DOI: 10.61782/fa.2025.0057

FORUM ACUSTICUM EURONOISE 2025

ACOUSTIC ANALYSIS OF A SINGLE-NAVE HALL WITH AN APSE IN THE CELLARS OF DIOCLETIAN'S PALACE IN SPLIT

Mateja Nosil Mešić[1*] **Zoran Veršić** [1]
Marko Horvat[2] **Kristian Jambrošić**[2]
[1] Faculty of Architecture, University of Zagreb, Croatia
[2] Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia

ABSTRACT[*]

The present work examines a single-nave hall located within the Cellars of Diocletian's Palace in Split, Croatia, constructed during the period of ancient Rome, at the end of the 3rd century AD. Since the excavation of the Cellars, no acoustic treatment has been implemented to adapt the hall for contemporary usage. Currently, the hall is not utilized for musical performances, as they require acoustic conditions different from that were considered ideal during the Roman era. An acoustics analysis of this basilica-shaped hall was conducted in room acoustics simulation software to evaluate its potential for contemporary musical performances. The study revealed that the empty hall exhibits inadequate values of room acoustic parameters in terms of excessively high reverberation time and early decay time, as well as low values of speech and music clarity and definition, which is in line with the physical characteristics of the hall. Nevertheless, the hall is deemed suitable for acoustic adaptation which would increase its potential for hosting musical performances. Comparable spaces from various historical periods with similar physical characteristics such as interior shape, proportions and material reflectivity were analysed using data from literature to contextualize the acoustic value of this hall and its historical significance.

Keywords: *Cultural heritage; ancient Roman architecture; archaeoacoustics; acoustic quality, room acoustics modelling*

[*]***Corresponding author***: mnosilmesic@arhitekt.hr

1. INTRODUCTION

Acoustics as a scientific discipline began to develop in antiquity, although there are traces from earlier periods. The first records of the empirical study of acoustics were observed in ancient Greece (Aristotle, 384 - 322 BC), while Vitruvius (80 - 25 BC) in his "Ten Books on Architecture" even mentions the resonant properties of space [1]. Many later studies of the acoustic properties of ancient theaters confirm the belief that the Romans had a basic understanding of sound as a science [2]. The first spaces, where great attention was paid to acoustics, were Greek theaters and Roman amphitheaters [3], [4], after which Roman basilicas and then Catholic churches took over this role.

Roman basilicas contributed to the study of good acoustic qualities with harmonious proportions and moderately high wooden ceilings, which were later replaced by masonry vaults due to the risk of fire. From some sources it can be concluded that in the past, preferences for reverberation length were more pronounced than today. The amount of available information on the acoustics of churches is incomparably less than that of concert halls, as well as theatres and amphitheaters.

In churches, for the purpose of worship, listening to the word, prayer and music had priority in the construction criteria. Further development led to significant changes in materialization and design, with regard to unequal proportions, focalization of sound and clearly reflective wall mass, especially at the transition to Gothic [5]. The primary material for the construction of theatres, amphitheaters, churches and cathedrals was stone, whose reflective surface plays an important acoustic role, enabling long reverberation, a sense of spaciousness and a rich depth of sound for instruments. Acoustically, churches have a more complex task, because their spaces must meet the requirements for speech and music, which is often not compatible due to the optimal values of acoustic parameters for speech and music [6], [7]. After these achievements the connection between music and acoustics with the planning and design of the built environment was lost until the mid-20th century [8].

This paper deals with the topic of the single-nave hall with a semi-apse in Diocletian's cellars in Split. First, the acoustic quality of the space will be investigated through different acoustic parameters having optimal values shown in Table 1. The acoustic parameters considered in this study include reverberance (estimated using reverberation time *T30* and early decay time *EDT*), perceived clarity (estimated using parameters clarity C_{80} and definition D_{50}), speech intelligibility (estimated using the speech transmission index *STI*), perceived loudness of sound (estimated with sound strength *G*), and the perception of source width and spaciousness (estimated using lateral fraction LF_{80}). Figure 1 shows spaces where great attention has been paid to acoustic parameters throughout history. All examples have many reflective surfaces, are rectangular in shape, but of different volumes, and were built in different time periods, which allows us to trace the development of acoustic treatment approaches over time.

