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Acoustic characterisation and quality assessment of Cremona's Ponchielli theatre in the post-epidemic period.

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Abstract: After a fire destroyed the previous wooden building in Cremona, the Ponchielli theatre was constructed there in 1808. The shape of the interior design, architecture and floor plan is reminiscent of the famous Teatro alla Scala, a masterpiece by architect Piermarini. The Ponchielli theatre captures the typical attributes of an Italian opera theatre from the nineteenth century. In this research, acoustic measurements were conducted for the full hall and a few chosen boxes in accordance with the ISO 3382-1 standard. In-depth comparisons between the primary acoustic parameters obtained from the measurements and acoustic simulations of a three-dimensional model depicting the performing arts space have been made. The study of the Ponchielli theatre's acoustic behaviour is the focus of this paper. Furthermore, how the number of audiences in the post-Covid-19 period affects the quality of musical performances in the theatre is discussed. The simulation results indicate that the number of audiences has no impact on the acoustic characteristics of the theatre. The Ponchielli theatre's acoustic quality, while not excellent, can still be regarded as a competitive venue for the performance of speech and music, according to a comparison with four other theatres that have satisfactory acoustic quality.

Keywords: cultural heritage; acoustic simulations; Opera theater; Ponchielli theater; acoustic quality assessment.

1. Introduction

Music, drama, and opera can be found all over Europe. They are a component of both global and European civilisations. As a specific venue for the sensation of sound, the theatre structure is a lasting

embodiment of this type of art. Each theatre venue provides details about the time it was built, the creators' intentions, the interaction between audience and performer, the cross-cultural collaboration of artists, and the development of society. Furthermore, in the 17th century, the modern architectural shape emerged in Italy and spread throughout Europe. The theatre represents one of the very few distinctly European building types. But performing arts and musical pursuits were significantly impacted by the global economic crisis. The Italianate-style opera houses and traditional theatres among these were especially hard hit by the plague. The growth of these theatre structures in the post-epidemic era, as well as the documentation and preservation of their architectural and acoustic features, are therefore important and worthwhile studies.

Two major areas of theatre acoustics research are currently being investigated: theatrical acoustic simulations, such as the influential work of L. Tronchin et al. [1], and the investigation of the acoustic evolution of the theatre, as done, for instance, by K. Chourmouziadou et al. [2] and Gino Iannace et al. [3]. In the article by Tsung-Chi Cheng [4], the focus of recent research on audience attendance has been on identifying the factors that influence attendance. Additionally, a collection of academics focuses on modern forms of attendance, such as online attendance. (Daniela Mueser [5]). The acoustic quality of theatre attendance has received little study, and relevant results are reviewed in the work of L. Tronchin and B. Antonella [6].

The current Ponchielli theatre in Cremona is the product of a two-century-long process of reconstruction, rebuilding, maintenance, and renovation. The Ponchielli theatre, which dates back to the nineteenth century, was purchased from the town in 1986 and has been completely renovated, adapted, and upgraded since 1989 [7]. It has been managed by the Foundation since 2003. (Comune di Cremona). This ancient, typically Italian theatre is regarded as one of the most beautiful in Cremona and continues to support the rich cultural life of the local people.

Impulse responses (IRs) were recorded at various locations throughout the seating area by employing acoustic measurements in accordance with ISO 3382-1 [8]. The acoustic characteristics of the Ponchielli theatre are discussed in this paper after the model has been calibrated for three different crowd-size scenarios. The results show that the acoustic characteristics of the theatre are unaffected by audience occupancy and that, despite the EDT value, it is considerably higher than the other two occupancy states in the absence of an audience. Even if the theatre's occupancy remains affected by the post-Corvid-19 period, the audience continues to enjoy the best opera performances. Given that this style of construction is designed for theatrical events, the Ponchielli theatre's acoustic response is appropriate for lectures and music performances [9]. However, when the outcomes of the acoustic quality assessment of the Ponchielli theatre are compared to the results of other theatres with high-quality acoustic characteristics, it is clear that the Ponchielli theatre leaves much to be desired. This analysis should be regarded as preliminary research before further acoustic modelling in various scenarios, particularly to investigate the adaptation of the historic theatre to new forms of musical performance in a new era.

2. History and Architectural Features of the Ponchielli Theatre of Cremona

2.1. History of the Ponchielli Theatre

The Ponchielli theatre of Cremona, originally a wooden structure constructed in the 18th century, suffered destruction by fire. In 1747, a consortium of nobles resolved to erect a new public theatre in lieu of the previous aristocratic theatres. The responsibility for designing the new theatre was conferred upon Giovanni Battista Zaist, a Cremonese architect. In 1785, the theatre was named after Nazari, the marquis who had commissioned its construction. However, in 1806, another fire destroyed the building [7]. The students of the renowned drama architect L. Canonica, who had studied under Piermarini, were entrusted with reconstructing the theatre.

