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How Much Does the Variety of Scenery and the Different Percentages of Audience Occupancy Affect the Indoor Acoustics at the National Theater of Zagreb?

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Abstract: The performance of opera and the post-pandemic slow recovery of the public, who have been hesitant to return to frequent attendance of cultural venues, has inspired the authors to analyze the acoustic behavior of the National Theater of Zagreb, by reflecting five specific scenarios. Starting from acoustic measurements undertaken inside the National Theater of Zagreb without any scenery in place, this research study compares the main acoustic parameters simulated with the scenery of *Tosca* in three different acts. A numerical model was realized by reproducing the geometry and the architectural features of this historic performance arts space. Before the simulations, the absorption coefficients applied to the digital entities were calibrated with the values gathered from the recorded impulse responses. After the calibration process, the acoustic simulations were also carried out with the presence of an audience at two percentages of occupancy.

Keywords: cultural heritage; acoustic simulations; opera theater; Zagreb National Theater; scenery

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1. Introduction

The National Theater of Zagreb is considered to be the oldest and most important cultural center in Croatia due to its three activities: opera, theater, and ballet. The artistic production is so fruitful; an average of 220 shows are performed in a season [1]. Because of its national influence over a wide territory, the National Theater of Zagreb is used to promote a seasonal program which is broadly varied, including the performance of local artists representative of different styles and historical periods [2]. Nonetheless, the recitals of classic and contemporary masterpieces attract the biggest audiences.

Furthermore, the National Theater of Zagreb hosts foreign theatrical companies on its stage, and has become one of the centers that supports the social and cultural life of the Croatian capital city. Presently, it is part of international projects, such as the World Theater Festival, promoted by the European Community, FEDORA, and other international organizations [1].

It is a good practice to interconnect different arts as essential parts of the life of a theater. In particular, this paper studies how different types of scenery can affect the acoustic behavior of the hall, since operas have been always performed and appreciated by the Croatian audience at the National Theater of Zagreb [3]. The volumetric shape of the main hall, composed of stalls geometrically inscribed into a square and with the upper gallery exceeding the length of the elevated boxes, allows a uniform distribution of the values related to the main acoustic parameters [4]. Furthermore, the inclination of the ceiling along the main axis is beneficial to avoid any focusing effect that could affect specific areas of the volume.

An acoustic survey was undertaken inside this historical building to record the impulse responses (IRs) at different positions across the seated areas. The acoustic measurements were used to calibrate a digital model built up by following the architectural features of the National Theater of Zagreb. After the calibration process, the support of different digital models reflecting the conditions of all the selected scenarios contributes to deepening the analysis of the acoustics along with the presence of an audience simulated at different occupancy percentages.

This methodology follows the practice of the acoustic simulation process in order to have the accuracy of the results related to the different scenarios herein considered. The limitations of this research study could be represented by the simplification of the 3D models and by the employment of only one software for the acoustic simulations. However, not so much difference can be found between the digital reconstruction and the real design of the theater, given the linearity of a neoclassical style dominating the overall shape, except for the statues' profile, which can contribute to producing very negligible changes. Regarding the numerical computation, the results of the acoustic parameters obtained by simulation could be compared with the simulated values gathered using another software. Nonetheless, the accuracy of the simulation using only one software is still considered of high quality level since the application of the absorption coefficients has been calibrated with the measured results of the main acoustic parameters.

2. History of the Croatian National Theater

The first fixed theater in Zagreb was built in 1834 and was financed by the rich landowner K. Stanković. The construction of the theater started after the donation of land located at the corner of St Mark Square and Freudenreich street, which was private property until 1851. The design of the project was assigned to the Italian architects Cragnolini (i.e., father Cristoforo and son Antonio) who let the neoclassical style prevail, with a capacity of 750 seats [1].

The first exhibitions were exclusively performed by Germans. Finally, in 1840, the theatrical company Novi Sad produced the heroic comedy by Ivan Kukuljevic with autochthone and Turkish artists for the plays [1].

In 1848 part of the national theater, specifically the hall reserved for ceremonial ballets, became the house of the Croatian Parliament until 1895, when the theater has been transformed into administrative offices, used also for public assemblies [1].

The influence of new theater constructions in other cities in Croatia (e.g., Zara, Dubrovnik, Spalato, etc.) heightened the need for the construction of a new theater in the capital city. On this basis, an architectural project was already designed in 1871 but any execution of the works followed afterward [1]. When a heavy earthquake damaged the existing theater of Zagreb, the committee of the theater, led by the writer M. Derenčin, in 1880 started a campaign to fund the erection of a new theater, an idea that was approved the year after by Emperor Franz Joseph I. A long debate took place over the location of the new construction and it was decided by Khuen-Héderváry that the theater should be in the center of the city, in the middle of the area dedicated to the expo, along the existing Republike Hrvatske road, as shown in Figure 1.

The new project was conducted by the Viennese architects Helmer and Fellner who ran the site from spring of 1894 to October 1895. The architects involved all local artisans who numbered more than 200 when starting the construction [5]. The curtain separating the main hall from the fly tower was realized by Vlaho Bukovac, while the painting decorations of the hall were carried out by A.D. Goltz.

During the 125 years of its life, the National Theater of Zagreb carried out two campaigns of restoration works: in 1937 the electrical devices for meeting the safety regulations were installed, and between 1967 and 1969 the restoration works improved the west wing of the building [1].

