

Alma Mater Studiorum Università di Bologna  
Archivio istituzionale della ricerca

Acoustic study of different sceneries at the São Carlos national theatre of Lisbon

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

*Published Version:*

Tronchin L., Bevilacqua A. (2021). Acoustic study of different sceneries at the São Carlos national theatre of Lisbon. APPLIED ACOUSTICS, 180, 1-11 [10.1016/j.apacoust.2021.108102].

*Availability:*

This version is available at: <https://hdl.handle.net/11585/821543> since: 2021-06-06

*Published:*

DOI: <http://doi.org/10.1016/j.apacoust.2021.108102>

*Terms of use:*

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>).  
When citing, please refer to the published version.

(Article begins on next page)

This is the final peer-reviewed accepted manuscript of:  
L. Tronchin, A. Bevilacqua, *Acoustic study of different sceneries at the São Carlos national theatre of Lisbon*, Applied Acoustics, Volume 180, 2021, 108102.

The final published version is available online at:

<http://dx.doi.org/10.1016/j.apacoust.2021.108102>

#### Rights / License:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>)

**When citing, please refer to the published version.**

# Acoustic study of different sceneries at the São Carlos National Theatre of Lisbon

Lamberto Tronchin<sup>1</sup>, Antonella Bevilacqua<sup>2</sup>

(1) Department of Architecture, University of Bologna, Italy

(2) Department of Engineering, University of Parma, Italy

## ABSTRACT

The wide variety of Opera taking place inside the São Carlos theatre of Lisbon suggested the authors to study the acoustic characteristics of three specific scenarios, which are given by the empty stage and by including the sceneries of *Traviata* and *Italiana in Algeri*. The florid artistical venues occurring throughout the centuries make this building an important icon for the capital city of Portugal. As such, an acoustic survey was carried out in order to define the acoustic parameters of this historical building and a numerical digital model was realized and validated by simulating three selected scenarios, whose results have been analysed and commented.

## Keywords

Architectural acoustics; cultural heritage; theatre scenery.

## 1 Introduction

The acoustic characteristics of the historical theatres have been studied considerably during the last decades [1], especially because this type of buildings is considered an important patrimony to preserve as an intangible cultural heritage to posterity [2]. The São Carlos is one of the historical theatres of the 18<sup>th</sup> century having an oval plan shape, as designed by José da Costa e Silva [3]. To obtain a complete description of the spatial sound propagation, acoustic impulse responses have been measured by paying attention to all of the features and properties that characterise this place, including the resonance box below the orchestra pit. This paper aims to analyse the acoustical parameters extracted from the measurements and the virtual simulations for each of the three different configurations [4, 5]. In addition, the effects produced by the two selected sceneries have been compared with the simulation obtained without any scenery.

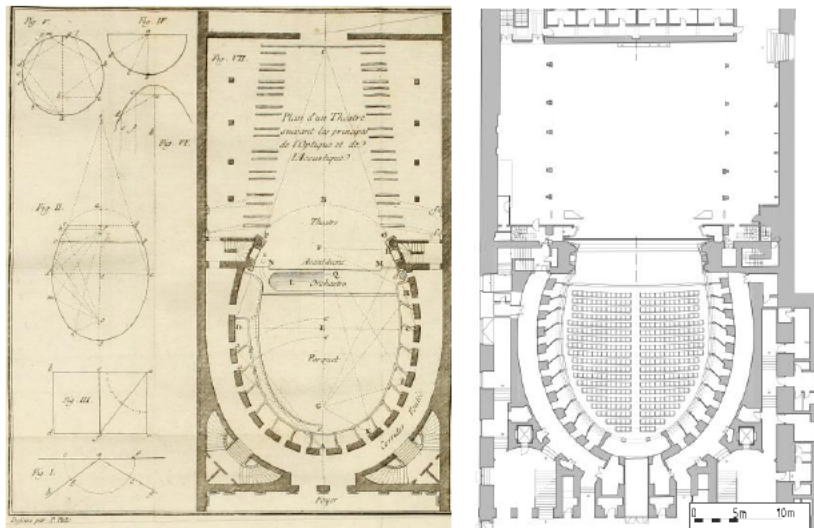
## 2 Historical background

The Opera, as a music style, landed dominantly in Portugal in 1706 with the occasion of the marriage between the future king D. João 5<sup>th</sup> and Anne-Marie of Austria. The new queen promoted many musical events and during this florid period the arrival of Domenico Scarlatti helped to develop such art. The passage from the temporary exhibitions to a real theatre was owed to the increase of artists operating in Lisbon, mainly coming from Italy [6]. The first shows, called *Pateos das Comedias*, were performed outdoor, during a day-light time [7]. The places dedicated to the outdoor artistical performance were used as a sort of Greek/Roman theatres, with the lower classes of the society sitting in the *popularia*, the aristocracy onto the *palanques*, and the members of the royal family in the grandstand [7]. The successor of João 5<sup>th</sup> was Don Josè, who came up to the throne in 1750 and would like to rise Lisbon to the same artistical level of other European capital cities, in the name of the culture and the prestige [3]. The necessity of building an Italian style theatre gave the opportunity to Giancarlo Bibiena to draw the first *Casa de Opera*: construction of 60m length and 32.4m width, with 4 floors of stalls, including the royal grandstand in the middle, and with a stage having dimensions twice the stalls. Unfortunately, the earthquake of 1755 destroyed completely all the construction. After 1755, when the shows were back to be performed and when the middle class tried to be confirmed, the comedy was preferred by the audience against the tragedy [7]. Through an easy way, the theatre assumed an added value, that was the function of spreading education and civilization across the society [7]. This concept brought to the realization of the new São Carlos theatre, financially supported by a pool of capitalists and built in the core of the city: *Largo de Picadeiro* [3].

### 3 Architectural characteristics

#### 3.1 Geometry

The architect of the São Carlos theatre was José da Costa e Silva, who travelled across Italy and was mostly inspired by the historical buildings drawn by Palladio and Vanvitelli [6]. He was a keen observer of the new-born theatres of Naples and Milan. When he was called to design the theatre of Lisbon, José da Costa e Silva had to deal with the site slope running along the longitudinal axis, most accentuated on the side of *Rua Serpa Pinto* [8]. The entire structure is given by a combination of two main volumes: an elliptical cylinder, related to where the audience stands, and a cubic stage for the artists [6]. The original capacity was 1446 seats, nowadays reduced to 1150 [6]. The influence of the *La Scala* theatre of Milan, designed by Piermarini, is evident in the organization of the stairwells and the vaulted corridors, other than having similarities regarding the arched entrance, as it is visible from the front elevation [6]. In relation to the elliptical shape, the architect took inspiration from a pamphlet by Pierre Patte, called *Essai sur l'architecture théâtrale ou de l'Ordonnance la plus avantageuse à une Salle de spectacle relativement aux principes de l'Optique et de l'Acoustique*. Because of the direction of reflecting rays, the shape of the plan layout was the main factor in determining the sound quality of the theatre [9]. As such, the ellipse was considered the only geometry suitable to combine the acoustical and the optical principles with the purity of neoclassicism in order to obtain an ideal performing arts space [10]. Figure 1 indicates a comparison between general studies of geometry conducted by Pierre Patte and the project designed by José da Costa e Silva for the São Carlos theatre.



