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Digital Soundscape of the Roman Theatre of Gubbio: Acoustic Response from Its Original Shape

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Abstract: The present work deals with the acoustic analysis of the Roman theatre of Gubbio, located in Italy, which has already been the subject of architectural studies. Using four specific scenarios, acoustic simulations were carried out to highlight the contributions of different architectural elements to the acoustic response of this open-air theatre. The results were evaluated assuming that unamplified classical music and prose were the main functions of the space, as was the case in the past. The simulated results show that the values of the main acoustic parameters are closer to the optimal ranges borrowed from studies on enclosed theatres, since no criteria are available for Roman theatres. The comparison among different scenarios highlights the poor acoustic response of the existing conditions for a performing arts space. Some suggestions are presented regarding how the outcomes of this research study should be employed.

Keywords: architectural acoustics; cultural heritage; Roman theatres; acoustic simulations; archaeo-acoustics; Gubbio

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1. Introduction

Many Roman theatres discovered through archaeological excavations lack several parts [1]. This can be attributed to human intervention, due to the habit of using the stone blocks of Roman and Greek theatres to build new cities, a practice that became very common during the Middle Ages and the Renaissance. Human intervention also includes the transformation of these places into catacombs, as practiced during the diffusion of Christianity, or into residential areas through the construction of private properties, which eliminated all traces of the theatres. Another common explanation for the reconstruction of ancient theatres is the impact of natural calamities (i.e., earthquakes, fire, meteorological exposure, etc.). All these factors have contributed to the conditions that open-air theatres are found in nowadays.

In the Roman theatre of Gubbio, the lower steps of the seating area (*ima cavea*) and a small number of external arches that compose the external elevation have been preserved. The radial walls that should support the upper steps (*summa cavea*) reach the height of the first circular corridor (*praecinctio*). Up to 1 m of the erected blocks related to the scenic building have survived.

Nowadays, it is common practice to adapt Roman and Greek theatres for use as live venues [2]. The most popular type of performance that these archaeological sites are intended for is classic music, although the tendency toward hosting other musical genres requiring amplified audio systems is becoming considerably more common [3]. This can lead to the organisation of pop or jazz music festivals, as is the case in Verona, Volterra, Ostia, and other cities that belonged to the Roman Empire.

The authors of this paper have already investigated the acoustic characteristics of other Roman theatres located in Italy, as summarised in previous studies [4–6]. The determination of which types of construction elements are the most important for the acoustic environment is challenged in the present research. Many acoustic simulations were carried out based on the potential configurations that the Roman theatre of Gubbio could have had in its original state. In this context, the contributions of the architectural elements (e.g., the roof over the stage floor (*pulpitum*), the colonnade porch above the seating area (*porticus in summa cavea*), etc.) were assessed by adding them to the main structure of the steps [7]. As such, the effect of the building elements on the acoustic response was scientifically determined. A full description of the Latin terms is provided in Appendix A.

2. Historical Background of Gubbio

The origin of the city of Gubbio dates back centuries. During the Roman Republic, Gubbio assumed a neutral position during the war between the Romans and the Sannits, which ended in 295 BC. This date is important because the village stipulated an alliance with Rome due to the possibility of them being attacked by the Etrurians. Rome assigned the name of *Iguvium* to the town. In 89 BC, under Augustus's dominion, *Iguvium* became a municipality (*municipium*); on this occasion, the town developed, constructing bridges, roads, temples, baths and theatres [8].

The construction of the theatre was completed in the first century, with the addition of two public spaces (*basilicae*) being ordered by Gneo Satrio Rufo.

Gubbio was invaded and destroyed by the Goths in 552, but it was restored by the Byzantines, who added two massive towers. In 772, Gubbio was invaded by the Longobards. The ancient theatre was located in a valley and was composed of two orders of arches; the seating area (*cavea*) was organised into four wedged sectors [8].

After becoming a stone cave following the reconstruction of the new town, the Roman theatre was discovered in 1561 for the first time. Nowadays, it is host to different spectacles, running especially during the summer season.

3. Architectural Characteristics of the Roman Theatre of Gubbio

3.1. Cavea

The main geometry of the Roman theatre of Gubbio is based on a four-sided regular polygon (i.e., square), which is very typical of the Roman design for small-sized theatres, besides the equilateral triangle that Vitruvius suggests is the basis of the design [9]. It is important to understand the angle between the staircases in the stepped audience area, which is 40° for the lower (*ima*), the middle (*media*), and the upper parts (*summa cavea*).

The width of the orchestra is about 16.5 m, and its arc is not semicircular since the cord does not correspond to the diameter of the circle where it is inscribed. The outer diameter of the seating area without the ambulatory is 64 m, measuring 70 m when including the ambulatory. The lower part of the seating area is divided into four wedge-shaped sectors composed of 20 steps each; this arrangement is also repeated in the middle and upper parts, specifically composed of eight and four steps, respectively.

The Vitruvian rule, according to which the line from the lowest to the highest seat should touch the top edge of each step [10], is not found in Gubbio because a different angle is in place between the lowest and the upper steps. The total capacity would have been about 6000 spectators.

3.2. Scenic Building and Stage

The scenic building of the theatre of Gubbio is characterised by two levels of Corinthian style, whose height is equal to 6.5 m for both levels. The scenic building (*scenae frons*) is provided with three doors: the two laterals (*valvae hospitalia*) are square-framed, with pairs of columns that delimit the doorway, while the central door (*valva regia*) has a curved frame [9]. Additional doorways located on the lateral wings lead to a total of five doors to access the stage floor (*pulpitum*). The acting stage floor is 1.4 m above the level of the orchestra and was originally composed of wooden planks, creating a resonance cavity underneath the stage floor, which was useful for the amplification of sound. The dimensions of the stage floor were 42 m in length and 5.75 m in width. All the architectural characteristics are summarised in Table 1.

Table 1. Architectural characteristics of the Roman theatre of Gubbio.

Description	Gubbio
Cavea max diameter (m)	70
Orchestra diameter (m)	16.5
Stage floor width (m)	5.8
Stage floor length (m)	42
Capacity (no. seats)	6000

The orchestra would have been covered with calcarean stone blocks, placed on top of ducts that were used to collect the rainwater under the stage floor.

3.3. Mathematical and Armonic Discoveries in the Roman Theatre of Gubbio

According to previous architectural research studies [9], the layout of the *cavea* in the theatre of Gubbio is based on a nonagon, as shown in Figure 1. This scheme is against the 12-sided regular polygon proposed by Vitruvius, which is not the dominant geometry in theatre design [11]. If a nonagon is the main geometry, the angle between staircases is approximately 40° [12]. This construction determines a shorter distance between actors and spectators. However, the lower part of the seating area is divided into four wedged sectors, while the length of the cords is divided by two, with a total number of eight sectors.

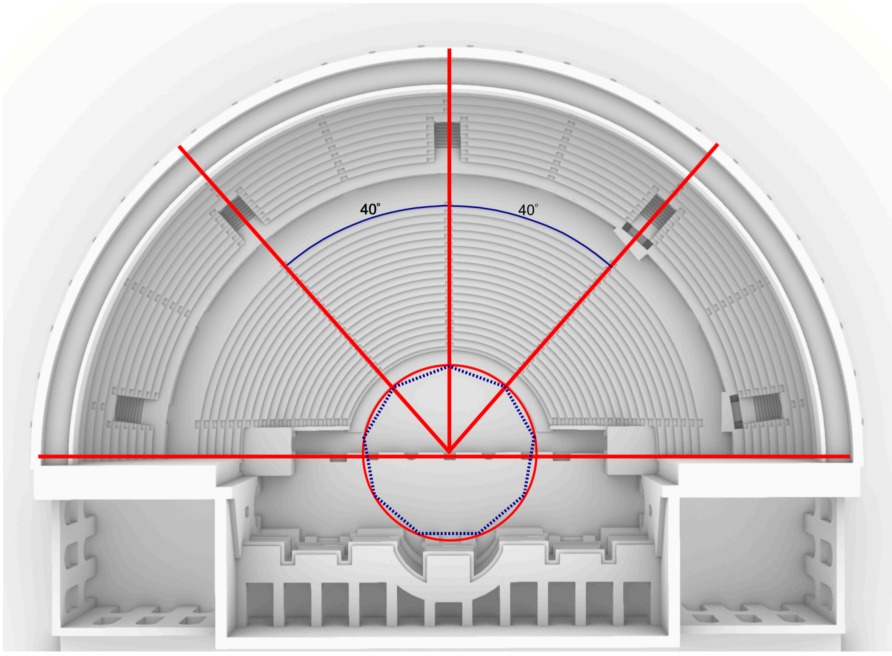


Figure 1. Basic geometry in the Roman theatre of Gubbio. A blue-dotted nonagon is inscribed in a circle, having the centre in the middle of the *pulpitum*. The *vomitoria* of the *summa cavea* are obtained by connecting the centre of the circle with the corner of the nonagon.

