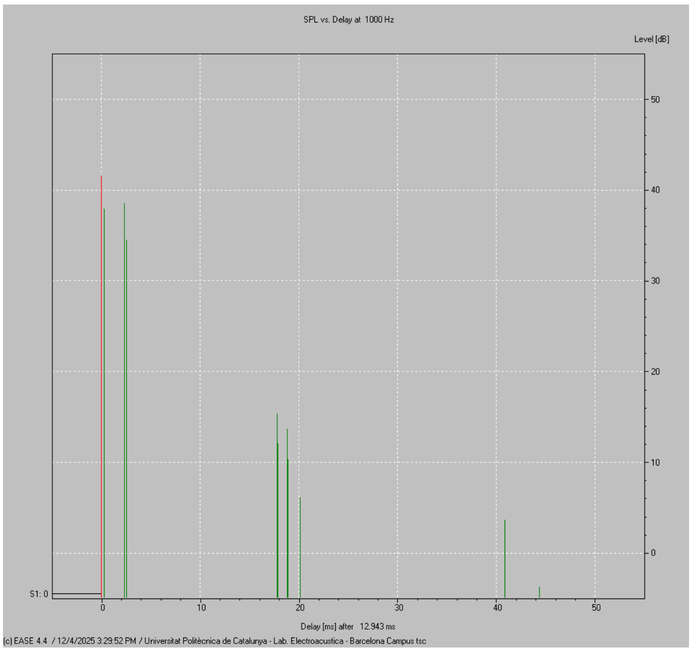


Figure 21: Echogram [Seat 2, 1kHz]

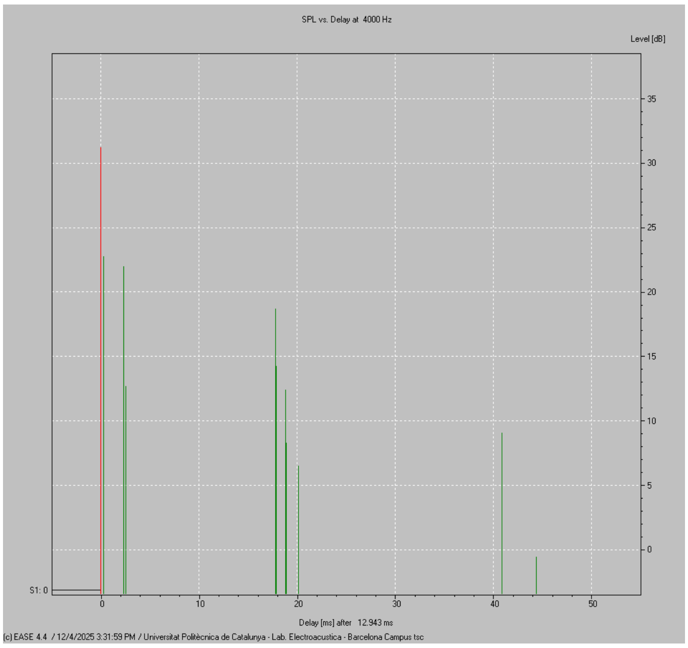


Figure 22: Echogram [Seat 2, 2kHz]

The echograms for Seat 2 show very early reflections due to its position close to the source. The reflection levels remain well below the Haas diagram's critical region, indicating good clarity and minimal interference from late reflections.

Seat 4:

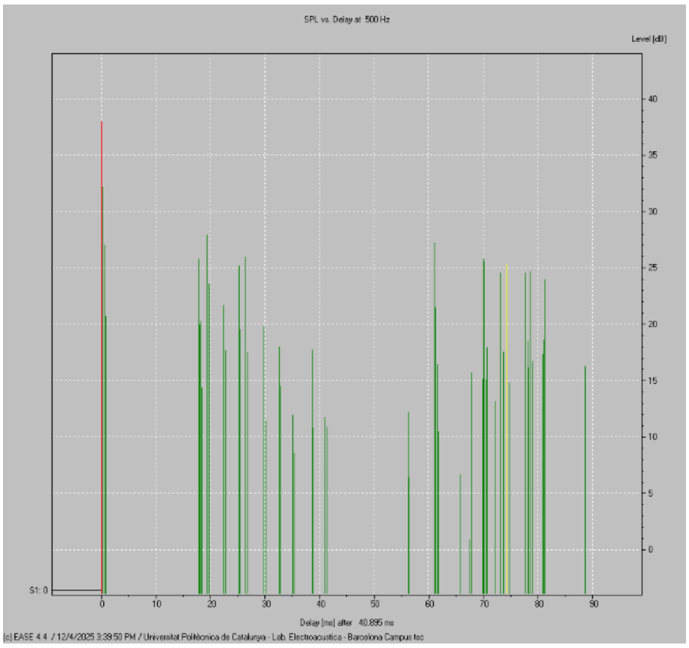


Figure 23: Echogram [Seat 4, 500Hz]

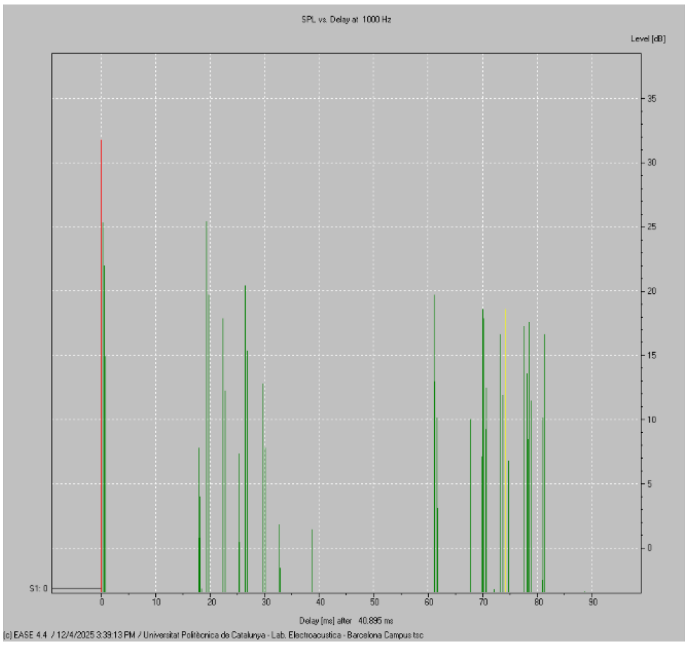


Figure 24: Echogram [Seat 4, 1kHz]

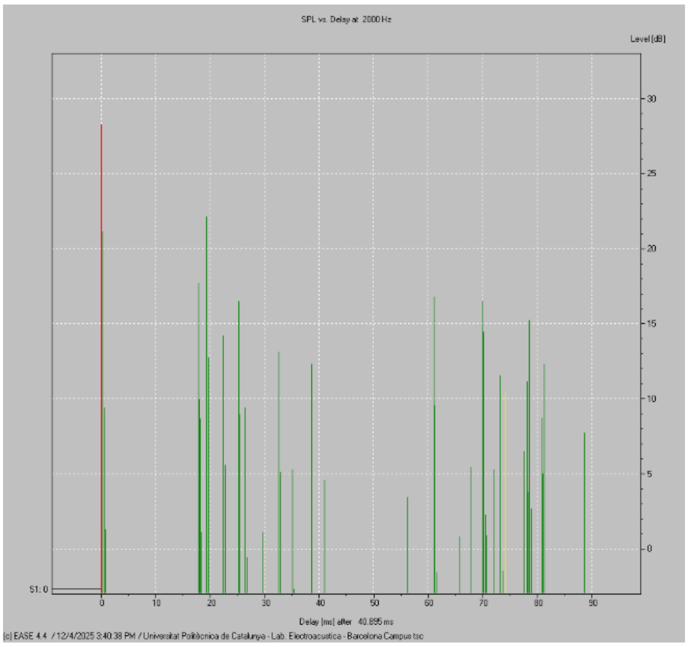


Figure 25: Echogram [Seat 4, 2kHz]

Seat 4 presents a balanced reflection pattern, with early reflections arriving at moderate delays typical of a central listening position. The echograms remain within acceptable limits, suggesting stable clarity across the main frequency bands.