**Figure 1.** Plan layout drawn by Pierre Patte (on left) and by José da Costa e Silva (on right).

#### 3.2 Orchestra pit

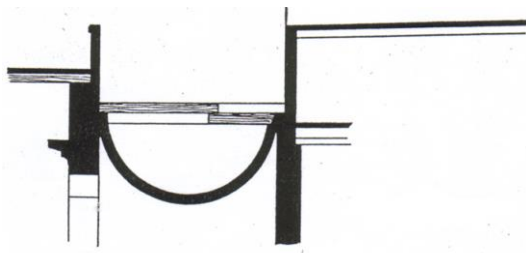
The original volume dedicated to the pit was different than what it is now [6]. The first modification occurred in 1877 when the need to allocate a larger orchestra had the effect on the proscenium to be cut by 1m towards the stage [6]. A few years later, further amputation occurred by 80cm, determining the limelight to be overall drawn back of approximately 2m [6]. As such, the second focal point of the ellipse was moved from the proscenium to the pit, inducing a continuous balance to be searched by the vocal and instrumental sound because the actors were deprived of an important part of the floor as the first reflector to make robust their voices [10].

The second set of changes were undertaken by the refurbishment works that occurred in 1936-40, that tried to improve both the acoustics and the comfort of the musicians [6]. The banister separating the audience from the orchestra was filled in between the columns with wood panels [6], changing in this way the overall sound directivity and becoming more merged with the voices of the stage [9]. The floor of the pit is composed of wooden boards placed above an empty volume running parallelly to the length of the pit, as shown in Figure 2. This empty volume, important under the acoustical point of view for its resonance, during the refurbishment works was found filled with electrical wires and holed towards the stage.



**Figure 2.** Empty volume underneath the orchestra pit with the function of a resonance box.

The resonance boxes of many historical theatres have been heavily damaged being filled with concrete or similar materials in order to allocate machinery for stage changing [9]. This construction element, so meaningful since the design stage, characterizes the acoustics of the whole theatre [11], supporting especially the low frequencies and making the sound deeper other than softer [12]. A schematic section of a generic resonance box has been shown in Figure 3 below, out of scale.



**Figure 3.** Typical scheme of a resonance box.

Nowadays the orchestra pit of the São Carlos theatre has a surface area of approximately  $86\text{m}^2$  [6]. 70 orchestral elements can be distributed over the space despite the complaints of the musicians, who consider this space very small and uncomfortable.

### 3.3 Stage

The stage is a fixed wooden floating floor inclined by 6.5% [6]. A view of the stage from the stalls is given in Figure 4. During the restoration works of 1936-40 the stage was provided with a cyclorama, a rigid wooden prompt installed to give a visual effect to the audience [6]. The cyclorama was widely discussed by musicians, who would like to create instead an acoustic shell with a different shape: the curvature should avoid the sound to be focused on the stage and, furthermore, should be also provided with a curvature on the vertical section in order to spread the sound uniformly to all the directions and towards the audience [13]. The proscenium arch of São Carlos theatre is composed of a horizontal beam supported by a couple of columns on both sides [6]. The proscenium is considered the construction element dividing the elliptical cylinder from the cubic stage.





**Figure 4.** View of the stage, São Carlos theatre of Lisbon.

### 3.4 The elliptical hall

The main hall is composed of twenty rows of seats allocated in the stalls and of 122 stalls organised onto 5 levels [6], including the royal tribune that is in place of 12 stalls [6], as shown in Figure 5. The floor of the stalls is slightly inclined to give the audience a good view of the show [6], while the seats are divided into 2 sectors by a central corridor along the main axis of the ellipse. The ceiling of the stalls is generally flat and concave only at the junction to the galleries of the top floor [6].

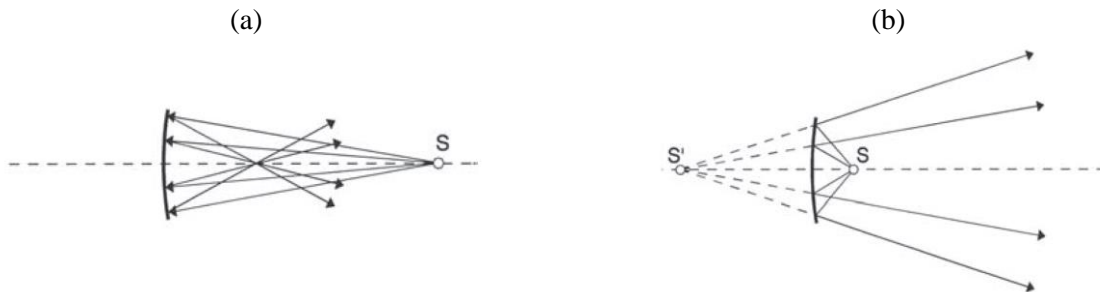


**Figure 5.** Elliptical hall, São Carlos theatre of Lisbon.

From an acoustical point of view, the ellipse is a very specific geometry having the two foci as the most representative elements. In particular, any outgoing sound emitted from one focus would be directed to the other by following a straight-line direction [14]. For this reason, the enclosures with elliptical floor plans are plagued by quite an unequal sound distribution, even if neither the sound source nor the listener is in a geometrical focus. On the basis of this, if the source is not in one of the focal points, the laws of concave and convex mirrors can be applied, as known from optics. Considering  $R$  the radius of curvature,  $a$  the source distance, and  $b$  the distance of the focus, these 3 entities are related together by the following equation (1).

$$\frac{1}{a} + \frac{1}{b} = \frac{2}{R} \quad (1)$$

If the source  $S$  is generated at a distance greater than  $R$ , the reflections at boundaries will be focused on a point, from which the rays diverge [15]. But if the source  $S$  is generated at a distance smaller than  $R$ , the reflections will be scattered as against a convex surface, as shown in Figure 6.



**Figure 6.** Reflection of rays from concave surfaces: focus effect (a) and scattering (b) [15].

This literature, as applied to the plan layout of the São Carlos theatre, clearly validates the spatial distribution of the calculated acoustical parameters, which a few of them have been reported in Figures 21 and 22. Furthermore, the complaints of the singers that see themselves deprived of an important part of the stage floor,

since it has been cleaved of 2m to create the space of the orchestra pit, justify the reason why they are not equally perceived by the audience.

Table 1 below summarizes the dimensions and the architectural characteristics of the theatre.