Figure 1. (**a**,**b**) Views of the National Theater of Zagreb during its construction. Provision courtesy from Hrvatsko Narodno Katalište u Zagrebu.

3. Architectural Features and Characteristics

The National Theater of Zagreb has a capacity of 765 seats: 345 in the stalls and 420 seats on the elevated boxes and top balcony. The geometry of the plan layout is a U-shape inscribed into a square with a side dimension of 17.6 m, as shown in Figure 2. The main hall is crowned by a decorated ceiling, with a chandelier hung in the center of the vault, as shown in Figure 3. The golden walls clearly contrast against the brilliant white columns and against the oxidized-green copper roofing, as this was the effect that the painter would like to transmit [6].

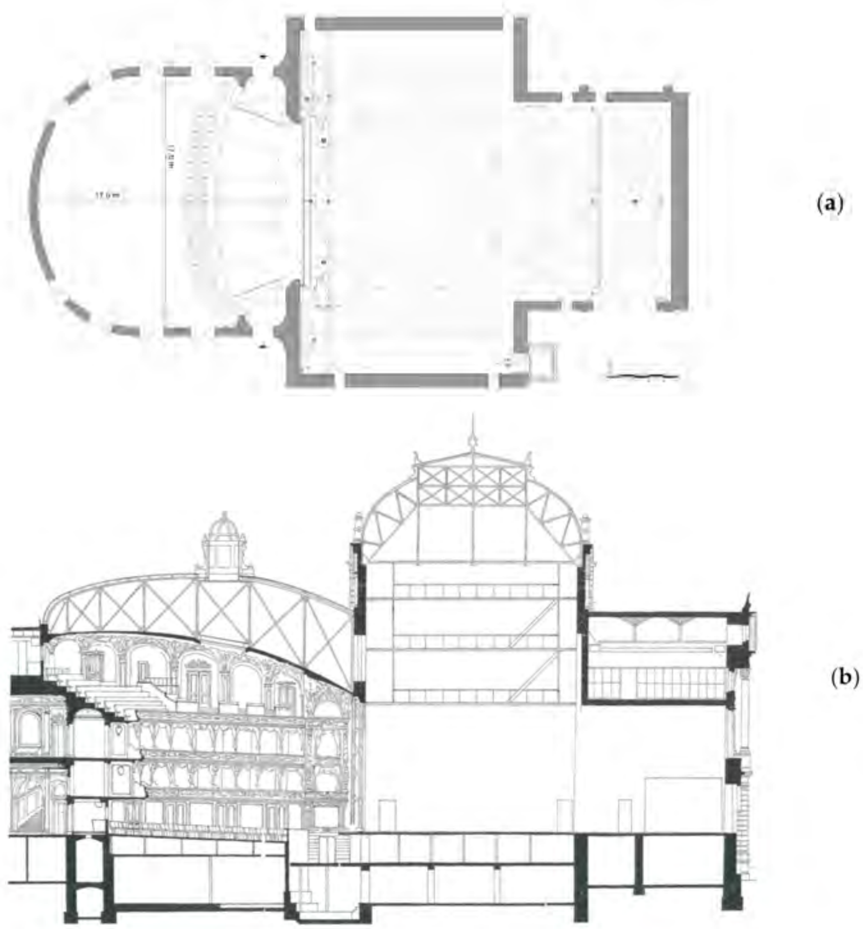


Figure 2. Internal organization of the National theater of Zagreb: plan layout of ground floor (**a**) and longitudinal section (**b**).

Figure 3. View of the main hall from the stage.

The stage has dimensions of 24.1 × 15 m (L × W) and has a turntable platform of 8.5 m radius. The proscenium arch is 11 m wide and the orchestra of up to 80 musicians can be allocated onto three available levels: at the height of the stage floor, at the same level of the stalls floor, or 1.5 m lower than the latest in a proper pit. The partition terminations of the boxes in the first order are statues representing the Muses, but this kind of decoration is not repeated on the upper balcony floor where floral motifs are instead.

The reproduction of the National Theater of Zagreb was carried out digitally with a model created using the software AutoCAD. All the entities inside the model have been drawn as 3D faces, to be simplified from the complexity of the architectural features, as shown in Figure 4.

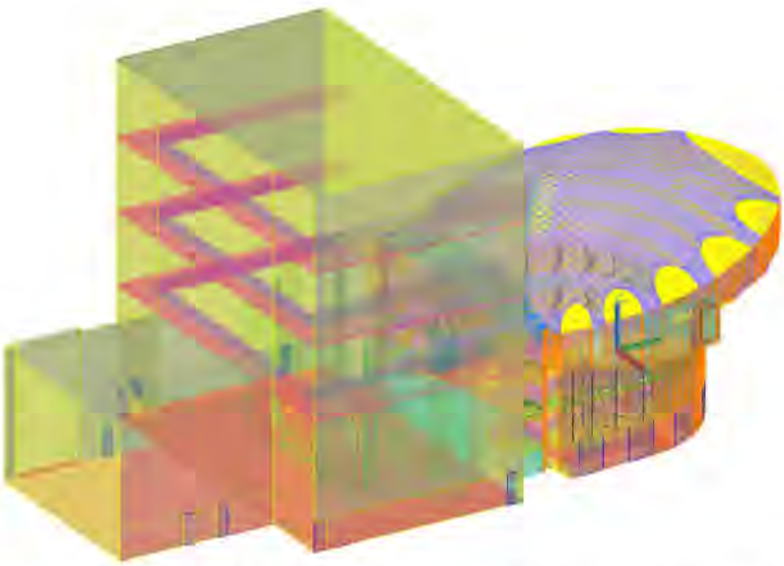


Figure 4. Digital model of the National Theater of Zagreb: axonometric view of the entire complex.

