

Churches acoustics as intangible **cultural heritage: experimental and numerical characterization of the Temple of San Biagio**

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The acoustic properties of churches are, to date, as much a cultural asset as their architectural features. The study, understanding and conservation of acoustic phenomena that characterize liturgical spaces, to date, make use of new technologies and methodologies that facilitate their practice.

The study presented here analyzes the acoustic phenomena that characterize the Temple of San Biagio (Montepulciano, Tuscany, Italy). It makes use of experimental acoustic surveying and the aid of the laser scanning surveying technique for the creation of the geometry, subsequently adopted for numerical acoustic modeling of the church in Odeon Acoustics software, used for the study of its acoustic characteristics.

The selected methodology allowed us to delve into dynamics often encountered in acoustic simulations, such as the calibration of numerical models and the influence of the mesh number of the generated geometric models, and to understand the acoustic characteristics of the church.

The aid of geometrical acoustics also allowed us to delve into the relationships between architectural features and the acoustic characteristics of the space, specifically through the use of Odeon's Grid feature.

Keywords: acoustics; church acoustics; cultural heritage; intangible cultural heritage;

1. Introduction

Since 2003, when UNESCO's Convention for the Safeguarding of the Intangible Cultural Heritage (ICH) became a reality, historically relevant churches' acoustic characteristics have seen a substantial increase in the number of studies (Girón, Álvarez-Morales, and Zamarreño 2017; **Brezina 2013**). This critical step in recognizing those cultural heritage qualities had lightened up a research branch, influencing its growth, powered by the need to understand the acoustic phenomena directly connected to the relative architectural spaces and features.

Although the assessment in churches' acoustic characteristics as been rising in the past years, the amount of literature is not comparable to that of architectural acoustics. Correlations between acoustic characteristics and churches typologies have been investigated and specific indexes for chuches acoustics have been introduced; however,

the research could be implemented. (Navarro, Sendra, and Muñoz 2009; Berardi 2012; Kosala and Engel 2013; Álvarez-Morales et al. 2016).

The field's importance has been shown, especially throughout Europe, by the foundation of projects as CHARISMA and CAMERA (Fausti, Pompoli, e Prodi 2003).

The topic that carried most of the studies has been Archaeoacoustics: an interdisciplinary subfield of archaeology centered on exploring the acoustic properties of Cultural Heritage Buildings and studying ancient sites where the natural acoustical phenomenon occurs (Primeau, s.d.).

Looking at the state of the art through S.Girón et al. "Church acoustics: A state-of-the-art review after several decades of research" (Girón, Álvarez-Morales, and Zamarreño 2017) it is possible to grasp the evolution in the various techniques used to fulfill the objectives and overcome the encountered problems in this complex field. Though the study of CH is strictly connected with architectural acoustics, it is safe to say that these kinds of buildings show different peculiarities.

CH buildings often carry a geometry complexity not always found in traditional buildings. The same complexity is encountered in the interaction between sound and the architectural organism, requiring more sophisticated tools and experimental procedures to analyze the related phenomenon, such as Acoustic Simulation (Alvarez-Morales and Martellotta 2015). Not only that, the acoustic properties of churches' materials and object such as pews or art pieces we find inside are way harder to define and not yet standardized as contemporary materials we often encounter in modern days architectural acoustics (Girón, Álvarez-Morales, and Zamarreño 2017).

The state-of-the-art techniques share a methodology strictness that revolves around acoustic standards, well established in the architectural field, such as UNI EN ISO 3382, both in measurement and data evaluation. Also, scientific literature on CH acoustics underlines that even though the nature of the subject proves a standardized methodology hard to redact, numerous studies and research have reached results helpful in building a streamlined CH acoustical analysis process (Ettore Cirillo and Martellotta 2003; Martellotta et al. 2009).

This work aims to describe a methodology for the acoustic analysis of CH, and model a valuable tool for the representation, analysis, and preservation of buildings' intangible cultural heritage. The selected case study is San Biagio's Temple, a late renaissance centric plan church that presents the proper complexity to test the methodology.

The contents of the following paper are organized into eight paragraphs. The case study is first identified, describing its architectural and historical characteristics, and then its methodology is presented. Following these, the techniques used for the geometrical and

acoustical survey, and the numerical modeling of the church are reported. The paper, the data obtained from the study and the achieved results are analyzed and discussed.

