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Original article

Investigations on the acoustic response of two heritage buildings designed by Galli Bibiena and disappeared from history in the 18th century: The Nancy and Tajo opera theatres

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ABSTRACT

The development of melodrama during the 16th and 17th centuries brought the architects to the elaboration of a different variety of geometry for the main halls of opera theatres. Unfortunately, nowadays there are only a few theatres designed and built during the Baroque period since most of them are completely destroyed. The architectural investigations carried out on two case studies belonging to the Galli Bibiena family have been taken over for a complete acoustic assessment. The digital models related to the Nancy and Tajo opera theatres were built from the outcomes and discoveries on the historical resources consisting of drawings, sketches and general documents. The digital models were used for the acoustic simulations carried out on the main acoustic parameters that evaluate the quality of speech and music inside these two case studies. The simulated results indicate that the acoustic response in the Nancy and Tajo opera theatres is very similar to each other, although the small difference between the two theatres is mainly in function of the volume size rather than other architectural features. Overall, the simulated values are found within or closer to the optimal range set by the criteria, which support the assumption of speech and musical performances given in the royal palaces, the place in which they were erected.

1. Introduction

The dynasty of Galli Bibiena dominated the European architecture of the 17th and 18th centuries. Their masterpieces in Baroque style inspired family members to realise memorable sceneries and opera theatres [1], whose shape developed along with the *melodrama.* The theatrical shows represented an important vehicle of diffusing art, culture, and literature through acting.

The first opera theatres were realised inside private court-palaces of dukes and kings. This explains why the structural frame was in wood, which is a lightweight material that should not overload the existing brickwork construction. The first members of the Bibiena's family were two brothers: Ferdinando (1657–1743) and Francesco (1659–1739), followed by their sons [2]. Their handwriting style was very similar to each other such that it was difficult to assign some drawings to a specific member [3]. The Bibiena's family was specialised in designing stage sets and architecture, from a general overview of the space organization to very detailed ornaments.

Regarding the variety of sketches preserved to our days, many drawings survived because they were engraved, as part of museums and art galleries, while so many sketches ended to be destroyed, such as those related to the Teatro Filarmonico of Verona and Nancy opera theatre [4].

2. Research aim

This paper deals with the acoustic study of two opera theatre designed by Galli Bibiena that are disappeared and no more existing. The resources available on this topic is only referring to the architectural discoveries carried out by the students at the University of Lisbon, whom the authors are very grateful of, but none of other research has been conducted on how the acoustic response within these opera theatres would be. Furthermore, many drawings by Galli Bibiena have been lost and some of them attributed to different buildings than what referring to. A clearance on such confusion has been made based on a comparison regarding the

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main acoustic parameters with other opera theatres by Galli Bibiena that have been simulated and/or measured by the authors. The absorption and scattering coefficients related to the materials have been considered based on the accurate description given by the resources and on the extensive experience by the authors on acoustic measurements within other opera theatres designed by Galli Bibiena.

3. Historical background of Nancy opera theatre

Francesco Galli Bibiena worked between Italy and the court of Vienna when he was called by Leopold 1st, Duke of Lorraine, to design a new opera theatre in the French city after the great success of the Grosses Hoftheater that the brothers Bibiena realised in Vienna [1]. The reason why the duke called an Italian specialist in France is not clear; some theories assume that there was a request of a great architect for the renovation of the front elevation of the palace in Versailles and that Francesco Galli Bibiena was already in France, but this is not confirmed. Leopold 1st decided to build an opera theatre in Nancy, although the troops of King Louis 14th invaded Nancy in 1709 during the war between Bourbons and Habsburgs; the duke, already moved in Luneville, was not able to attend to the opening of his preferred construction [5]. The erection of the Nancy opera theatre was commissioned in April 1708 and finished in November 1709. When Leopold 1st returned to Nancy in 1714 with no financial wealth, the artistic performances were not economically supported such that the building was used for different purposes. A further transformation occurred also during the war between 1740 and 1748 and continued until it was destroyed in 1818 [5].

4. Historical background of Tajo opera theatre

The Portuguese architecture knew its magnificent period during the 18th century because King Joseph 1st of Portugal (1750–1777) was a great prompter of arts and music. Like many other European capital cities, King Joseph commissioned the construction of a memorable opera theatre in Lisbon [6]. A member of the Bibiena's family was called to design the new theatre for the king: his name was Giovanni Carlo Sicinio (1713–1760), who was Francesco's son. Giovanni Carlo Sicinio, who belongs to the second generation of the dynasty accepted this role and moved to Portugal in 1754 [7]. Unfortunately, this opera theatre survived only 7 months since it was inaugurated on 31st of March 1755 and was destroyed by an earthquake on 1st November of the same year [8].

5. Materials and methods: memory through the drawings

5.1. Sketches related to Nancy opera theatre (NOT)

The main reference drawings related to the Nancy are grouped in four sets:

- The first set of drawings is archived in the Musée Lorrain [5,9], which are the first designed by Francesco himself [10].
- The second set is preserved in the National Museum of Ancient Art of Lisbon, that reflect the project finally built [5,9]. Researchers assume that these drawings were executed by Francesco's workshop collaborators, who could have produced a copy of the originals now preserved in Nancy [10].
- The third set of sketches are saved at the Musée du Louvre in Paris. These drawings are found very similar to those preserved in Lisbon [5,9]. Like those archived in Lisbon, these sketches could be attributed to Francesco's students [10].
- The fourth set of drawings is preserved at the Metropolitan Museum in New York city. They consist of a longitudinal section, a floor plan of the audience and stage, grouped with inventory No. 1972.713.61. Another group of drawings consist of a theater plan, a cross-section by the proscenium and the royal stateroom, and a ceiling plan, according to the inventory No. 1972.713.60 [1,9]. Research studies assume that these drawings were made upon completion of the opera theatre, meaning that they correspond to the construction existed in reality [10].

Based on the description of the resources, the authors of this manuscript refer to the drawings preserved in New York city for the acoustic analysis.

5.2. Sketches related to Tajo opera theatre (TOT)

The reference drawings found in relation to the Tajo are grouped only in two sets.