**Table 1.** Architectural characteristics of São Carlos theatre.

	Description	São Carlos Theatre
Elliptical hall	Inclination of stalls (%)	5
	Major axis (m)	24
	Minor axis (m)	17
	Height (m)	15
	Type of ceiling	Flat; curved at the junction with stalls
	Levels of boxes	5
	Volume (m <sup>3</sup> )	19000
Scenic arch	Orchestra pit (m <sup>2</sup> )	86
	Inclination (%)	6.5
	Length (m)	20
Stage	Width (m)	31
	Height (to the reticular wooden structure) (m)	16
Fly Tower	Volume (m <sup>3</sup> )	10000
Hall + Fly Tower	Volume (m <sup>3</sup> )	29000

#### 4 Measurements

During 1992-93 Daniel E. Commins, enrolled as an acoustic consultant for the works in the theatre measured the acoustics of the theatre which resulted drier than what it should be [6]. As such, he decided to remove the excessive absorbing material that was added throughout the decades, including curtains, upholstery installed at the balconies, carpet as finish floor of the stalls.

The measurements of the acoustical parameters presented by the authors have been undertaken after the Commins' corrections, paying attention also to the thermo hygrometric conditions in the theatre [16].

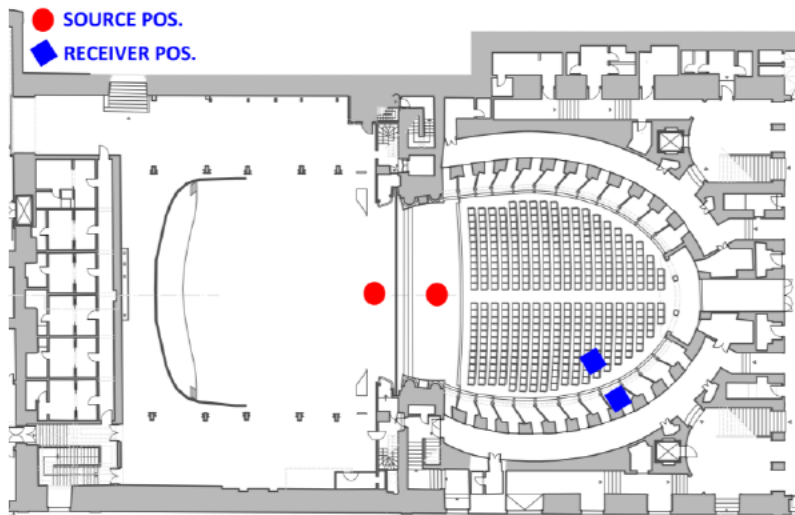
The acoustic measurements were performed by using the following equipment:

- Equalised omnidirectional sound source (i.e. LookLine);
- Dummy head (i.e. Neumann KU100),
- B-format microphone (i.e. Soundfield MK-V).

The sets of measurements were organised by placing the sound source in two different positions:

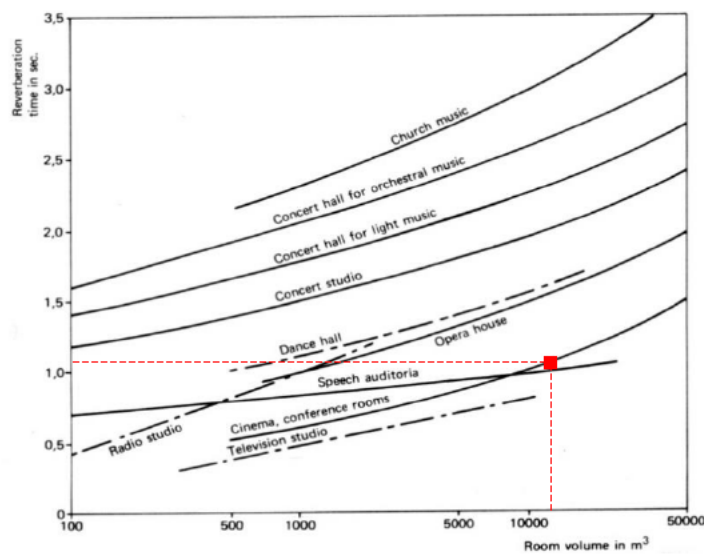
- On the stage, and
- Inside the orchestra pit.

Differently, the microphones were installed in the stalls and on the 3<sup>rd</sup> order of boxes, as shown in Figure 6 below. Since the plan layout is specular with respect to the medium axis, the 2 receiving points would be characterising the main critical points of all the sitting areas. The excitation signal was an exponential sine sweep (ESS) having a frequency range between 40 Hz and 20 kHz [17, 18]. The acoustic measurements were performed without the presence of an audience (in unoccupied conditions) [19] and without any scenery mounted [20].



**Figure 6.** Source and receiver positions during acoustical measurements.

The data analysis of the impulse response (IR) shows that the reverberation time ( $T_{20}$ ) is approximately 1s across all the frequency bands. These values seem to be a little “deaf” [21] if we consider what has been suggested by the optimal curves of different space functions, in relation to the room volume [22], as indicated in Figure 7, where the opera houses should have a  $T_{20}$  between 1.4s and 2.0s [23].

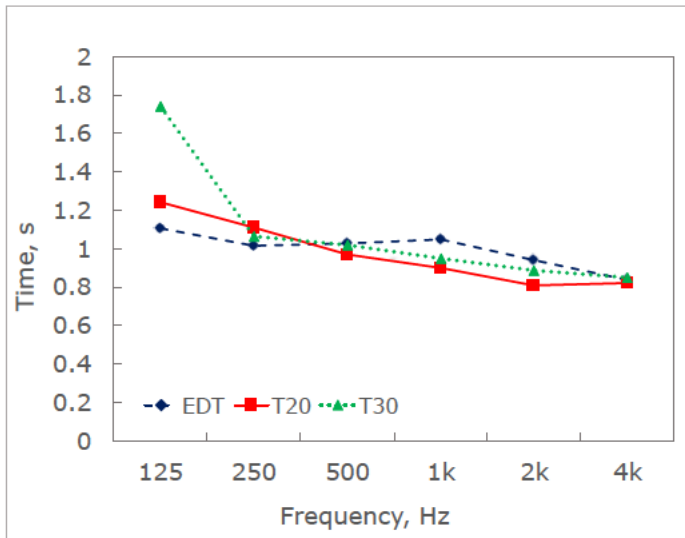


**Figure 7.** Optimal reverberation time (RT) for different function types, with the red dot representing the RT of São Carlos theatre of Lisbon.

The graphs showing the results of the measured acoustical parameters are obtained by considering the average values of all the measuring points.

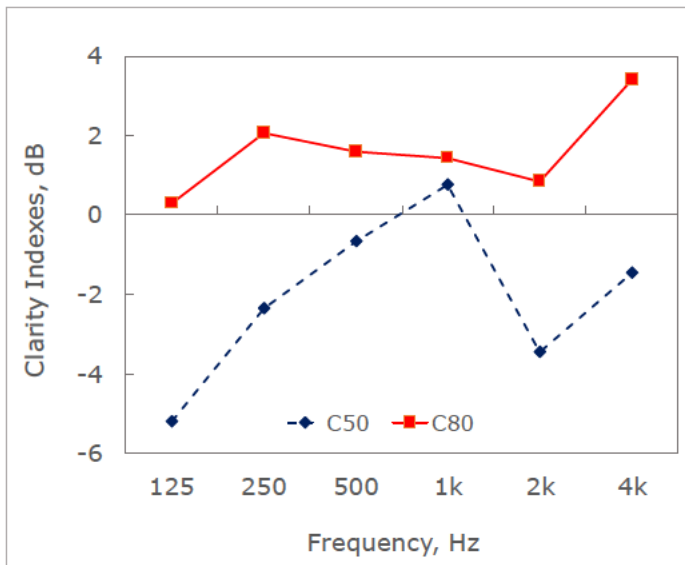
From the graph of Figure 8 it is possible to see that both EDT and  $T_{30}$  have values similar to  $T_{20}$ , approximately around 1s, with the exception at 125 Hz, where the EDT has an upward pick. It means that EDT resulted slightly below the lower limit range, considered that a good response is included between 1.8s and 2.6s [23].