The 3D model is characterized by a total number of 16,660 entities, covering a surface area equal to 6413 m^2, and having a volume of the main hall (including balconies) approximated to 4760 m^3.

4. Acoustic Measurements

Acoustic measurements were carried out inside the National Theater of Zagreb to understand the acoustic response of the hall based on the standard requirements as stated in ISO 3382-1 [7], considered the international reference standard for objective acoustic parameters. During the surveys, thermos-hygrometric conditions were taken into consideration [8]. The equipment employed for the survey is the following:

- Equalized omnidirectional loudspeaker (Look Line);
- Binaural dummy head (Neumann KU-100);
- B-Format microphone (Sennheiser Ambeo);
- Omnidirectional microphone (Bruel&Kjaer 4165);
- 32-channel spherical array (Mh Acoustic em32 Eigenmike®).

The sound source was placed at 1.6 m from the finished floor, simulating the actor singing on the stage, while the receivers were installed at 1.2 m across the stalls and inside a few selected boxes to cover the audience areas. Given the axial symmetry of the volume, the receiver points selected for measurements were considered enough to understand the acoustic response of the hall. The excitation signal feeding the sound source was an Exponential Sine Sweep (ESS) [9] with a duration of 15 s in a uniform sound pressure level from 40 Hz and 20 kHz. The employment of an ESS signal feeding the loudspeaker instead of a white/pink noise is due to a good level of signal to noise ratio (S/N), other than to minimize the variability of directivity and repeatability that other types of sound sources (e.g., balloon pops, clapper boards) are more subject to [10]. This follows the reference standard to employ an excitation signal that should have sufficient energy at each relevant octave band. The measurements were undertaken in unoccupied conditions and with the stage completely empty [11]. Figure 5 shows the measurement positions of the instrumentations across the sitting areas.

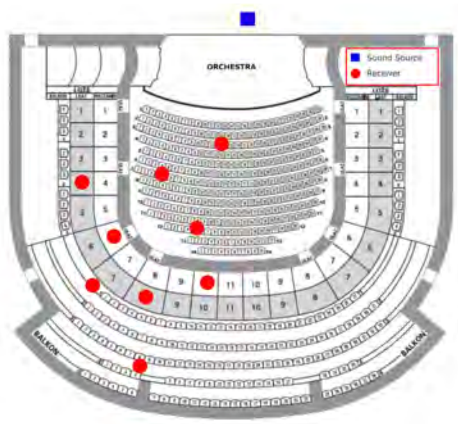


Figure 5. Scheme of the equipment location during the acoustic survey.

During the post-processing analysis, the impulse responses (IRs) can be obtained by the convolution of the recorded sine sweep signals (measured in the hall) with the inverse filter generation. Once we obtained the IRs, the acoustic parameters can be calculated using Aurora [12], a plugin suitable for Audition 3.0.

5. Acoustic Calibration

Before analyzing the effect of different types of scenery across the audience areas, the 3D model was simplified from the complexity of the architectural features, as shown in Figure 6. The layers were grouped and therefore the 3D model was exported in DXF format, to be ready for the acoustic calibration of the absorption coefficients related to the different materials. The software Ramsete makes calculations based on the principles of ray-tracing geometrical acoustics characterized by a triangular-base pyramid spreading [13]. This principle characterizes Ramsete with other software used for acoustic simulations, since many of them are based on conical spreading, with the risk of having bugs but at high degree of reflections. The other advantage of Ramsete is that it does not suffer the calculations time of up to 4,000 receivers inserted into the model, since the traceable time is invariant. Rather, the high number of receivers is linked to the calculation time involved in the spatial distribution of the acoustic parameters.

The source on the stage and the microphone positions were reproduced at the same location of the real measurements, with the addition of 362 receivers created in Ramsete, homogeneously distributed across the seats of the main hall [14]. Since Ramsete can uneventfully calculate the response of up to 4000 microphones, the time computation by the software does not suffer for the number of receivers inserted into the model.