The theatre was completed in 1808 and named the Concordia theatre. In the early 19th century, Ponchielli arrived at the theatre and undertook extensive renovations, enlarging the stage and improving the architecture. Unfortunately, the theatre suffered partial destruction by fire in 1824. It was restored to its current appearance by F. Rodi and L. Voghera. In the early 20th century, the theatre was named in memory of the celebrated Cremonese opera composer A. Ponchielli. The theatre was purchased by the municipal real estate in 1986, and since 1989, it has undergone extensive renovations and technical upgrades [7].

The theatre's wooden beam structure from the 1800s is still intact and meticulously maintained. The horseshoe-shaped hall, with four balconies and a top gallery, embodies the typical characteristics of Italian Opera houses of the 19th century. Figure 1 illustrates the contemporary interior design of the theatre.

Figure 1. The interior view of the Ponchielli theatre [7].

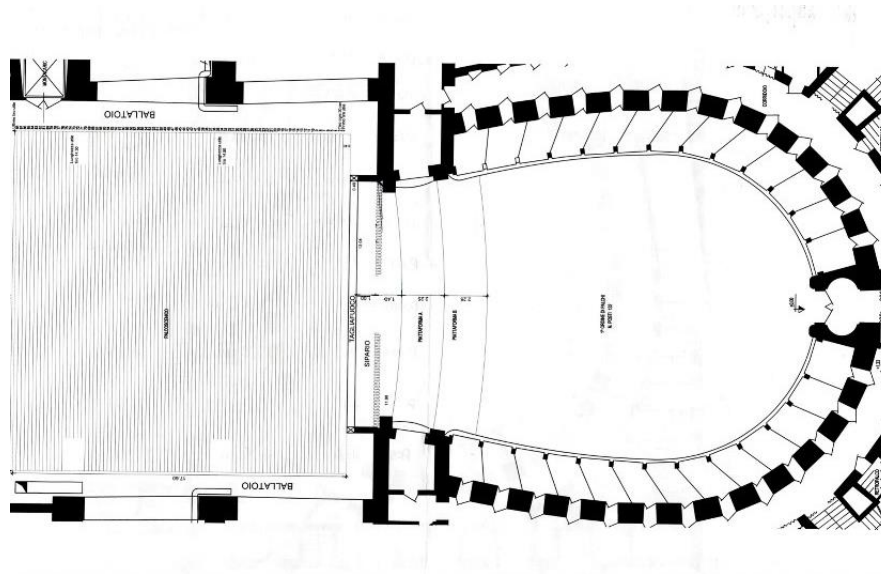


2.2. Architectural Features of the Ponchielli Theatre

The Ponchielli theatre in Cremona boasts a rich history spanning over 250 years and is considered one of the premier theatres of its era. The theatre's horseshoe-shaped hall, depicted in Figure 2, is crowned by four tiers of balconies and a gallery, providing a seating capacity of 780. The theatre's

unique design and expansive seating arrangement make it a notable cultural landmark within the region.

Figure 2. The plan layout of the Ponchielli theatre of Cremona.



The theatre preserves the original wooden frame structure. The framework is $20 \times 20 \times 16$ m (L, W, H). Table 1 provides a comprehensive summary of the essential characteristics of the Ponchielli theatre by comparing its seating capacity against the recommended range. According to the literature [10], a minimum of $10 \text{ m}^3/\text{seat}$ is the usual preference, although for opera theatres, the optimal range is $7\text{-}9 \text{ m}^3/\text{seat}$, and for drama theatres, it is $4 \text{ m}^3/\text{seat}$. The Ponchielli Theatre, with a main hall volume of 3600 m^3 and a seating capacity of 800, has a calculated ratio of $4.5 \text{ m}^3/\text{seat}$. This outcome falls in the moderate range, considering that the 18th and 19th-century opera houses were historically significant venues suited for a broad range of theatrical and musical performances, including symphonies and operas.

Table 1. The architectural characteristics of the Ponchielli theatre.

	Category	Values
Main Hall (A)	Total capacity (No. of seats)	Up to 800
	Major axis (m)	21
	Minor axis (m)	16
	Hieght (m)	13.8
	Volume (m^3)	3600
	Length (m)	32
	Width (m)	25
Scenic Building (B)	Hieght up to the grid (m)	15
	Volume (m^3)	12,000
A + B	Volume (m^3)	15,600

The Ponchielli Theatre holds a significant place in the history of Italian theatre, being one of the first to incorporate electric lighting. The magnificent chandelier, featuring up to 80 lights, is carefully maintained using specialised techniques. The lobby's design incorporates subtle tones of gold, creating an atmospheric ambience. The Rizzi curtain, painted in oil on fabric by the esteemed artist Antonio Rizzi in 1891, is used for all performances throughout the musical season. These curtains enhance the performance space's absorption factor and minimise reverberation time, contributing to an immersive auditory experience. Figure 3 provides details of the theatre's main hall, showcasing its unique features.

