

Comparative analysis of acoustic parameter measurements over time: A case study of the National Theatre in Zagreb

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Abstract—This paper presents a comparative acoustic study of the National Theatre in Zagreb based on two measurement campaigns conducted in 2022 and 2025. Standard room acoustic parameters, including EDT, T_{30} , C_{80} , D_{50} , and IACC, were evaluated to assess temporal stability and spatial distribution across audience areas. Results indicate consistent reverberation characteristics over time, with minor shifts in clarity favoring the stalls in recent measurements. Spherical array recordings combined with panoramic imaging enabled detailed visualization of direct sound and reflection patterns. The findings contribute to the ongoing monitoring and acoustic maintenance of historical performance spaces.

Keywords—acoustic measurements, Croatian theatre, comparative analysis.

I. INTRODUCTION

Multi-year acoustic assessments are essential for evaluating stability and possible variation of room acoustic performance over time. In historic theatres, where both architectural preservation and active use intersect, repeated measurements help detect subtle changes due to aging materials, renovations, or evolving operational conditions.

This paper presents a comparative acoustic study of the National Theatre in Zagreb, Croatia, based on measurement campaigns conducted in 2022 and 2025 [1]. Standard room acoustic parameters were obtained using omnidirectional sources and microphones, focusing on reverberation time, early decay time, clarity, definition, and sound strength. Identical measurement procedures and equipment configurations were adopted through both campaigns to ensure consistency and allow for direct comparison.

As built toward the end of the 19th century, it was common practice to design opera theatres with a horseshoe-shaped plan, following the *Teatro all'Italiana* tradition [2]. However, the optimal shape for both acoustics and unobstructed audience sightlines was a subject of much debate. An

alternative was the elliptical plan, as proposed in the treatises of Pierre Patte [3], which was implemented in the Communal-Pavarotti Theatre of Modena [4] and the National Theatre of Lisbon [5], to cite a few examples. The National Theatre in Zagreb, however, reflects Eastern European influence, as already discussed in previous literature [6, 7].

In this study, the measured results have been analyzed following the standard requirements, as per ISO 3382-1 [8], with particular attention to changes in acoustic behavior over the three-year interval. The study provides insights into the temporal stability of acoustic characteristics in historic performance spaces and contributes reference data for monitoring heritage buildings in continued use.

II. HISTORICAL BACKGROUND OF THE NATIONAL THEATRE IN ZAGREB

The Croatian National Theatre, located in the heart of Zagreb, is one of the most important symbols of the country's cultural and artistic identity. It was opened in 1895, thanks to Emperor Franz Joseph I, and designed by the famous Viennese architects Herman Helmer and Ferdinand Fellner, who built many beautiful theatres across Europe. Built in a Neo-Baroque style, the theatre stands out for its elegant architecture: a symmetrical façade, golden domes, grand columns, and richly decorated interiors with frescoes, marble staircases, and ornate chandeliers [1]. The main auditorium, with its deep red velvet and golden details, creates a space that feels both majestic and welcoming. The theatre can hold up to 765 people. Its floor plan is U-shaped, fitting inside a square that measures 17.6 meters on each side [9]. Inside, the audience seating is arranged across three levels: two rows of balconies and an upper gallery, which is gently sloped towards the stage. A view of the theatre is shown in Figure 1.



Fig. 1. Internal view of the National Theatre, Zagreb.

III. ARCHITECTURAL FEATURES

The National Theatre in Zagreb accommodates a total of 765 spectators, with 345 seats located in the stalls and an additional 420 distributed across the elevated boxes and the uppermost balcony. The floor plan follows a U-shaped configuration inscribed within a square footprint, each side measuring 17.6 m [10]. Overhead, the main auditorium is enclosed by an ornate vaulted ceiling, centrally adorned with a chandelier. A striking contrast is observed between the golden-hued walls and the bright white columns, further accentuated by the oxidized green of the copper roof, an aesthetic intentionally crafted by the original painter [9].