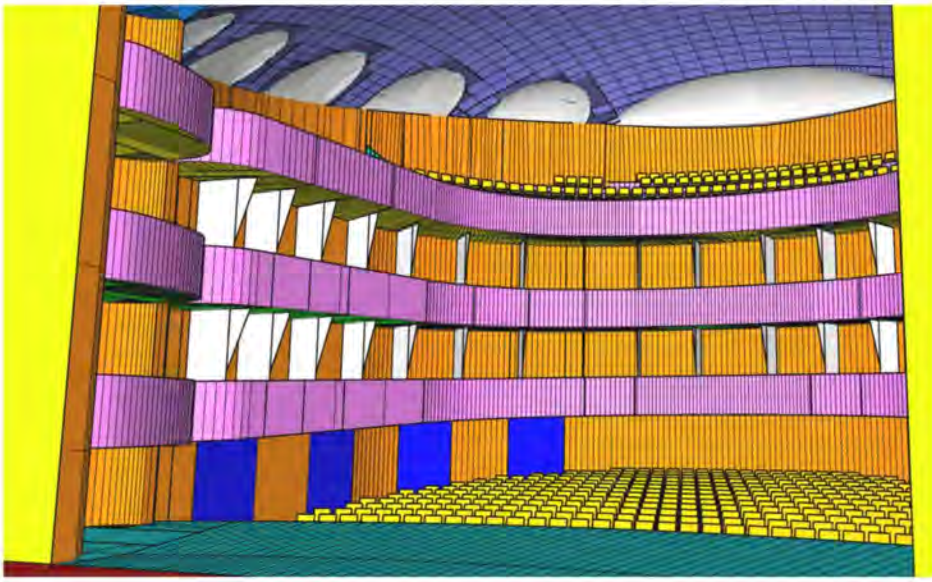


Figure 6. Digital model of the National Theater of Zagreb: perspectival view of the main hall.

Table 1 indicates the absorption and scattering coefficients for all the materials considered in the digital model, considered to be the result of both calibration process and extensive experience on acoustic simulations carried out for other Opera houses [15].

Table 1. Surface, absorption and scattering coefficients of the materials considered in the model of the National Theater of Zagreb.

Materials	Area (m^2)	Absorption Coefficients—Octave Frequency Bands (Hz)						Scattering
		125	250	500	1 k	2 k	4 k	
Solid wood—Boxes perimetral walls	2766	0.11	0.12	0.12	0.12	0.10	0.10	0.05
Wood—Boxes party walls	247	0.29	0.29	0.73	0.88	1.00	1.00	0.05
Timber wood—Boxes floor	303	0.05	0.05	0.10	0.20	0.30	0.59	0.05
Floating floor—Stalls	200	0.29	0.29	0.73	0.88	1.00	1.00	0.05
Floating floor—Stage	878	0.64	0.71	0.58	0.52	0.50	0.72	0.05
Solid wood—Parapets	302	0.04	0.05	0.06	0.07	0.07	0.06	0.05
Upholstery—Seats	192	0.65	0.80	0.90	1.00	0.99	0.94	0.05
Light Wood—Ceiling	1140	0.23	0.30	0.29	0.30	0.35	0.43	0.35
Doors	55	0.11	0.12	0.12	0.12	0.10	0.10	0.05
Wood—Stairs	223	0.53	0.59	0.39	0.35	0.50	0.72	0.05

The measured and calibrated results were compared and tuned until the difference between the two types of values is minimized to not exceed 5% across all the octave bands. Figure 7 shows the comparison of the main acoustic parameters, where the values shall be considered the average of all the receivers [16]. The spectrum bandwidth herein analyzed in octaves ranges between 125 Hz and 4 kHz. This methodology complies with a good practice since the very low (e.g., 16 Hz, 31.5 Hz) or very high (10 kHz, 16 kHz) frequency bands can be affected by distortion, as they are microphone dependent. Hence, the results at these latest octaves cannot be trusted and can be excluded by the acoustic analysis.

Details of the acoustic parameters being selected for the calibration are described as follows:

- Early Decay Time (EDT), defined in seconds as this is the metric unit, represents the time related to the decay curve that the sound pressure level takes to drop by 10 dB after the interruption of the sound signal. It is a parameter variable with microphone position.
- Reverberation Time (T_{20}), also defined in seconds as this is the metric unit, is the time related to the sound pressure level to drop by 20 dB after the interruption of the sound signal. Using Sabine's equation, this parameter is sensitive to the volume size of the room and the quantity of absorption applied to the surface areas. Since the absorption of materials varies with frequency, the reverberation time varies according to the considered frequency bands.
- Speech clarity index (C_{50}), with dB as the metric unit, represents the descriptor of speech goodness based on the ration of the energy arriving to the receiver within the first 50 milliseconds and the energy arriving in the following instants.
- Definition (D_{50}) can be calculated based on the energy arriving to the receiver within the first 50 ms and the entire energy of the signal bouncing inside a room until its total dissipation.