Figure 3. Details of the main hall.



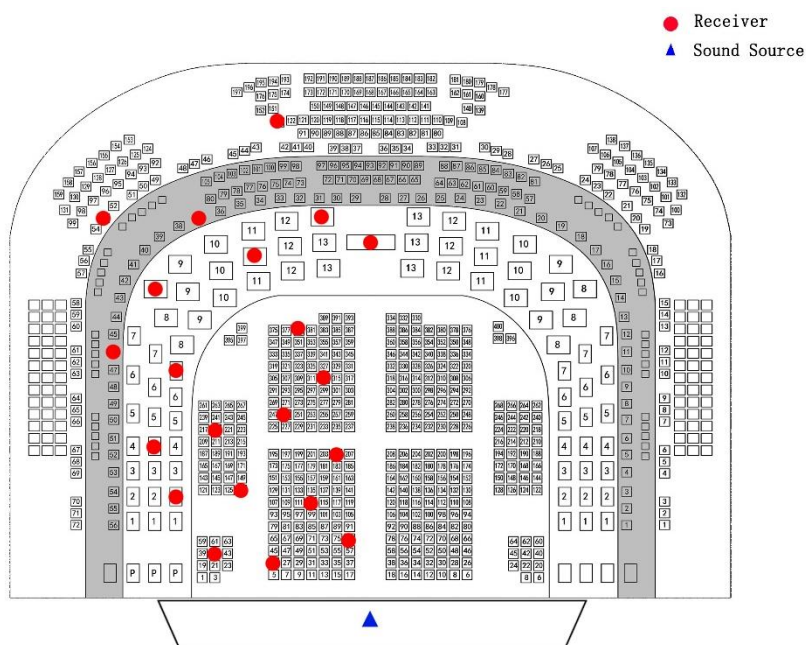
3. Measurements

To comprehensively study the acoustic characteristics of the Ponchielli theatre, impulse responses (IR) were measured at different locations, including the stalls and selected boxes. Multiple acoustic metrics were computed and compared based on the collected data. The ultimate aim was to better understand the theatre's acoustical properties. After calibration of the model, the influence of simulated audience occupancy variances on the theatre's acoustic properties was studied in post-processing. This approach enabled a more detailed analysis of the theatre's acoustical characteristics and provided insights into how the simulated audience can affect the overall sound quality.

3.1. Measurements Points

The measurement setup for the acoustic analysis of the Ponchielli theatre involved placing the sound source 1.4 m above the finished floor while the receivers were systematically moved across the stalls and selected boxes. A total of 10 measurement points were identified in the stall and 11 points on the balconies, considered adequate for comprehending the acoustic response of the hall due to its axial symmetry. The measurements were conducted under unoccupied conditions with the stage left empty, as documented in [11]. Figure 4 presents an overview of the instrumentation positions during the survey, providing valuable insights into the measurement setup.

Figure 4. Scheme of the equipment location during the acoustic survey.



3.2. Measurements Techniques and Equipment

For the measuring session at the Ponchielli theatre, a setup comprising a dummy head, a b-format microphone, an omnidirectional microphone, and a dodecahedral speaker was utilised to reproduce the Exponential Sine Sweep (ESS) from 20 Hz to 20 kHz, covering all the frequencies in the human audible range. Signals from each microphone were recorded using a Zoom F8 audio interface wirelessly controlled by an Apple iPad Mini. Thermo-hygrometric conditions were taken into account during the survey [12]. For each measurement point, three ESS signals were successively recorded. The b-format microphone was positioned horizontally above the dummy head, while the omnidirectional microphone was positioned vertically in front of the dummy head, centred on its nose, as shown in Figure 5. To simulate the sound source, a dodecahedron speaker was mounted on a 1.4 m high pedestal, as shown in Figure 6. The measurements were conducted in unoccupied conditions with the stage empty. Given the axial symmetry of the volume, eight measurement points were taken in the stalls and ten measurement points on the balconies, which were considered sufficient to understand the acoustic response of the hall.

Figure 5. Complete set up including B-Format microphone, an omnidirectional microphone and a dummy head.



Figure 6. Dodecahedron speaker on stage.



The omnidirectional dodecahedron speaker is a portable yet effective sound source for acoustic measurements in rooms and structures. It is made up of twelve specially developed dynamic drivers that ensure equal acoustic test signal emission.

