# The Acoustic Adaptation of the Aula Magna at the University of Bologna: Auditorium and Conference Hall Scenarios Simulated in the Main Nave of Santa Lucia's Church

**Antonella Bevilacqua – University of Parma, Italy – antonella.bevilacqua@unipr.it**
**Ruoran Yan – University of Bologna, Italy – ruoran.yan2@unibo.it**
**Maria Cristina Tommasino – ENEA, Italy – cristina.tommasino@enea.it**

## Abstract

The main Auditorium of Bologna was created inside the original monastery built during the 16th century by the Jesuits. In the following century, the building was modified to become a Catholic church by the architect G. Rainaldi. After the French invasion led by Napoleon during the 18th century, the church was adapted to fulfil different uses. Nowadays, the main hall, composed of three naves but having audience seats in the central one only, is used for celebrations and civil events organized by the University of Bologna. Numerical simulations have been undertaken considering two different scenarios: acoustic adaptation to become an auditorium and to become a conference hall. The model representing the existing conditions has been calibrated on the measurements undertaken across the seating areas. The two scenarios simulated have been compared with the existing conditions of the Aula Magna: the outcomes highlight an improvement in speech comprehension across all the seating areas by achieving the optimal range of each acoustic parameter analyzed. A historical background has also been introduced to understand the adaptation of the original construction to the different room functions assigned throughout the centuries.

## 1. Introduction

Increased demand for the utilization of cultural heritage buildings has caused experts and scholars to study the existing historical patrimony (Vecco, 2010). On this basis, this paper deals with the acoustic simulations of two conditions that the old church of Santa Lucia could have: the adaptation to become an auditorium for classical music and to become a conference hall, both room functions in line with academic activities run at the University (Dordevic, 2016). A digital model was utilised for the simulations after being calibrated with the measured values (Vorländer, 2007). The design project of the acoustic measures was digitally tested with the application of absorbing plaster on walls, installation of acoustic panels and addition of heavy curtains to close the main nave from the laterals. The results highlight a significant improvement in the outranges values related to the main acoustic parameters.

## 2. Historical Background

The main auditorium of the University of Bologna, the Aula Magna, was located inside Santa Lucia's church, and is now no longer in use. It was built during the 11th century, while the surrounding college buildings were erected in the 17th century.

During the 16th century, the original monastery became property of the Jesuits, and, on this occasion, the building was modified into a Catholic church by the architect G. Rainaldi (Wittkower et al., 1992). When the Jesuit order was suppressed by Pope Clement XIV, the church complex was transferred to the Barnabites at the end of the 16th century, and then turned into a military camp at the end of the 17th century. During the 18th century, under the French invasion led by Napoleon, the church was converted to fulfil different uses.

In the 1960s, the buildings were involved in a serious fire. From the 1970s to the 1980s, the restoration and modernization (Bettarello et al., 2010) project began to adapt the buildings to the needs of the

Part of
Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2023. Building simulation applications BSA 2022. bu,press.
https://doi.org/10.13124/9788860461919

University of Bologna and finally opened to the public in 1988. At the end of the 20th century, Santa Lucia's church was also transformed into a university facility.

Fig. 1 – Internal view of the Aula Magna of Bologna

Nowadays, the Aula Magna is composed of three naves, having walls and ceilings decorated with transparent and hard plaster. The auditorium, with lightly upholstered seats in the central nave, is surrounded by wooden balconies, in place for the occasion of degree celebrations and civil events, as shown in Fig. 1.

## 3. Architectural Organization

The Aula Magna at the University of Bologna, whose current form can be traced back to 1843, has a total capacity of about 1000 seats. It consists of the main hallway and two high, wide, and solemn side passageways, with a total area of about 30000 m$^3$, as shown in Fig. 2 and Fig. 3.