- The first set was revealed in 1993 by José de Figueiredo [11], consisting of drawings realised by Giovanni Carlo Sicinio himself [10], that are now preserved in the Academia Nacional de Belas Artes in Lisbon (ANBA.Lx).
- The second set of sketches is attributed to Pedro Miguel Gomes Januário [12]. It consists of a longitudinal section (No. 1696), a plan layout of the royal tribune (No. 1670); these two drawings are archived in the Drawing Office of the National Museum of Ancient Art in Lisbon (MNAA.Lx). Other drawings consist of a ceiling plan (No. 91), a transversal section of the proscenium (No. 91), and plans of the second and the third level of the main hall (No. 110) [10]. These drawings are preserved in the National Library of Brazil in Rio de Janeiro (BN.RJ), in the Iconographies Section, in a collection called Desenhos de Arquitecturas, Plantas de Obras em Lisboa e Rio de Janeiro.

From these resources, previous research studies tried to reconstruct the Tajo [13], thereafter completed with some adjustment in the metric unit [10]. Based on different types of sources, the authors of this manuscript refer to the drawings analyzed by recent studies for the assessment of the acoustic parameters [10].

6. Architectural similarities in the two opera theatres

Both Nancy and Tajo opera theatres were located inside the royal palaces of their cities. From an overview of the internal organization, they are composed of three main spaces: the audience area, the stage, and a zone representing an atrium or a lobby that connects the opera theatre with the royal palace [10]. In Nancy, the stage area was provided with two side wings, which represents the only architectural elements that change the profile of the external walls, while in Lisbon, a change of sectional area is found between the acting/stage zone and the corridor connecting this space to the rest of the palace. Fig. 1 shows the drawings obtained from the historical sources, as previously mentioned.

These two lost opera theatres were designed by Bibienas to host the drama for music (*melodrama*), with the same logics used for the royal leisure, on the trace of the Italian opera theatres. Therefore, the atrium placed for accessing the seating area is connected to the circulation space at all levels around the balconies. Other similarities found between these two opera theatres are represented by the royal balcony provided with double height, four orders of boxes in total, and an orchestra pit placed between the stalls and the stage. The details of the architectural features are summarized in Table 1, in comparison with the characteristics of other two theatres designed by Galli Bibienas that are still existing: the Scientific theatre of Mantua and the Communal theatre of Bologna. The comparison in terms of acoustic response within these other two opera theatres is given in Section 9.

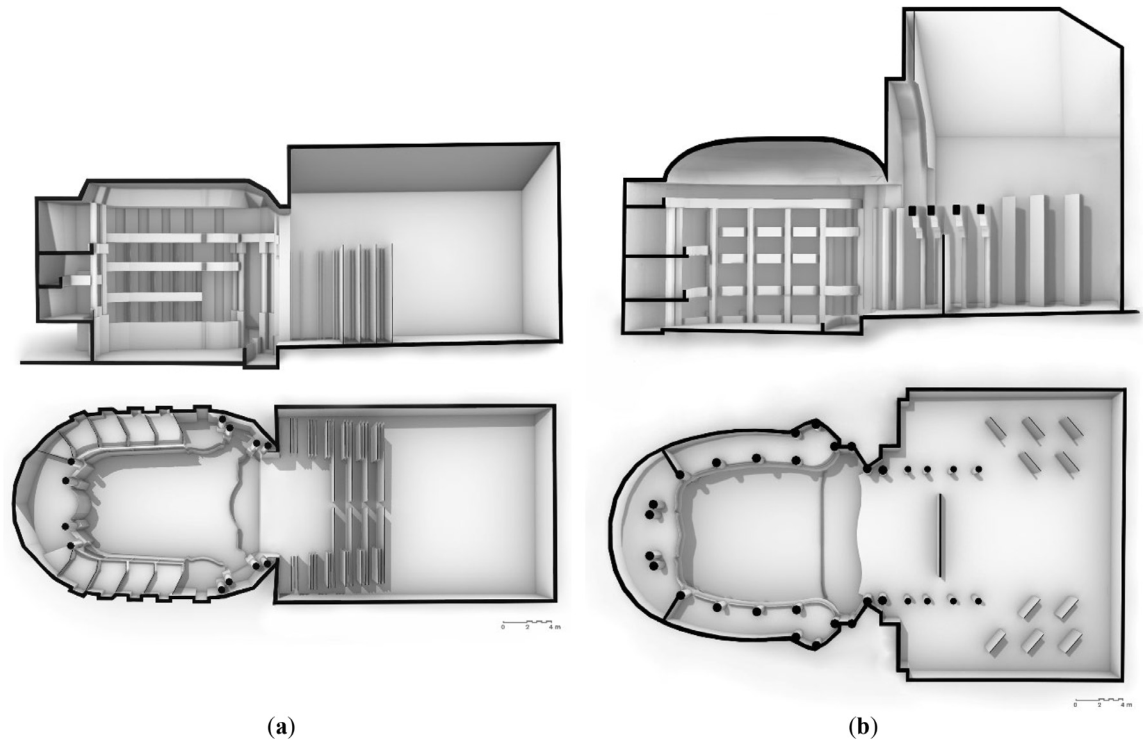


Fig. 1. Plan layout and longitudinal section of the Nancy opera theatre (**a**) and Tajo opera theatre (**b**). The drawings reflect the final version studied by E.D. Antunes [10].

Table 1
Architectural characteristics of Nancy and Tajo opera theatres in comparison with two other opera theatres designed by Galli Bibienas still existing: Scientific theatre of Mantua and Communal theatre of Bologna.

	Description	Scientific Mantua	Nancy	Tajo	Communal Bologna
Main Hall	Inclination of stalls (%)	–	0	1	2
	Longitudinal axis (m)	14.7	17.5	18.5	19.6
	Transversal axis (m)	9	9.7	13.2	18
	Height at the center of vault (m)	13	14.3	17.7	16.5
	Levels of boxes	4	4	4	5
	Volume (m^3)	Approx. 2100	Approx. 3143	Approx. 4100	Approx. 5190
Scenic Arch	Orchestra pit (m^2)	–	25.6	57	66
Stage	Inclination (%)	1	2	2	2
	Length (m)	12.8	22.5	23	23
	Width (m)	6	17 (no wings)	25.7	24
	Height (to the reticular wooden structure) (m)	11	11.5	9	13
Fly Tower	Volume up to the wooden grid (m^3)	Approx. 890	Approx. 4398	Approx. 5319	Approx. 8370
Hall + Fly Tower	Total volume (m3)	2990	7541	9419	13,560

6.1. Peculiar bell-shape plan of the main hall

The most important characteristic of these two opera theatres is represented by the bell-shape plan of the main hall, that was purely created by the Galli Bibiena family, although no theories have been written by them that explain the reasons why their choice fall onto this particular geometry. It should be remembered that the time between the 15th and 18th centuries was dominated by the discussions regarding the shape for the audience space. Different geometries were proposed by architects, one of them was the U-shape designed for accommodating more attendees to the shows, as adopted for the Farnese theatre of Parma by Aleotti (1610); another was the ellipse developed with the theories by Pierre Patte (1792) that could combine the acoustic and optical principles in a pure geometry [14]. The bell-shaped geometry in Italy was criticized by F. Algarotti, especially for the reasons related to the direct sightline of the spectators that was considered not comfortable in some positions, although Algarotti appreciates the bell shape for creating a good vocal strength, referring to the Scientific theatre of Mantua [15].