The acoustic parameters involved in this investigation are the reverberation time (T_{60}). In practice, however, obtaining an SNR high enough to allow for a 60dB decline is problematic. Consequently, the T_{30} or the T_{20} are typically employed (30dB and 20dB of decay, respectively); the Early Decay Time

(EDT). If the sound system is increasing information transmission from source to listener, it may be seen from the comparison of the T_{60} and the EDT; the clarity indexes, the musical performance hall size indicated by the subscript "80" (C_{80}) is; the subscript "50" (C_{50}) is used when evaluating the clarity of spoken performances; the definition (D_{50}). The omnidirectional microphone, the ECM8000 by Behringer, which is excellent for room equalisation and high-quality studio recording and live applications, is used to calculate all of the aforementioned parameters.

A professional dummy head made by Neumann, the KU100, is used. It has a very low self-noise and can handle high sound pressure levels of up to 135 dB without sound distortion. The "Ambeo" B-Format microphone from Sennheiser was used to capture 360° spatial audio. A new set of 4-channel, Ambisonics B-Formats must be created from the Sennheiser Ambeo capsule's raw 4-channel A-Format. The sound field around the microphone is represented by W, X, Y, and Z in B-Format. W is the total of all four capsules, whereas X, Y, and Z are three virtual bi-directional microphone patterns that indicate front/back, left/right, and up/down.

The Zoom F8 audio interface is used to record microphone signals. Seven audio channels were used in the recording; channels 1 through 4 were used for Ambeo microphones, channels 5 and 6 were utilised to record dummy heads binaurally, and the final channel was applied to record omnidirectional microphones in mono.

3.3. Acoustic Parameters Calculation

Different software was used to post-process the obtained data. Automatic extraction of two stereo files (Binaural and WY, W and Y signals to compute LF, LFC and LE.) and one mono file (Mono) from the 7-channel audio files (1-2 channel WY, 5-6 channel Binaural, seven-channel Mono) captured during the measurements using a custom MATLAB script.

In the post-processing analysis, the IRs are obtained by convolving the recorded signal with the inverse filter. Once the IRs have been obtained, the values of the main acoustic parameters can be calculated using the Aurora plugin in Audition 3.0 [13]. Aurora is a plugin suite created by Angelo Farina to measure and control room acoustical impulse responses, perform acoustical parameter analysis, and auralization. Three Aurora plug-ins were used, involving convolution, the "Convolve with clipboard v4.4b" plugin; acoustic parameters, Acoustical Parameters 4.3" plugin; and STI (Speech Transmission Index) calculations, "STI & Octave Band Analysis v 4.4" plugin.

3.4. Acoustic Simulation

Acoustic simulations have been carried out using Ramsete software, which is based on the principle of raytracing acoustics and considers a triangular base pyramid propagation of the sound rays [6]. Compared to other software, Ramsete is not affected by the calculation time of up to 4000 receivers in the model due to its constant time for computing the values [14]. Ramsete was configured with the parameters listed in Table 2 for the simulations.

Table 2. Parameters set by Ramsete.

Subdivision Level	Time	Values Time Resolution	Humidity	Temperature
10	2s	0.01s	50%	20°C

4. Acoustic Simulations

4.1. Acoustic Calibration

The 3D model was simplified from the complex architectural features, as shown in Figure 7, before simulating the effect of the difference in audience occupancy on the acoustic characteristics of the theatre. The hall is 5,000 m³ in size and contains cushioned seating. The theatre currently has 400 seats in the stall, 200 in the loggione, 92 in the boxes on the balconies and 105 seats in the gallery on the top.

The JND (Just Significant Difference) is taken into consideration to compare the adjusted simulation results to the values obtained from field measurements. The JND value is the smallest variation in that parameter that can be detected by the human ear for each acoustic parameter. Hence differences between measurements below JND are absolutely negligible because humans would not be able to hear them.

Figure 7. A digital model of the Ponchielli theatre of Cremona: whole building (a), perspectival view of the main hall (b).