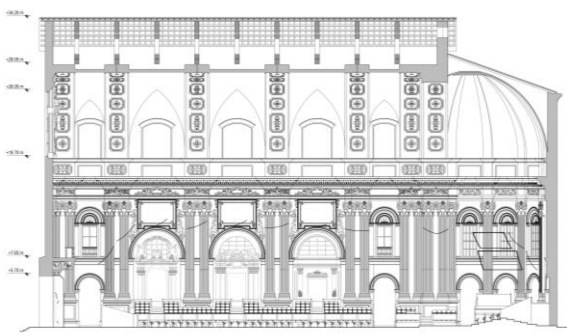

Fig. 2 – Longitudinal section of the Aula Magna of Bologna

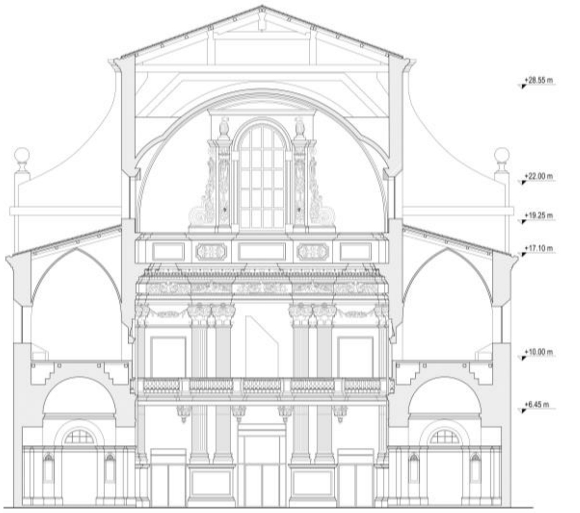

Fig. 3 – Transversal section of the Aula Magna of Bologna

The walls of the main hall are completely plastered, and the central area is decorated with stucco and is 10 to 15 m high. Wooden galleries and low padded seating platforms have been built on the sides of the nave, leaving full view of the auditorium.

### 3.1 Digital Model

From the architectural drawings, as well as for energy building and musical instruments simulation, (Fabbri et al., 2014; Farina et al., 1998; Manfren et al., 2019, 2021a, 2021b, and 2022; Tronchin, 2005) a digital model was realised to be composed of 3700 surface entities. The vault was realised with polyhedric geometry composed of 16 sides (Antlej, 2022). In a similar way, the apse was modeled by adopting the same methodology, as well as the capitals and the bases of the columns (Bettarello et al., 2021). As such, the model was exported in DXF format (Caniato et al., 2020a and 2020b), ready to be used within Ramsete software.

Attribution of the absorbing and scattering coefficients was carried out based on the acoustic measurements (Caniato et al., 2019), as indicated in Fig. 4.

In particular, the sound source and the receivers were placed in the same positions used during the survey (Caniato et al., 2021).

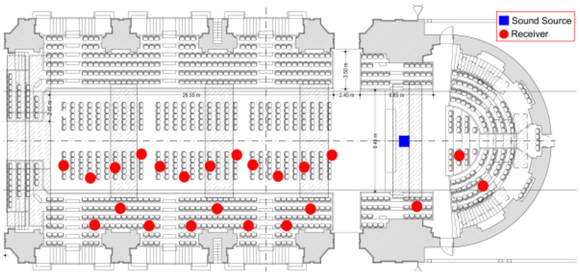


Fig. 4 – Equipment positions during the acoustic survey

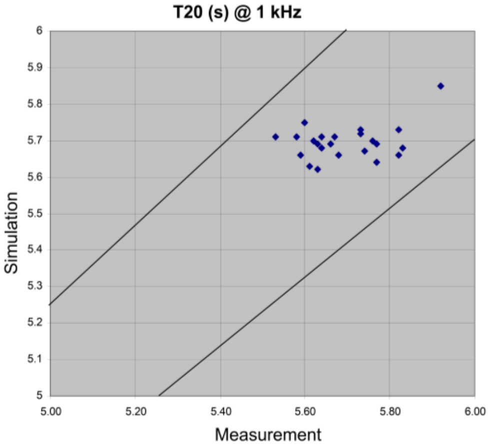


Fig. 5 – Reverberation Time ($T_{20}$) calibration between simulated and measured results of the existing conditions

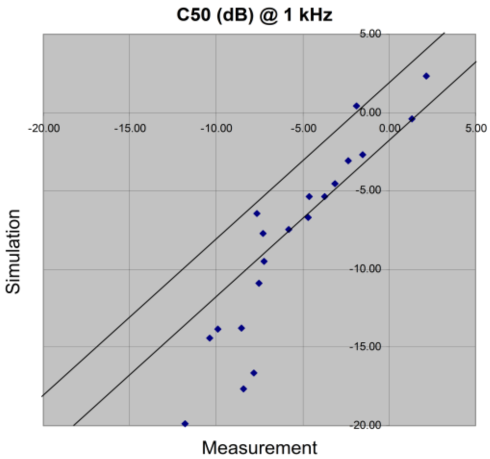


Fig. 6 – Clarity Index ($C_{50}$) calibration between simulated and measured results of the existing conditions