3.4. Interaction between Acoustics and Architecture

In many architectural research works on Roman theatres, the assessment of the acoustic response is missing [13]. There are several construction elements that contribute to good acoustics in an open-air theatre. Starting with the scenic building, the walls behind the action are useful vertical surfaces that direct sound toward the audience [14]. The absence of this important structure, as seen in many existing sites where the scenic building is only partially erected or has almost disappeared, results in a loss of sound strength as the sound travels in other directions as it propagates.

Likewise, the ceiling above the stage is characterised by a specific inclination so that the sound can reach the last rows of seats. In terms of sound diffusion, the columns and other convex construction elements contribute to distributing the sound more evenly over the seating area [15].

The presence of an ambulatory crowning the perimeter of the *cavea* has always been seen, with the function of accommodating more attendees [16]. Apart from this practical function, the ambulatory, with its vertical surfaces, helps to amplify the sound and increase the feeling of envelopment, typical of enclosed spaces.

Acoustic simulations of a digital reconstruction show that the Roman theatre of Gubbio would have been very reverberant due to the numerous surfaces (i.e., scenic building, ambulatory, etc.). The presence of the porch at the top of the seating area may have had the function of influencing the overall sonic environment for singing and instruments [14].

Other than the sound properties, Roman theatres are also affected by visual deteriorations, as the structure is damaged or covered by grass, because of new cities built after the fall of the Roman Empire [1].

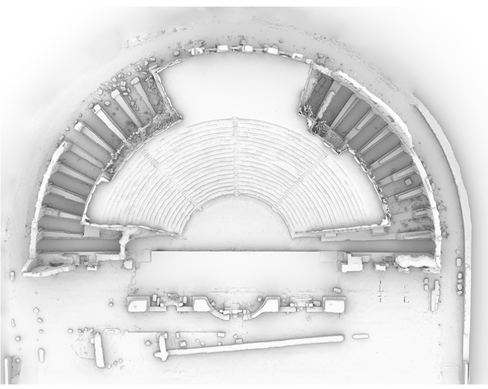
The following materials were used for the construction of a Roman theatre:

- Stone, which was used to cover the steps and the masonry of the scenic building;
- Wood, which was used as flooring for the stage; it was also used for the coffered roof over the drama stage and for the roof of the ambulatory;
- Cloth (linen or wool), used to produce the fabric (*velarium*), which aimed to protect the audience from overheating.

4. Numerical Models

Starting with a 3D laser scanner, two digital models were created: one reproducing the existing condition and another reflecting the original Roman era form. The digital model referencing the existing conditions was created based on a survey of the site using a laser scanner [17], a popular method for the capture of 360° panoramic 3D coordinates of different points on a site. The geometric measurements were taken in June 2020. Laser pulses measure the distance between the device and the target. The data collected during this type of geometric measurement consist of a point cloud, from which the reconstruction of the theatre was obtained in combination with 2D drawings [18]. The digital reconstruction of the original shape, on the other hand, was based on archaeological findings.

The 3D models were simplified by fine ornaments, as shown in Figures 2 and 3, in order to perform acoustic simulations, which are otherwise a difficult process. The individual digital elements were grouped by material before being exported in DXF format for the acoustic simulations [19].



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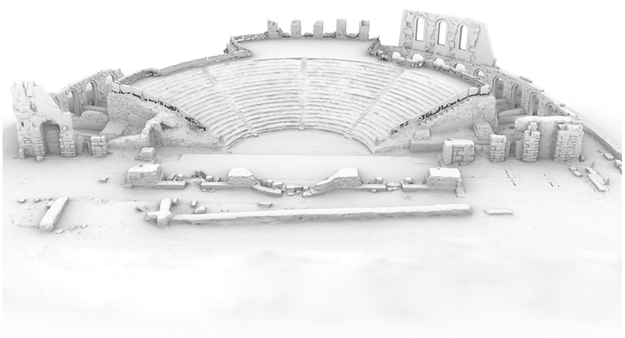
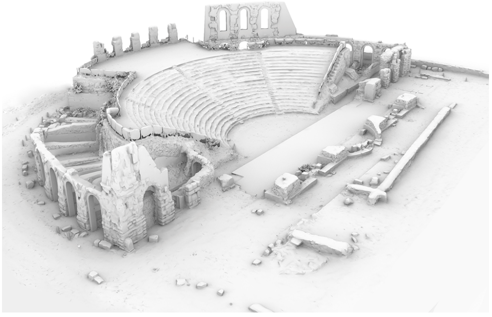


(**b**)

Figure 2. *Cont.*



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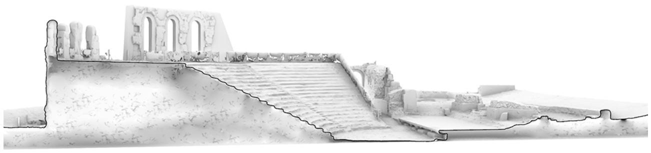
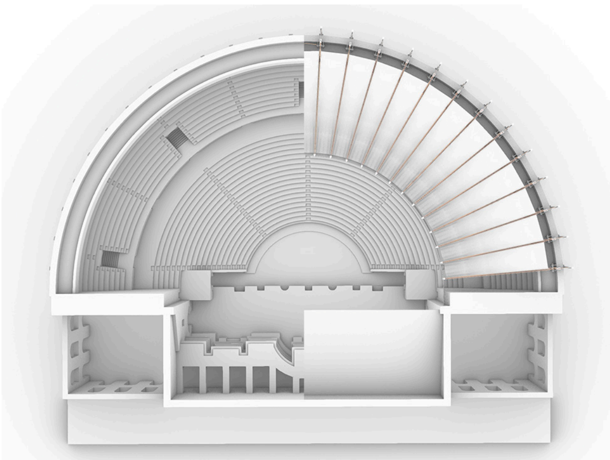


(**d**)

Figure 2. The 3D model related to the existing conditions of the Roman theatre of Gubbio: plan layout (**a**), front view (**b**), perspectival view (**c**), and transversal section (**d**).



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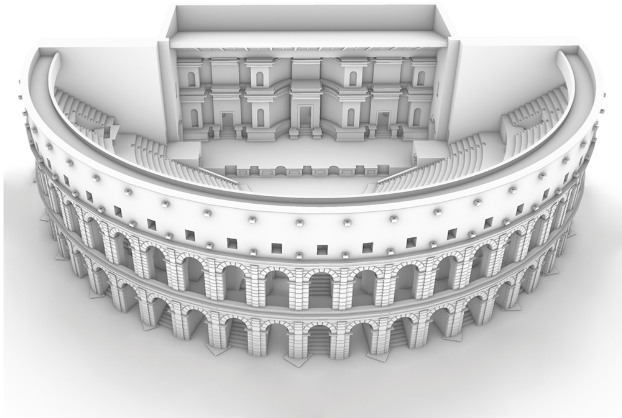

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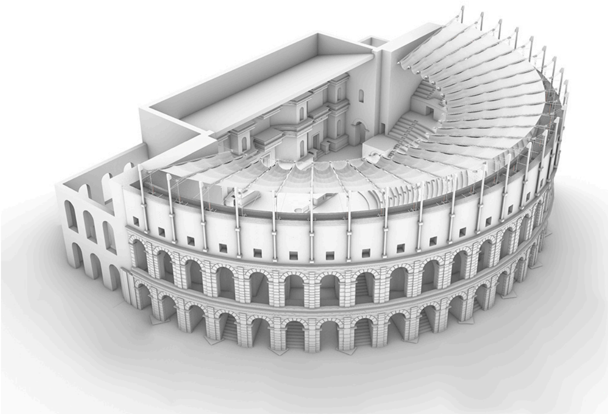

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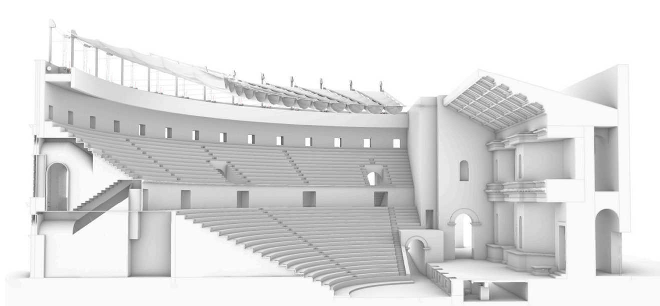


(**d**)

Figure 3. The 3D model related to the original reconstruction of the Roman theatre of Gubbio: plan layout (**a**), front view (**b**), perspectival view (**c**), and transversal section (**d**).