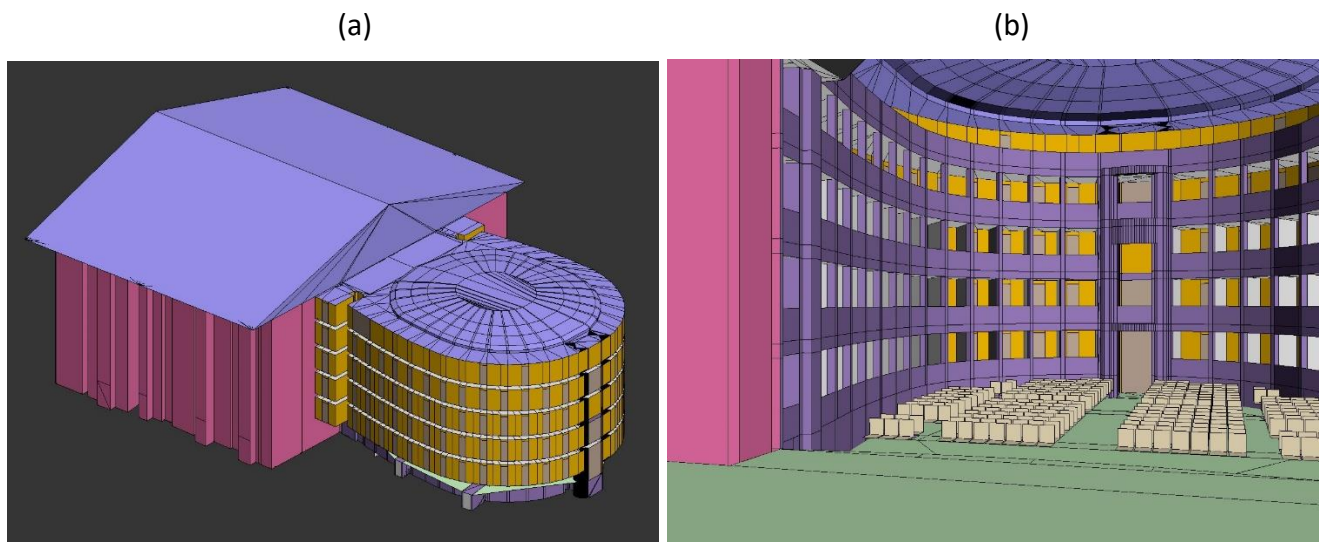


Table 3 displays the absorption and scattering coefficients for all the materials, obtained from the calibration process and previous acoustic simulations conducted in other opera houses [15-16]. The coefficients serve as valuable indicators for the sound transmission properties of the materials under investigation. The calibration process was performed meticulously to ensure accurate measurements and reliable data. The acoustic simulations were carried out using state-of-the-art techniques, providing a comprehensive understanding of the sound behaviour of the materials. The coefficients

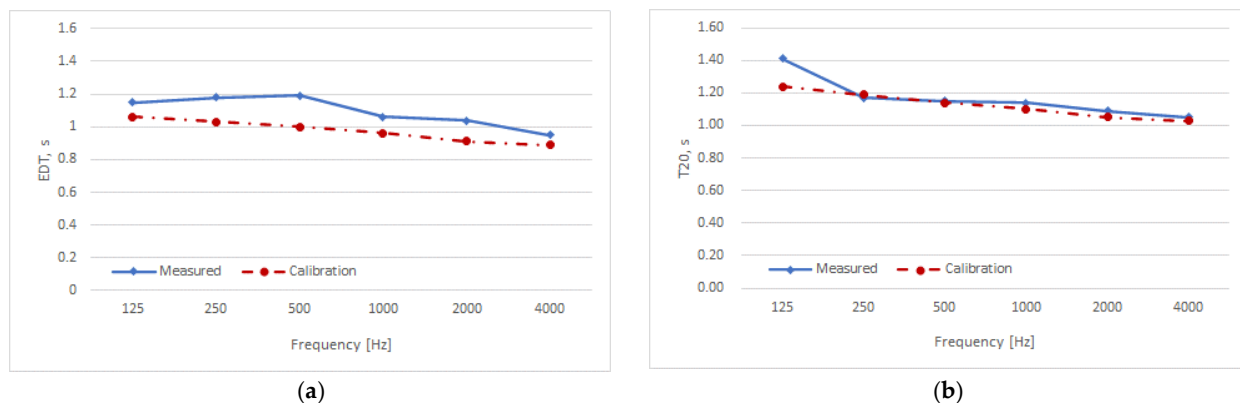
presented in Table 3 are expected to aid in the optimization of acoustic design for opera houses and other similar venues.

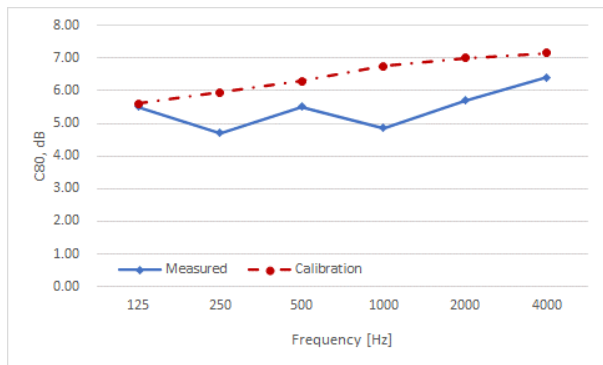
Table 3. Absorption coefficients (ac) and scattering coefficients (sc) for the materials.