Seat 5:

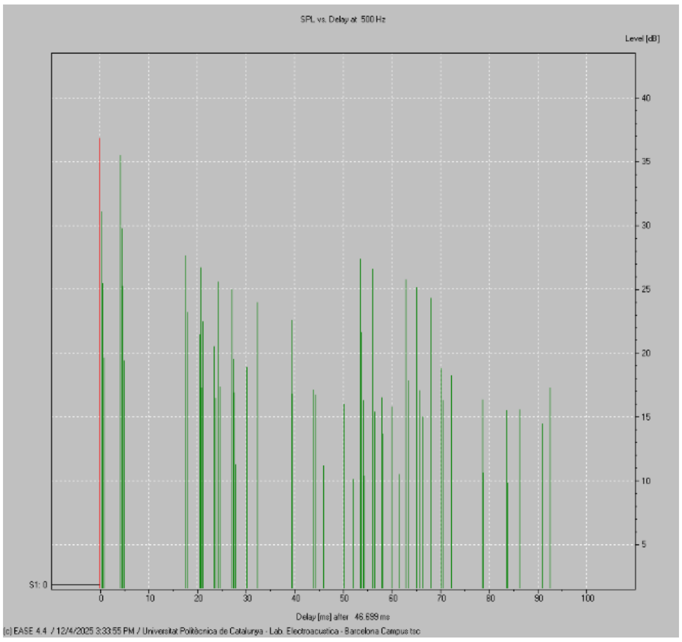


Figure 26: Echogram [Seat 5, 500Hz]

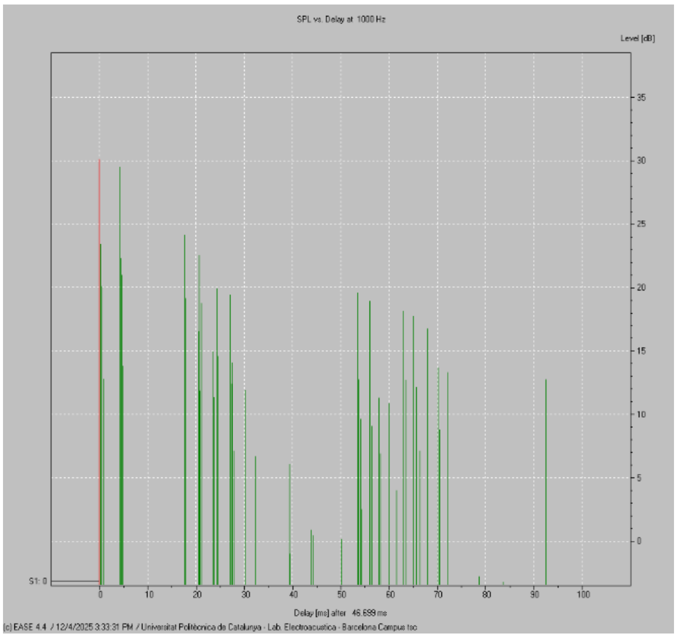


Figure 27: Echogram [Seat 5, 1kHz]

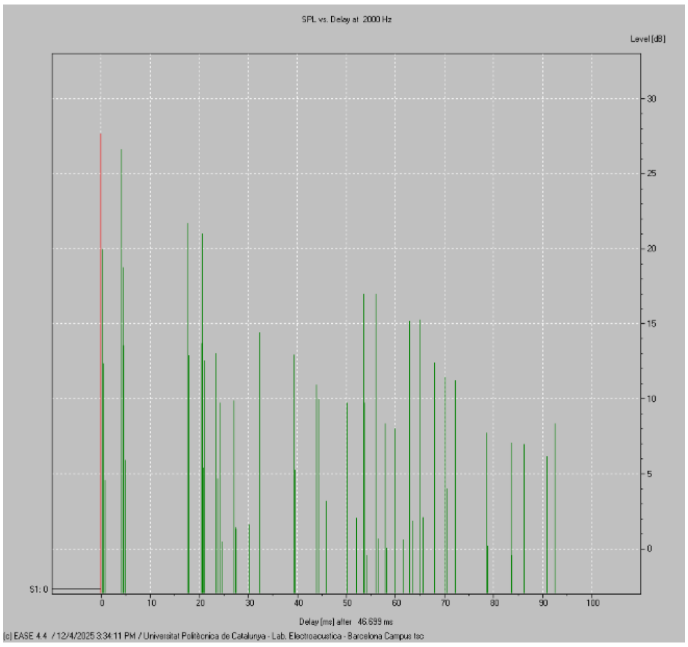


Figure 28: Echogram [Seat 5, 2kHz]

From the side seating position of Seat 5, some reflections arrive slightly later due to the increased distance to certain surfaces. However, the echograms do not show any reflections entering the problematic Haas region, meaning no significant intelligibility issues are expected.