Ramsete 3.13 was the software used to calculate the main acoustic parameters based on the absorption and scattering coefficients of the materials [20]. Two virtual omnidirectional sound sources were integrated into the models, placed at a height of 1.7 m, exactly in the centre of the stage floor, in front of the central door, while the other location was selected as the centre of the orchestra, at the intersection of the diameter. In the 3D model, 484 virtual microphones were installed across the seating area at a height of 1.3 m above the relative finish floor, which corresponded to the height of the ears of the audience.

The Ramsete software is based on the calculation of the source image and is provided with a pyramid-shaped propagation with a triangular base. A number of virtual microphones of up to 4096 does not affect the computation, since the tracking time is invariant; the difference between a large and a small number of microphones can affect the resolution of the acoustic maps in terms of acoustic parameters. In general, the smaller the number of microphones, the more pixelated the contour planes of the acoustic maps.

5. Acoustic Simulations

The numerical simulations were carried out to highlight the differences in the acoustic response under the existing conditions and the original form of the Roman theatre of Gubbio.

For the original form, four specific scenarios were simulated to evaluate the individual contributions of the coffered ceiling, the crowning porch, and the addition of both to the main architecture consisting of the seating area and the scenic building.

All five scenarios are summarised and described below.

- Scenario **A**: existing conditions.
- Scenario **B**: original reconstruction provided with seating area and scenic building.
- Scenario **C**: original reconstruction provided with only the coffered roof added over the stage floor.
- Scenario **D**: original reconstruction provided with only the crowning porch added.
- Scenario **E**: original reconstruction provided with addition of roof and porch.

All five scenarios were simulated without and with an audience at 100% occupancy [21]. The geometric features of the two digital models are summarised in Table 2.

Table 2. Characteristics of the two digital models used for the acoustic simulations: existing conditions (EC) and original reconstruction with all architectural elements (OR).

Description	EC	OR
Total number of surfaces	18,286	21,054
Total surface area (m^2)	16,353	19,192

The standard procedure for performing acoustic simulations begins with calibrating the model based on measured values [22]. If acoustic measurements are not available, the absorption and scattering coefficients are taken from the literature and are based on previous experience with acoustic simulations performed at other ancient theatres [23].

The scattering coefficients are based on the properties of the material of the external surface. The materials corresponding to the existing conditions are considered to be more non-uniform than the original marbles from antiquity. In order to take into account the possibility of different degrees of deterioration of the stone (e.g., grass/soil covering the blocks in *opus quadratum*, carved stone in *opus siliceum* while exposed to meteorological conditions), the simulation of the existing conditions was conducted based on two different scattering coefficients at medium frequencies (500–1000 Hz): $s = 0.3$ and $s = 0.5$ [2,24]. Figure 4 shows the current state of the stone in the Roman theatre of Gubbio. Table 3 summarises the absorption and scattering coefficients used for the simulations of the existing conditions, while Table 4 summarises the absorption and scattering coefficients used for the simulations related to the original shape of the theatre.

Figure 4. View of the Roman theatre of Gubbio in the current state.

It must be noted that the results of the simulations related to the Roman theatre of Gubbio are not to be considered as absolute values but should be taken as a reference to understand the acoustics of the existing condition compared to the reconstructed shape, with limitations represented by the variability related to the properties of the materials. In addition, the contribution of each architectural element to the overall acoustics was evaluated in the five different scenarios.

The scattering coefficients are equally as important as the absorption coefficients [25], as they allow the full calibration of the digital models to compensate for the geometric simplifications applied to obtain the results with the acoustic software. The calibration process consists of a loop reiterated several times, based on the adjustment of the absorption and scattering coefficients associated with the digital entities of the model [26]. In general, the tuning process is considered valid if the difference between the simulated and reference values does not exceed 5% across all the frequency bands. However, a negligible drift deviation is attributed to physical factors, such as air absorption, and not to the quantity of surfaces that make up the geometric model.

The absorption behaviour of the terrain/soil was compared with that of high-silica sand, which is considered a granular material, whose coefficients have been measured in previous research studies [27].

The absorption coefficients of stone and wood were taken from the measurements performed by the authors in the Greek–Roman theatre of Tyndaris. A detailed explanation of the methodology of site inspection with the application of the laser Doppler vibrometer on hard materials can be found in [28].

The absorption of the fabric used to simulate the *velarium* was taken from a previous research study [29], assuming that the mass of the material was equal to 0.5 kg/m^2.

The absorption coefficients of the audience were taken from the literature [30]; although the coefficients referred to light seat upholstery, they were applied to the surfaces representing the audience.

All scattering coefficients were determined based on the theory explained by Zeng et al. [31], taking into account the geometry drawn for the digital models and the properties of the materials to be reproduced in the simulations.

Table 3. Absorption (in *italic*) and scattering (in **bold**) coefficients for all the materials considered for the acoustic simulations of the existing conditions.

Materials	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Terrain/soil [27]	*0.06*	*0.20*	*0.32*	*0.55*	*0.60*	*0.55*
	0.10	**0.11**	**0.11**	**0.12**	**0.12**	**0.12**
Brick masonry [28]	*0.02*	*0.01*	*0.02*	*0.01*	*0.01*	*0.01*
	0.18	**0.18**	**0.19**	**0.20**	**0.20**	**0.18**
Tuff stone (*a*1) [28]	*0.01*	*0.06*	*0.05*	*0.02*	*0.08*	*0.05*
	0.10	**0.15**	**0.30**	**0.31**	**0.24**	**0.22**
Tuff stone (*a*2) [28]	*0.01*	*0.06*	*0.05*	*0.02*	*0.08*	*0.05*
	0.15	**0.25**	**0.50**	**0.51**	**0.44**	**0.30**
Audience [30]	*0.51*	*0.64*	*0.75*	*0.80*	*0.82*	*0.83*
	0.20	**0.25**	**0.37**	**0.40**	**0.38**	**0.31**

Table 4. Absorption (in *italic*) and scattering (in **bold**) coefficients for all the materials considered for the acoustic simulations of the original shape.

Materials	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Tuff stone [28]	*0.01*	*0.06*	*0.05*	*0.02*	*0.08*	*0.05*
	0.10	**0.11**	**0.11**	**0.12**	**0.12**	**0.12**
Timber wood [28]	*0.08*	*0.20*	*0.10*	*0.05*	*0.03*	*0.02*
	0.15	**0.12**	**0.10**	**0.08**	**0.04**	**0.04**
Fabric/cloth	*1.00*	*1.00*	*0.54*	*0.16*	*0.04*	*0.01*
(m = 0.5 kg/m^2) [29]	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
Audience [30]	*0.51*	*0.64*	*0.75*	*0.80*	*0.82*	*0.83*
	0.20	**0.25**	**0.37**	**0.40**	**0.38**	**0.31**

6. Analysis of Results

The optimal range of the main acoustic parameters is considered in relation to prose and classical music as the main artistic performance types, which means that both speech intelligibility and music are the subjects of evaluation. The main acoustic parameters are defined based on the ISO 3382-1 standard [32], namely the early decay time (EDT), reverberation time (T_{20}), clarity indexes (C_{50}, C_{80}), definition (D_{50}), and strength (G). These acoustic parameters are presented in the form of graphs, as shown in Figure 5, and, where appropriate, in the form of spatial distributions, as indicated in Figures 6–8, when the acoustic parameters depend strongly on the position in the seating area. The analysis was performed for the frequency range between 125 Hz and 4 kHz. The results were averaged for all sources and receivers placed in the digital model [33].