6.2. Interior design and finish materials

Based on the resources analyzed by E.D. Antunes, it is possible to determine the interior design and the indoor materials placed into the two opera theatres. The main material used by the scenographers Bibienas was wood, a local material always available in the two cities [16]. As previously mentioned, both opera theatres were realized inside royal palaces such that the internal construction should not overload the main masonry structure; as such, wood was the lightweight material selected for this reason other than to express more creativity in the details by carving the mass. The acoustic properties of wood have been adopted in both opera theatres for the acoustic simulations, employed for the half-height walls separating the cabins and the floor of balconies [17]. The perimetral walls are considered plastered as well as the roof [17].

7. Digital models and validation of the acoustic simulations

The digital models are built based on the drawings realized by Eduardo Durão Antunes, from the School of Architecture at the

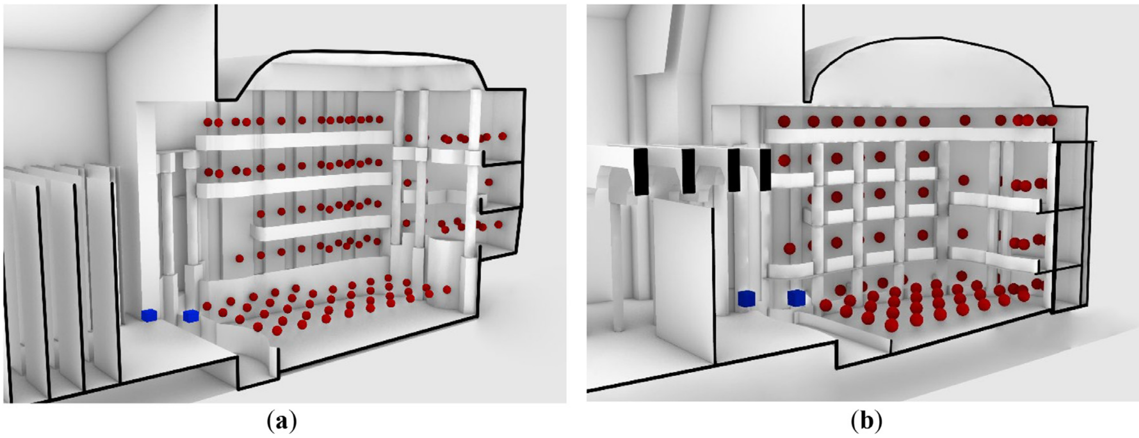


Fig. 2. View of the virtual equipment installed in the stalls and balconies for the acoustic simulations,within Nancy opera house (**a**), and Tajo opera house (**b**).

Table 2
Characteristics of digital models used for acoustic simulations.

Item Description	Nancy	Tajo
Total number of 3D-faces	1965	2451
Total surface area (m2)	4926	8512
No. of virtual microphones	189	332

University of Lisbon, after the analysis that he carried out on the variety of resources. The digital models were realised with AutoCAD software by the authors of this research study, to be composed of 3D faces, thereafter exported in DXF format.

The acoustic simulations are obtained by using Ramsete 3.13 software [18], that is based on ray-tracing computation and a triangular-base pyramid (instead of conical) spreading [19]. The virtual sound sources were placed onto the stage in two different positions, on and off centre of the longitudinal axis, at the height of 1.8 m, while the receivers were homogeneously distributed across the seating areas, at the hight corresponding to the listeners' ears. The setting of the Ramsete Tracer is the following:

- Maximum duration of the IR: 3 s.
- Time resolution: 0.01 s.
- Humidity: 50%.
- Temperature: 20 °C.
- Diffraction level: 2.
- Diffusion: included.

The characteristics of the digital models related to both Nancy and Tajo opera theatres are described in Table 2, while Fig. 2 shows the placement of the virtual sources and microphones across the stalls and balconies of both Nancy and Tajo opera houses.

The absorption and scattering coefficients for all the materials considered in the acoustic simulations are reported in Table 3. The scattering coefficients were obtained from literature [20,21], while the absorption coefficients are applied by considering the descriptions found in the historical documents and by comparing the material used for the simulation of similar opera theatres undertaken by the authors. This practice is extensively described in a previous research study carried out by the same authors of this paper [17].

The goal of this research study is not to investigate the precise absorption and scattering coefficients that were used at the time of the construction of the two buildings, therefore they cannot be considered as absolute values until further archaeological discoveries on material properties. The goal of the acoustic simulations is to highlight any difference, in terms of acoustic parameters, between the two lost heritage buildings by assuming that they were built with similar materials and technology, as typical of architects belonging to the same family. The variability of the simulated results is highly dependent on the values of absorption and scattering coefficients assigned to the materials [22,23]; therefore, the reference to each material property is discussed as follows:

- The balustrade as well as the surfaces separating the cabins are considered highly absorbing since they were wooden sticks; these coefficients are considered the most appropriate way to represent perforated surfaces.
- The coefficients related to the floor of the balconies are taken from recent literature [24], where the authors calibrated the values based on the acoustic measurements.
- The properties related to the curtains are taken from M. Barron [25], as well as the pit floor and the stalls floor, taken from the same source and considered made of thin wood.
- The coefficients related to the partitions of the cabins are assimilated to the pasted paper as existing in the Teatro di Corte at Reggia of Caserta [26], an opera theatre that is acoustically analysed by the authors and is characterised by a high level of reverberation time due to the lightweight materials and the cavity gap at the core of the partitions separating the boxes. These properties have been assigned to the half-height specimens that separate the boxes only for a space delimitation and not acoustically as it occurs between two adjacent sensitive spaces.
- The roof coefficients are taken from recent literature [24], due to the similarity of the structural construction that is a fall ceiling.
- The properties of the stage floor are taken from the previous research on the Tajo opera theatre [17].
- The characteristics of a solid timber are taken from measurements on an archaeological site with the technique using the laser doppler, as extensively described in [27,28].
- The coefficients related to the audience are simulated like light upholstery [25]. The audience has been placed in the stalls as in the elevated balconies, that can be standing or seating. A single surface has been given to each spectator, which is simulated to be 1.7 × 0.45 m if standing, and 0.8 × 0.45 m if seated.