Table 1. Optimal values of acoustical parameters acc. to literature [9]–[11] and IEC 60268-16

Acoustic quality / Acoustic parameters			Optimal values for speech and music
Reverberance			
Early decay time	*EDT* [s]	speech	0.8 < *EDT* < 1.0
		music	2.1 < *EDT* < 4.2
Reverberation time	*T30* [s]	speech	1.6 < *T30* < 2.2
		music	1.8 < *T30* < 1.2
Speech intelligibility			
Speech Transmission Index	*STI* [-] acc. to IEC 60268-16	excellent	0.75 < *STI* < 1.00
		good	0.60 < *STI* < 0.75
		fair	0.45 < *STI* < 0.60
		poor	0.30 < *STI* < 0.45
		bad	0.00 < *STI* < 0.30
Perceived clarity of sound			
Definition	D_{50} [-]	speech	D_{50} < 0.5
		music	0.5 < D_{50}
Clarity	C_{50} [dB]	speech	0 < C_{50} < 5
	C_{80} [dB]	music	-2 < C_{80} < 2
Perceived loudness of sound			
Sound strength	*G* [dB]	speech	> 0
		music	> 3
Perceived source width and spaciousness			
Lateral fraction	LF_{80} [-]	speech	LF_{80} > 0.20
		music	LF_{80} > 0.25

a) b) c) d)

Figure 1. Reference buildings: a) Repurposed church in Budrio [12], b) Church of St. Mary in Sastamala [13], c) Chapel of the Royal Palace of Caserta, Italy [14], and d) Blaibach Concert Hall [15]

Table 2. Acoustic parameters of comparable examples throughout history from Figure 1

Building	Shape	Building condition / Occupany level	Volume [m^3]	*T30* [s]	*EDT* [s]	*STI* [-]	C_{80} [dB]	*G* [dB]	LF_{80} [-]
Church in Budrio, Italy, 1517 [12]	Rectangular with a dome	Before renovation, audience included	1 500	1.9	2.4	n/a	-2.2	13	n/a
		After renovation, audience included		1.4	1.6	n/a	0.9	14	n/a
Church of St. Mary in Sastamala, Finland, 1777 [13]	Rectangular	1777, audience on wooden chairs included	6 300	2.3	2.3	0.39	-3.0	7.5	0.22
		Present day, audience on wooden chairs included	5 700	1.9	1.8	0.45	-0.9	7.5	0.24
Chapel of the Royal Palace of Caserta, Italy 1784 [14]	Rectangular with a semi-apse	Renovated to original conditions, Audience included	22 860	2.6	4.8	0.45	-1.8	9	n/a
Blaibach Concert Hall, Germany, 2014 [15], [16]	Rectangular, sloped in section	New building with contemporary standards, audience included	1 260	1.4	1.7	n/a	-0.7	13.1	n/a

After assessing the acoustic quality of the Hall, its performance will be compared with churches and concert halls from other time periods. The reference examples from Figure 1 and Table 2 were selected for their distinct approaches to acoustic treatment, all demonstrating careful consideration of the desired room acoustics. Additionally, these examples share similar geometric proportions and extensive use of reflective materials, suggesting acoustic values comparable to those of the Hall. Table 2 presents the values of *T30*, *EDT*, *STI*, C_{80}, *G*, and LF_{80} for the reference buildings.

2. THE CASE STUDY

Although the investigated hall was built in late antiquity (295-305 AD), its shape is more similar to that of a Roman basilica or a single-nave church (Figure 2). The single-nave hall is part of a complex of about forty smaller halls in the substructure of Diocletian's Palace, and is located in the southwestern part of the Cellars. The hall is 20.86 m long, 6.96 m wide, and 6.82 m high, as shown in Figure 3. It is vaulted with a barrel vault, and in its northern part there is an apse with a curvature radius of 2.65 m. The total volume of the hall is approximately 920 m^3. The hall is not completely closed; it has openings on all sides to the adjacent spaces in the lower and upper zones.

Figure 2. Photo of the interior of the single-nave hall.

The lower part of the hall is built of high-quality limestone blocks, while the upper part is built using the *opus mixtum*[1] technique. As can be seen in Figure 2, the vaults are made of tufa, which has the characteristics of natural aerated concrete and is easily processed due to its porosity. In the midst of the penetration of large amounts of water through the stone under the streets, the tufa was damaged in places. The lower part of the barrel vault up to the inclination of approximately 30° was built using the *opus mixtum* technique without formwork, while above that, the tufa vault in combination with rows of bricks was built on wooden formwork, the imprints of which can still be seen in the mortar today [17].