**Figure 8.** Measured values of the reverberation times.

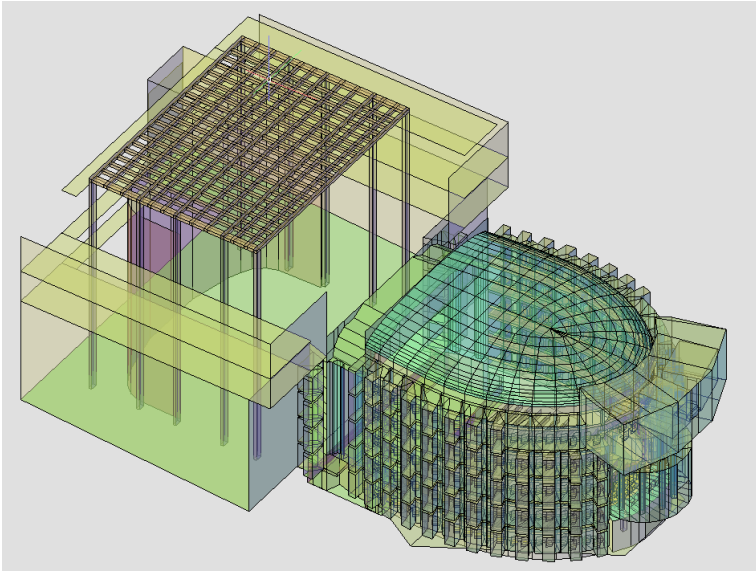
Considered that the clarity index in relation to music ( $C_{80}$ ) should be comprised between -4 and 2 [23] in São Carlos theatre it is pretty good over all the frequency bands, with a small shortfall at 125 Hz. While the clarity index in relation to speech (i.e.  $C_{50}$ ) is slightly out of range at low frequencies, considered that a good performance is for values  $C_{50} > 3$  dB [23], even if it should not be considered as a disrupting outcome. Figure 9 below indicates the two clarity indexes, for music and speech [24].



**Figure 9.** Values of clarity indexes.

## 5 Numerical model

Very accurate geometrical drawings were recently realized by Pedro Fidalgo, from the Faculty of Social and Human Science at the Institute of Contemporary History of the New University of Lisbon, Portugal. From these drawings, a simplified 3D model was realised in order to perform acoustical simulations, which could include the diffusing effects [25, 26].



**Figure 10.** 3D model of São Carlos Theatre.

From Figure 10 it is possible to see that all the element surfaces have been drawn as flat planes, which provide a simplification even to the complex architectural decorations that, otherwise, cannot be handled by the ray-tracing software. The AutoCAD layers were grouped to consider the existing finish materials.

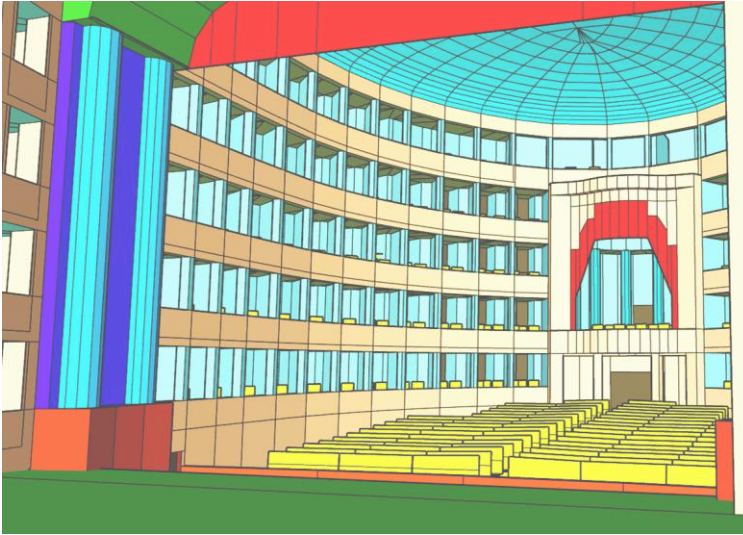
## 6 Acoustical simulations

After creating a simplified 3D model by using AutoCAD software, as shown in Figure 11, the digital construction of the theatre was exported in dxf format in order to compute the acoustical simulations by using Ramsete [27], a software that calculates the ray-tracing reflections following a triangular-base pyramid (instead of conical) spreading [28].

The acoustic simulations have been performed in three different ways, as follows:

- Having an empty stage;
- With the scenery of *Traviata*; and
- With the scenery of *Italiana in Algeri*.

The source onto the stage and the microphone positions were reproduced at the same location of the real measurements, with the addition of 173 receivers created into the model, homogeneously distributed over the sitting areas, on both stalls and balconies. 173 receivers are not considered a big number to be managed by Ramsete, since it can govern uneventfully a maximum number of 4096 microphones. In addition, Ramsete does not suffer the calculation time with the presence of 173 microphones, because the traceable time is invariant. The high number of microphones in the digital model increases rather the post-processing time for the acoustical parameters and for the realization of their spatial distribution. The less is the number of receivers, the more misleading are the contours levels of the acoustical maps.



**Figure 11.** Digital reproduction. Perspectival view from the stage.

The virtual model had the following geometrical characteristics:

- Total number of surfaces: 5431;
- Total surface area: 10703 m<sup>2</sup>; and
- Volume: approximately 4700 m<sup>3</sup>, considering only the audience area including the balconies and excluding the scenic tower.

Table 2 reports the absorption and scattering coefficients for all the materials considered in the simulations. The scattering coefficients were obtained from the literature [29, 30], while the absorption coefficients are the results of both calibration process and previous experience on simulations undertaken for similar opera houses.