The stage area measures 24.1 meters in length and 15 meters in width and features a rotating platform with a radius of 8.5 meters. The proscenium arch spans 11 meters in width. The orchestra, comprising up to 80 musicians, may be positioned at one of three distinct levels: flush with the stage floor, aligned with the stalls floor, or recessed 1.5 meters below in a dedicated orchestra pit. The first-order box partitions are embellished with statues symbolizing the Muses, whereas the upper balcony level is decorated with floral motifs, reflecting a variation in ornamental approach across different tiers [9]. The plan and longitudinal sections are shown in Figures 2 and 3.

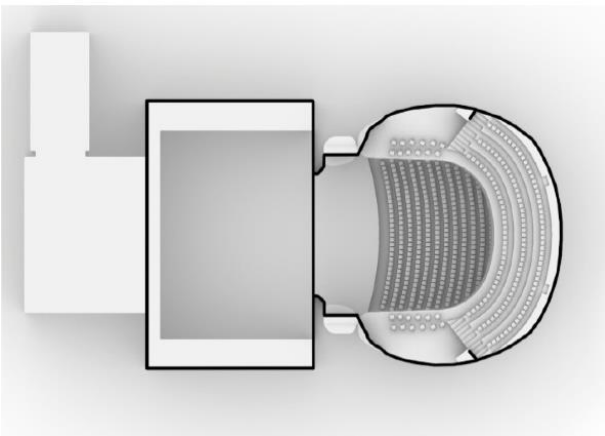


Fig. 2. Plan the layout of the National Theatre in Zagreb.

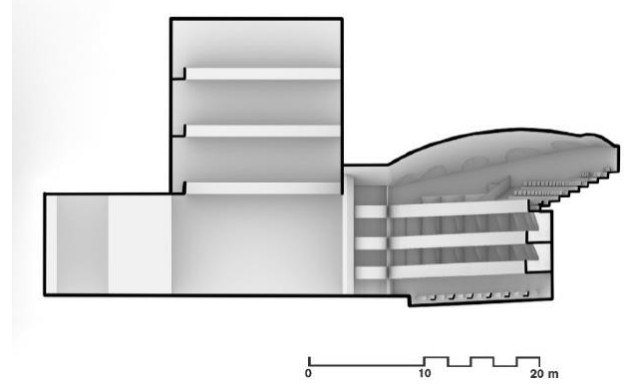


Fig. 3. Longitudinal section of the National Theatre in Zagreb.

TABLE I summarizes the architectural features of the Teatro Sociale.

TABLE I. ARCHITECTURAL FEATURES OF THE NATIONAL THEATRE IN ZAGREB.

Description	Features
Type of plan layout	U-shape
Total capacity (No. of seats)	765
Main Hall axes (m)	17.6 × 17.6
Stage dimension (m)	24.1 × 15
Inclination of stalls	0%

IV. ACOUSTIC MEASUREMENTS

An acoustic measurement campaign was conducted to assess the current room response characteristics of the main hall of the National Theatre in Zagreb. To enable a direct comparison with the 2022 survey [6, 7], in exception for a new sound source point, the 2025 measurements strictly replicated the earlier setup, both in terms of equipment and receiver-source positioning [11]:

- An equalized omnidirectional sound source (Look Line);
- A suite of microphones comprising:
 - a) A binaural dummy head (Neumann KU-100);
 - b) A B-format ambisonic microphone (Sennheiser Ambeo);
 - c) An omnidirectional microphone (Brüel & Kjær);
 - d) A 64-channel spherical array (MH Acoustics em64 Eigenmike®);
- A personal computer interfaced with the source and all microphone systems for synchronized signal emission and data capture.

The loudspeaker was mounted at a height of 1.5 meters from the stage floor, while microphone positions were set at 1.2 meters above the ground to simulate the average ear height of a seated listener. An Exponential Sine Sweep (ESS) signal [12], spanning the 40 Hz to 20 kHz frequency range and lasting 15 seconds, was used as the excitation signal.