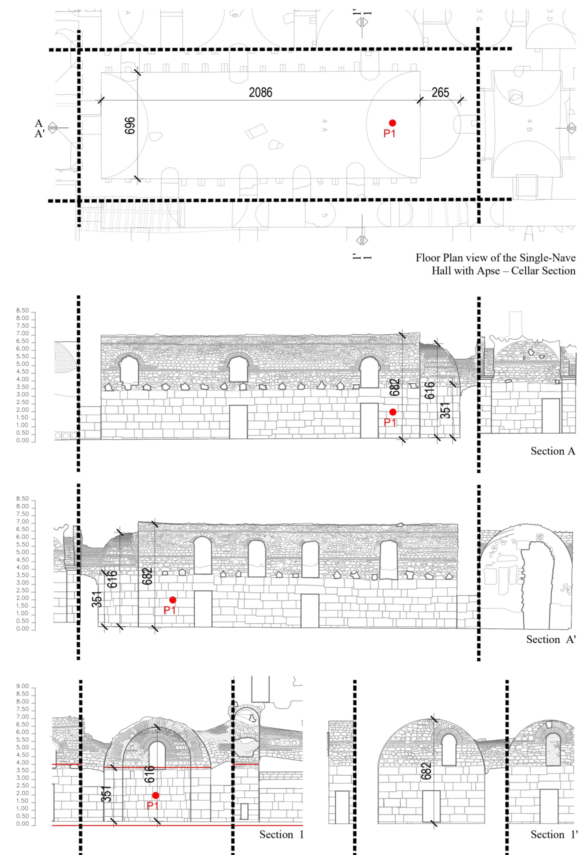


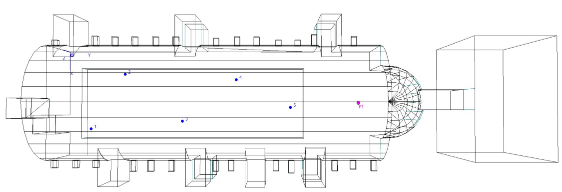
Figure 3. Drawings of a single-nave hall with an apse (author: Miljenko Žabčić, M.Geod.).

3. METHODOLOGY

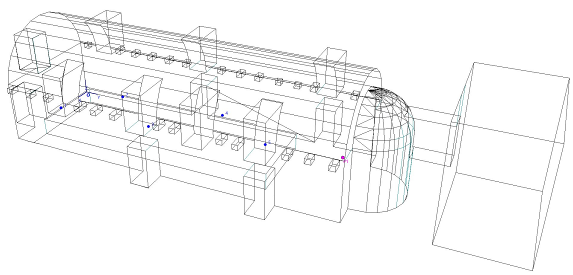
The model of the hall was first created in Sketchup based on drawings from the archive, as shown in Figure 3. After creating the simplified simulation model, the room acoustic modelling of the space was performed using the room acoustic software ODEON 18 where, in addition to the materials and their acoustic characteristics, the positions of the sound source (P1) and the receivers were added, as shown in Figure 4. During the creation of the model, some simplifications were made, considering that the simulated room acoustics parameters will not be significantly affected. Since the hall is a part of a large basement complex, the

[1] Lower quality crushed stone with four rows of bricks approximately every 150 cm in height

openings were created as semi-absorbing surfaces toward the contact spaces behind (transparency set to 50%). Also, the walls, made of stone blocks and *opus mixtum*, were treated as flat surfaces, additionally defined by appropriate scattering coefficients.



a)



b)

Figure 4. a) The floor plan and b) the 3D representation of the model in ODEON

Table 3. Scattering coefficients and absorption coefficients of certain types of materials within the single-nave hall (ODEON)

Material	Scattering	Absorption in octave bands					
	σ [-]	125	250	500	1000	2000	4000
Limestone floor	0.05	0.01	0.01	0.02	0.02	0.02	0.05
Limestone walls	0.05	0.01	0.01	0.02	0.02	0.02	0.05
Opus mixtum – fractional	0.05	0.01	0.01	0.02	0.02	0.02	0.05
Tufa –fractional	0.2	0.05	0.05	0.05	0.08	0.14	0.20
Audience – wooden chairs	0.7	0.24	0.40	0.78	0.98	0.96	0.87
Audience – lightly upholstered seats	0.7	0.51	0.64	0.75	0.80	0.82	0.83