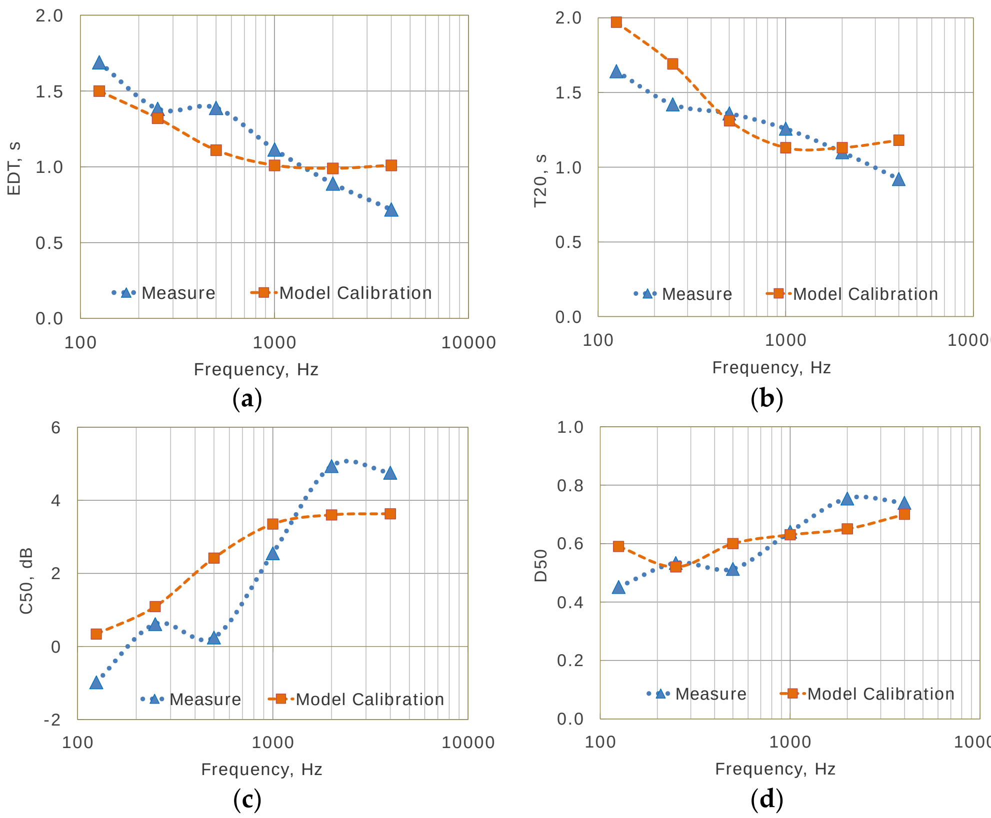


Figure 7. Model calibration based on main acoustic parameters: early decay time (**a**), reverberation time (**b**), clarity index (**c**), and definition (**d**).

Figure 7 indicates a small drift between the two curves in each graph, due to physical factors affecting the survey, such as the thermo-hygrometric variance. In addition, the simplification of the model and consequently a reduced number of surface areas, which the absorption coefficients are applied to, contributes to making a further difference between the measured and calibrated curves since they are crucial input data. Nonetheless, scope of this paper is to highlight any difference, in terms of acoustic parameters, between the three acts of *Tosca* and also the difference occurring by simulating Act I without and with different percentages of audience occupancy [17].

6. Acoustic Simulations

After the calibration of the model based on measured IRs, the acoustic simulations were performed with the scenery of *Tosca*, considered for all three acts. The source was placed in the same location of the measurements while 371 receivers were homogeneously distributed across the stalls and inside the balconies. The choice of having a high number of microphones in the model was due to the increased accuracy to be adopted for the spatial distribution of the acoustic parameters across the layout, without any concern for the calculation time since the traceable time in Ramsete is invariant.

The acoustic simulations consider five specific scenarios, as summarized as follows:

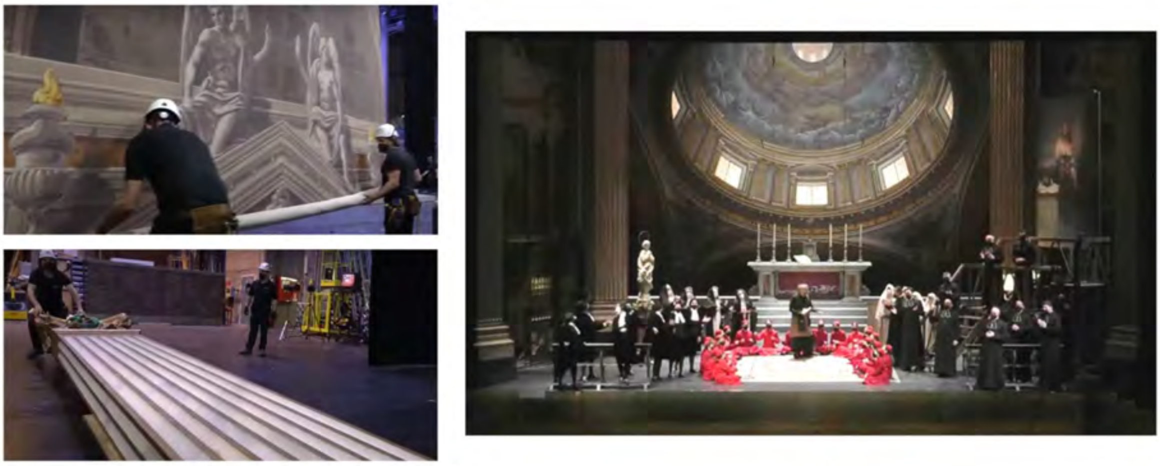
- Act I of *Tosca*, no audience;
- Act II of *Tosca*, no audience;
- Act III of *Tosca*, no audience;
- Act I of *Tosca*, 50% occupancy;
- Act I of *Tosca*, 100% occupancy.

These acoustic simulations are mainly focused on how much difference the acoustic parameters make with many actors are on the stage (a maximum of 40 elements) and when only the main characters (one or two) play on; furthermore, the research studies put in relationship the outcomes obtained by simulating the Act I of *Tosca* without any audience and with the presence of audience at different percentage of occupancy. Since the results as indicated in Section 7 are shown to be very comparable between all the three acts, only Act I was chosen for simulating the different percentages of occupancy. The scenery of *Tosca* was analyzed since it represents one of the most popular shows performed at the National Theater of Zagreb.