2. Case study

The San Biagio's Temple (**Fig.1**), one of the most important works of Antonio Cordini (known as Antonio Da Sangallo - the elder), is in Montepulciano, a town in Siena's province that played a significant role in Tuscany's architecture Renaissance (Benci 1641). This settlement lies in the Chiana's valley, a fertile stretch of land situated between Rome and Florence (Del Corto 1898), a theater of many battles and a place full of history where Montepulciano stood as a strategic point, obtaining immense value for both Florence and Siena (Barcucci 2000). The Temple stands on an ancient parish church, the same described by the documents concerning the first developments of Montepulciano. Its central plan, in the form of a Greek cross, with its omnidirectionality, varied only by the bell towers appropriately detached from the body of the building, responds to the context, making the Temple, together with its architectural quality, an icon of the late Renaissance (Giorgi and Pasanisi 1999).

The historical research underlines the particular attention paid to the materials used for the church realization.

As shown by the community resolutions, the first stone was laid on April 28, 1518. The church was almost finished in 1545 when the majolica cladding of the dome was completed.

The church is flanked by a rectory not foreseen in the initial project and erroneously attributed to the architect.

The centric church was a crucial and common theme in the construction of Marian temples at that time. The choice of this solution was, in this specific case, only emblematic.



Figure 1, San Biagio's Temple

The reduced liturgical needs and the position of the land on which the church was built were an integral part of the choice of such design typology, which was most likely addressed by Sangallo earlier in his studies. It is assumed that the project was prior to the decision itself to erect the Temple, also given the time elapsed between the miracle and the approval of the design and that a wooden model was created, which remained for the whole realization of the work and used as a reference. These hypotheses are based on the preliminary drawings and architect's studies, now kept in the Cabinet of Drawings and Prints of the Uffizi.

The proportions of the plant are approximately 5:4, and the design is built on the fundamental figures of the circle and the square (Fig. 2). The geometry that generates the plant has an average diameter of 13.01 meters (22.27 times the Florentine arm). The side arms of the church, on the other hand, are built based on the circle circumscribed to the square erected on the extension of the sidewalls of the arms, excluding the thickness of the pilasters.

This ratio determines the depth of the arms of the church, which is 9.25 meters on average (15.84 times the Florentine arm).

In terms of total dimension, the internal volume of the church is 14207 m³.