Separate layers were created for the floors and walls in the lower zone (limestone), the walls in the upper zone (*opus mixtum*), and the vault of the hall and apse (tufa), as shown in Table 3. The walls in the upper zone, the vault above the hall, and the vault above the apse were also defined as fractional surfaces, due to their curved form. All materials were assigned a corresponding scattering coefficient, which were estimated empirically, with values set at 0.05 for predominantly smooth surfaces (e.g., stone), 0.2 for irregular surfaces (e.g., tufa) and 0.7 for the audience. The absorption coefficient values were chosen from the ODEON material library. Absorption coefficient values for tufa were taken from literature [18], as equivalent to porous concrete blocks without surface finish (density 400-800 kg/m^3).

Additionally, three main occupancy scenarios were considered. The first scenario represents the hall as completely empty, with no furniture or occupants. The second scenario includes an audience seated on wooden chairs, with a density of 2 persons per square meter [19]. The third scenario involves an audience seated on lightly upholstered seats [20].

4. RESULTS

4.1 Reverberance

The early decay time (*EDT*) is often used as an indicator of a space's perceived ‘liveliness' (reverberance). A shorter *EDT* suggests a dry, controlled sound, ideal for speech-oriented spaces, while a longer *EDT* creates a feeling of spaciousness and ‘richness', which is desirable in concert halls. In the mid-frequency range (500–1000 Hz), the *EDT* in the empty hall ranges from 3.50 s to 2.86 s. When the audience is included, the *EDT* decreases to range from approximately 1.20 s to 1.00 s with wooden seats and 1.09 s with upholstered seats (Figure 5). Due to the longer duration of reverberation in the empty hall, sound overlaps occur, reducing speech intelligibility. Long *EDT* is favorable for slow-tempo music, but negatively affects speech clarity. However, as shown in Figure 5, when the audience is included in the calculation, the *EDT* decreases to near-optimal values.

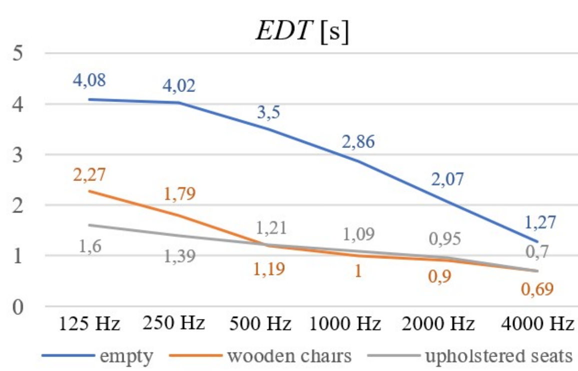


Figure 5. Early decay time *EDT* obtained from the simulation model

The simulation model showed that the mean reverberation time (T_{30}) is 3.35 seconds in an empty hall, 1.78 seconds with an audience on wooden chairs, and 1.86 seconds with the audience on lightly upholstered seats. Figure 6 shows how in the empty hall, reverberation is pronounced due to the predominance of reflective surfaces, and the absence of absorbing materials, except for the worn tufa on the vault. Some echo also returns through the side openings as the space is not in contact with the free field environment. Reverberation time decreases more noticeably with increasing frequency when scattering increases. It is significantly reduced in the occupied state, as more absorbing surfaces are introduced. Furthermore, higher frequencies – triggered by symphonic music, choral singing, or even slower speech (since mostly vowels typically contain more high-frequency energy than consonants) – lead to a further decrease in reverberation.