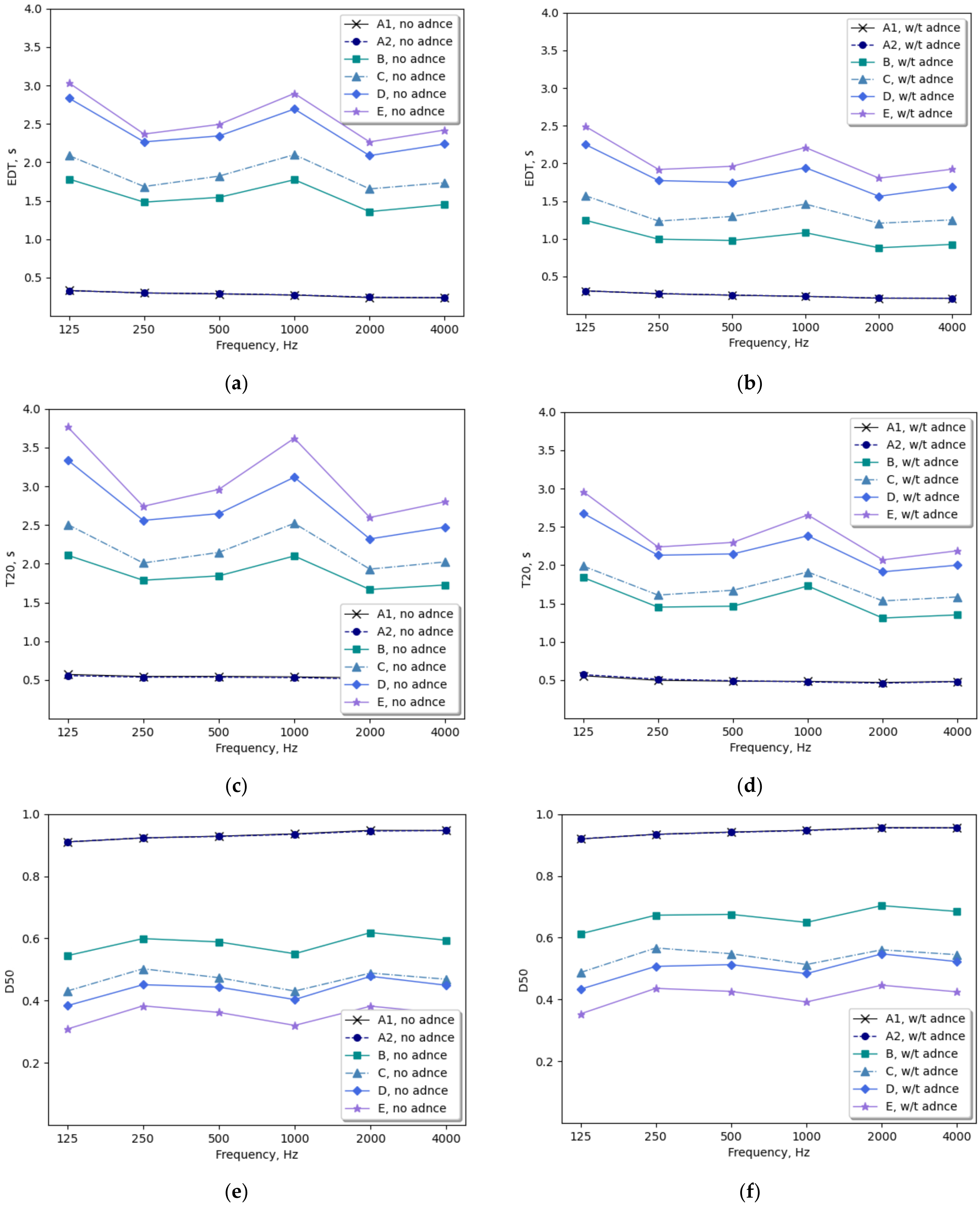


Figure 5. Comparison of scenarios A to E applied to the Roman theatre of Gubbio in relation to the acoustic parameters: EDT without audience (**a**), EDT with audience (**b**), T_{20} without audience (**c**), T_{20} with audience (**d**), D_{50} without audience (**e**), and D_{50} with audience (**f**).

6.1. Definition of the Main Acoustic Parameters

Before the analysis of the main acoustic parameters, it is important to explain the main characteristics of them.

- The early decay time (EDT) is computed by considering the direct sound and the early reflections occurring between 0 dB and −10 dB of the decay, after the interruption of the sound impulse [34]. This computation is based on the integrated Schroder curve.
- The reverberation time is related to the time for which the sound energy will be absorbed by the surfaces of a room. To determine the optimal range of reverberation time, the room function, or destination of use, is of primary importance [35].
- The definition (D_{50}) was introduced as a parameter to link the energy level and the delay in late reflections with respect to direct sound [36]. The optimal values for speech definition can range from 50% to 100%, while, for music, the values should range from 0% to 50%.
- The clarity index is an acoustic parameter based on the ratio between the sound energy arriving within 50 ms (for speech) or 80 ms (for music) and the sound energy arriving in the following decay instants. Clarity can be compared to the transparency of the perceived signal, having the optimal value fixed at 0 dB, representing the best balance, with some tolerance ranging from −2 to +2 dB [37,38].
- Another acoustic parameter that is a function of the position assumed in the seating area is strength (G), which is directly related to the power level of the sound source [39]. In general, for outdoor spaces, G can vary between 0 dB and 6–7 dB, while, for enclosed spaces, G can be higher, depending on the surface finishes and the volume of the space.

6.2. Comments on Simulated Results

Figure 5a shows that the simulated EDT results range from 1.5 s to 3.0 s, except for scenario A1 and A2, which represent the existing conditions, where the EDT is about 0.4 s, for the application of the two types of scattering coefficients. It can be seen that the addition of the roof makes the acoustic response slightly less reverberant than the scenario where only the porch is added. When both architectural elements are added to the seating area, the EDT results reach about 2.5 s over the entire frequency bandwidth, which is appropriate for an open-air theatre and meets the criteria for enclosed spaces, as indicated by Jordan [34]. Scenario E's results provide the best combination to support early reflections.

For 100% occupancy, as shown in Figure 5b, the difference does not change for scenarios A1 and A2. For all other scenarios, the EDT values shift downward by about 0.5 s under occupied conditions. Previous research studies have demonstrated that the presence of an audience in open-air theatres does not significantly affect the acoustic response [40]. This result was found for scenario A, where the absence of a scenic building and porch made no difference regardless of whether the audience was present.

Particular attention should be paid to the peak at 1 kHz, which is more pronounced in unoccupied conditions; this effect is due to the diffraction of the steps, as this is a typical phenomenon that occurs in other theatres.

As for the reverberation time (T_{20}), the reconstruction of the Roman theatre of Gubbio shows that the simulated results for all scenarios are between 1.8 s and 3.0 s, as indicated in Figure 5c, except for scenario A, where the T_{20} is around 0.55 s. The room volume is of the utmost importance to determine the optimal range of reverberation time in a room.

Assuming a room volume of approximately 6400 m^3, the acoustic response of the theatre associated with the reconstruction of the entire seating area (excluding the roof and porch) can be approximately compared to the acoustics of a concert hall suitable for light music, as indicated in Figure 6. With the addition of the audience, the results for the same scenario shift downward by 0.25 s, as indicated in Figure 5d, so that they are comparable to those of a concert studio with a similar room volume. For all other scenarios, the T_{20} results shown in Figure 5c are up to 1.5 s higher than for scenario B, as discussed above, reaching 3.5 s when all the architectural elements are in place.