All measurements were performed under unoccupied conditions. Microphones were distributed across various

listener positions, covering both the stalls and the elevated boxes at different levels [13]. Receiver placements were identical to those used in the previous campaign to ensure consistency in spatial sampling and to isolate any variations in acoustic parameters from temporal changes rather than experimental setup. The source and receiver locations are shown in Figure 4.

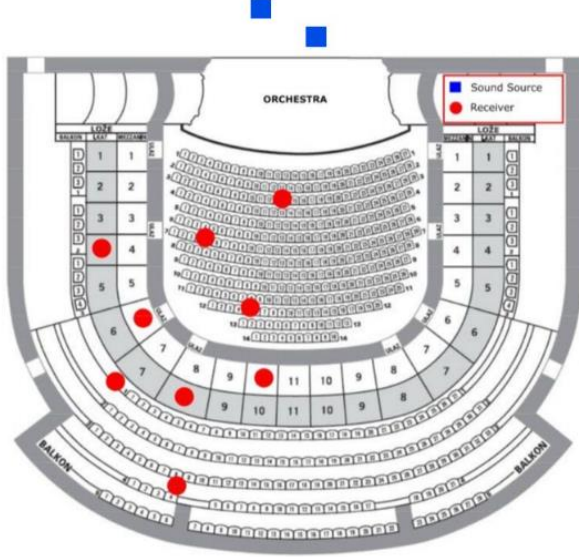


Fig. 4. Position of the equipment during the acoustic measurements.

V. ANALYSIS OF RESULTS

A. Comparative results of the ISO acoustic parameters

The collected impulse responses (IRs) were post-processed and analysed using the Aurora plugin [14], which operates within the Adobe Audition environment. Key room acoustic parameters, including both monaural and binaural metrics, were extracted following the procedures defined in ISO 3382-1 [8]. The final results reflect the averaged values across all receiver locations.

Figures 5 and 6 present the frequency-dependent values of Early Decay Time (EDT) and Reverberation Time (T_{30}), respectively, comparing results obtained from the boxes and stalls in the National Theatre during the 2022 (past) and 2025 (current) measurement campaigns.

Both parameters exhibit a similar overall trend: values systematically decrease as frequency increases, which is consistent with typical acoustic behaviour in enclosed spaces due to greater absorption of high-frequency energy. However, subtle differences between EDT and T_{30} , as well as between different seating areas and measurement years, offer insight into the evolving acoustic conditions of the theatre [15].

In terms of EDT (Figure 5), a noticeable difference is observed between the past and current measurements, particularly in the boxes. While in the earlier measurements the boxes showed significantly shorter EDT values in the mid-to-high frequency range (notably at 1000–2000 Hz), the current measurements reveal a more uniform distribution of EDT between boxes and stalls across all frequencies [16]. This suggests that early reflections in the boxes may have been enhanced in recent years, potentially due to changes in surface materials or seating configurations that increased the

reflectivity or reduced the absorptivity of the surrounding elements [17].

T_{30} (Figure 6), which represents the reverberation time over a longer decay interval, shows a more consistent pattern between all curves. Both past and current data for boxes and stalls are closely aligned, particularly from 250 Hz to 1000 Hz. Compared to EDT, the temporal variation in T_{30} is less pronounced, indicating that the overall reverberant field of the space has remained stable over time. Small increases in T_{30} in the stalls at 2000 Hz and 4000 Hz in the current measurements may reflect minor changes in high-frequency reflectivity or background noise conditions, but these are within an acceptable range [18].

The discrepancy between EDT and T_{30} trends, especially in the boxes, highlights the sensitivity of EDT to early reflections and local geometries, whereas T_{30} is more indicative of the global reverberation characteristics of the room.