Scenery of Tosca

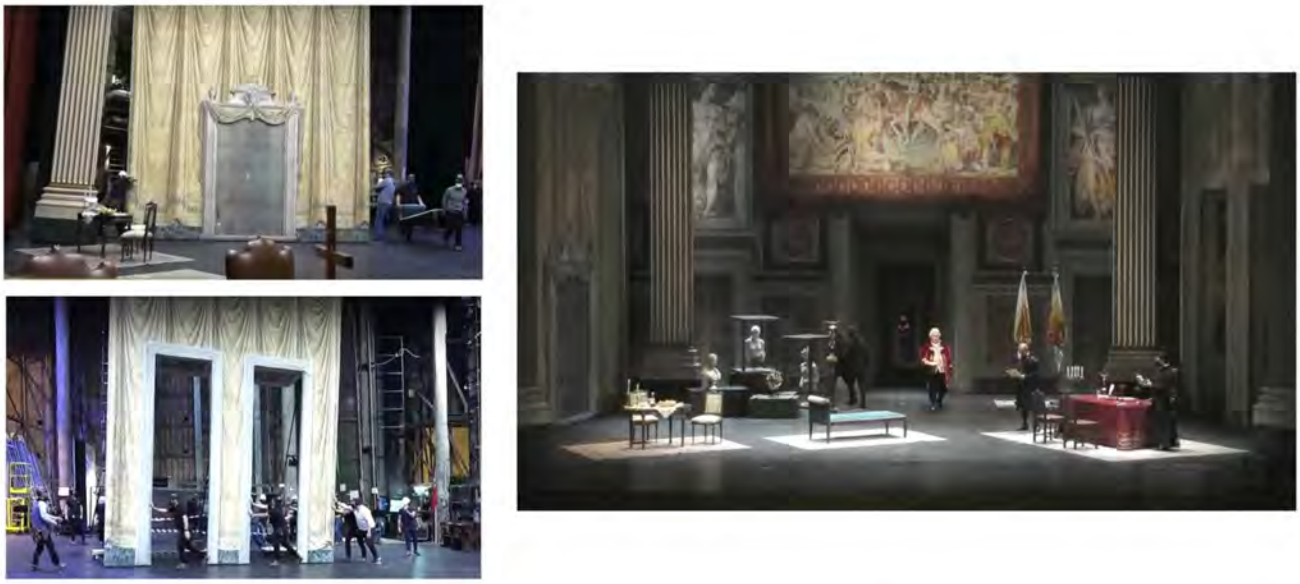
The scenery of *Tosca* selected for the acoustic simulations is related to the venue recently realized for the Teatro Massimo of Palermo in April 2022. For this occasion, the scenery of *Tosca* was directed by Mario Pontiggia and designed by Francesco Zito. One of its characteristics consists of the usage of printed curtains in combination with wooden prompts to define the space for acting [18,19]. In particular, the description of the sceneries related to the three acts is given as follows:

- Act I: installation of the altar framed by squared columns and delimited by a parapet. Another piece of furniture is composed of a statue on a pedestal and a little stair to reach an elevated painting. A carpet was installed in the center of the stage and the space is limited by printed curtains, representing the interior design of a church, as shown in Figure 8. This is the only part of the Opera where 40 actors are performing simultaneously on the stage.
- Act II: installation of wooden prompts for the doors' frames and the squared columns. The printed curtains simulate the decorated walls of a church while two tables and a few chairs with a baldachin are part of the furniture, as shown in Figure 9.
- Act III: installation of a small double-ramp open staircase decorated with the symbol of St Peter's cathedral. The whole space is surrounded by printed curtains, with the presence of wooden prompts only for the squared columns. Objects like luggage and boxes are spread on the stage floor, as shown in Figure 10.



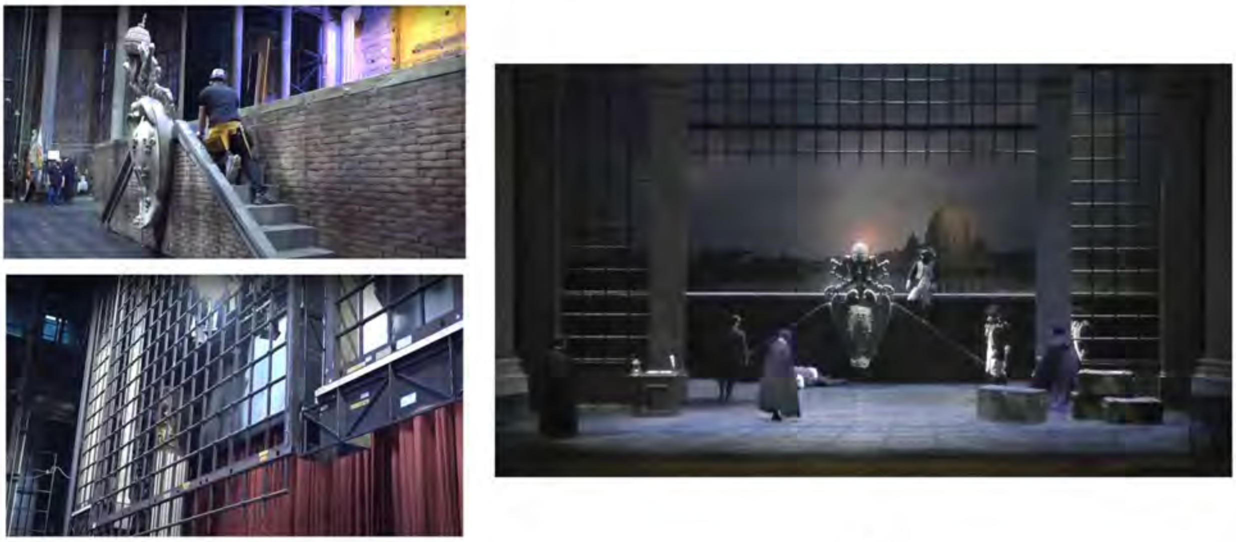
(**a**) (**b**)

Figure 8. Act I of *Tosca* at the Teatro Massimo of Palermo (2022): installation (**a**) and final scenery during the performance (**b**).