Seat 6:

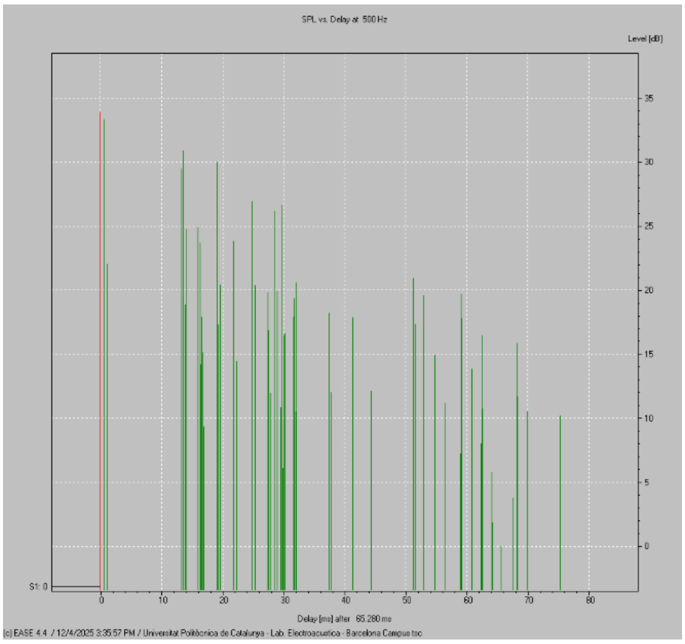


Figure 29: Echogram [Seat 6, 500Hz]

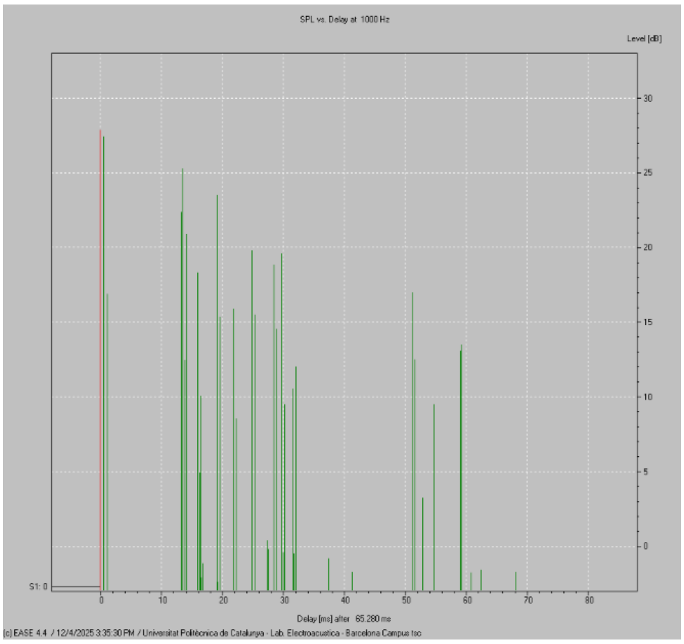


Figure 30: Echogram [Seat 6, 1kHz]