8. Outcomes and simulated results

As previously discussed, the model simulation is based on the material knowledge carried out by previous architectural research [10,13] with some limitations considered for their properties and following assumption of the values based on experience on acoustic simulations applied onto other opera theatres. The analysis of the simulated results takes into account the optimal range of the

Table 3
Absorption and scattering coefficients for all the materials considered in the acoustic simulations.

Materials	Area (m2)		Absorption - Octave Centre Frequency (Hz)						Scattering (@500–1k Hz)
			125	250	500	1k	2k	4k	
	NOH	TOH							
Balustrade	107	333	0.67	0.70	0.74	0.75	0.75	0.78	0.15
Wooden floor – cabins	499	553	0.05	0.15	0.25	0.33	0.35	0.35	0.05
Brick walls	634	967	0.05	0.05	0.04	0.05	0.02	0.02	0.15
Curtains – on stage	1012	550	0.06	0.31	0.44	0.80	0.75	0.65	0.25
Partition - cabins	161	157	0.67	0.70	0.74	0.75	0.75	0.78	0.05
Orchestra pit	22	92	0.30	0.19	0.09	0.06	0.06	0.06	0. 05
Roof	202	337	0.45	0.41	0.38	0.35	0.32	0.30	0.05
Stage floor	394	932	0.55	0.50	0.40	0.30	0.30	0.27	0.05
Stalls floor	195	188	0.30	0.19	0.09	0.06	0.06	0.06	0. 05
Solid timber – perimetral walls	1442	2025	0.08	0.2	0.1	0.05	0.03	0.02	0. 05
Audience	196	289	0.51	0.64	0.75	0.8	0.82	0.83	0.25

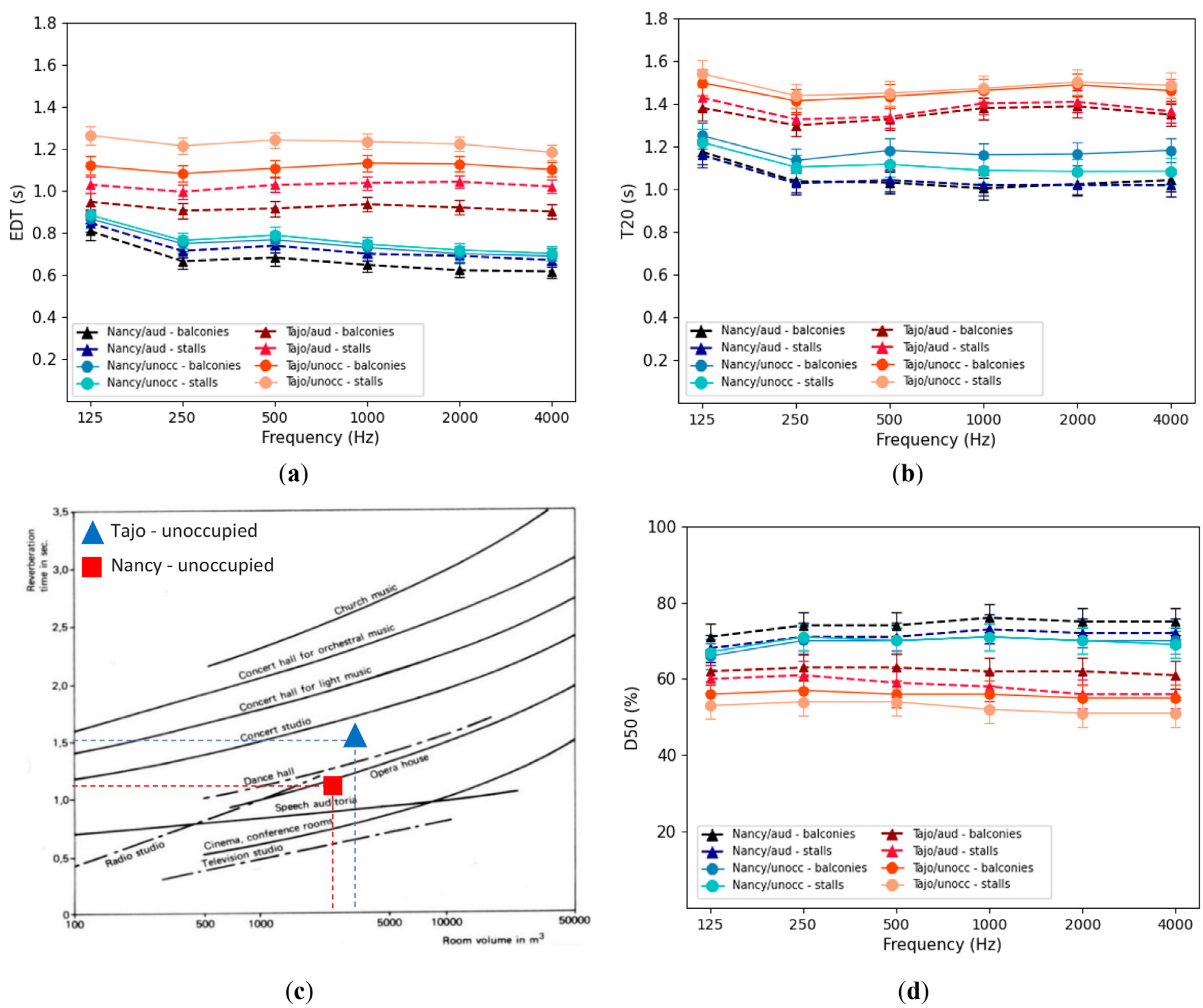
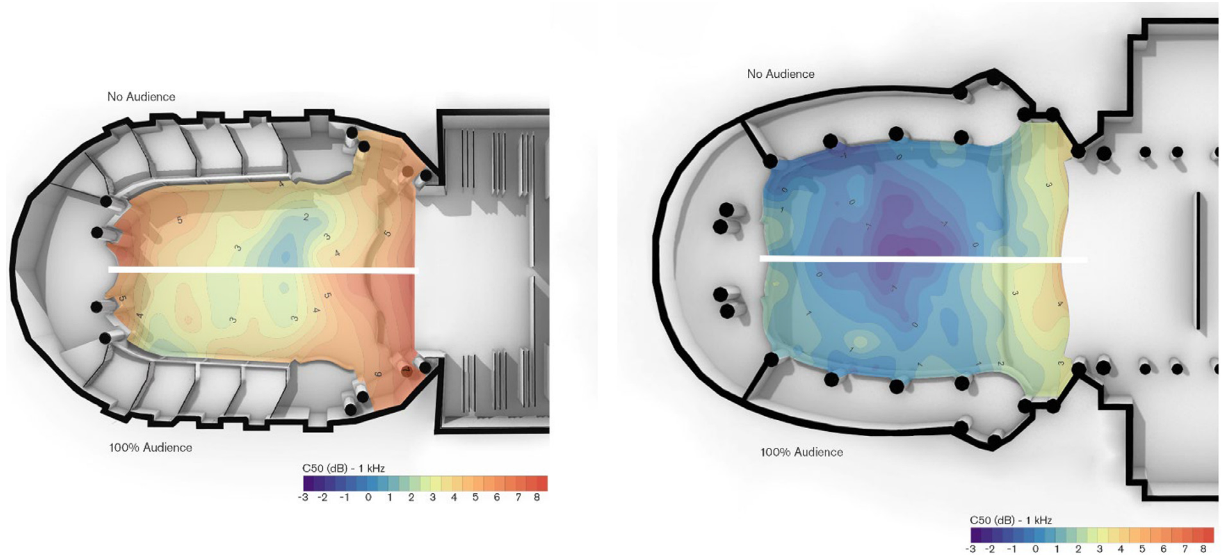