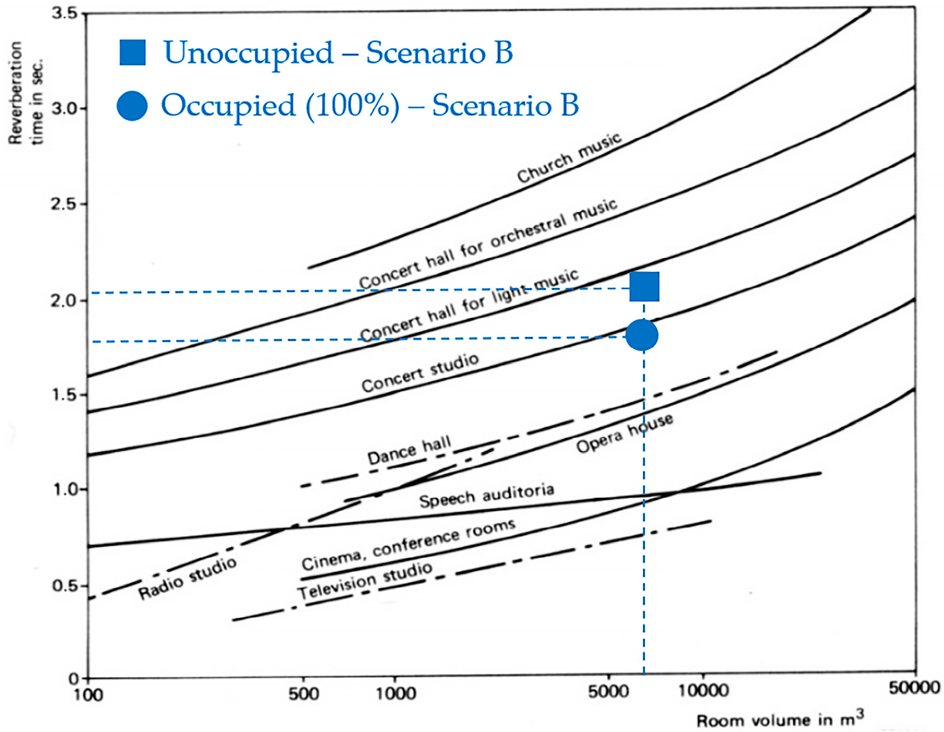
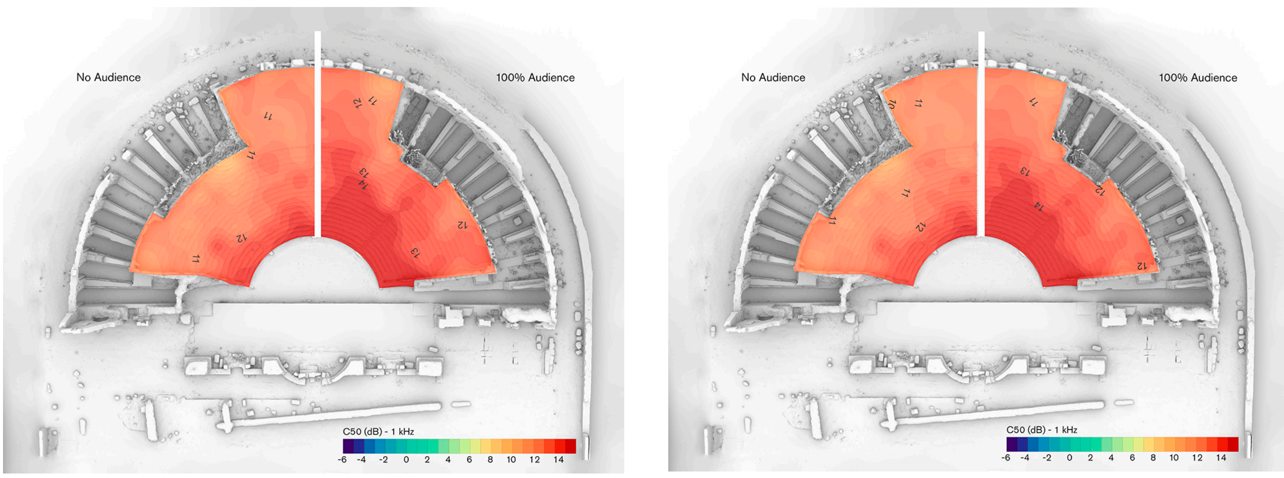


Figure 6. Optimal reverberation time T_{20} at mid-frequency (500–2000 Hz) for the Roman theatre of Gubbio, as a function of volume size and building type [41].

The simulated results presented in Figure 5e indicate a difference of up to 0.2 (20%) between all scenarios, except for scenario A, for which the result is about 0.9 (90%), indicating that it is suitable for speech intelligibility.

A very small change can be observed in Figure 5f when the *cavea* is occupied by listeners. In Figure 5f, scenarios C and D have a similar response in terms of definition, while the results of scenario E with and without an audience are 0.38 and 0.40, respectively.

Since clarity strongly depends on the considered position in the seating area, the spatial distribution of speech and music clarity can be more accurately represented with spatial acoustic maps, plotting the values referenced to 1 kHz, as shown in Figures 7 and 8.



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

Figure 7. *Cont.*

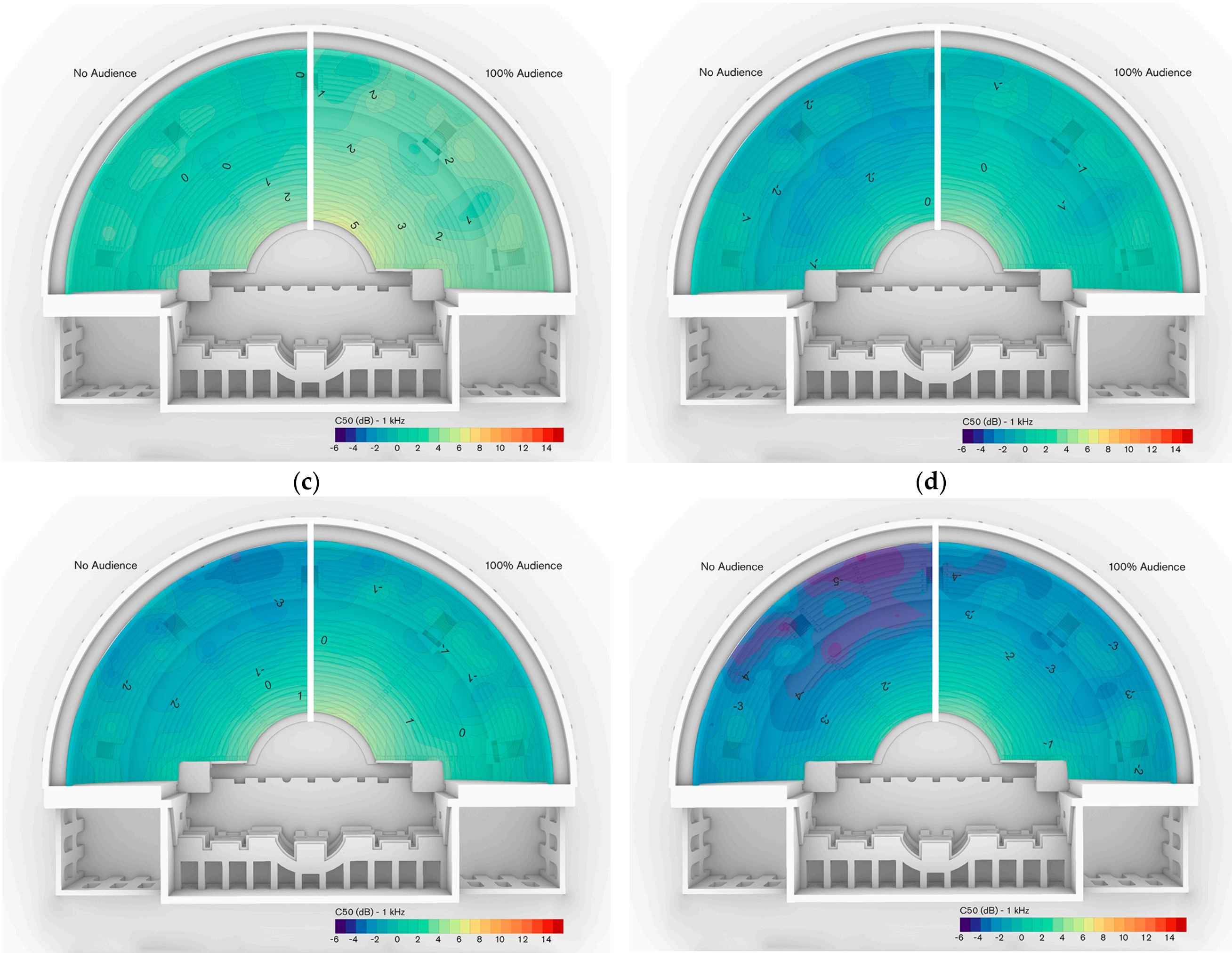


Figure 7. Spatial distribution of speech clarity index (C_{50}) at 1 kHz, with and without audience: scenario A1 (**a**), scenario A2 (**b**), scenario B (**c**), scenario C (**d**), scenario D (**e**), and scenario E (**f**).

Figure 7a,b show that the C_{50} results are 13–14 dB, with higher values for the seats closer to the stage. This is considered too clear for a speech performance, although it is typical and/or similar for other ancient open-air theatres that are damaged or ruined and missing several original structures. The simulations with two types of scattering coefficients make very little difference.

Figure 7c shows that the C_{50} results without an audience range from 0 dB to 3 dB, with levels shifted upward by about 2 dB with full occupancy. This result indicates that the speech clarity is within optimal values when the *cavea* does not have a roof over the stage and there is no porch crowning the seating area.

Figure 7d,e show that the results are very similar and range from −2 dB to +1 dB, which is exactly in line with the criteria. This means that adding only the roof or only the upper porch improves the speech clarity in the theatre, so that it is within the optimal values. The addition of both architectural elements, as shown in Figure 7f, indicates that the C_{50} values are between −3 dB and 0 dB, with some small areas at the top of the steps where the values are closer to −4 dB. This configuration is more advantageous for male singers than for female ones, but, in general, it is very close to the optimal values.