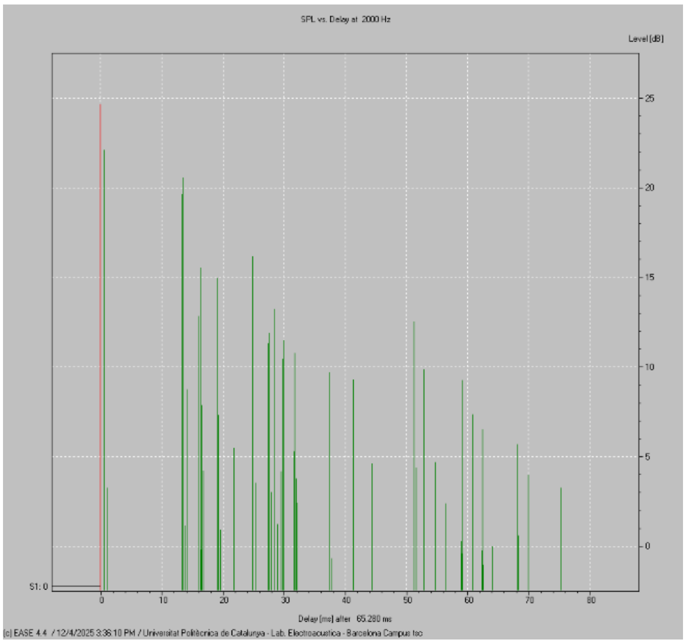


Figure 31: Echogram [Seat 6, 2kHz]

Seat 6 shows longer reflection delays, which is consistent with being located at the rear of the theatre. Although reflections arrive later than in the other seats, none appear strong enough to fall into the Haas diagram’s critical region, so clarity remains adequate.

2.3.3. STI map

We wanted to verify that the space would provide good speech intelligibility. To assess this, we generated an STI (Speech Transmission Index) map. STI ranges from 0 to 1 and reflects how clearly speech is understood, based on factors such as reverberation, background noise, and loudspeaker placement. The resulting color-coded map allowed us to visualize intelligibility throughout the theatre and confirm whether our design met the required performance.

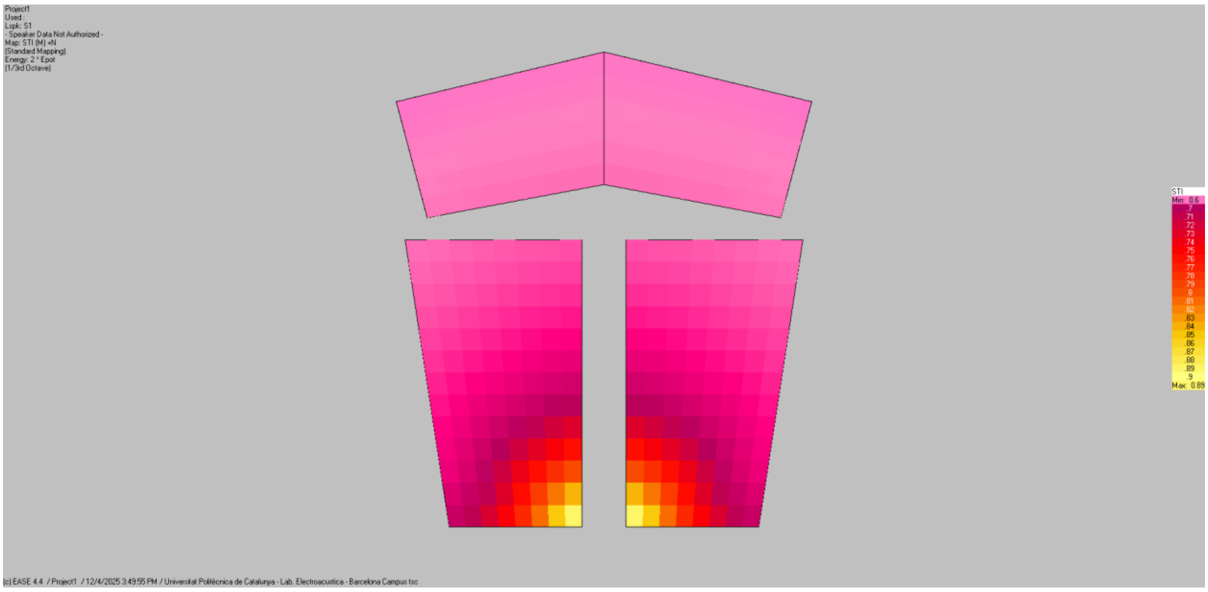


Figure 32: STI map

The STI map shows a clear gradient in intelligibility across the room. The front rows (bottom area of the map) achieve the highest STI values, indicating excellent speech clarity and a strong direct-to-reverberant ratio. Moving toward the middle of the seating area, STI values remain stable and generally within the “good” range, confirming that the loudspeaker coverage is uniform in the central zone. In the rear seats (top of the map), STI decreases slightly due to the longer distance from the source and increased influence of late reflections. However, the values still remain within acceptable limits for theatre and cinema applications. Overall, the STI distribution suggests that the current design provides consistent and adequate intelligibility throughout most of the audience area.