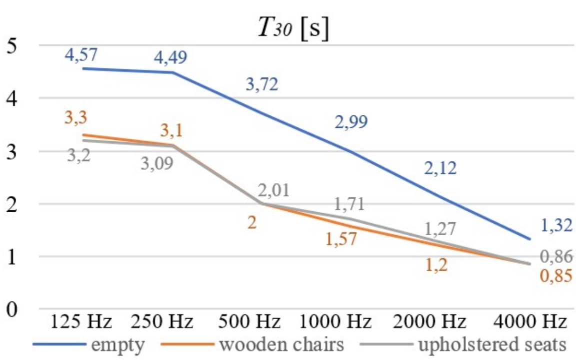


Figure 6. Reverberation time T_{30}

4.2 Speech intelligibility

Speech intelligibility reflects the quality of speech transmission, and is commonly assessed the speech transmission index (STI. At sound source position (P1), the *STI* value is 0.43 in the empty hall, 0.58 with an audience seated on wooden chairs, and 0.59 with an audience on upholstered seats. According to IEC 60268-16, this corresponds to poor to fair speech transmission in the empty state, and fair but approaching good conditions with the audience is included in the calculation.

4.3 Clarity and definition

Figure 7 shows the definition D_{50}, a parameter used to assess speech clarity a space. It measures the ratio between early reflected energy to total sound energy in space.

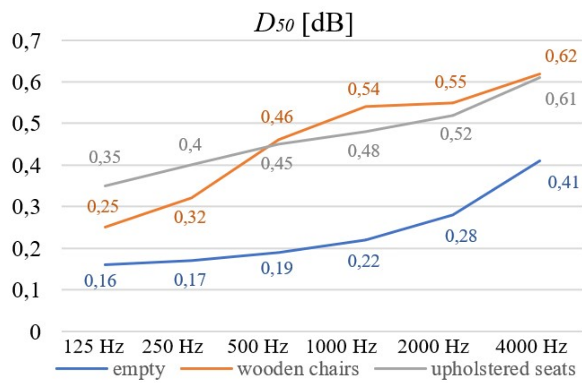


Figure 7. Definition D_{50}

Higher D_{50} values indicate that a greater proportion of sound arrives early, which enhances clarity. In general, D_{50} values above 0.5 are considered to represent good speech clarity, as they suggest that most of the sound energy is delivered through early reflections. However, for the simulated position in an empty state, D_{50} remains below 0.5 within the typical speech frequency range, indicating poorer speech clarity due to the dominance of late reflections. Introducing the audience, definition improves to almost 0.5, providing satisfying clarity.

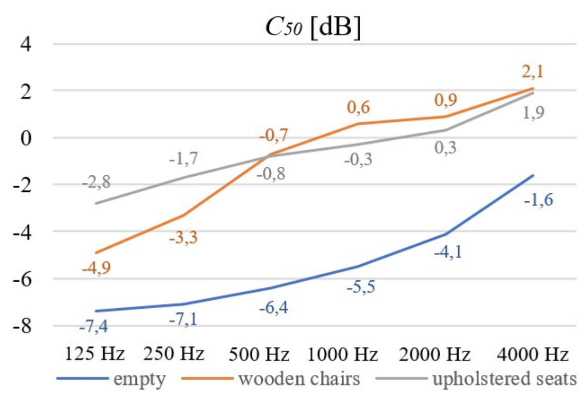


Figure 8. Speech clarity C_{50}

On the other hand, the clarity of sound – designated as C_{50} for speech (Figure 8) and C_{80} for music (Figure 9) – measures the ratio of early reflected energy (within 50 ms or 80 ms, respectively) to later reflections (after 50 ms or 80 ms). This parameter provides insight into the purity and clarity of the sound – that is, how clear it is. From Figures 8 and 9 it can be observed that clarity improves as the frequency increases. For speech clarity (C_{50}, Figure 8), the values are consistently poor in the empty hall. However, with an audience seated on wooden chairs, optimal clarity is achieved above approx. 1500 Hz, while with audience seated on upholstered seats, optimal values are reached above around 750 Hz.

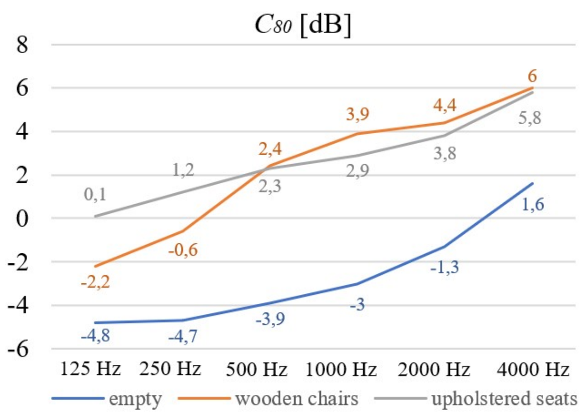


Figure 9. Music clarity C_{80}

For music clarity (C_{80}, Figure 9), optimal values in the empty hall are only achieved at frequencies higher than approximately 1300 Hz. Additionally, both audience seating configurations (wooden chairs and upholstered seats) show optimal clarity values already at low frequencies, below around 400 Hz. With this in mind, it is possible to manipulate and adapt sound clarity depending on the intended use or preferred performance type – simply by adjusting the presence and quantity of the audience.