**Table 2.** Surface, absorption and scattering coefficients for all the materials considered in the simulations.

Materials	Area (m <sup>2</sup> )	125 Hz	250 Hz	500 Hz	1k Hz	2k Hz	4k Hz	Scattering
Wood of scenic arch	116	0.34	0.37	0.39	0.39	0.40	0.52	0.05
Solid wood	1185	0.21	0.22	0.22	0.22	0.20	0.20	0.05
Wooden boards - walls	2752	0.31	0.32	0.32	0.32	0.30	0.30	0.05
Curtains	41	0.28	0.39	0.54	0.60	0.50	0.45	0.05
Floating floor	1457	0.55	0.50	0.40	0.30	0.30	0.27	0.05
Timber wood - doors	274	0.27	0.30	0.31	0.32	0.28	0.22	0.05
Upholstery on balconies	57	0.44	0.60	0.77	0.89	0.82	0.70	0.05
Upholstery on seats	483	0.51	0.64	0.71	0.77	0.81	0.85	0.05
Carpet on floor	475	0.08	0.10	0.20	0.25	0.30	0.35	0.05
Wooden ceiling	498	0.11	0.12	0.12	0.12	0.10	0.10	0.05
Plaster	2046	0.02	0.02	0.03	0.04	0.04	0.03	0.50
Wooden cyclorama	503	0.19	0.20	0.18	0.18	0.20	0.20	0.50

In this study, the calibration of the model was conducted by comparing experimental measurements with simulated data. To be noted that the results obtained with simulating the digital model without any scenery have little variations compared to the values obtained by the measurements [31]. This variance is owed to the lack of deep knowledge in simulating precisely the quantity of surface areas and the exact absorption coefficients that try to be close to reality. However, the values of the sound absorption coefficients were chosen from a database in accordance with the literature [28].

The purpose of simulating the acoustics of the theatre in three different settings is to highlight how the acoustical parameters change based on the artistical performance and different scenery installed for the occasion. The choice of these two sceneries is in line with the type of Opera that has been offered at the São Carlos theatre, considered the most popular shows loved by the audience of Lisbon throughout the last decades.

### 8.1. Scenery of *Traviata*

The scenery of *Traviata*, realized for the lyric theatre of Cagliari, has been considered now applied to the São Carlos theatre. As such, this set designed by Karl-Ernst and Ursel Herrmann evokes the old spirit that inspired Verdi in composing his music, as the public reported and testified in the occasion of the exhibition completed in 2014.

The architecture created for this scenery is composed of an enclosed space, looking like a mirror of the main elliptical hall, given the similar geometry in reduced dimensions [32]. Figure 12 and 13 indicate how the scenery has been mounted by hanging the ceiling while the vertical prompts were in phase of installation.



**Figure 12.** Coverage of the scene *Traviata* at the lyric theatre of Cagliari, 2014.



**Figure 13.** Concave prompts of the scene *Traviata* at the lyric theatre of Cagliari, 2014.

The interior design preferred at the walls and ceiling was made of a light upholstery in chesterfield texture wrapped by fabric. The glass panes at the windows were composed of translucent plastic sheets and the floor was covered by fabric in order to simulate a carpet, as shown in Figure 14.



**Figure 14.** Scenery of the Act III of *Traviata* at the lyric theatre of Cagliari, 2014.



### 8.2. Scenery of *Italiana in Algeri*

Conversely, the scenery proposed for *Italiana in Algeri* has been realized by Vittorio Borrelli for the Regio theatre of Turin in 2018. By itself, *Italiana in Algeri* is a dynamic opera, which involves a multitude of actors in ballet. As such, the necessity of a large space was not disrupted by the prompts, which do not enclose the stage but, being free on the sides, they interconnect the spaces of the stage and backstage [33]. In addition, the prompts have been designed to pretend to be the arched porch of the Venetian palaces.



**Figure 15.** Scenery of *Italiana in Algeri*, installed at the Regio theatre of Turin in 2018.

The linear design of the layers, most of them composed of grids instead of opaque surfaces, matches the transparency as it is essential for this type of scenography, in order to filter and mime the variable intensity of light [34].

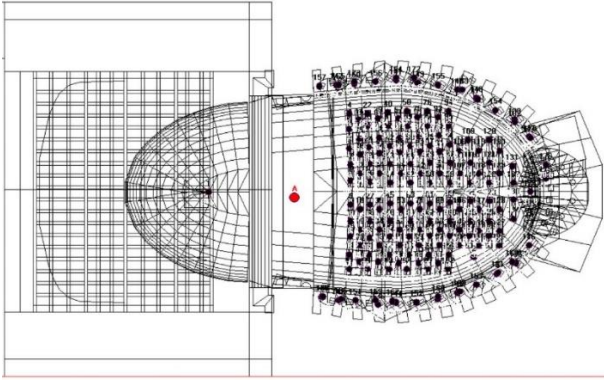


**Figure 16.** Act I of *Italiana in Algeri* at the Regio theatre of Turin, 2018.

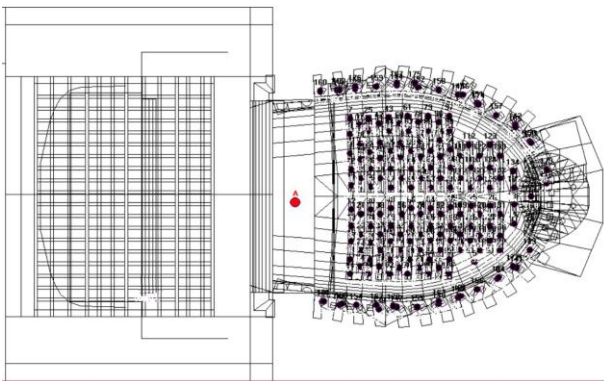
At the top, the framed scenery is open at the whole height of the stage tower, without any additional ceiling. In this way there was no need of building a secondary lighting system because the scenery takes advantage of the system already existing in the theatre.

## 7 Analysis of results

By installing the sceneries, as previously discussed, on the stage of the theatre, it is possible to see how the spreading of sound reflections changes for the different acoustical parameters [35]. Therefore, the room acoustics' characteristics vary visibly with the presence of the selected sceneries, compared to the empty stage [36]. Figure 17 and 18 show in plan the geometry of the two sceneries mounted on the stage, indicating the design respectively of Karl-Ernst and Ursel Herrmann for the *Traviata* and of Vittorio Borrelli for the *Italiana in Algeri*.

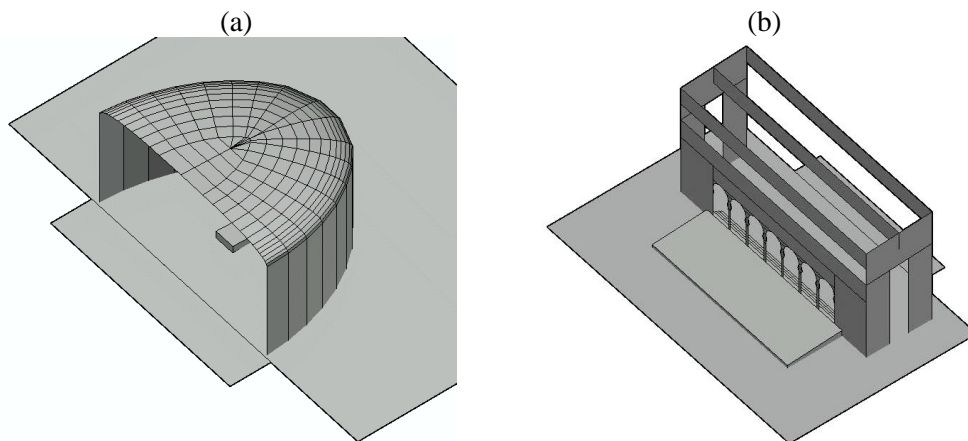


**Figure 17.** Virtual model of the theatre with the scenery of *Traviata*. One sound source placed onto the stage and 173 receivers in the hall.