2.3.4. Auralization

Auralization of a room model consists in creating an audio file that allows listening to how a chosen acoustic source would sound to a listener at a given position in the room. To do this, we must first create an Impulse Response for a chosen source position and listener seat. This is similar to an echogram, and we can also use ray-tracing to obtain it.

Here’s a schematic of our theatre room useful to easily locate every simulated seat and a link to a video with the audio simulations we did for seats 2, 4, 6 and 7.

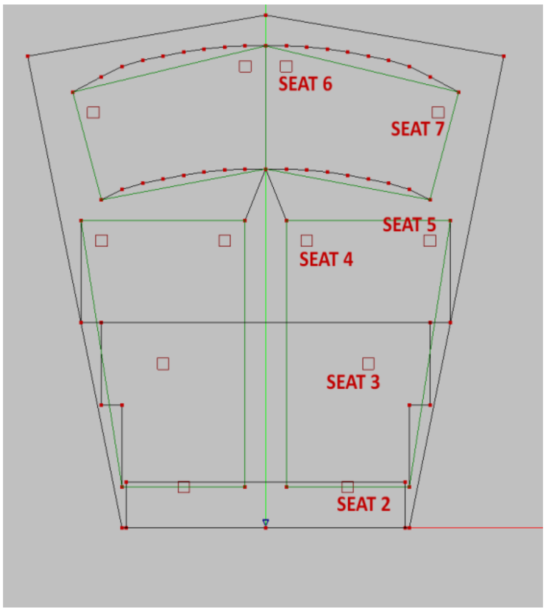


Figure 33: Seats map

Figure 34: Video with the audio simulations

https://youtu.be/JPpB_tDrtKk

Seat 2 – Front
At Seat 2, the audio is perceived as loud and highly intelligible. The direct sound dominates over the early and late reflections, resulting in very clear speech and minimal coloration.

Seat 4 – Centre of the Room
Seat 4 presents the strongest sense of reverberation among all the simulated positions. Being in the middle of the room, this seat receives several delayed sound paths that still retain enough energy to produce noticeable echoes and reduce clarity slightly compared to the other seats.

Seat 6 – Rear Centre
Seat 6 offers good intelligibility, although the perceived loudness is slightly lower than in the front seats. Reflections are present but generally well controlled, leading to a balanced and understandable audio experience. Compared with Seat 7, it sounds a bit louder.

Seat 7 – Rear Side
Seat 7 also provides clear and intelligible audio, but at a slightly lower level than Seat 6 due to its position farther to the side. Reverberation is somewhat reduced compared to the centre rear seat, likely because of fewer strong reflections reaching this position.

3. CINEMA

3.1. ROOM CHRACTERISTICS

To sum up the process, we made some adjustments to the original theatre design. First, we removed the reflecting panel, then we installed two new loudspeakers (JBL model 3622N) provided in the folder. To meet the SPL criteria (a difference of no more than 6 dB between different audience areas), we ensured that both loudspeakers were properly oriented. With a few adjustments, we finally achieved the correct SPL.

The two cinema loudspeakers were placed on the upper left and right sides of the screen, as shown in the image below (from the point of view of one of the loudspeakers).