Fig. 3. Simulated results related to the Nancy and Tajo opera theatres: early decay time (**a**), reverberation time (**b**), and definition (**d**). Optimal reverberation time T20 at medium frequencies (500–2000 Hz), as a function of the volume size and building type (**c**) [30].

main acoustic parameters. This means that the evaluation is done with respect to speech and music, as these two were the main functions of the Nancy and Tajo opera theatres, specifically with the performance of opera, symphonic music and prosa. The acoustic parameters are presented in graphical form; the spatial maps have been created for the parameters that depend on the position of the listener in the seating area. Fig. 3 summarizes the main acoustic parameters according to ISO 3382 [29], in the frequency bands between 125 Hz and 4 kHz. The results of the graphs are averaged for all receivers placed in the models, while the values for each individual receiver are plotted in the acoustic maps.

The simulations were performed in both occupied and unoccupied conditions. The reference resources report [10,13] report the scenario of standing spectators when attending the performance; this is the circumstance that has been taken into account for the acoustic simulations.



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

Fig. 4. Spatial distribution of speech clarity index (C50) at 1 kHz, with and without audience: Nancy opera theatre (**a**), Tajo opera theatre (**b**).

Fig. 3(**a**) shows that the EDT values in Nancy fluctuate around 0.7 s, with a difference of 0.1 s between occupied and unoccupied conditions. The difference between stalls and boxes in Nancy is very negligible. The EDT values related to Tajo are found slightly higher, to be around 1.2 s without any occupancy and around 1.0 s when occupied, with a difference of 0.1 s between boxes and stalls at the same condition of occupancy. This means that both values are considered below the minimum threshold set by Jordan in terms of opera theatres [31], based on which the EDT values should range between 1.8 s and 2.6 s.

In terms of reverberation, Fig. 3(**b**) shows that the T20 values are around 1.0 s in Nancy and around 1.5 s in Tajo, with a difference of 0.2 s between boxes and stalls at the same condition of occupancy. In relation to the room volume of the main halls, Fig. 3(**c**) shows that both Nancy and Tajo are very close to the optimal trend line related to opera theatres in unoccupied conditions; specifically, the values at medium frequencies in Nancy are slightly below criteria, and in Tajo are above. This means that the results are appropriate either for speech or vocal/instrumental music, in both spaces.

Results related to definition, as shown in Fig. 3(**d**), are found around 70% in Nancy, and 60% in Tajo. According to the criteria [32], the D50 values resulting > 50% are more suitable for speech intelligibility; the values that have been simulated are around the mid-way, meaning that the acoustic response has a good speech and music definition in both Nancy and Tajo opera theatres.

It has been considered that the spatial distribution maps would be more suitable for representing the values of speech and music clarity, due to the highly dependency of these parameters to position taken in the seating area. As such, the C50 and C80 values are plotted in Figs. 4 and 5, corresponding to 1 kHz. This distribution maps are possible to be plotted due to the high number of virtual receivers deployed in the simulation model, such that each microphone is represented with an own value of clarity at 1 kHz and the interpolation between grid points is done with the creation of contour lines.

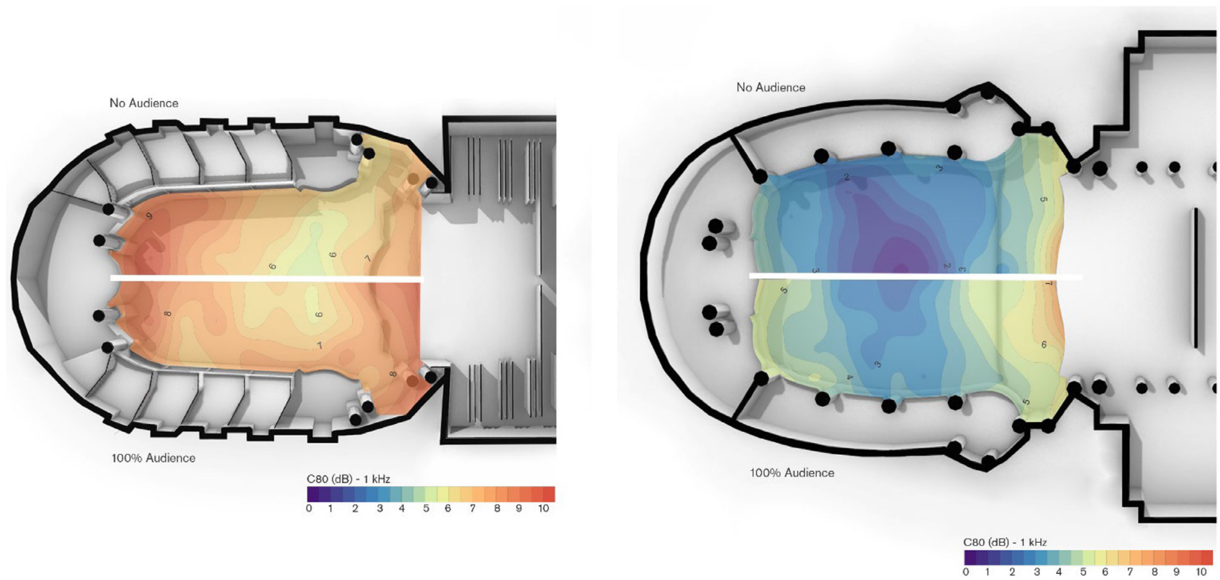
Fig. 4(**a**) shows that the C50 values in Nancy in unoccupied conditions are fluctuating between 1 dB, found in the middle of the hall, and 5 dB, found closer to the stage and on the back of the hall. The same trend occurs with the audience, but the values are shifted of 2 dB upwards. Overall, these values are slightly above the upper range limit set for speech clarity (+2 dB) but it is reasonable and similar to what measured in other opera theatres [33,34].