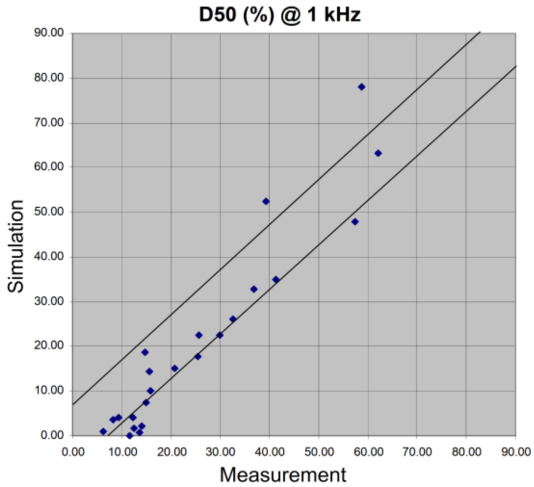


Fig. 7 – Definition ($D_{50}$) calibration between simulated and measured results of the existing conditions

The tuning process (Tronchin & Knight, 2016; Wang et al., 2004) was carried out upon the reverberation time ($T_{20}$), clarity index ($C_{50}$), and definition ($D_{50}$), as reported in Figs. 5, 6 and 7. The results simulated to be closer to the measured values should stand along the median line between the defined boundaries.

## 4. Acoustic Simulation

Two sets of simulations were carried out for the Aula Magna of Bologna, based on the functions that were attributed. The first set of simulations adapts the acoustics to auditorium functions, to be used for classical music, while the second set is more centred on speech intelligibility, since the purpose is to adapt the acoustics to suit a conference hall.

During the simulations of the auditorium, an omnidirectional sound source was placed in the location where the orchestra was intended to be located. Based on the room volume of the central nave of Santa Lucia's church being equal to 24000 m$^3$, the optimal $T_{20}$ value at 500 Hz should be around 2.8 s, as shown in Fig. 8.

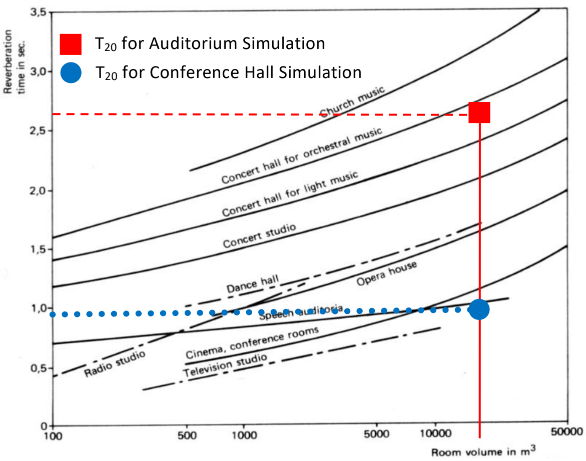


Fig. 8 – Optimal T20 values at 500 Hz, based on room volume

When the simulations have the purpose of adapting the acoustics to suit a conference hall, the sound source was introduced in Ramsete by reproducing the characteristics of the human voice, in terms of spectrum, power, and directivity (Tronchin, 2005). In addition, the existing amplified system was also reproduced with further sound sources having the features of the loudspeakers in place. On this basis, the optimal $T_{20}$ value at 500 Hz for a room of such a volume size used as a conference hall should be around 1.1 s, as indicated in Fig. 8.

In both scenarios, the adopted acoustic measures involve the reduction of reverberation and an improvement in terms of speech intelligibility (Tronchin & Bevilacqua, 2022). Specifically, the measures consist of the following solutions:

- substitution of the standard plaster with an absorbing plaster, to be applied mainly to the surface area of the vault of the central nave;
- introduction of carpet along the corridors serving the seats;
- installation of heavy drapery to close off the lateral naves during conferences.

The application of the absorbing plaster was carried out on a surface area of 853 m², while the introduction of the reflecting panels covers a surface area of 331 m². Table 1 indicates the absorption coefficients of the materials listed above.

Table 1 – Absorption coefficients of the materials used for the project design

| Material | Abs. Coeff. $\alpha$ - Octave Bands (Hz) | | | | | |
|---|---|---|---|---|---|---|
| | 125 | 250 | 500 | 1k | 2k | 4k |
| Abs. plaster | 0.23 | 0.30 | 0.59 | 0.64 | 0.67 | 0.082 |
| Carpet | 0.08 | 0.10 | 0.20 | 0.25 | 0.30 | 0.35 |
| Drapery | 0.08 | 0.29 | 0.44 | 0.50 | 0.40 | 0.35 |

## 4.1 Auditorium For Classical Music

Based on the acoustic measures being a common factor for the two scenarios, the simulation of the auditorium is focused on the insertion of reflecting panels to be installed above the area of the orchestra and above the stalls. The panels were designed to be in polycarbonate, with a transparency of 90 %, and suspended with steel wires hung to the existing beams. Fig. 9 and 10 show the configuration of the model for an auditorium.