Materials	Octave Frequency Bands (Hz)											
	125		250		500		1000		2000		4000	
	ac	sc	ac	sc	ac	sc	ac	sc	ac	sc	ac	sc
Floating floor—Stalls	0.33	0.25	0.37	0.20	0.42	0.15	0.45	0.10	0.55	0.05	0.58	0.05
Floating floor—Stage	0.43	0.20	0.47	0.15	0.52	0.10	0.55	0.05	0.65	0.05	0.65	0.05
Timber wood—Boxes floor	0.41	0.55	0.42	0.50	0.44	0.40	0.46	0.30	0.47	0.20	0.42	0.15
wood—Boxes perimetral walls	0.43	0.55	0.46	0.50	0.50	0.40	0.54	0.30	0.50	0.20	0.55	0.15
Light Wood—Ceiling	0.73	0.20	0.68	0.15	0.61	0.10	0.51	0.05	0.48	0.05	0.42	0.05
Upholstery—Seats	0.51	0.40	0.64	0.30	0.71	0.25	0.73	0.20	0.76	0.15	0.80	0.15
Doors	0.31	0.10	0.12	0.08	0.32	0.05	0.32	0.05	0.32	0.05	0.30	0.05
Bricks—External walls of fly tower	0.08	0.60	0.07	0.53	0.05	0.42	0.04	0.35	0.06	0.28	0.04	0.17

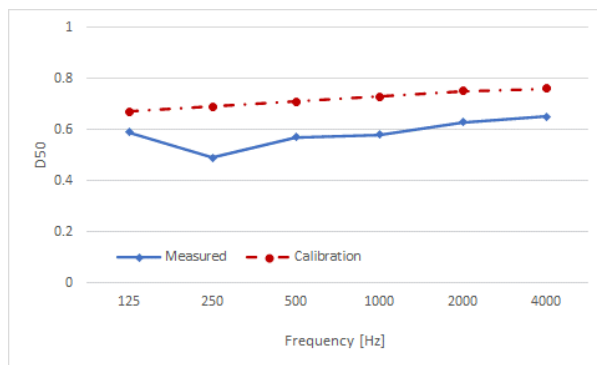
The calibration process was conducted on the acoustic parameters of EDT, T_{20} , C_{80} , and D_{50} , as illustrated in Figure 8. The results indicate that some degree of deviation between the measured and calibrated values was observed across all parameters, which can be attributed to environmental factors such as humidity and air absorption during field measurements. The observed drift values were found to be within 5% for all octave ranges of reverberation time and EDT. However, the parameters of the clarity index and definition exhibited a higher degree of sensitivity to the exact location of the field measurements. The values have been averaged over all the receivers. The bandwidth considered is between 125 Hz and 4000 Hz, by the regulation [17]. The noise level in the hall is below the 20 dB standard [18].

Figure 8. Model calibration based on main acoustic parameters: early decay time (a), reverberation time (b), clarity index (c), and definition (d).





(c)



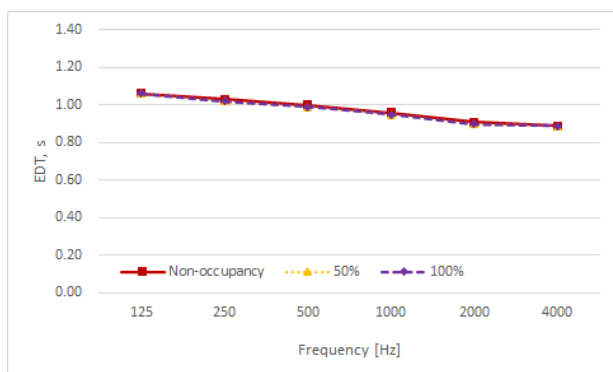
(d)

4.2. Simulated Results

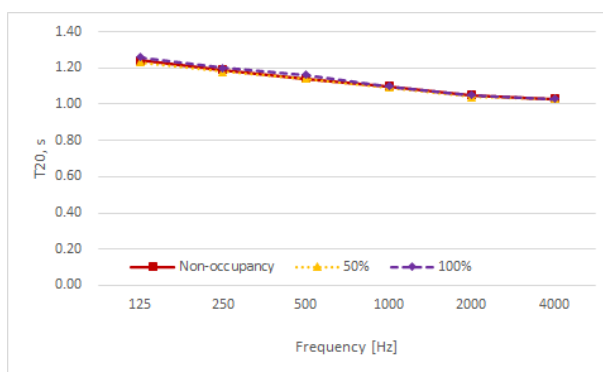
The recorded ESS signals have been processed by using the plugin Aurora suitable for Audition 3.0. Different acoustic parameters defined by the international standards ISO 3382-1 [13] have been analysed and commented on, including the Early Decay Time (EDT), Reverberation time (T_{20}), Clarity indexes (C_{80} and C_{50}), and Definition (D_{50}). The main acoustic parameters are reported in the octave bands between 125 Hz and 4 kHz.