4.4 Perceived loudness of sound

Sound strength (G), as shown in Figure 10, displays significantly higher values in an empty hall. With audience included, sound strength is still pretty high, affected by the volume and high quantity of the reflective surfaces.

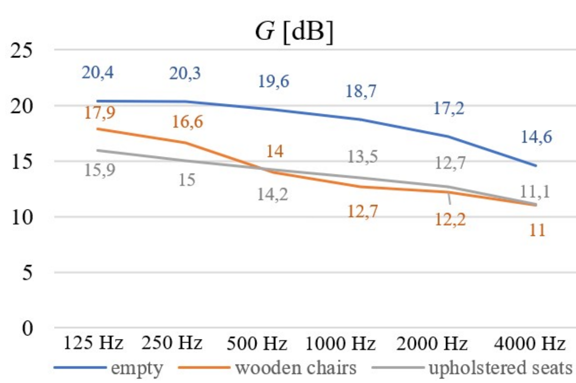


Figure 10. Sound strength G

4.5 Perceived source width and spaciousness

Perception of source width and overall spaciousness is influenced by reverberance represented with EDT and T_{30}, but even more so by lateral reflections represented with lateral fraction LF_{80}, which measures the ratio of the energy of early lateral reflections (which come from the sides within the first 80 ms after the direct sound) to the total energy of early reflections. It is important for the perception of localization and spatial spread of sound and allows listeners to perceive the sound as more natural and richer. As an average for all receiver points defined in the audience area (or in the hall space in general), with the source positioned at P1, an average of 0.398 of the sound energy comes from the sides in the empty hall, 0.436 with audience on wooden chairs, and 0.438 with audience on upholstered seats, as shown in Figure 11. Since all LF_{80} values above 0.25 are considered favorable and higher late lateral energy provides stronger sense of spaciousness and good envelopment, all three scenarios can be considered to have an exceptionally good value.

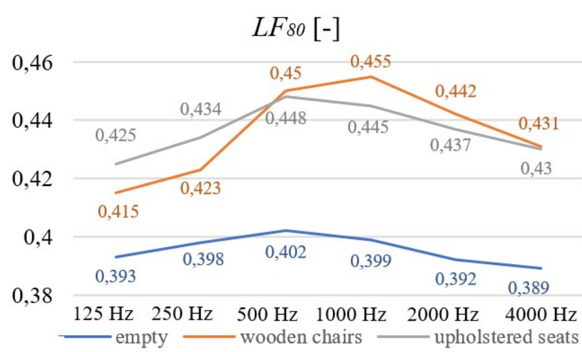


Figure 11. Late lateral sound energy LF_{80}

4.6 Summary

Considering all the investigated acoustic parameters, the average values of acoustic parameters across the three different occupancy scenarios are summarized in Table 4. If the results are compared with the optimal values from Table 1, it is evident that the values exceed the values required for optimal acoustic comfort in an empty hall but show much better results when both audience scenarios are included in the calculation.

4.7 Comparison with reference buildings

Finally, a comparison is made with the reference buildings presented in Table 2. These examples were selected due to their varied approaches to acoustic treatment, and their careful attention to achieving desired spatial acoustics. To ensure comparable conditions, only scenarios without renovation, but audience occupancy included were considered. Similarly, in the single-nave hall, scenario featuring an audience seated on wooden chairs was included, as it offers the most flexibility. Based on the data from Tables 2 and 4, summarized in Figure 12, the acoustic parametersT_{30}, *EDT*, C_{80}, *G*, and LF_{80} complemented with *STI* demonstrate results that are even better than initially anticipated. These values are comparable to those observed in high-performance halls, even post-renovation. Specifically, the hall's acoustic performance falls within the optimal range for T_{30}, lies between speech and music conditions for *EDT*, approaches a favorable value for *STI*, and shows high LF_{80} values. Due to the limited presence of sound-absorbing surfaces, sound strength *G* is notably higher than in reference examples.