Fig. 9 – Acoustic project design for the adaptation of Santa Lucia's church to an auditorium. Apse side

Fig. 10 – Acoustic project design for the adaptation of Santa Lucia's church to an auditorium. Entrance side

The reflecting panels were installed in such a way as to distribute the sound across the audience uniformly. The results of the conditions simulated for the auditorium scenario are shown in the acoustic maps highlighting the spatial distribution of the main parameters. Fig. 11 shows the $T_{20}$, while Fig. 12 reflects the results of $C_{80}$, simulated with and without the audience.

## 4.2 Conference Hall

The second set of simulations adapts the acoustics of the Aula Magna to a conference hall. The main difference compared with the other configuration consists of the use of heavy curtains and coconut fibres (Fabbri et al., 2021) to be kept closed during conferences to avoid disturbance from people walking in the lateral naves as well as to increase the absorbing surfaces that are useful for lowering the reverberation time (Tronchin et al., 2021a and 2021b). With the acoustic measures, the speech transmission index (STI) values are found to be more than 0.6, falling into a "good" category, as defined by the intelligibility rating according to ISO 9921 (Farina et al., 1998; Tronchin & Bevilacqua, 2021).

# 5. Results

The results are presented graphically with the plan distribution of the main acoustic parameters, by highlighting the difference between the existing conditions and the simulated environments, as indicated in Figs. 11 to 13. The simulated results shall be considered in unoccupied conditions.

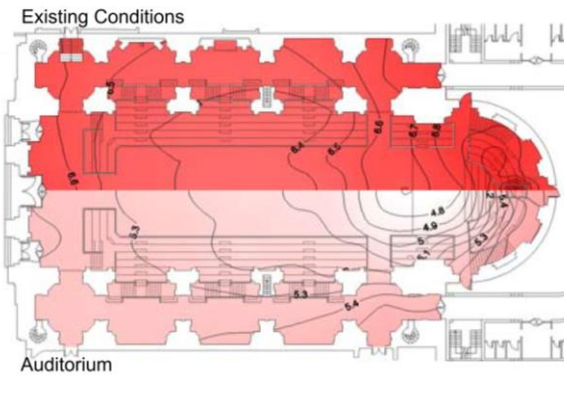


Fig. 11 – Spatial distribution of Reverberation Time ($T_{20}$)

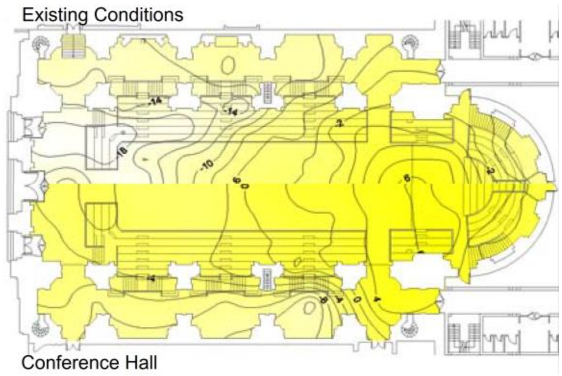


Fig. 12 – Spatial distribution of speech clarity index ($C_{50}$)

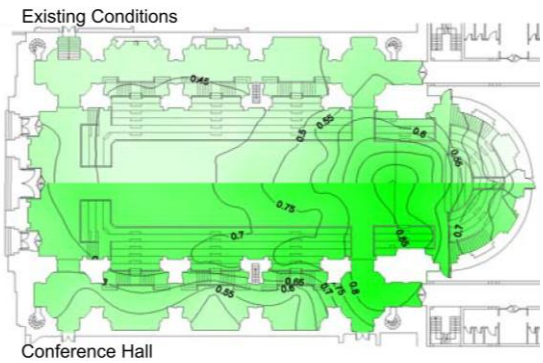


Fig. 13 – Spatial distribution of speech transmission index (STI)

Fig. 11 indicates that the $T_{20}$ values decrease significantly with the introduction of the acoustic measures, passing from 8-9 s to 4.5 s. Such values result in greater uniformity across the plan layout (Mickaitis et al., 2021; Puglisi et al., 2021).