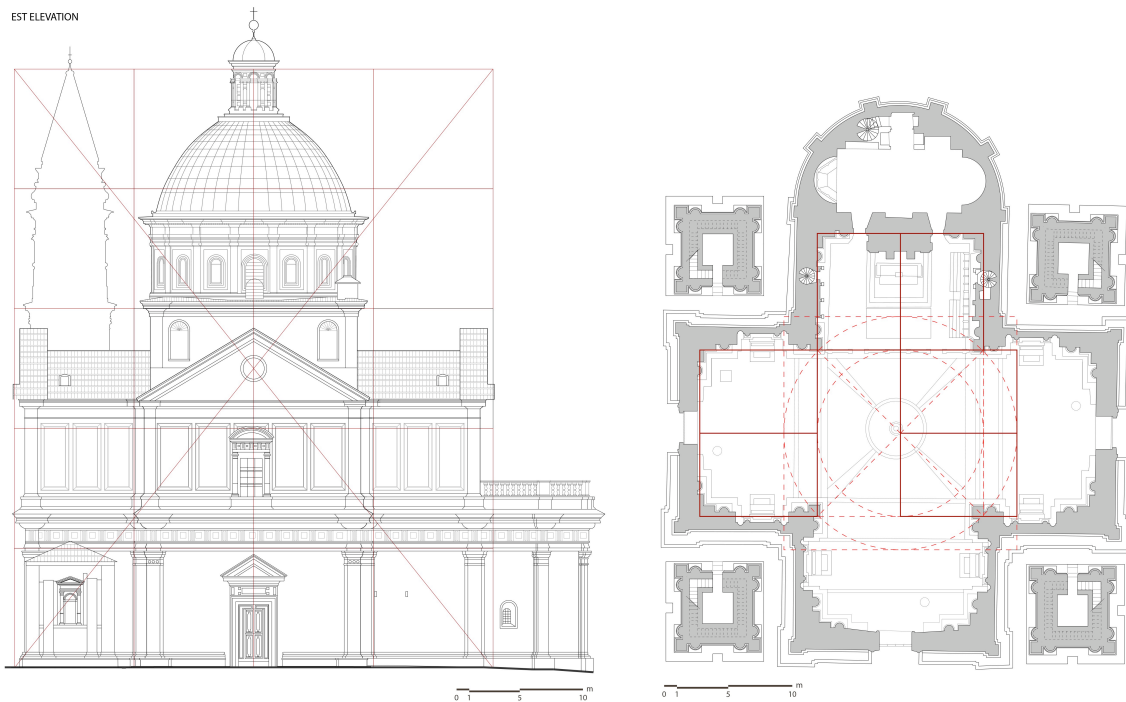


Figure 2, left: east façade's proportions; right: plan's proportions.

3. Methodology

The proposed methodology integrates the acoustic data collected during the experimental campaign with the geometric data obtained by the elaboration of the Terrestrial Laser Scanning survey's data into a multidisciplinary approach. In this regard, geometric and acoustic surveys of the church have been therefore planned and carried out.

The first step is the photographic survey, subsequently followed by the geometrical and experimental acoustic ones, collecting the geometric information by adopting the Terrestrial Laser Scanner technique (Wu et al. 2021) with the [Leica BLK360](#) instrument, and the output data were managed through the software [Leica Cyclone REGISTER](#), [Autodesk RECAP](#), and [Leica JetStream](#). The geometric data were converted into a high-resolution model for numerical modeling. This methodology is increasingly adopted in cultural heritage analyses (Hassan and Fritsch 2019). However, the transition from the point cloud to the geometric model is not a standardized process (Canciani et al. 2013) and varies significantly.

Subsequently, experimental acoustic measurements with the impulse response method were performed. The experimental facilities are described in the fifth paragraph of this paper.

The complex nature of the analyzed CH requires additional attention and methodological needs concerning the guidelines of UNI EN ISO 3382 (ISO 2009). Martellotta et al. (2009) proposed a set of guidelines to standardize the acoustic measurement of churches, both in the choice of the location of receivers and sound sources and in the selection of

an appropriate combination of hardware. In the present work, the UNI EN ISO 3382 and Martellotta guidelines are taken into account and adapted to achieve high-quality results. These steps and the obtained results were subsequently reprocessed to perform numerical modeling. Over the years, as research has continued to develop, various tools have been used for numerical modeling and analysis of results. The more significant part of the software for the acoustic simulation shares the typology of the algorithm with the base of the calculation, that is, the raytracing. The software commonly adopted are CATT-Acoustics (Dalenbäck 1996), Ramsete (Buratti, Mariani, and Costarelli n.d.) and Odeon Acoustics (Witze et al. 2002); the last one is the chosen in this research.

A three-dimensional model is realized from the point cloud. Then, the numerical model is calibrated using the results obtained from the experimental measurement employing multiple genetic algorithms. This procedure, as previously cited, consists in calibrating the absorption coefficients of the materials by alternating them with a multiple genetic algorithm in order to match the measured results.

Once the calibration is performed, the numerical results are compared with the experimental outputs on the JND (Just Noticeable Differences) reference basis (Martellotta 2010) as suggested by the UNI EN ISO 3382. Besides, to further prove the effectiveness of the methodology and the weaknesses and strengths of the raytracing computation, two numerical models having a mesh model with, respectively, low and high definition are generated and compared.

4. The geometrical survey

First and foremost, a photographic survey was carried out to gather data about the building. This first step is fundamental to planning the additional experimental campaigns: the geometrical and the acoustical ones.

The geometrical survey is carried out in two different steps. During the first part of the work, the targets are applied and scans of the interior and the connection with the outside were collected. For the interior of the church, its two main axes are followed, and, in the nave of the main altar, shots are taken to connect with the sacristy located in the apse. On the other hand, the doors located on the east and north façade are chosen using targets placed on supports positioned outside the dome.