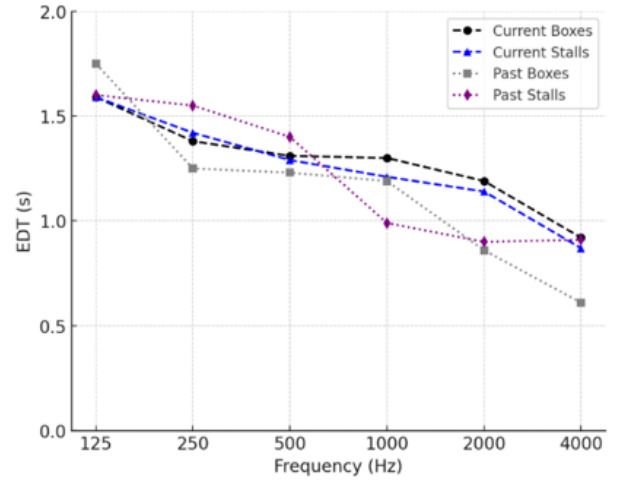


Fig. 5. Comparative results of Early Decay Time (EDT).

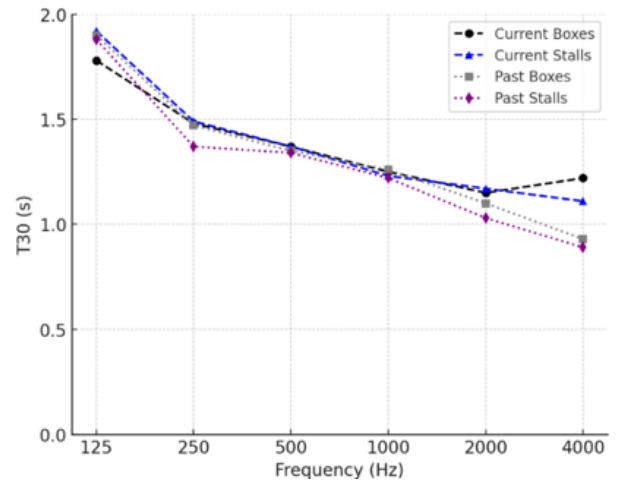


Fig. 6. Comparative results of Reverberation Time (T_{30}).

Figure 7 displays the clarity index (C_{80}) values for both stalls and boxes, compared to past and current measurements.

In general, C_{80} values increase with frequency, consistent with expectations, as higher frequencies contribute more to early-arriving energy. Compared to the past data, the current

boxes show lower C_{80} values across most frequencies, particularly above 1000 Hz, indicating a slight reduction in perceived clarity in that area, while still in the ideal range. In contrast, the current stalls exhibit improved clarity at higher frequencies (2000–4000 Hz) relative to past measurements, suggesting more favourable early-to-late energy ratios in the stalls in recent conditions [19].

Past measurements indicate higher C_{80} in the boxes than in the stalls, especially above 1000 Hz, while the current data show the reverse: stalls now exhibit higher C_{80} than boxes. This inversion implies a spatial redistribution of clarity, possibly linked to localized changes in surface reflection, audience area materials, or subtle architectural modifications [20].

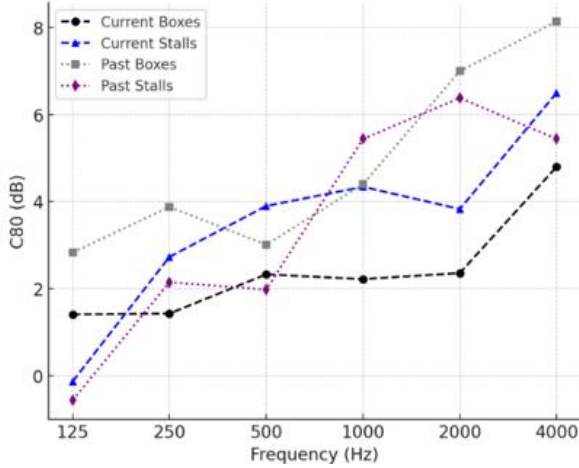


Fig. 7. Comparative results of music clarity (C_{80}).