Fig. 12 shows the spatial distribution of the $C_{50}$ values, improved to be within the optimal range as defined by the literature. The $C_{50}$ values equal to -14 dB, especially at the back of the hall, were increased to up to 0 dB in the centre of the hall, and were more uniformly distributed (ISO, 2003; Jeon et al., 2009; Ortega & Rivera, 2012; Steeneken & Houtgast, 1980).

Fig. 13 shows the STI values to be around 0.7, which indicates a good rating. It should be noted that the results with full occupancy of the hall improve the simulated conditions even more, bringing the values closer and within the optimal range limits.

## 6. Conclusion

The application of the acoustic measures for the Aula Magna at the University of Bologna outlined by the design project has revealed an important benchmark achieved with the accuracy of the digital simulations. The installation of acoustic panels floating at different heights across the plan, along with the absorbing plaster to the vault and the curtains at the openings to the lateral naves, was considered the best option for a cultural heritage site of such historical value. In addition, the criteria of transparency for the suspended panels were assessed to leave the wide view of the indoor space intact as well as to filter the natural lights from the large windows. In summary, the outcomes of the simulated values compared with the existing conditions of the room outline a considerable improvement in speech comprehension, resulting in more appropriate functions assigned to the Aula Magna.

## References

Antlej, K. 2022. “Digital Heritage Interpretation of Modernist Modular Architecture: The K67 Kiosk.“ In: Bartolomei, C., A. Ippolito, S. H. T., Vizioli (eds) *Digital Modernism Heritage Lexicon*. https://doi.org/10.1007/978-3-030-76239-1_23

Bettarello, F., P. Fausti, V. Baccan, and M. Caniato. 2010. “Impact Sound Pressure Level Performances of Basic Beam Floor Structures.” *Building Acoustics* 17(3): 305-316. https://doi.org/10.1260/1351-010X.17.4.305

Bettarello, F., M. Caniato, G. Scavuzzo, and A. Gasparella. 2021. “Indoor Acoustic Requirements for Autism-Friendly Spaces.” *Applied Science* 11: 3942. https://doi.org/10.3390/app11093942

Caniato, M., F. Bettarello, C. Schmid, P. Fausti. 2019. “The use of numerical models on service equipment noise prediction in heavyweight and lightweight timber buildings.” *Building Acoustics* 26(1): 35-55. Doi: https://doi.org/10.1177/1351010X18794523

Caniato, M., C. Schmid, and A. Gasparella. 2020a. “A comprehensive analysis of time influence on floating floors: Effects on acoustic performance and occupants’ comfort.” *Applied Acoustics* 166: 107339. doi: https://doi.org/10.1016/j.apacoust.2020.107339

Caniato, M., F. Bettarello, P. Bonfiglio, and A. Gasparella. 2020b. “Extensive Investigation of Multiphysics Approaches in Simulation of Complex Periodic Structures.” *Applied Acoustics* 166:107356. doi: https://doi.org/10.1016/j.apacoust.2020.107356

Caniato, M., F. Bettarello, and A. Gasparella. 2021. “Indoor and outdoor noise changes due to the COVID-19 lockdown and their effects on individuals’ expectations and preferences.” *Scientific Reports* 11:16533. https://doi.org/10.1038/s41598-021-96098-w

Dordevic, Z. 2016. “Intangible tangibility: Acoustical heritage in architecture”. *Structural Integrity and Life* 16(1): 59–66.

Fabbri, K, L. Tronchin, and V. Tarabusi. 2014. “Energy Retrofit and Economic Evaluation Priorities Applied at an Italian Case Study.” *Energy Procedia* 45: 379-384. https://doi.org/10.1016/j.egypro.2014.01.041

Fabbri, K., L. Tronchin, and F. Barbieri. 2021. “Coconut fibre insulators: The hygrothermal behaviour in the case of green roofs.” *Construction and Building Materials* 266:1-9. https://doi.org/10.1016/j.conbuildmat.2020.12102

Farina, A., A. Langhoff, and L. Tronchin. 1998. “Acoustic characterisation of "virtual" musical instruments: using MLS technique on ancient violins.” *Journal Of New Music Research* 27(4): 359-379. doi: https://doi.org/10.1080/09298219808570753

ISO. 2003. ISO 9921:2003. *Ergonomics - Assessment of speech communication*.