**Figure 18.** Virtual model of the theatre with the scenery of *Italiana in Algeri*. One sound source placed onto the stage and 173 receivers in the hall.

Figure 19 shows the digital reconstruction of the sceneries inserted into the model. It can be visible how the geometry is completely different, which justifies the results of the acoustical parameters.



**Figure 19.** Digital reconstruction of the two sceneries: (a) *Traviata* and (b) *Italiana in Algeri*.

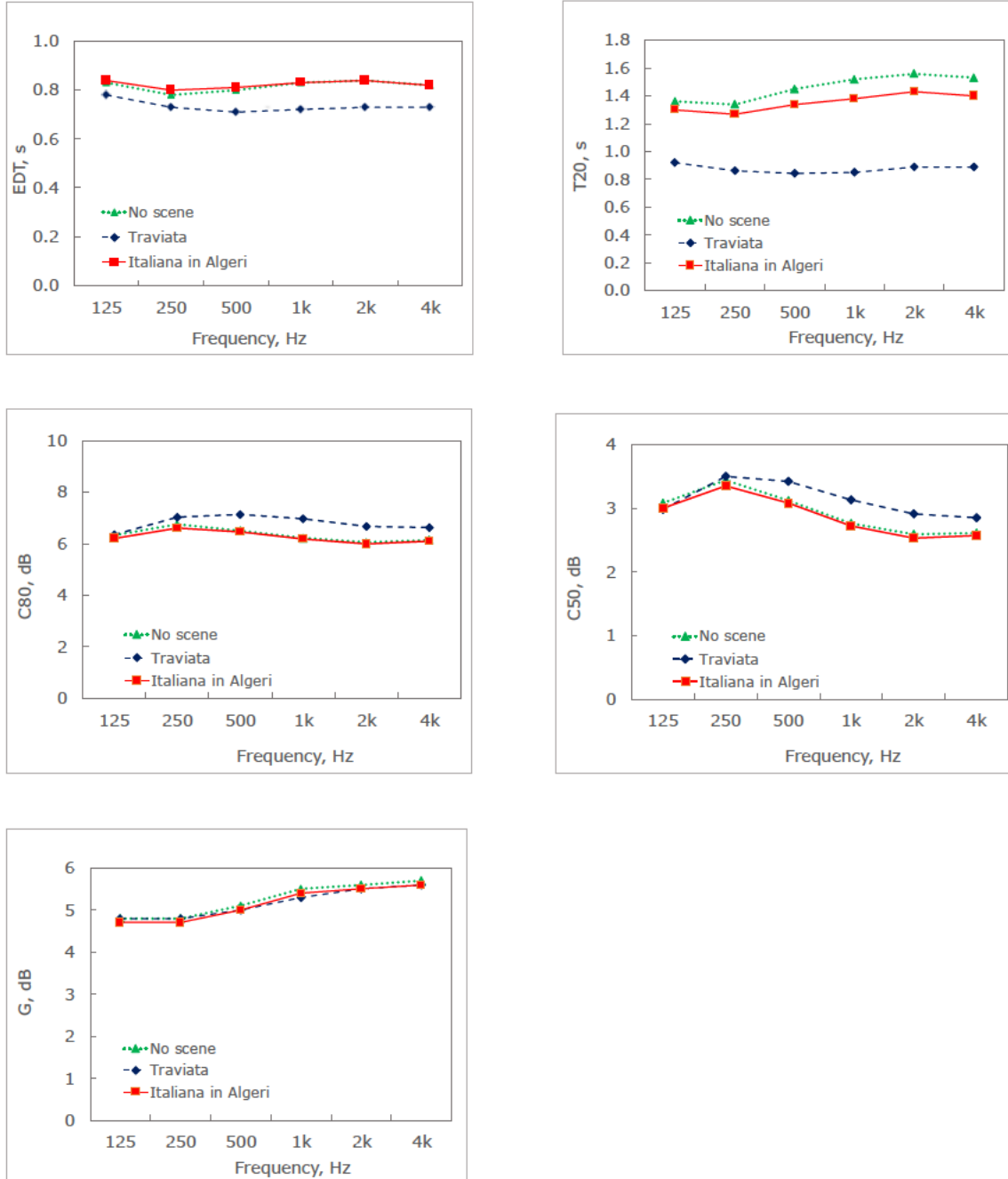
The graphs in Figure 20 are the results of the acoustic simulations carried out for all the three scenarios in absence of audience or, in other words, in unoccupied conditions. Before comparing the three scenarios, it should be said that the virtual reproduction of the acoustics without any sceneries do not faithfully match the real values, due to a lack of knowledge in relation to the characteristics of materials (e.g. thickness, surface area, etc.) that are crucial as input data for the realization of a simulated model [37]. Although this little



variation, the scope of this research study is to highlight the difference occurring between the three aforementioned scenarios [38].

The graphs showing the results of the simulated acoustical parameters are obtained by considering the average values of all the receiver points.

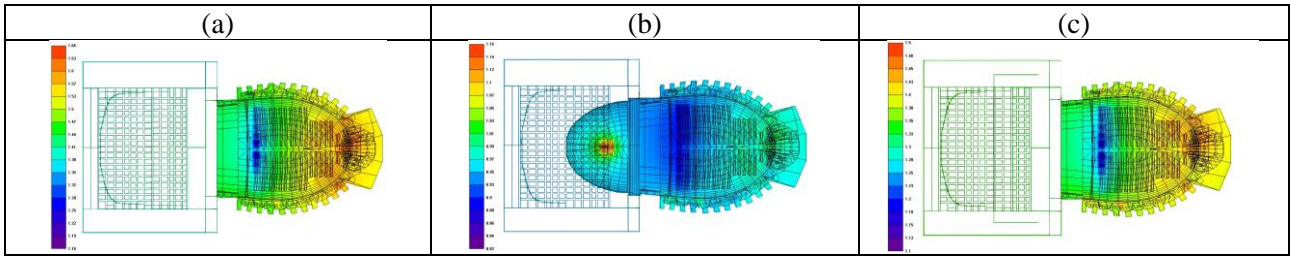
In particular, the graphs in Figure 20 show that the early decay time (EDT) has a pretty flat response upon all the frequency bands, which is a good indicator. However, the volume reduction of the scenic tower by installing the scenery of *Traviata* has a significant effect on the reverberation time ( $T_{20}$ ), which indicates, in these conditions, to be around 0.6s lower than the  $T_{20}$  obtained with the feature of *Italiana in Algeri* [39].