Figure 9 shows the graphs of the simulated results of the main acoustic parameters. A comparison of the simulated results is related to three scenarios: no audience, with the audience at 50% and 100% occupancy. These variations in occupancy will be modelled by increasing the absorption factor of the seats, and this increment will be approximated using the bibliography [19].

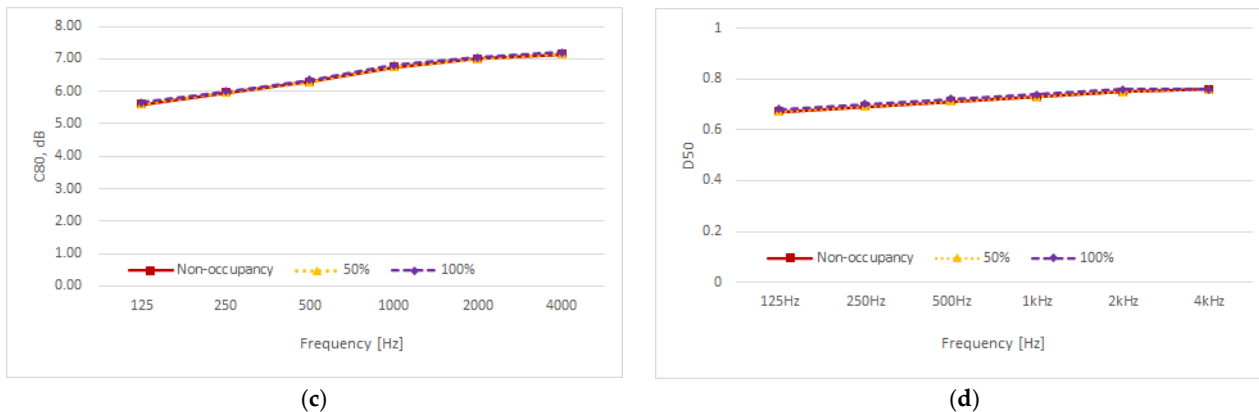
Figure 9. Simulated results of main acoustic parameters: early decay time (a), reverberation time (b), clarity index of music (c), and definition (d).



(a)



(b)

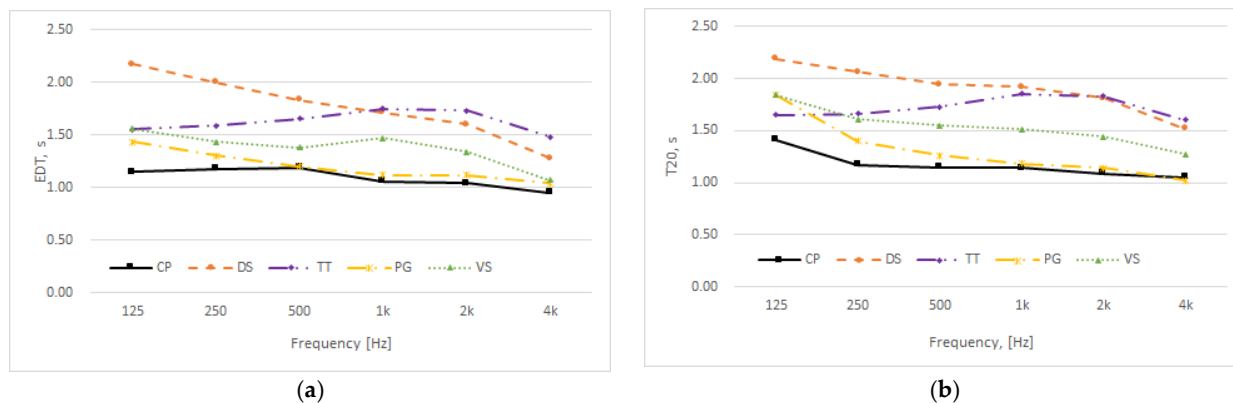


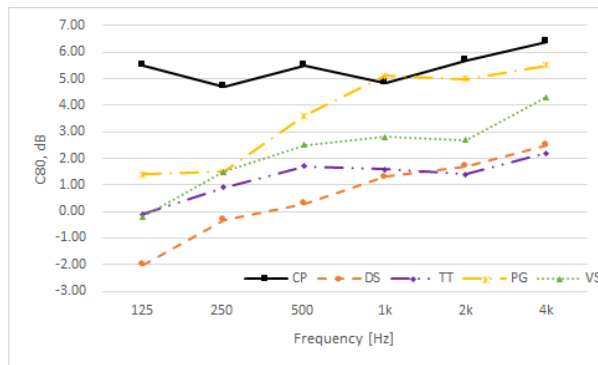
The graphs in Figure 9 indicate the presence of audiences does not affect the acoustics of the Ponchielli theatre, demonstrating that the acoustics of the Ponchielli theatre do not change based on the degree of occupation [20]. This outcome is advantageous, particularly for musicians and actors who do not need to adjust their performance style between public rehearsals and live performances [16]. Additionally, even when attendance is inadequate, the audience recognises hearing the best performances. Due to the high absorption coefficient of the seats, which is very comparable to that of the human body, the difference between 50% and 100% occupancy is negligible.