Jeon, J. Y., J. K. Ryu, Y. H. Kim, and S. Sato. 2009. “Influence of absorption properties of materials on the accuracy of simulated acoustical measures in 1:10 scale model test.” *Applied Acoustics* 70(4): 615–25. https://doi.org/10.1016/j.apacoust.2008.06.009

Manfren, M., B. Nastasi, E. A. Piana, and L. Tronchin. 2019. “On the link between energy performance of building and thermal comfort: An example.” *AIP Conference Proceedings* 2123:1-9. doi: https://doi.org/10.1063/1.5116993

Manfren, M., B. Nastasi, L. Tronchin, D. Groppi, D. A. Garcia. 2021a. "Techno-economic analysis and energy modelling as a key enablers for smart energy services and technologies in buildings." *Renewable and Sustainable Energy Reviews* 150:1-14. https://doi.org/10.1016/j.rser.2021.111490

Manfren, M., M. Sibilla, and L. Tronchin. 2021b. "Energy Modelling and Analytics in the Built Environment—A Review of Their Role for Energy Transitions in the Construction Sector." *Energies* 14:1-29. https://doi.org/10.3390/en14030679

Manfren, M., P. A. B. James, and L. Tronchin. 2022. "Data-driven building energy modelling – An analysis of the potential for generalisation through interpretable machine learning." *Renewable and Sustainable Energy Reviews* 167:1-13. https://doi.org/10.1016/j.rser.2022.112686

Mickaitis, M., A. Jagniatinskis, and B. Fiks. 2021. "Case study of acoustic comfort in conference room". *Proc. 27th International Congress of Sound & Vibration*.

Ortega, G. V., and J. I. S. Rivera. 2012. "Acoustic study of Madrid auditorio nacional de musica: comparison between simulation and measurements." *41st International Congress and Exposition on Noise Control Engineering* (INTER-NOISE 2012).

Puglisi, G. E., A. Warzybok, A. Astolfi, and B. Kollmeier. 2021. "Effect of competitive acoustic environments on speech intelligibility". *Journal of Physics* 2069(1): 175180. https://doi.org/10.1088/1742-6596/2069/1/012162

Steeneken, H. J. M., and T. Houtgast. 1980. "A physical method for measuring speech-transmission quality." *Journal of Acoustic Society of America*, 67(1): 318-326.

Tronchin, L. 2005. "Modal analysis and intensity of acoustic radiation of the kettledrum." *The Journal Of The Acoustical Society Of America* 117(2): 926-933. https://doi.org/10.1121/1.1828552

Tronchin, L, and D. J. Knight. 2016. "Revisiting Historic Buildings through the Senses. Visualising Aural and Obscured Aspects of San Vitale, Ravenna." *International Journal of Historical Archaeology* 20: 127-145. https://doi.org/10.1007/s10761-015-0325-2

Tronchin, L., and A. Bevilacqua. 2021. "Acoustic study of different sceneries at the São Carlos national theatre of Lisbon." *Applied Acoustics* 180:1-11. https://doi.org/10.1016/j.apacoust.2021.108102

Tronchin, L., F. Merli, and M. Manfren. 2021a. "On the acoustics of the Teatro 1763 in Bologna." *Applied Acoustics* 172: 1-9. https://doi.org/10.1016/j.apacoust.2020.107598

Tronchin, L., F. Merli, and M. Dolci. 2021b. "Virtual acoustic reconstruction of the Miners' Theatre in Idrija (Slovenia)." *Applied Acoustics* 172: 1-9. https://doi.org/10.1016/j.apacoust.2020.107595

Tronchin, L., and A. Bevilacqua. 2022. "Historically informed digital reconstruction of the Roman theatre of Verona. Unveiling the acoustics of the original shape." *Applied Acoustics* 185: 1-18. https://doi.org/10.1016/j.apacoust.2021.108409

Vecco, M. 2010. "A definition of Cultural Heritage: From the tangible to the intangible". *Journal of Cultural Heritage* 11: 321–324. https://doi.org/10.1016/j.culher.2010.01.006

Vorländer, M. 2007. "Fundamentals of Acoustics, Modelling, Simulation. Algorithms and Acoustic Virtual Reality".

Wang, L. M., J. Rathsam, and S. R. Ryherd. 2004. "Interactions of model detail level and scattering coefficients in room acoustic computer simulation". *Proceeding International Symposium on Room Acoustics*.

Wittkower, R., I. B. Jaffe, and M. Parizzi. 1992. "Architettura e arte dei Gesuiti". Electa.