Fig. 4(**b**) shows that the C50 values in Tajo range between −3 dB and 0 dB, with an upward increase of 1 dB with the audience. With the exception of the values around 3–4 dB that are found in the orchestra pit, these C50 results are within the optimal range set by the criteria [35], meaning that the speech is more suitable to be performed in the Tajo opera theatre than Nancy.

Fig. 5(**a**) shows that the results related to the music clarity in Nancy are shifted by 2 dB upward compared to those related to speech, for both occupied and unoccupied conditions. In Tajo, Fig. 5(**b**) shows that the C80 values range between 0 dB and +2 dB when the hall is not occupied, and between 3 dB and 5 dB with the presence of spectators. This means that the C80 values in Nancy are found up to 5 dB above the upper range limit, while in Tajo opera theatre the C80 values are within of closer to the optimal range.

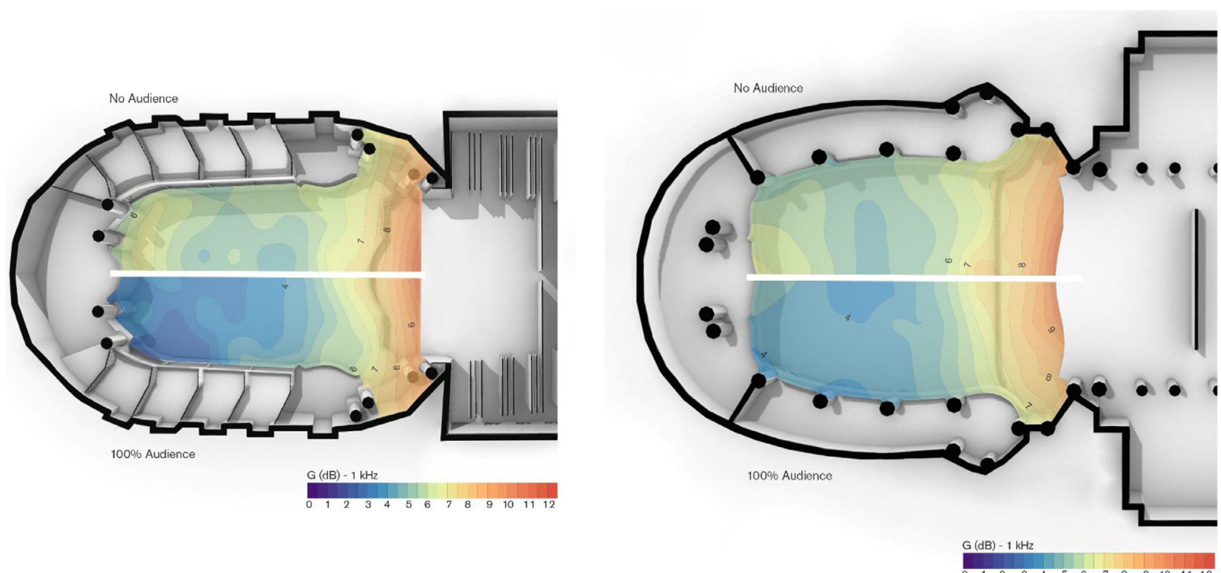
Another acoustic parameter that is a function of the position assumed in the seating area is strength (G) [36]. Fig. 6 shows the spatial distribution maps of this parameter related to the two opera theatres. In particular, the simulated results in Nancy, as shown in Fig. 6(**a**), are found between 7 dB (close to the orchestra pit) and 5 dB (at the back of the stalls), as typical of other opera theatres. These G values drop by 3–4 dB in occupied conditions, especially in the middle and in the back of the hall. A similar condition of unoccupied condition is found in Tajo, as shown in Fig. 6(**b**), but the G values are attenuated only up to 2 dB with audience, such that the difference is not very accentuated. This means that the singers and the musicians in Nancy should put more effort during live performances compared to the rehearses, phenomenon that was not considered a matter in Tajo.

The analysis of the impulse responses (IRs) gathered from the acoustic simulations allows a clear visualization of the reflections delay after the direct sound, as shown in Fig. 7. In particular, the positions of the virtual microphones are selected from the centre of the stalls (green triangle) and from the royal balcony placed at the 1st order (red circle), while the sound source is selected to be on the longitudinal axis (blue square), as indicated in Figs. 7(**a**) and 7(**b**). The analysis involves the first 7000 frames of the curve decay, as shown in x-axis, for both fully occupied and unoccupied conditions.



(a) (b)

Fig. 5. Spatial distribution of music clarity index (C80) at 1 kHz, with and without audience: Nancy opera theatre (**a**), Tajo opera theatre (**b**).



(a) (b)

Fig. 6. Spatial distribution of strength (G) at 1 kHz, with and without audience: Nancy opera theatre (**a**), Tajo opera theatre (**b**).

Taking into consideration the same position in the centre of the stalls, Fig. 7(**c**) shows that the early reflection in Nancy is arriving before what occurring in Tajo (Fig. 7(**d**)), which is mainly due to the room volume of the hall, although other factors can contribute to the determination of the early reflections, like the width of the proscenium arch and the with of the side walls of the hall. In all graphs it is possible to notice the delay of the direct sound recorded in the centre of stalls and in the royal balcony, resulting in a loss of energy as well, as shown in Fig. 7(**e**) and 7(**f**).

All the graphs in Fig. 7 show that there is not so much difference between occupied and unoccupied conditions, highlighted in blue and red continuous line, respectively. The strong reflections are always pronounced with the spikes found at the same delay with respect to the direct sound, but the reflections characterised by a small amplitude in unoccupied conditions populate more the time gap between the strong reflections due to a more resonant environment and less absorption in place.

9. Discussions on a comparison with the measured results related to other existing theatres designed by Galli Bibienas

It is a good practice to compare the simulated outcomes with some acoustic measurements in order to validate and complete the acoustic analysis. Two other existing opera theatres designed by Galli Bibienas and characterised with a bell-shaped plan of the main hall have taken into consideration: the Communal theatre of Bologna (1763) and the Scientific theatre of Mantua (1769). Both theatres were built in the middle of the 18th century and have been extensively analysed by the authors of this research study in previous literatures [37,38].