(**a**) (**b**)

Figure 9. Act II of *Tosca* at the Teatro Massimo of Palermo (2022): installation (**a**) and final scenery during the performance (**b**).



(a) (b)

Figure 10. Act III of *Tosca* at the Teatro Massimo of Palermo (2022): installation (**a**) and final scenery during the performance (**b**).

To make clearer the geometry of all the sceneries, Figure 11 shows how they were built digitally and used for acoustic simulations. In particular, the scenery of Act I is composed of two pairs of parallel prompts of different lengths that cross diagonally the acting area. The altar was faithfully reproduced as well as the stairs where the painting stands on.

(a) (b) (c)

Figure 11. Reconstruction of the scenery of *Tosca* realized for the Teatro Massimo of Palermo (2022): Act I (**a**), Act II (**b**), Act III (**c**).

The scenery of Act II is composed of only the large diagonal prompts, while the frontal background was created with a further two frames that create a perspective illusion.

The scenery of Act III was created with double-slope stairs placed in front of the background curtain and with the diagonal prompts with a smaller length, placed on both sides.

The absorption coefficients attributed to the additional digital entities are related to the actors on the stage, assumed to be wearing heavy traditional clothes, and to the audience, which are summarized in Table 2. Both actors and audience were simplified to rectangle surfaces in the model, as shown in Figure 11.

Table 2. Surface, absorption and scattering coefficients of the additional materials considered during the acoustic simulations.

Materials	Area (m^2)	Absorption Coefficients—Octave Frequency Bands (Hz)						Scattering
		125	250	500	1 k	2 k	4 k	
Heavy cloth—Actors	33 (Act I) 6 (Act II) 6 (Act III)	0.80	0.80	0.80	0.80	0.80	0.80	0.05
Audience	51 (50% capacity) 102 (100% capacity)	0.60	0.60	0.60	0.60	0.60	0.60	0.05

7. Data Analysis and Results

Graphs in Figure 12 show the results of the simulations related to all the different scenarios, considered to be the average values of all the receivers inserted in the model. The virtual sound source in the digital model has been installed in the center of the stage, where most of the time the action takes place and simulates the actor singing other than to reproduce the location of the sound source placed during the acoustic survey. The characteristics of the sound source has been simulated to be provided of 1W at 1m, equal to a sound pressure level of 110 dBA.

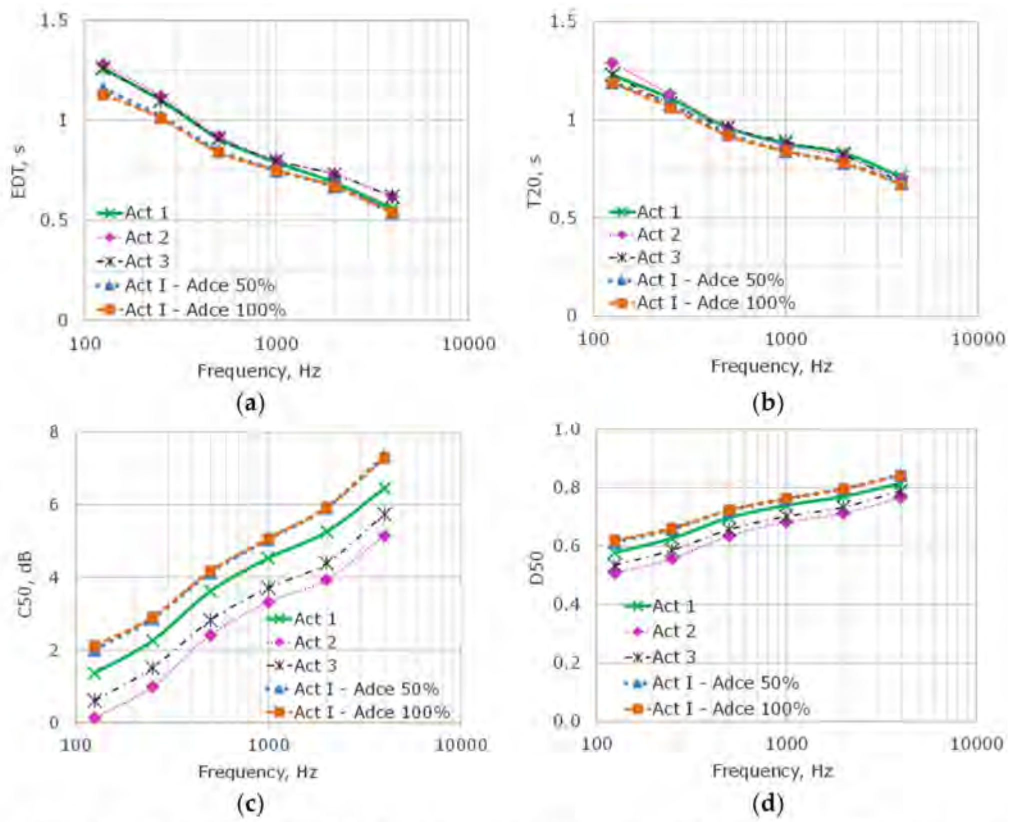


Figure 12. Simulated results of the main acoustic parameters: early decay time (**a**), reverberation time (**b**), clarity index (**c**), and definition (**d**).