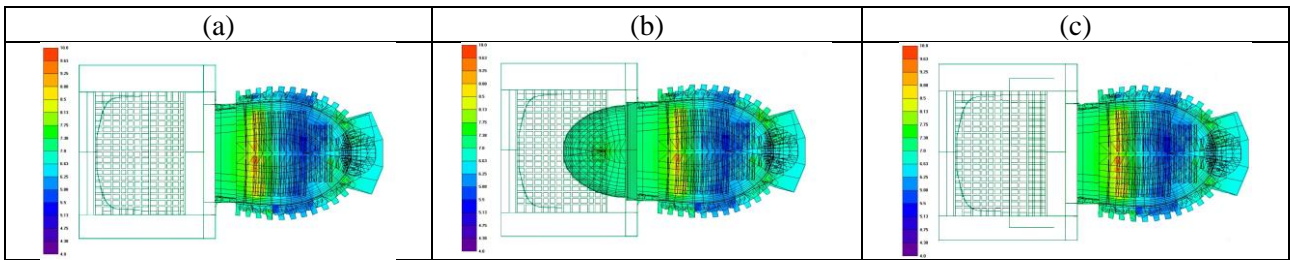
**Figure 20.** Average values of the simulated acoustical parameters, in frequency domain.

The clarity index ( $C_{80}$ ) indicates that the musical performance is very similar for all the three configurations, with a slight variance of 0.4 dB obtained with the scenery *Traviata*, resulting above the other two scenarios. In a similar way, the trend for the clarity of speech ( $C_{50}$ ) resulted to be more accentuated with the scenery *Traviata*, especially at high-frequency bands. The strength (G) has a good response for all three scenarios, which indicates that the sound reaches every seat position.

We can also see the results considering a different way of representation, which indicates the spatial distribution of the same parameters. Figures 21 and 22 report the example of a few parameters.



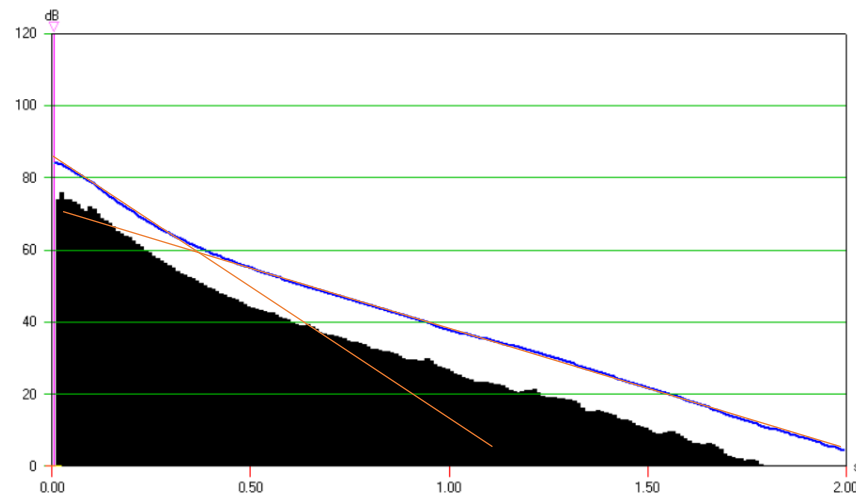
**Figure 21.** Spatial distribution of  $T_{20}$  at 500 Hz for the three scenarios: (a) without any scenery; (b) with scenery of *Traviata*; (c) with scenery of *Italiana in Algeri*.



**Figure 22.** Spatial distribution of  $C_{80}$  at 500 Hz for the three scenarios: (a) without any scenery; (b) with scenery of *Traviata*; (c) with scenery of *Italiana in Algeri*.

## 8 Outcomes and discussions

The average EDT and reverberation time ( $T_{20}$ ) obtained by simulation without an audience and with the scenery of *Traviata* is found to be lower than the other two scenarios due to the reduced volume of the stage. However, the trend line of EDT and  $T_{20}$  are almost linear, showing a slight double slope, as indicated in Figure 23. This phenomenon is explained by the absence of an audience because the reflections of the sound waves on the rows of seats pronounce the sound amplification especially at low frequencies [40-43].



**Figure 23.** Double slope trend of the  $T_{20}$  decay at 500 Hz, related to the scenery of *Traviata*.

The spatial distribution of the reverberation time ( $T_{20}$ ) is quite uniform in the elliptical hall with the scenery *Traviata* installed on the stage. It is dissimilar from the other two scenarios as it can be noticed that for *Italiana in Algeri* and the empty stage the  $T_{20}$  is higher at the last rows of seats of the stalls and on the balconies. In terms of clarity index for music ( $C_{80}$ ) the spatial distribution is very similar across all the scenarios, showing a good clarity at the middle rows of the stalls while it was found higher at the rows of seats closer to the stage.

## 9 Conclusions

Starting from the historical development and the architectural features characterising the São Carlos theatre, this paper describes the acoustic behaviour of this historical building by presenting the measurement results undertaken in 2003, which show a slightly “deaf” sound perception for musical performances.

However, acoustical simulations have been elaborated for three selected scenarios in order to highlight how the sound diffusion behaves differently inside the sitting areas based on the type of scenery installed on the stage. In particular, the scenarios in comparison involve the absence of any scenery on the stage, the installation of the scenery of *Traviata* and of *Italiana in Algeri*. All the simulations have been calculated in unoccupied conditions. The results obtained from the elaboration of the virtual model showed that the lowest reverberation time was found with the scenery *Traviata* on. This is itself explicable due to the reduced volume of the scenic tower since the scenery *Traviata* creates an enclosed space given by the prompts and the ceiling assembled together.

Differently, the scenery of *Italiana in Algeri* resulted closer to the scenario having an empty stage because the layers are open to the ceiling and to the sides, interconnecting the spaces of the stage and the backstage.

Overall, since both types of sceneries (enclosing a part of the stage or provided with an open prompts) have been diffusively performed inside the São Carlos theatre throughout the last decades, it can be assumed that all of the musical performances have obtained a successful acceptance from the audience, without any desirable condition.

## 10 Acknowledgments

The authors wish to thank Angelo Farina for his valuable help during the work, and Pedro Fidalgo, who courteously provided his accurate drawings of the theatre. This research was carried out within the research project n.201594LT3F (Research for SEAP: a platform for municipalities taking part in the Covenant of Mayors) which is funded by PRIN (Programmi di Ricerca Scientifica di Rilevante Interesse Nazionale) of the Italian Ministry of Education, University and Research, and the project “SIPARIO - Il Suono: arte Intangibile delle Performing Arts – Ricerca su teatri italiani per l’Opera POR-FESR 2014-20” funded by the Regione Emilia Romagna under EU Commission.