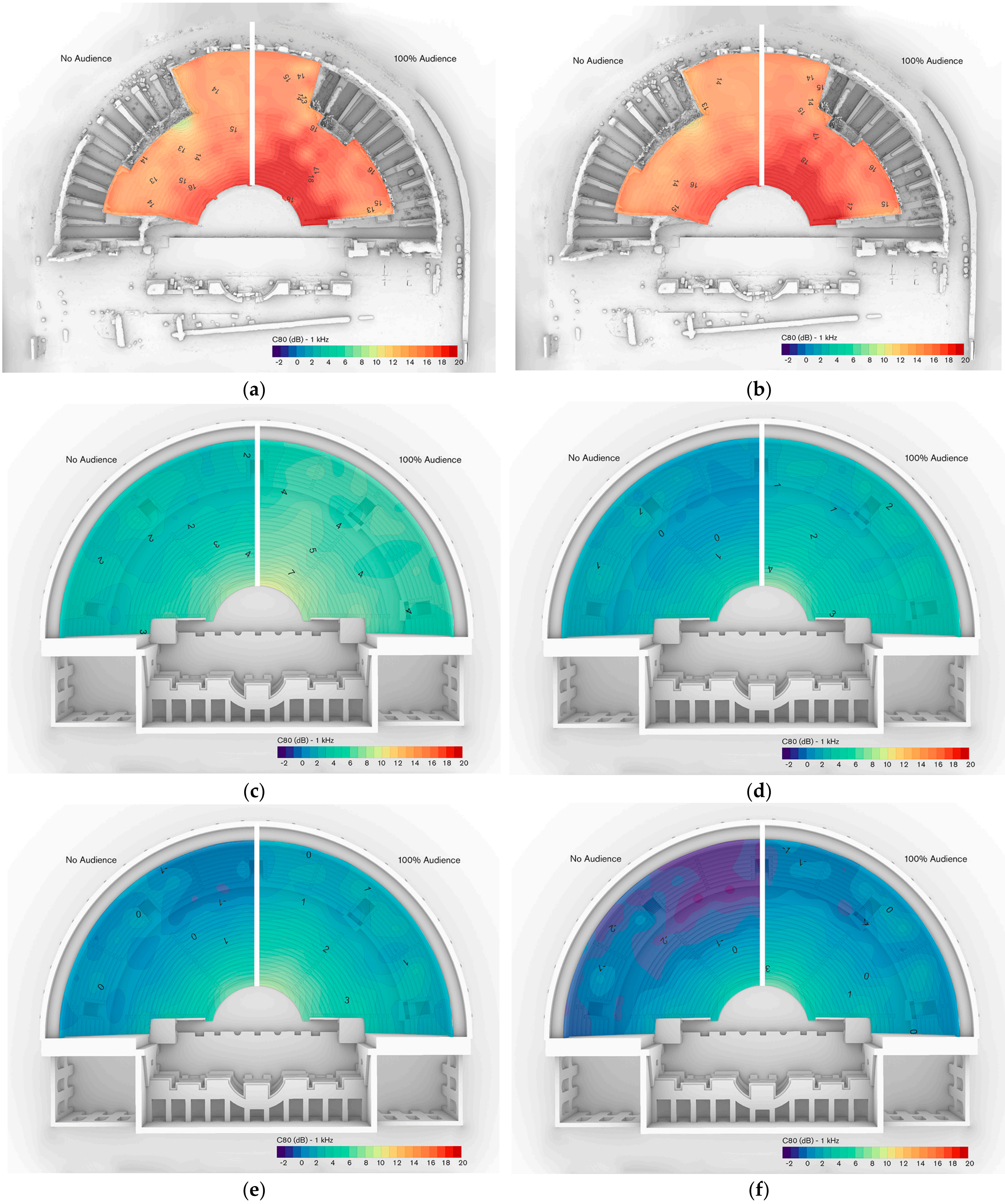


Figure 8. Spatial distribution of music clarity index (C_{80}) at 1 kHz, with and without audience: scenario A1 (**a**), scenario A2 (**b**), scenario B (**c**), scenario C (**d**), scenario D (**e**), and scenario E (**f**).

Similar to Figure 7, the plots in Figure 8 show the simulated results in terms of music clarity. In particular, Figure 8a,b show that the C_{80} values are between 14 dB and 18 dB, with a negligible difference between occupied and unoccupied conditions. As for speech clarity, the C_{80} results are far from the upper range limit.

Figure 8c shows that the C_{80} values, without a roof and upper porch, are better than those of scenarios A1 and A2, due to the presence of the scenic building at the steps of the *cavea*, with average values between 2 dB and 5 dB without an audience, and between 4 dB and 8 dB with an audience at 100% occupancy. This result is slightly higher than the upper limit established by the criteria (i.e., +2 dB), but acceptable for an open-air space.

Scenarios D and E, shown in Figure 8d,e, have similar C_{80} values, fluctuating between 4 dB and 5 dB on the steps near the orchestra and −1 dB or 0 dB in the last rows of seats. This means that the addition of a roof or an upper porch is useful to bring the music clarity values into the optimal range. A better situation is obtained when both architectural elements are added to the structure, as shown in Figure 8f.

The plots summarised in Figure 9 show the simulated results of the strength at 1 kHz with respect to all the considered scenarios of the Roman theatre of Gubbio.

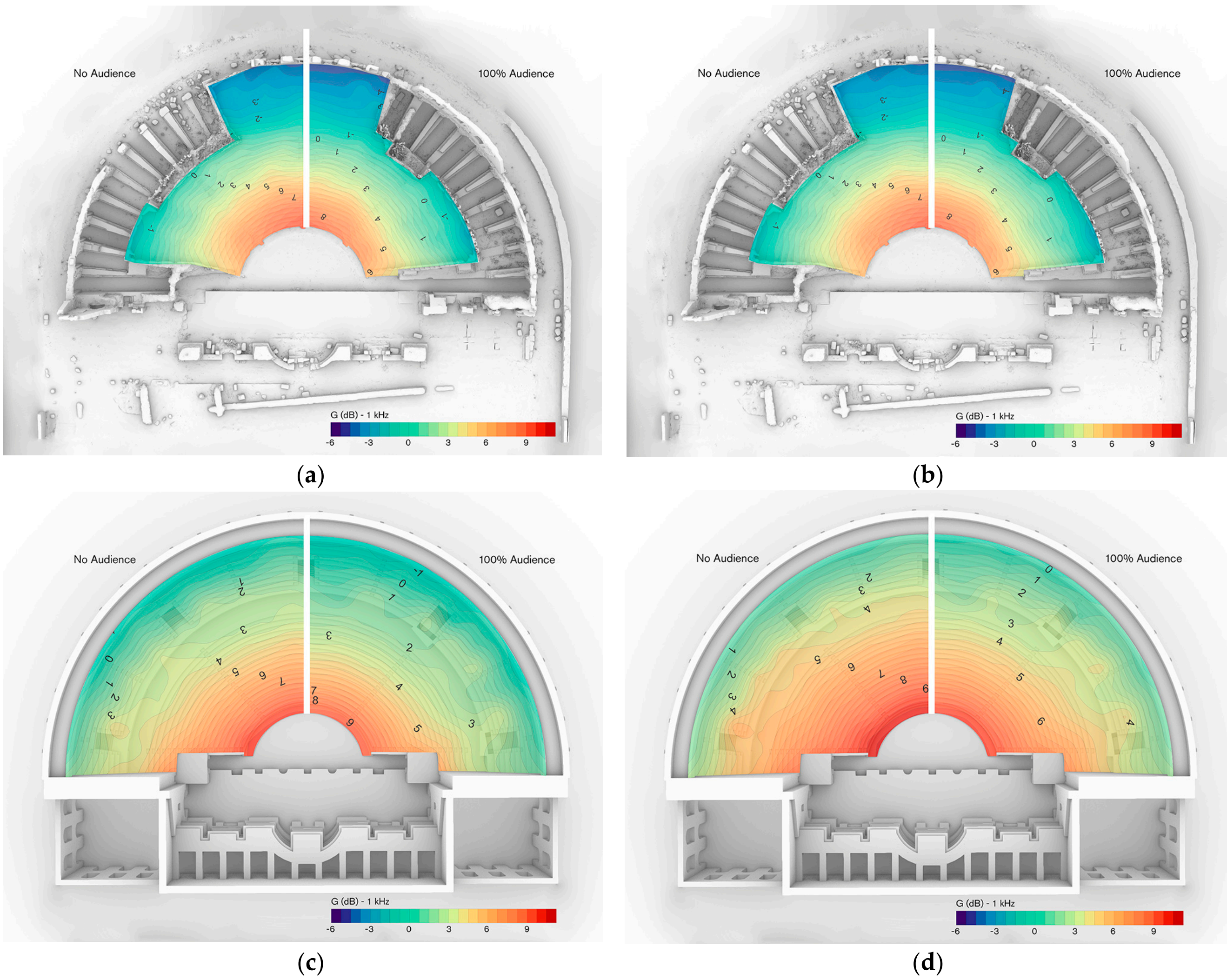
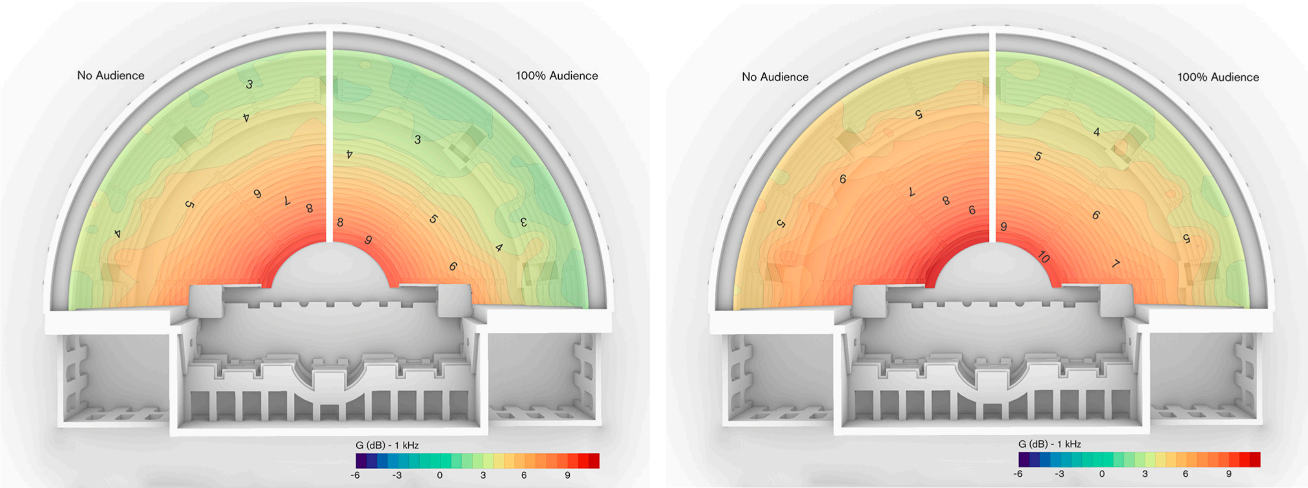