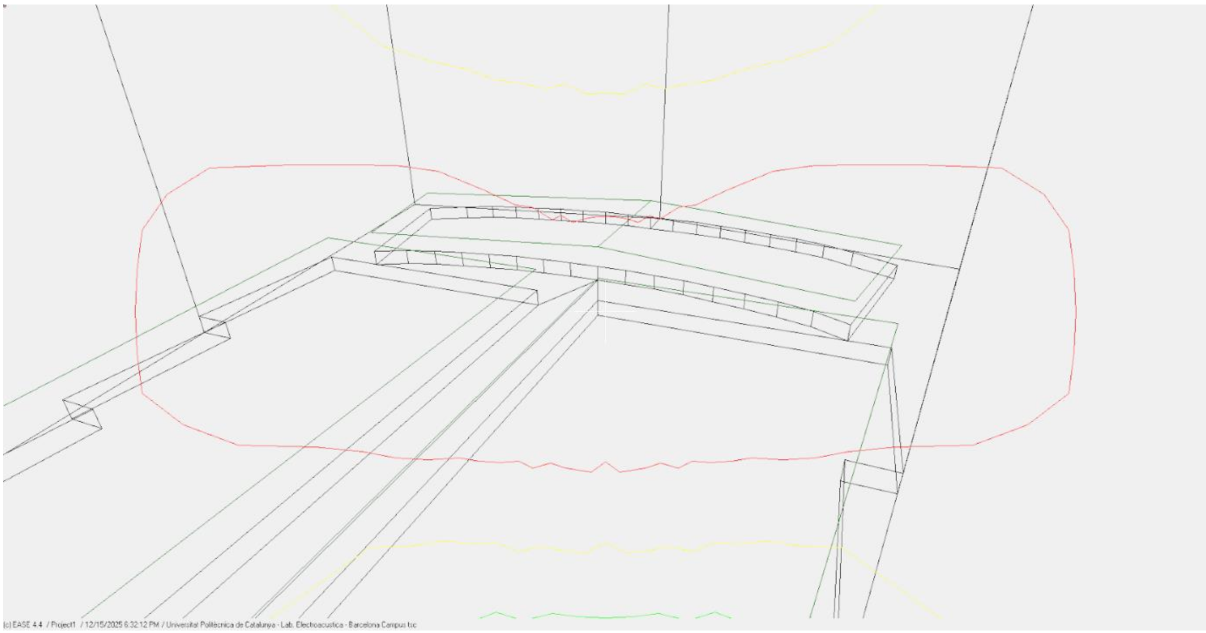


Figure 35: Loudspeaker View

3.2. TOTAL SPL

The criteria we have to meet at this particular stage of the cinema design, as stated before, are; a total SPL of at least 90 dB at every audience position and uniformity of coverage, no more than a 6 dB difference between the lowest and highest total SPL throughout the audience area.

In the images below, we can clearly see that the cinema design meets the SPL level requirements, since all levels are above 90 dB and the largest SPL difference is 1.31dB.

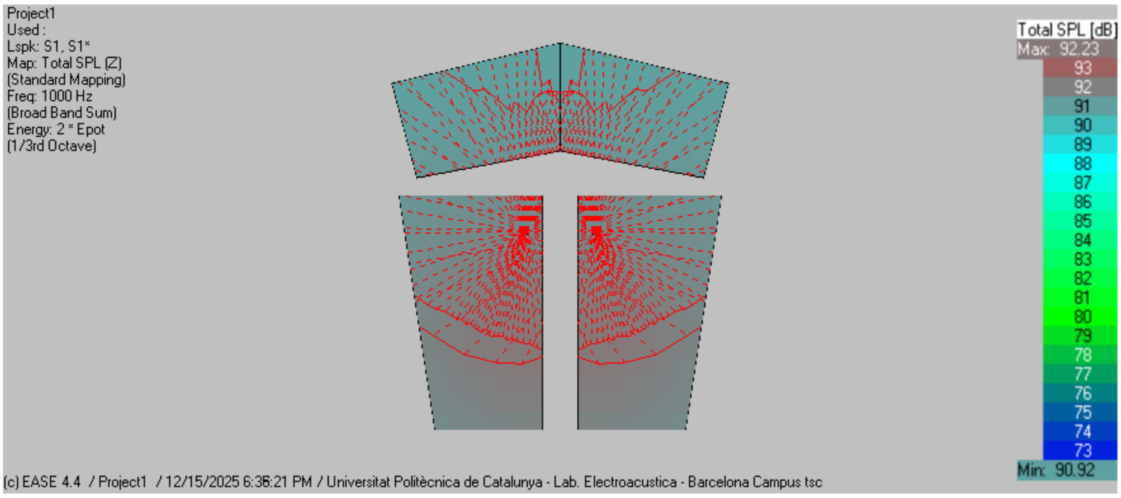


Figure 36: SPL map of the cinema

3.3. STI MAP

The intelligibility criterion was to guarantee, for the entire room, an STI index of at least 0.65. STI predicts the likelihood of syllables, words, and sentences being understood. As an example, for native speakers this likelihood is given by the following ranges:

STI Range	Qualitative Description	Meaning
0.00 – 0.30	Very Poor / Unintelligible	Message is barely understood; unsuitable for public address systems.
0.30 – 0.45	Poor	Few words are intelligible; only for very simple, non-critical contexts.
0.45 – 0.60	Fair / Minimum Acceptable	Simple messages and familiar words are understood; lower limit for public systems.
0.60 – 0.75	Good	Most messages are clear; suitable for general sound reinforcement.
0.75 – 1.00	Excellent	Very clear speech, easy to comprehend; typical in well-designed studios.

As we can see in the image below, our cinema has a minimum STI of 0.67 and a maximum of 0.76, which means that all seats and audience areas in the cinema achieve good or excellent intelligibility.

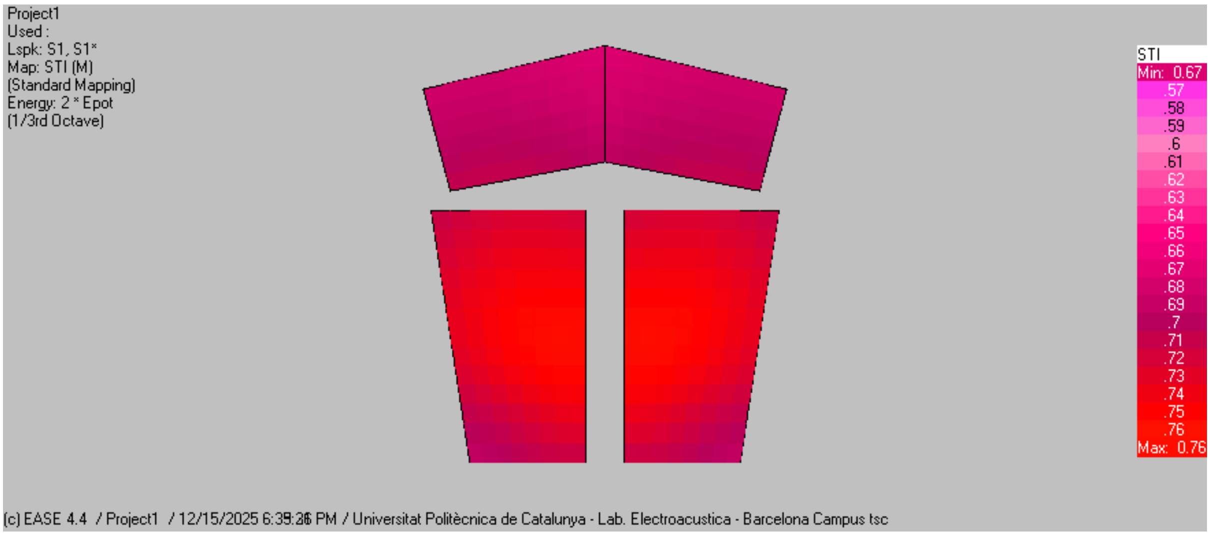


Figure 20: STI Map of the Cinema

4. CONCLUSIONS

To conclude, this project has developed a theater that meets a set of specific requirements, creating a space suitable for both theatrical performances and cinema use. To achieve this objective, materials with appropriate absorption coefficients were selected in order to minimize potential echoes in areas where the ceiling above the audience is relatively high.

The analysis of the results shows that the designed theater can operate both as an auditorium and as a cinema, since it satisfies the criteria defined for each case, including speech intelligibility indicators such as STI and RASTI, where applicable. With regard to possible delays at each seat, the echograms indicate that, although some areas are more exposed to reflections that could distort the received signal, these effects are not severe enough to pose a real problem.

Overall, the enclosure design complies with all the specified requirements and does not exhibit any major issue that would hinder or prevent its use, so it can be regarded as a suitable solution for both theater and cinema applications.