5. Acoustic Quality Comparison with the Other Opera Theatres

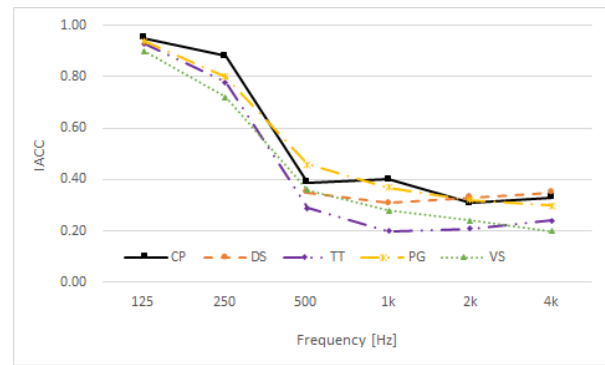
Four theatres throughout the world with objective measures, similar in size to the Cremona, Ponchelli theatre (CP), and good acoustic quality ratings were selected [19]: Dresden, Semperoper (DS), Tokyo, New National Theatre (TT), Paris, Opera Garnier (PG), Vienna, Staatsoper (VS). DS and TT were rated as having excellent acoustic quality, while the other two theatres were rated as good. All measurements were carried out without audiences. The comparison between the measured results of the selected theatres is given in Figure 10.

Figure 10. Comparison with the other four opera house measurements: EDT (a), T_{20} (b), C_{80} (c) and IAAC (d).





(c)



(d)

The results presented in Figure 9 (a), reveal that the Ponchelli theatre exhibits a shorter early decay time (EDT) across the frequency range when compared to the Semperoper of Dresden and the New National Theatre of Tokyo, which are regarded as having exceptional acoustic quality. While the Ponchelli theatre's EDT values are found to be comparable to those of the Opera Garnier of Paris and the Staatsoper of Vienna, with an overall fluctuation of approximately 1.2 s. This outcome is considered a favourable result for both speech and music perception [19-21].

The graph (b) in Figure 9 demonstrates that the values of reverberation time (T_{20}) is noticeably higher in the full frequency band of Semperoper of Dresden and the middle and high-frequency bands of New National Theatre of Tokyo than in the other three theatres, with Ponchelli theatre, Opera Garnier of Paris and Staatsoper of Vienna having similarities in that the values in the middle and high frequencies fluctuate between 1.1 s and 1.5 s, making these theatres more suitable for traditional opera performances [22], for speech as well as for music.

Regarding the music clarity index (C_{80}), Figure 9 (c) shows slightly higher than ideal values for Ponchelli theatre and Opera Garnier of Paris compared to the other three opera theatres [19], particularly in the higher frequency bands. However, this is an identity shared by many traditional opera theatres with comparable characteristics.

The trend in the interaural cross correlation (IACC) of Figure 9 (d) has been found to be very similar for all the theatres. As lower values of IACC are better [19], these four theatres have a better performance in the mid and high-frequency bands, with fluctuations between 0.2 and 0.4.

6. Discussion`

The acoustic survey carried out inside the Ponchielli theatre is the baseline for the analysis of the acoustic behaviour of this heritage building. The geometrical description, as well as the details of the interior design, are important for the analysis of the results obtained from the acoustic simulations. The values of the reverberation time and early decay time are somewhat short in both the mid and high frequencies. Although the shorter reverberation time is suitable for theatres, it allows the lead singer to hear every note of the accompaniment. However, recent performances at the Ponchielli theatre have been of orchestral and symphonic music, such as *Flavien Boy*, which requires longer reverberation times to avoid them being perceived as too 'dry'. This can be achieved by reducing the

size of the acoustic curtains or changing the material of the seats, for example, by replacing cotton upholstery with leather upholstery.

There is no significant impact on the acoustic characteristics of the theatre, regardless of the size of the audience. This suggests that although attendance at the theatre will drop significantly after Covid-19, audiences will still be able to hear the best musical performances that the theatre has to offer. On the other hand, better audience attendance will provide incentives for artists and generate more income for the ongoing maintenance of the theatre. Both sides should put in the effort. Society and relevant practitioners should work to encourage the preservation and protection of collections of cultural works, both tangible and intangible.

The results of the comparison with the other four theatres with a quality acoustic environment indicate that the acoustic quality of the Ponchelli theatre, while not yet at the level of a top venue, is still satisfactory for a wide range of performances.

Future research will focus on the acoustic simulation of different types of scenes, including those realised with modern materials, to highlight the adaptability of the old theatre space to modern performances.

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