D_{50} increases steadily with frequency in all cases, reflecting the greater proportion of early-arriving energy at higher frequencies shown in Figure 8. The current stalls consistently exhibit higher D_{50} values than the current boxes, particularly above 500 Hz, indicating improved speech intelligibility in the stalls [21].

Compared to past values, current boxes show a modest increase only at higher frequencies (2000–4000 Hz), while current stalls maintain or slightly improve upon earlier values across all bands. The past boxes continue to show the highest D_{50} overall, particularly from 1000 Hz upwards.

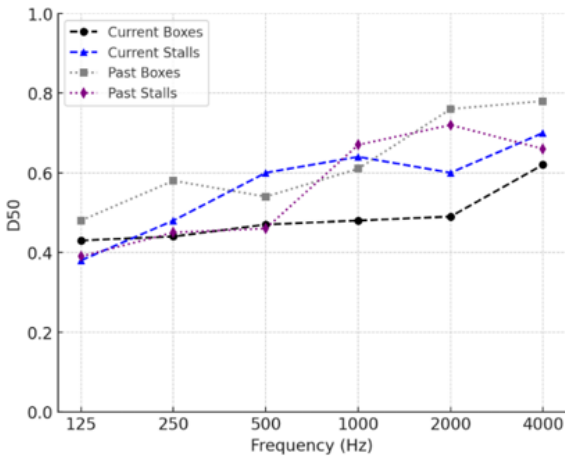


Fig. 8. Comparative results of Definition (D_{50}).

As shown in Figure 9, the current Interaural Cross-Correlation Coefficient (IACC) exhibits a clear frequency-dependent trend. At low frequencies (125–250 Hz), IACC values are close to 0.9, indicating a high degree of similarity between signals reaching the left and right ears. This is consistent with the omnidirectional nature of low-frequency sound waves, which produce minimal spatial separation and thus contribute little to lateral perception [22].

As frequency increases, IACC values decrease significantly. In the mid-frequency range (500–1000 Hz), IACC drops to approximately 0.3, and at high frequencies (2000–4000 Hz), values further decline, with the balcony positions exhibiting IACC values around 0.2. These lower values at higher frequencies suggest an enhanced perception of spatial separation and a greater presence of lateral reflections, which are important for the listener's sense of envelopment and spatial impression [23].

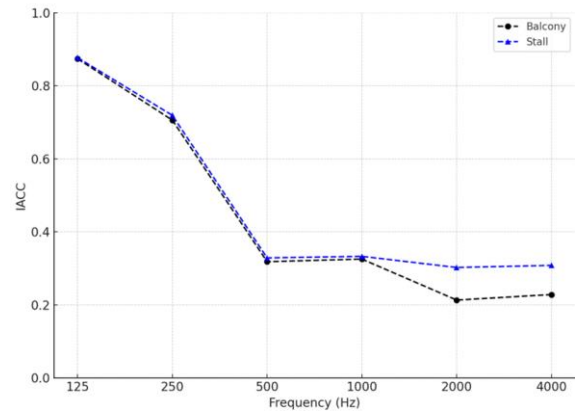


Fig. 9. Measured results of Interaural Cross-Correlation (IACC).

B. Acoustic maps

The use of the spherical array microphone em64 Eigenmike® and the panoramic camera (Qoocam) enabled the elaboration of the sound maps obtained in the same positions [24] as illustrated in Figure 10. The direct sound wave impacting the microphone probe is distinguishable as the initial and most intense energy front. The wavefront appears sharply defined and symmetrical, indicating a direct propagation path from the source to the receiver with minimal early reflections at this early stage [25]. The associated sound pressure level is concentrated in the range of approximately 90–92 dBA, represented by the red contour zones, which denote areas of highest energy concentration.

This direct arrival confirms the correct alignment of the source and receiver and provides a time reference for subsequent reflections. The wavefront's shape and uniform intensity distribution also suggest a clear line of sight and low diffraction interference at this measurement position [26]. As expected, the direct sound precedes any boundary reflections in the time-domain impulse response shown below the contour map, marking the point of peak amplitude and establishing the onset of the acoustic event.