Graph (a) in Figure 12 indicates that no difference was obtained between the scenery of the three different acts, except for 2 kHz and 4 kHz, where EDT values related to Acts I and II are slightly higher than values related to Act I [20]. However, by considering only Act I, the values obtained by simulating the presence of the audience at 50% and 100% occupancy are lowered by up to 0.1 s at low frequencies, while no difference has been found at high octaves [21].

In terms of reverberation time, the difference of the T_{20} values among all the five scenarios, as shown in graph (b), is very minimal such that it can be considered negligible. However, the T_{20} value at 500 Hz equal to 0.9 s is considered optimal for an Opera theater with this volume size [22].

Graph of Figure 12c indicates that the speech clarity index is within the optimal values at low frequencies, because it is between 0 and +2 dB [23], and is up to 4 dB above the upper range limit. In addition, the C_{50} values related to all the acts have similar trends; however, graph (c) shows an upward shift of 0.3 dB between values of Act II and III, and a further upward shift of 0.4 dB between values of Act III and I. The simulations carried out with the presence of the audience, although no variance has been found between 50% and 100% occupancy, shift upward the curve of similar trend, to be 0.3 dB above the values related to Act I [24].

The values of definition (D_{50}), as shown in graph (d) of Figure 12 have been found to be fluctuating between 0.5–0.6 at low frequencies and 0.75–0.85 at high-frequency bands, meaning that the speech definition is considerably good inside the National Theater of Zagreb, considered very suitable for Opera [25].

An alternative way of representation has been carried out in terms of spatial distribution. This is another output data that can be obtained with Ramsete software and it consists of the contour levels describing the variation of the acoustic parameters across the audience areas. The setup options allow the determination of the selected octave frequency band to be analyzed other than the range limits of the values. On this basis, Figure 13 indicates two examples of spatial distribution related to two acoustic parameters: the reverberation time (T_{20}) and the speech clarity index (C_{50}), considered at 500 Hz and related to the scenery of Act I without any audience.

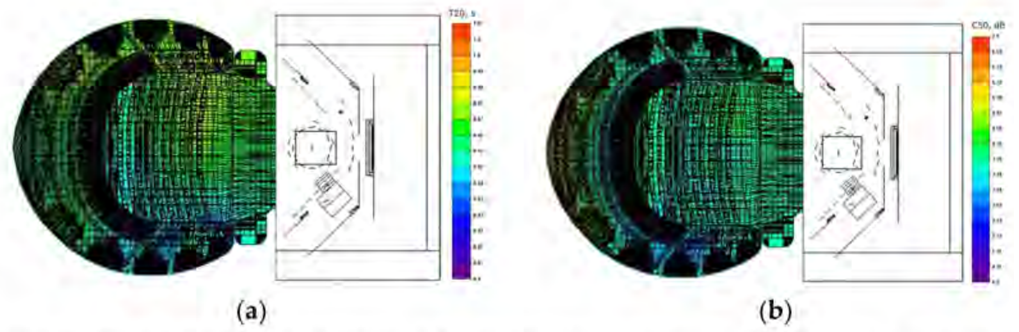


Figure 13. Spatial distribution at 500 Hz of Act I without any audience, related to reverberation time (**a**) and speech clarity index (**b**).

Figure 13 shows that the T_{20} is quite uniform across the plan, to be fluctuating around 0.96 s, with the right side slightly dropping to 0.93 s. In a similar way, the spatial distribution of the C_{50} has been found to be around 4.5 dB across the stalls and to be up to 6 dB in the central rows of the upper gallery.

8. Discussions

The acoustic survey undertaken inside the National Theater of Zagreb was the starting point for the analysis of the acoustic behavior of such an important cultural heritage. The geometrical description of the entire architecture, along with the details of the interior design, is very important for the analysis of the results obtained by the acoustic simulations. The five selected scenarios, representing the scenery of *Tosca* over three acts with the effect of the audience occupancy confirm how the acoustics of the National Theater of Zagreb is within or close to the optimal range limits set up for opera houses [26]. The outcomes revealed no difference in terms of values between scenarios with 50% and 100% occupancy, respectively [27]. This shall be encouraging to both artists and public that put all their effort into making every show successful. *Tosca* has been widely performed inside the National

Theater of Zagreb, found to be a success, and is loved by the Croatians, who also love performances created by local artists.

Many other operas could be simulated other than *Tosca* inside the National Theater of Zagreb. It is important to faithfully reproduce the geometry and the disposition of the prompts across the stage along with the absorption coefficients of the materials to be applied to the surface areas of the digital model. On this basis, future research studies will be focused on the acoustic behavior of the main hall when ballets are performed on the stage and the orchestra play in the pit. This configuration will allow an understanding of how the values of the main acoustic parameters vary if considered that the pit will be the location of the sound source. For this future scope, acoustic simulations could even include the scenario of modeling a curtain that excludes the volume of the fly tower.

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