It is useful to understand the dimensions and the materiality of the interior design related to these two theatres. In particular, the main hall of the Communal theatre of Bologna has the axes measuring 20 m and 18 m, with the maximum height equal to 17 m. The levels of balconies are five, including the upper gallery,

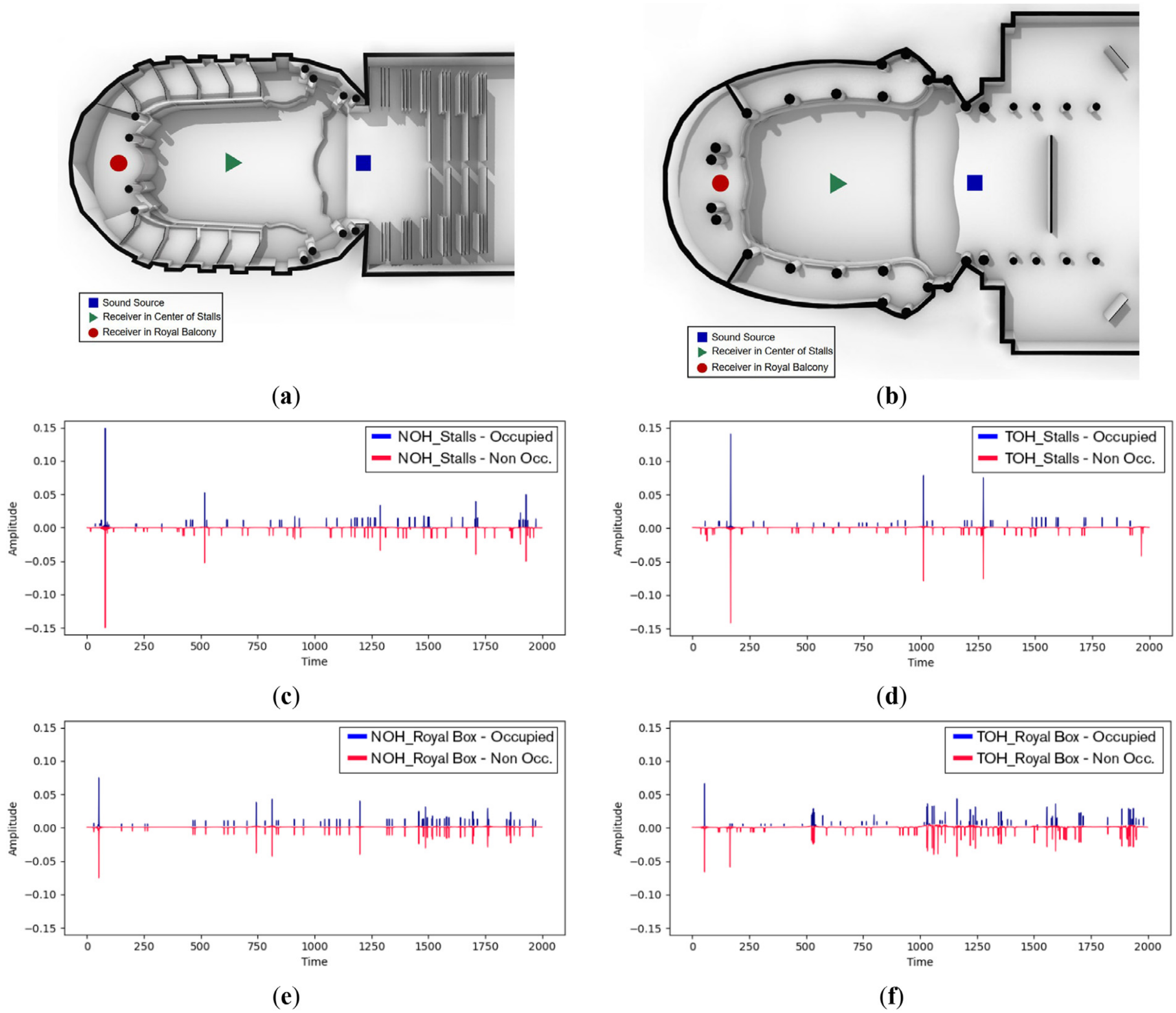


Fig. 7. Simulated impulse responses (IRs) in comparison. Positions selected in the Nancy opera house (NOH) (**a**) with relative IRs obtained in in the stalls of NOH with and without occupancy (**c**) and in the royal box of NOH with and without occupancy (**e**). Similarly, positions selected in the Tajo opera house (TOH) (**b**) with relative IRs obtained in in the stalls of TOH with and without occupancy (**d**) and in the royal box of TOH with and without occupancy (**f**).

contributing to a room volume equal to 5190 m3. The structural frame is made of timber.

The Scientific theatre of Mantua has the axes measuring 15 m and 9 m, with the maximum height equal to 13 m. The boxes are organised onto four levels and the room volume is 2100 m3. The structure is made of brickwork to prevent the risk of fire.

A comparison between the simulated (in Nancy and Tajo) and measured results (in Communal and Scientific theaters) is carried out for the main acoustic parameters in unoccupied conditions, as shown in Fig. 8.

Fig. 8(**a**) shows that the highest EDT values are related to the Communal theatre, around 1.6 s at middle frequencies, followed by the Scientific theatre which has a similar trend line and is 0.1 s shifted downward. The simulated values related to Nancy and Tajo are up to 0.8 s shifted downward, due to the smaller volume of the main halls. This means that the EDT values of the Communal and Scientific theatres are within the optimal range as per the criteria of opera houses, while the response found in Nancy and Tajo opera theatres is drier.

In terms of reverberation, Fig. 8(**b**) shows that the highest T20 values are found inside the Communal theatre, having the highest peak at low frequencies equal to 2.35 s, while the response inside the Scientific theatre has similar trend line with the highest values equal to 2.0 s at 125 Hz and 1.4 s at 4 kHz. A similar response to the Scientific theatre is found in the Tajo opera theatre, with the exception of 125 Hz where the value is around 2.0 s. This means that the Tajo opera theatre, built in wood structure, has a reverberation time similar to the Scientific theatre, where the perimeter walls of the stalls are in brickwork, although the volume difference between the two theatres is another factor that determines these outcomes. The driest response is found in the Nancy opera theatre, due to the smallest dimensions of the main hall.