Table 4. The averaged simulated parameters for all three occupancy scenarios

Occupancy scenario	Acoustic parameter (average value)						
	T_{30} [s]	*EDT* [s]	*STI* [-]	D_{50} [-]	C_{80} [dB]	*G* [dB]	LF_{80} [-]
empty	3.35	3.18	0.43	0.21	-3.5	19.2	0.398
audience wooden chairs	1.78	1.09	0.58	0.5	3.2	13.3	0.436
audience, lightly upholstered seats	1.86	1.15	0.59	0.47	2.6	13.9	0.438

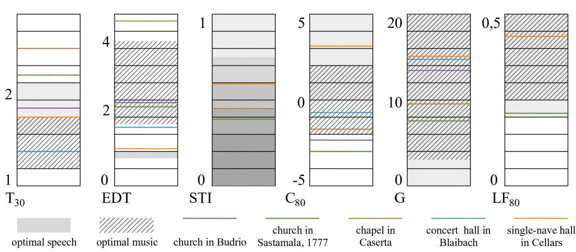


Figure 12. Comparison of the acoustic parameters with the reference buildings from Table 2

5. CONCLUSION

This study has demonstrated that the acoustic properties of the single-nave hall with an apse in the Cellars of Diocletian's Palace are significantly influenced by audience occupancy. Through a simulation model created in ODEON 18, three scenarios were examined—an empty hall and two levels of audience presence with varied seating arrangements. The results show that the hall, when empty, exhibits acoustically unfavorable conditions, particularly in the lower frequency range. However, the introduction of an audience leads to a marked improvement in all evaluated parameters.

Reverberance in the hall measured by, *EDT* and T_{30} revealed suboptimal values in the absence of an audience but approached desirable levels under occupied conditions, especially at higher frequencies. Speech intelligibility was determined by *STI*, while clarity and definition were presented with D_{50}, C_{50}, and C_{80}, also showing the benefit from audience presence. Definition D_{50}showed preferable values in higher frequency range, unsatisfying in an empty hall, but moderate in the mid-frequency range, when audience was introduced. Clarity was shown to be easily adaptable, depending on the quantity of audience occupancy. The spatial quality of the hall, indicated by the lateral energy fraction LF_{80}, was found to be excellent, especially for sound sources positioned in front of the apse.

By comparing the hall with reference examples of similar shape and proportions and treatment with reflective materials, it is evident that acoustic interventions can achieve significantly more favorable conditions. Future studies should focus on the integration of specific acoustic treatments and explore the hall's suitability for various performance types, ultimately contributing to the adaptive reuse and revitalization of this unique historical space.

6. ACKNOWLEDGMENTS

The authors would like to thank Prof. Katja Marasović, PhD, for information about the Cellars of Diocletian's Palace and Miljenko Žabčić, M.Geod. for providing the drawings of the Cellars.

7. REFERENCES

[1] Z. Đorđević, K. Penezić, and S. Dimitrijević, "Acoustic vessels as an expression of medieval music tradition in Serbian sacred architecture," *Muzikologija*, vol. 54, no. 22, pp. 105–132, 2017, doi: 10.2298/muz1722105d.

[2] U. Berardi and G. Iannace, "The acoustic of Roman theatres in Southern Italy and some reflections for their modern uses," *Appl. Acoust.*, vol. 170, p. 107530, 2020, doi: 10.1016/j.apacoust.2020.107530.

[3] K. Chourmouziadou and J. Kang, "Acoustic evolution of ancient Greek and Roman theatres," *Appl. Acoust.*, vol. 69, no. 6, pp. 514–529, 2008, doi: 10.1016/j.apacoust.2006.12.009.

[4] M. Galindo, S. Girón, and R. Cebrián,

"Acoustics of performance buildings in Hispania: The Roman theatre and amphitheatre of Segobriga, Spain," *Appl. Acoust.*, vol. 166, p. 107373, 2020, doi: 10.1016/j.apacoust.2020.107373.