Fig. 10. Direct soundwave hitting the microphone probe

Figure 11 shows the first prominent reflection originating from the ceiling, with an intensity reaching approximately 80–82 dB. The reflection is clearly visible in the upper-central region of the panoramic view, where the red and yellow contour lines indicate concentrated energy [27]. Due to the ceiling's smooth and curved surface, the reflected sound maintains coherence and arrives at the microphone probe shortly after the direct sound, without significant diffusion or edge interference.

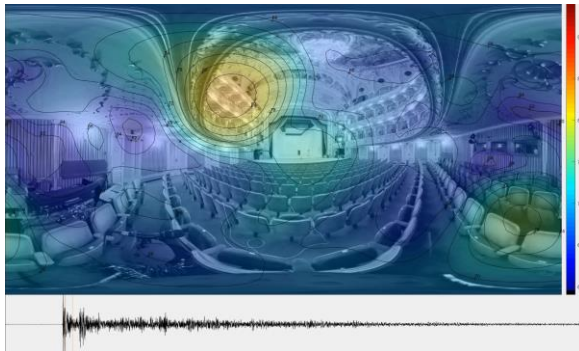


Fig. 11. First reflection hitting the ceiling.

Figure 12 captures a prominent late reflection arriving from the left side wall, with sound energy concentrated in the range of 86–88 dB, as indicated by the red and orange contours [28]. Unlike earlier direct or floor reflections, this reflection occurs later in time, as confirmed by its delayed peak in the impulse response shown below the map. The lateral arrival direction suggests that the sound wave has travelled across the room before reflecting off the vertical boundary, contributing to spatial impression and listener envelopment [29]. The smooth surface of the side wall results in a coherent reflection pattern with minimal diffusion.

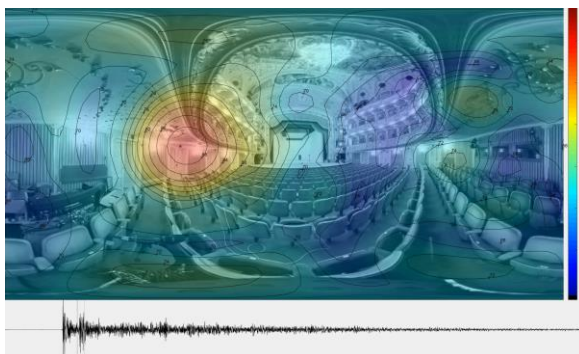


Fig. 12. Late reflection hitting the side wall.

CONCLUSIONS

This study presented a comparative acoustic analysis of the National Theatre in Zagreb, based on measurements conducted in 2022 and 2025. Key parameters such as EDT, T_{30} , C_{80} , D_{50} , and IACC were examined across audience areas to assess temporal changes and spatial variations [30].

Results show that EDT and T_{30} remained consistent over time, indicating stable reverberation characteristics. However, changes in clarity-related parameters (C_{80} , D_{50}) suggest a redistribution of acoustic energy, with improved performance in the stalls and slightly reduced clarity in the boxes. IACC values followed expected frequency-dependent trends, supporting adequate spatial impression [31].

Acoustic maps generated using the Eigenmike® and panoramic imagery provide visual confirmation of direct sound arrival and early and late reflections. These insights enhance understanding of the theatre's acoustic behaviour and support future preservation or adjustment efforts [32].

ACKNOWLEDGMENT

The measurements conducted for this research have been made possible by an Erasmus++ grant, co-funded by the European Union, KA210-VET - Small-scale partnerships in vocational education and training, titled AURALIZE - Project No. 2024-1-IT01-KA210-VET-000245142. Measurements were conducted by L. Tronchin, K. Jambrošić, M. Horvat, C. van Tonder, A. Farina, L. Battisti, and R. Yan.

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