## References

- [1] S. Weinzierl, P. Sanvito, F. Schultz and C. Büttner: *The acoustics of renaissance theatres in Italy*. Acta Acustica Vol. 101, pp 632-641 (2015).
- [2] Z. Đórdévić: *Intangible tangibility: Acoustical heritage in architecture*. Structural Integrity and Life, Vol. 16, pp 59-66 (2016).
- [3] J. Reese: *Teatro Nacional de São Carlos: Opera House, Lisbon, Maria I of Portugal*. String Publishing, pp 12-24 (2011).
- [4] M. Cairolì: *Petrarca Theatre. A case study to identify the acoustic parameters trends and their sensitivity in a horseshoe shape opera house*. Applied Acoustics, Vol. 136, pp 61-75 (2018).
- [5] G. B. Stan, J. J. Embrechts and D. Archambeau: *Comparison of different impulse response measurement techniques*. Journal of the Audio Engineering Society, Vol. 50 (4), pp 249-262 (2002).
- [6] J. Mascarenhas-Mateus and C. Vargas: *São Carlos, um teatro de ópera para Lisboa, património e arquitetura do Teatro Nacional de São Carlos*. Imprensa Nacional Casa da Moeda (2014).
- [7] M. de Carvalho: *Pensar é morrer, ou, O Teatro de São Carlos: Na mudança de sistemas sociocomunicativos desde fins do séc. XVIII aos nossos dias*. Imprensa Nacional Casa da Moeda (1993).
- [8] M. I. Cruz: *O Teatro Nacional de S. Carlos*. Lello Editores, pp 15-67 (1992).
- [9] T. Hidaka, L.L. Beranek, *Objective and subjective evaluations of twenty-three opera houses in Europe, Japan, and the Americas* Journal of Acoustics Society of America, Vol. 107 (368) (2000) doi.org/10.1121/1.428309
- [10] N. Pevsner: *A history of building types*. Mellon Lectures in the Fine Arts, Bollingen Foundation, pp 63-90 (1976).
- [11] M.R. Lautenbach, M.L.S. Vercammen, K.H. Lorenz-Kierakiewitz: *Acoustic aspects of stage and orchestra pit in opera houses*. Proc. of DAGA (2012).
- [12] M. Caniato, S. Favretto, F. Bettarello and C. Schmid: *Acoustic characterization of resonance wood*. Acta Acustica united with Acustica, Vol. 104 (6), pp 1030-1040 (2018).
- [13] H. Park, J. Y. Jeon. *Acoustical investigation of ambience sound for auditory environments in music performance spaces*. Building and Environment 107, 10-18 (2016).
- [14] L. L. Beranek and T. Hidaka: *Sound absorption in concert halls by seats, occupied and unoccupied, and by the hall's interior surfaces* Journal of Acoustics Society of America, Vol. 104 (6), pp 3169-3177 (1998).
- [15] H. Kuttruff: *Room Acoustics*. Ed. Spon Press, 5<sup>th</sup> edition, pp 131-135 (2009).
- [16] L. Tronchin: *Variability of room acoustic parameters with thermo-hygrometric conditions* Applied Acoustics, Vol. 177, 107933 (2021).
- [17] A. Farina: *Simultaneous measurement of impulse response and distortion with a swept-sine technique*. 110<sup>th</sup> AES Convention, pp 18-22 (2000).
- [18] G. B. Stan, J. J. Embrechts, D. Archambeau: *Comparison of different impulse response measurement techniques*. Journal of the Audio Engineering Society, Vol. 50 (4), pp 249-262 (2002).
- [19] A. Farina and L. Tronchin: *Measurements and reproduction of spatial sound characteristics of auditoria*. Acoustical Science and Technology, 26, pp 193-199 (2005).
- [20] L. Mazzarella, M. Cairolì, *Petrarca Theatre: A case study to identify the acoustic parameters trends and their sensitivity in a horseshoe shape opera house*. Appl. Acoust. Vol 136, pp. 61–75, (2018).
- [21] R. Shimokura, L. Tronchin, A. Cocchi, Y. Soeta: *Subjective diffuseness of music signals convolved with binaural impulse response*. Journal of Sound and Vibration, Vol. 330 (14), pp 3526-3537 (2011).
- [22] M. Kuster: *Reliability of estimating the room volume from a single room impulse response*. Journal of Acoustics Society of America, 124, pp 982-993 (2008).
- [23] L. Beranek: *Music, Acoustics and Architecture*. John Wiley & Sons, Inc. (1962).
- [24] D. Pavlović, M. Mijić, D. Mašović, *The influence of proscenium boxes on acoustic response in historical opera halls*. Journal of the Acoustical Society of America Vol 138 (3), pp. 1533-1536 (2015)
- [25] M. Vorländer: *Models and algorithms for computer simulations in room acoustics*. Proc. International Seminar on Virtual Acoustics, pp 24-25 (2011).
- [26] L. Shtrepi: *Investigation on the diffusive surface modeling detail in geometrical acoustics-based simulations*. Journal of Acoustics Society of America, 145 (3) EL 215 (2019).
- [27] A. Farina: *Aurora listens to the traces of pyramid power*. Noise & Vibration Worldwide, Vol. 26 (6), pp 6-9 (1995).

- [28] A. Farina: *Verification of the accuracy of the Pyramid Tracing algorithm by comparison with experimental measurements by objective parameters*. ICA95 International Conference on Acoustics (1995).
- [29] M. Vorländer: *Fundamentals of Acoustics, Modelling, Simulation, Algorithms and Acoustic Virtual Reality*. Springer Science & Business Media (2007).
- [30] T. J. Cox and P. D'Antonio: *Acoustic Absorbers and Diffusers: Theory, Design and Application*. CRC Press, Boca Raton, 3<sup>rd</sup> Ed. (2004).
- [31] J. Patynen: *Investigations on the development of the frequency response over time in concert halls*. Proc. of the Institute of Acoustics, pp 159-168 (2011).
- [32] S. Crabtree and P. Beudert: *Scenic Art for the Theatre*. Focal Press (1998).
- [33] J. Peacock: *The Stage Designs of Inigo Jones: The European Context*. Cambridge University Press (1995).
- [34] P. Bjurström: *Giacomo Torelli and Baroque Stage Design*. Almqvist & Wiksell (1961).
- [35] L. Tronchin, F. Merli and M. Manfredi: *On the acoustics of the Teatro 1763 in Bologna* Applied Acoustics, Vol. 172, 107598 (2021).
- [36] G. Iannace, C. Ianniello, L. Maffei and R. Romano: *Objective measurement of the listening condition in the old Italian opera house Teatro di San Carlo*. Journal of Sound and Vibration, 232 pp 239-249 (2000).
- [37] J.Y. Jeon, J.K. Ryu, Y.H. Kim, S. Sato: *Influence of absorption properties of materials on the accuracy of simulated acoustical measures in 1:10 scale model test*. Applied Acoustics, 70, pp 615-625 (2009).
- [38] L. M Wang, J. Rathsam, S. R. Ryherd: *Interactions of model detail level and scattering coefficients in room acoustic computer simulation*. Proc ISRA (2004)
- [39] J.K. Ryu, J.Y. Jeon: *Subjective and objective evaluations of a scattered sound field in a scale model opera house*. Journal of Acoustics Society of America, 124, pp 1538-1549 (2008).
- [40] J. Y. Jeon, J. H. Kim, J. K. Ryu, *The effects of stage absorption on reverberation times in opera house seating areas*. Journal of the Acoustical Society of America Vol 137 (3), pp. 1099-1107 (2015).
- [41] J.S. Bradley. *Review of objective room acoustics measures and future needs*. Applied Acoustics Vol 72 (10), pp. 713-720 (2011).
- [42] M. Barron, J. Lee: *Energy relations in concert auditoriums*. Journal of Acoustics Society of America, 84, 618-628 (1998).
- [43] L. Bortolotti and L. Masetti: *Teatri storici. Dal restauro allo spettacolo (Historical Theatres. From Renovation to Performance)*. Ed. Nardini, (1977).