The geometric characteristics of the audience room influence also the clarity index, found within the optimal range limits in the Communal and Scientific theatres, and slightly higher in the Tajo opera theatre, as shown in Fig. 8(**c**). The clarity response inside the Nancy theatre is far off the upper range limit, as discussed in the previous section.

Fig. 8(**d**) shows that the D50 values of the Communal and Scientific theatres are more suitable for music, while the results found in the Nancy theatre are more suitable for speech. Among all of them, a good balance is found in the Tajo opera theatre, where the D50 values are around 0.5 (50%).

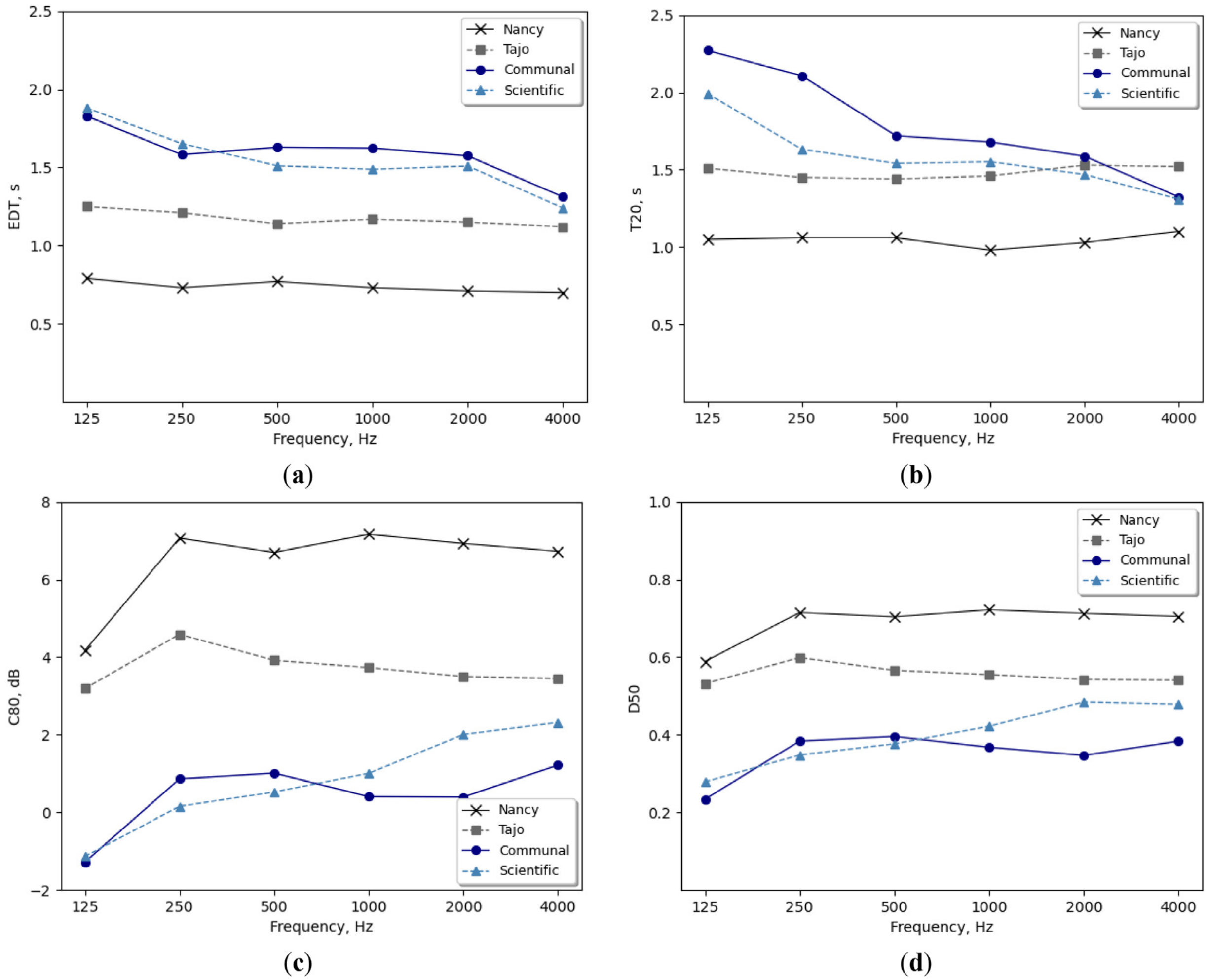


Fig. 8. Comparison between simulated (Nancy and Tajo) and measured (Communal and Scientific) results of early decay time (**a**), reverberation time (**b**), music clarity index (**c**), and definition (**d**).

Overall, the acoustic simulations carried out on the Nancy and Tajo opera theatres are comparable with the results measured inside the Communal and Scientific theatres; the difference between all responses is attributed to the room volume and the geometric characteristics of the balconies (i.e. characterised by half-height partitions separating the boxes).

10. Conclusions

Starting from the analysis of the documentations, this research study digitally rebuilds two heritage opera theatres that are dated back to the 18th century but, unfortunately, they have been destroyed and no more existing. The case studies refer to two masterpieces by Francesco and Giovanni Carlo Sicinio Galli Bibiena, father and son of the same family. This research unveils the acoustic response of the Nancy opera theatre, in comparison with the Tajo opera theatre of Lisbon already studied by the authors of this manuscript [17]. Although some assumptions in the absorption and scattering coefficients are mandatory to be made with respect to other opera theatres analysed by the authors since these theatres are no longer existing and there is no possibility to be acoustically measured, this study highlights the difference in the acoustic response between two similar opera theatres that were designed in the same period (18th century) and provided with similar geometric characteristics. The simulated results are compared with the values measured inside other two opera theatres designed by Galli Bibienas. This comparison highlights a difference in the acoustic response that is mainly attributed to the room volume and the geometric characteristics of the main hall, as summarised in Table 1, but also to the material properties; for example, although the volume of the Scientific theatre of Mantua is smaller than the other three theatres, the reverberation is higher in Mantua because of its perimeter wall in brickwork, that is more reflecting than the timber walls found in the other three theatres.

Overall, the simulated results show that the acoustic parameters of Nancy and Tajo are within or very close to the optimal values set for opera theatres.

The aim of this research is addressed to support the validation of the acoustic values found also in other opera theatres designed in the same period, other than to stimulate the research for other lost theatres designed by Galli Bibiena family members, whose attention to the bell-shape plan of the main hall was of primary importance. The acoustic discovery of lost heritage buildings can also be used by the movie industry when producing films set in past times or by virtual soundscape reconstruction within museums, in order to use accurate acoustic behaviour based on a scientific approach.

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