Figure 9. *Cont.*



(e) **(f)**

Figure 9. Spatial distribution of strength (G) at 1 kHz, with and without audience: scenario A1 (**a**), scenario A2 (**b**), scenario B (**c**), scenario C (**d**), scenario D (**e**), and scenario E (**f**).

Figure 9a,b show negative G values for the last rows of seats and for positions away from the orchestra. This reflects the definition of G, which should be equal to 0 dB at 10 m in a perfect anechoic environment; although the floor is reflective in the digital model, while all other vertical surfaces can be considered absorbent for both scenario A1 and A2, the minimum G values were found at about −4 dB.

Scenarios B and C, as shown in Figure 8c,d, have similar results, as the addition of the roof to the *cavea* does not contribute to a visible increase in strength, with values ranging from −1 dB to 8–9 dB.

With the addition of the upper porch, as shown in Figure 8e, the G values are between 3 dB and 9 dB, which is appropriate for an open-air theatre. The addition of both architectural elements (i.e., roof and upper porch), as shown in Figure 8f, results in the G response of the theatre in Gubbio ranging between 4 dB (in the last rows of seats) and 10 dB (on the steps near the orchestra).

Overall, the simulated results are comparable to those of other open-air theatres whose original reconstruction has been studied in previous research [4] and are in line with the expectations of this wok.

7. Discussions

The simulated results comparing the current acoustic response in the theatre of Gubbio with the original architectural shape show how poor the acoustics are nowadays when a speech or music performance is to take place. The simulated results for the different scenarios highlight the importance of some architectural elements for the acoustics in a Roman theatre. In particular, when the coffered roof and the upper porch are added individually to the main construction of the *cavea* and the scenic building, the improvement is marginal, while scenario E shows that the results obtained by adding both elements are very close to the optimal values for enclosed performance spaces.

Despite numerous indications regarding geometric and proportional rules to be followed in the construction of ancient theatres, the acoustic criteria in historical manuals are discussed only according to subjective perception and the intuitive effect that the sound energy would produce when interacting with the architecture. This is the main difficulty in evaluating the acoustics of ancient theatres, which can be done by comparing them with similar open-air theatres [42,43] or by using the criteria established for enclosed theatres with the explanation of assumptions and limitations [44].

The Roman theatre of Gubbio, in its current state, is not provided with a scenic front, a structure that is very important to direct the sound energy toward the audience. Moreover, only the lower part of the seating area is erected, while the upper rows of seats have been destroyed. This inconvenience determines a reverberation time of around 0.5 s, considered averaged over the entire frequency bandwidth, which creates a dry sonic perception but is very similar to that in other unroofed ancient theatres. Fortunately, no posthumous buildings were erected around the *cavea*, as was often the case at other sites, which could have interfered with the analysis of this Roman theatre, located in a natural landscape. The absence of the upper rows of seats, the lack of a scenic building, and the absence of an ambulatory and/or an upper porch crowning the entire volume make the existing theatre of Gubbio resemble a Greek theatre, with only the lower part of the *cavea* [45]. This may suggest a comparison with other ancient theatres, which can be made in future research studies.

8. Conclusions

Roman theatres have always been the subject of research from various perspectives. The synergy of different disciplines combines different expertise to obtain complete knowledge of ancient buildings, especially when documentation and archaeological sources are limited.

The acoustic analysis of the Roman theatre of Gubbio adopted the architectural and archaeological studies carried out in the previous literature on the subject. This research study was mainly focused on the discovery of the acoustic response related to the original shape of the Roman theatre of Gubbio in comparison with the existing conditions.

This research study is useful for different applications, as explained below.

- The simulated data can be used for auralisation as a basis for the convolution of the impulse response obtained from the simulations, with any sound signal to be potentially auralised at any point in the seating area.
- The data of the main acoustic parameters can be used as a reference for any architectural project that aims to design a shell that improves the acoustic response and is suitable for a desired and targeted type of performance.
- The spatial acoustic maps can be considered as a preliminary study for the design of an amplified audio system to be installed in the theatre of Gubbio, where the requirements to achieve this goal include the mapping of the seating area in order to obtain the most uniform response.

Future research studies will include the analysis of the acoustic measurements and compare them to the simulated results, which will need to be recalibrated.

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Appendix A. Definitions of Latin Terms Related to Roman Theatres

Balteum. Parapet.

Basilica. Public space, usually a square, where the Romans used to meet for public affairs.

Cavea. Seating area that corresponds to the circular steps. The *cavea* is usually horizontally divided into a lower part (*ima cavea*) and upper part (*summa cavea*).

Opus quadratum. Roman construction technique, in which squared blocks of stone of the same height were set in parallel courses.

Opus siliceum. Polygonal masonry that consists of superimposing unworked stone boulders, even of considerable size, without the aid of binders, grapples, or pins.

Orchestra. Place dedicated to performance.

Porticus. Circular porch covering the *summa cavea*. It is characterised by a wooden flat roof and by columns equidistantly spaced along the entire length of the porch.

Praecinctio. Circular corridor connecting the lower part of the *cavea* with the upper part.

Proedria. Seats composed of an armrest and backrest in stone, dedicated to the aristocrats, who would sit in the first row of the *cavea*.

Pulpitum. Stage floor.

Scaenae frons. Front of the scenic building, which could be characterised by two or three orders of columns.

Tribunalia. Seats located above the vaulted corridors laterally serving the orchestra.

Valva hospitalis. Lateral door of the scenic building, characterised by a squared frame. There were two lateral doors, in addition to other two doors placed in the lateral wings of the scenic building.

Valva regia. Central door of the scenic building, usually characterised by a circular niche.

Velarium. Cloth in linen or wool that was placed to shade the spectators from sunshine.