[5] C. Buratti, E. Belloni, F. Merli, M. Ambrosi, L. Shtrepi, and A. Astolfi, "From worship space to auditorium: Acoustic design and experimental analysis of sound absorption systems for the new auditorium of San Francesco al Prato in Perugia (Italy)," *Applied Acoustics*, vol. 191. 2022, doi: 10.1016/j.apacoust.2022.108683.

[6] D. Queiroz de Sant'Ana and P. H. Trombetta Zannin, "Acoustic evaluation of a contemporary church based on in situ measurements of reverberation time, definition, and computer-predicted speech transmission index," *Build. Environ.*, vol. 46, no. 2, pp. 511–517, 2011, doi: 10.1016/j.buildenv.2010.08.015.

[7] F. Martellotta, E. Cirillo, A. Carbonari, and P. Ricciardi, "Guidelines for acoustical measurements in churches," *Appl. Acoust.*, vol. 70, no. 2, pp. 378–388, 2009, doi: 10.1016/j.apacoust.2008.04.004.

[8] T. Oberman, B. B. O. Šćitaroci, and K. Jambrošić, "Unaprjeđenje zvučnog okoliša gradskih prostora: Utjecaj na urbanizam i pejsažnu arhitekturu," *Prostor*, vol. 22, no. 2, pp. 200–211, 2014.

[9] U. Berardi, "A double synthetic index to evaluate the acoustics of churches," *Arch. Acoust.*, vol. 37, no. 4, pp. 521–528, 2012, doi: 10.2478/v10168-012-0050-3.

[10] E. Bo, L. Shtrepi, D. P. Garcia, G. Barbato, F. Aletta, and A. Astolfi, "The accuracy of predicted acoustical parameters in ancient open-air theatres: A case study in Syracusae," *Appl. Sci.*, vol. 8, no. 8, pp. 1–22, 2018, doi: 10.3390/app8081393.

[11] T. Hidaka and N. Nishihara, "Objective evaluation of chamber-music halls in Europe and Japan," *J. Acoust. Soc. Am.*, vol. 116, no. 1, pp. 357–372, 2004, doi: 10.1121/1.1760112.

[12] D. D'Orazio, G. Fratoni, and M. Garai, "Acoustics of a chamber music hall inside a former church by means of sound energy distribution," *Can. Acoust. - Acoust. Can.*, vol. 45, no. 4, pp. 7–17, 2017.

[13] P. H. Sadeaho, M. Kylliäinen, and J. Lietzén, "an Archaeoacoustic Analysis of the Late Medieval St. Mary'S Church of Sastamala," *Proc.. Forum Acust.*, no. September, pp. 2387–2394, 2023, doi: 10.61782/fa.2023.0716.

[14] U. Berardi, G. Iannace, and C. Ianniello, "Acoustic intervention in a cultural heritage: The chapel of the Royal Palace in Caserta, Italy," *Buildings*, vol. 6, no. 1, pp. 1–14, 2015, doi: 10.3390/buildings6010001.

[15] O. C. Gomes, W. Lachenmayr, and E. Mommertz, "Spatial Energy Analysis for Room Acoustical Evaluation," *Proc. DAGA*, no. 1, pp. 834–837, 2020.

[16] W. Lachenmayr, N. Meyer-Kahlen, O. Colella Gomes, A. Kuusinen, and T. Lokki, "Chamber music hall acoustics: Measurements and perceptual differences," *J. Acoust. Soc. Am.*, vol. 154, no. 1, pp. 388–400, 2023, doi: 10.1121/10.0020066.

[17] K. Marasović, *Arhitekt Jerko Marasović: renesansni čovjek dvadesetog stoljeća*, 2024th ed. Split: Društvo arhitekata Splita; Arhitektonski fakultet Sveučilišta u Zagrebu, 2024.

[18] J. Kristensen, *Sound Absorption Coefficients - Measurement, evaluation, application*, Note no. 4. Statens Byggeforskningsinstitut, H¯rsholm, 1984.

[19] E. Meyer, D. Kunstmann, and H. Kuttruff, "Über einige Messungen zur Schallabsorption von Publikum (in German)," *Acustica 14*, pp. 119–124, 1964.

[20] L. L. Beranek and T. Hidaka, "Sound absorption in concet halls by seats, occupied and unoccupied, and by the hall's interior surfaces," *J. Acoust. Soc. Am. 104*, pp. 3169–3177, 1998.