References

1. Izenour, G.C. *Theatre Design*; McGraw-Hill: New York, NY, USA, 1977.
2. Cox, T.J.; D'Antonio, P. *Acoustic Absorbers and Diffusers: Theory, Design and application*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2004.
3. Amadasi, G.; Bevilacqua, A.; Iannace, G.; Trematerra, A. The acoustic characteristics of Hellenistic Morgantina theatre in modern use. *Acoustics* **2023**, *5*, 870–881. [CrossRef]
4. Tronchin, L.; Bevilacqua, A. Historically informed digital reconstruction of the Roman theatre of Verona. Unveiling the acoustics of the original shape. *Appl. Acoust.* **2022**, *185*, 108409. [CrossRef]
5. Bevilacqua, A.; Merli, F.; Tronchin, L. Acoustic measurements of the Roman theatre of Pompei by mapping the sound reflections. In Proceedings of the Immersive 3D Audio (I3DA): From Architecture to Automotive, Bologna, Italy, 7–9 September 2021.
6. Merli, F.; Iannace, G.; Bevilacqua, A.; Tronchin, L. The Roman theatre of Benevento: Reconstruction of sound propagation with a multichannel microphone. In Proceedings of the Immersive 3D Audio (I3DA): From Architecture to Automotive, Bologna, Italy, 8–10 September 2021.
7. Lokki, T.; Southern, A.; Siltanen, S.; Savioja, L. Acoustics of Epidaurus—Studies with Room Acoustics Modelling Methods. *Acta Acust.* **2013**, *99*, 40–47. [CrossRef]
8. McCracken, L. *Gubbio, Past & Present*; Andesite Press: New York, NY, USA, 2017.
9. Fuchs, W. The Geometric Language of Roman Theater Design, Part 1. *Nexus Netw. J.* **2019**, *21*, 547–569. [CrossRef]
10. Morgan, M.H. *Vitruvius. The Ten Books on Architecture*; Harvard University Press: Cambridge, MA, USA, 1914.
11. Carlevaris, L. Geometry, theory and practice: The construction of the ennagon in antiquity. *Disegnare Idee Immagin.* **2016**, *52*, 24–35.
12. Fuchs, W. A study of the geometric and architectural composition of the Roman theatre in Volterra. In *Velathri Volaterrae: La citta' Etrusca e il Municipio Romano*; Giorgio Bretschneider: Rome, Italy, 2021.
13. Deiana, R.; Previato, C. Geophysical surveys for archaeological research in urban areas: The case of the Roman theatre in Padua. *Heritage* **2023**, *6*, 946–956. [CrossRef]
14. Cox, T.J.; D'Antonio, P. Surface characterization for room acoustic modelling and design. In Proceedings of the International Symposium on Room Acoustics: Design and Science, Hyogo, Japan, 11–13 April 2004.
15. Wilson Jones, M. *Principles of Roman Architecture*; Yale University Press: New Haven, CT, USA; London, UK, 2009.
16. D'Espouy, H. *Greek and Roman Architecture in Classic Drawings*; Dover Publications Inc.: Mineola, NY, USA, 2003.
17. Bruno, N.; Mikolajewska, S.; Roncella, R.; Zerbi, A. Integrated processing of photogrammetric and laser scanning data for frescoes restoration. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. (ISPRS Arch.)* **2022**, *46*, 105–112. [CrossRef]
18. Cheng, L.; Chen, S.; Liu, X.; Xu, H.; Wu, Y.; Li, M.; Chen, Y. Registration of Laser Scanning Point Clouds: A Review. *Sensors* **2018**, *18*, 1641. [CrossRef] [PubMed]

19. Vorländer, M. *Fundamentals of Acoustics, Modelling, Simulation, Algorithms and Acoustic Virtual Reality*; Springer Science & Business Media: Berlin, Germany, 2007.
20. Farina, A. Verification of the accuracy of the Pyramid Tracing algorithm by comparison with experimental measurements by objective parameters. In Proceedings of the ICA95 International Conference on Acoustics, Trondheim, Norway, 26–30 June 1995.
21. Iannace, G.; Trematerra, A. The Audience Effect on the Acoustics of Ancient Theatres in Modern Use. In Proceedings of the 142nd Audio Engineering Society International Convention, AES 2017, Berlin, Germany, 20–23 May 2017.
22. Vorländer, M. Models and algorithms for computer simulations in room acoustics. In Proceeding of the International Seminar on Virtual Acoustics, Valencia, Spain, 24–25 November 2011.
23. Tronchin, L.; Bevilacqua, A. The Royal Tajo Opera theatre of Lisbon: From architecture to acoustics. *J. Acoust. Soc. Am.* **2023**, *153*, 400–414. [CrossRef]
24. Cox, T.J.; Dalenback, B.I.L.; D'Antonio, P.; Embrechts, J.J.; Jeon, J.Y.; Mommertz, E.; Vorländer, M. A tutorial on scattering and diffusion coefficients for room acoustic surfaces. *Acta Acust. United Acust.* **2006**, *92*, 1–15.
25. Shtrepi, L. Investigation on the diffuse surface modeling detail in geometrical acoustics based. *J. Acoust. Soc. Am.* **2019**, *145*, EL215–EL221. [CrossRef] [PubMed]
26. Bo, E.; Shtrepi, L.; Alerta, F.; Puglisi, G.E.; Astolfi, A. Geometrical acoustic simulation of open-air ancient theatres: Investigation on the appropriate objective parameters for improved accuracy. In Proceedings of the 16th Conference of the International Building Performance Simulation Association, Building Simulation, Rome, Italy, 2–4 September 2019.
27. Sikora, J.; Turkiewicz, J. Sound Absorption coefficients of granular materials. *Mech. Control* **2010**, *29*, 149–157.
28. Saccenti, L.; Armelloni, E.; Farina, A.; Bevilacqua, A.; Lavagna, L. In-situ measurements of normal impedance and sound absorption coefficient of hard materials by using a laser Doppler vibrometer. In Proceedings of the 153rd Convention on Audio Engineering Society (AES), New York, NY, USA, 18–21 October 2022.
29. D'Ambrosio Alfano, F.R.; Iannace, G.; Ianniello, C.; Ianniello, E. "Velaria" in ancient Roman theatres: Can they have an acoustic role? *Energy Build.* **2015**, *95*, 98–105. [CrossRef]
30. Barron, M. *Auditorium Acoustics and Architectural Design*, 2nd ed.; Spon Press: New York, NY, USA, 2010.
31. Zeng, X.; Christensen, C.L.; Rindel, J.H. Practical methods to define scattering coefficients in a room acoustics computer model. *Appl. Acoust.* **2006**, *67*, 771–786. [CrossRef]
32. *ISO 3382-1*; Acoustics-Measurement of Room Acoustic Parameters—Part 1: Performance Spaces. ISO: Geneva, Switzerland, 2009.
33. Jordan, V.L. A group of objective acoustic criteria for concert halls. *Appl. Acoust.* **1981**, *14*, 253–266. [CrossRef]
34. Jordan, V.L. Acoustic criteria for auditoriums and their relation to model techniques. *J. Acoust. Soc. Am.* **1970**, *47*, 408–412. [CrossRef]
35. Kurer, R.; Kurze, U. Integration method for the evaluation of reverberation measurements. *Acta Acust. United Acust.* **1967**, *19*, 313–322.
36. Reichardt, W.; Alim, O.A.; Schmidt, W. Definition and basis of making an objective evaluation to distinguish between useful and useless clarity defining musical performances. *Acta Acust.* **1975**, *3*, 126–137.
37. Martellotta, F. Just noticeable difference of center time and clarity index in large reverberant spaces. *J. Acoust. Soc. Am.* **2010**, *128*, 654–663. [CrossRef]
38. Bevilacqua, A.; Farina, A.; Saccenti, L.; Farina, A. New method for the computation of acoustic parameters according to the updated Italian Legislation. In Proceedings of the 154th Convention on Audio Engineering Society (AES), Helsinki, Finland, 13–15 May 2023.
39. Wenmaekers, R.; Hak, C. The sound power as a reference for sound strength (G), speech level (L) and support (ST): Uncertainty of laboratory and in-situ calibration. *Acta Acust. United Acust.* **2015**, *101*, 892–907. [CrossRef]
40. Pinardi, D.; Riabova, K.; Binelli, M.; Farina, A.; Park, J.S. Geometrical acoustics simulations for Ambisonics auralization of a car sound system at high frequency. In Proceedings of the Immersive 3D Audio (I3DA): From Architecture to Automotive, Bologna, Italy, 8–10 September 2021.
41. Available online: http://www.sfu.ca/sonic-studio-webdav/cmns/Handbook%20Tutorial/Sound-Environment.html (accessed on 6 October 2023).
42. Iannace, G.; Berardi, U.; Maffei, L. Virtual reconstruction of the historical acoustics of the theatrum tectum of Pompeii. *J. Cult. Herit.* **2016**, *19*, 555–566.
43. Vassilantonopoulos, S.L.; Mourjopoulos, J.N. Virtual acoustic reconstruction of ritual and public spaces of ancient Greece. *Acustica* **2001**, *87*, 604–609.
44. Ciaburro, G.; Iannace, G.; Lombardi, I.; Trematerra, A. Acoustic design of ancient buildings: The odea of Pompeii and Posillipo. *Buildings* **2020**, *10*, 224. [CrossRef]
45. Farnetani, A.; Prodi, N.; Pompoli, R. On the acoustics of ancient Greek and Roman theatres. *J. Ac. Soc. Am.* **2008**, *124*, 1557–1567. [CrossRef]