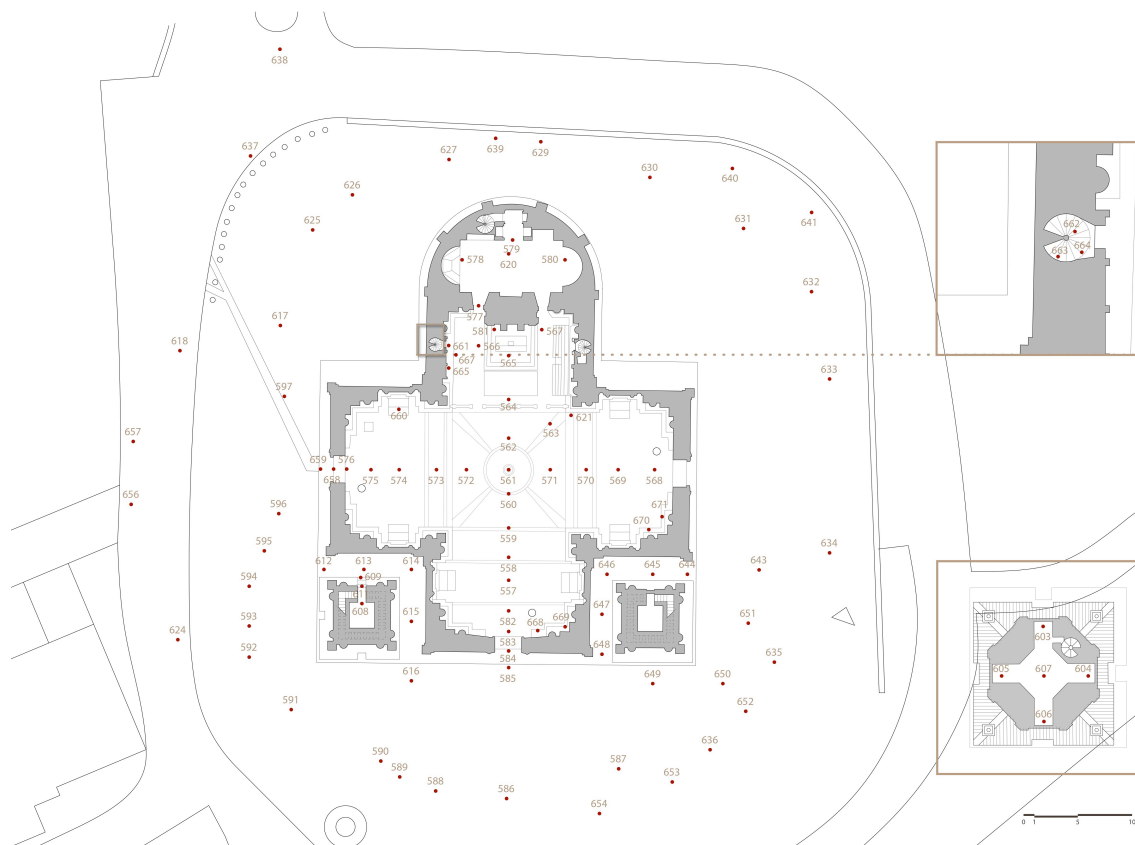


Figure 3, Laser scanning station positions

In the measurements of the inner spaces, the major problem to be solved is related to the symmetry of the Temple, which could negatively affect the registration phase of the scans. To overcome this matter, a proper quantity of targets was positioned following a pattern that avoids the similarities created by the symmetry. Subsequently, the exterior survey is carried out, starting from the north façade and continuing clockwise along with the church. In the second step, the main objective was to enrich the relief (as well as eliminate any shaded areas). At first, further exterior surveys were carried out, with particular attention to the bell towers and the rectory.

Then, scans of the choir and side altars were carried out, and once the acquisition campaign was completed, the point clouds were recorded. Additional stations were manually placed with the dedicated [Leica Cyclone REGISTER](#) software to create links and calibrate the survey error.

5. The acoustical survey

During the survey planning, thirty receivers and two source positions had been selected to better describe the acoustic distribution in the church's space. The first is placed in front of the altar and the second in the west aisle of the church where the musicians are usually placed during performances, for a total of sixty source-receiver combinations. The receivers have been positioned taking into account the ISO 3382, which suggests

their placement at the height of 1.2 meters above the floor and one-fourth of a wavelength distance (about 1 meter) from any reflective surface.

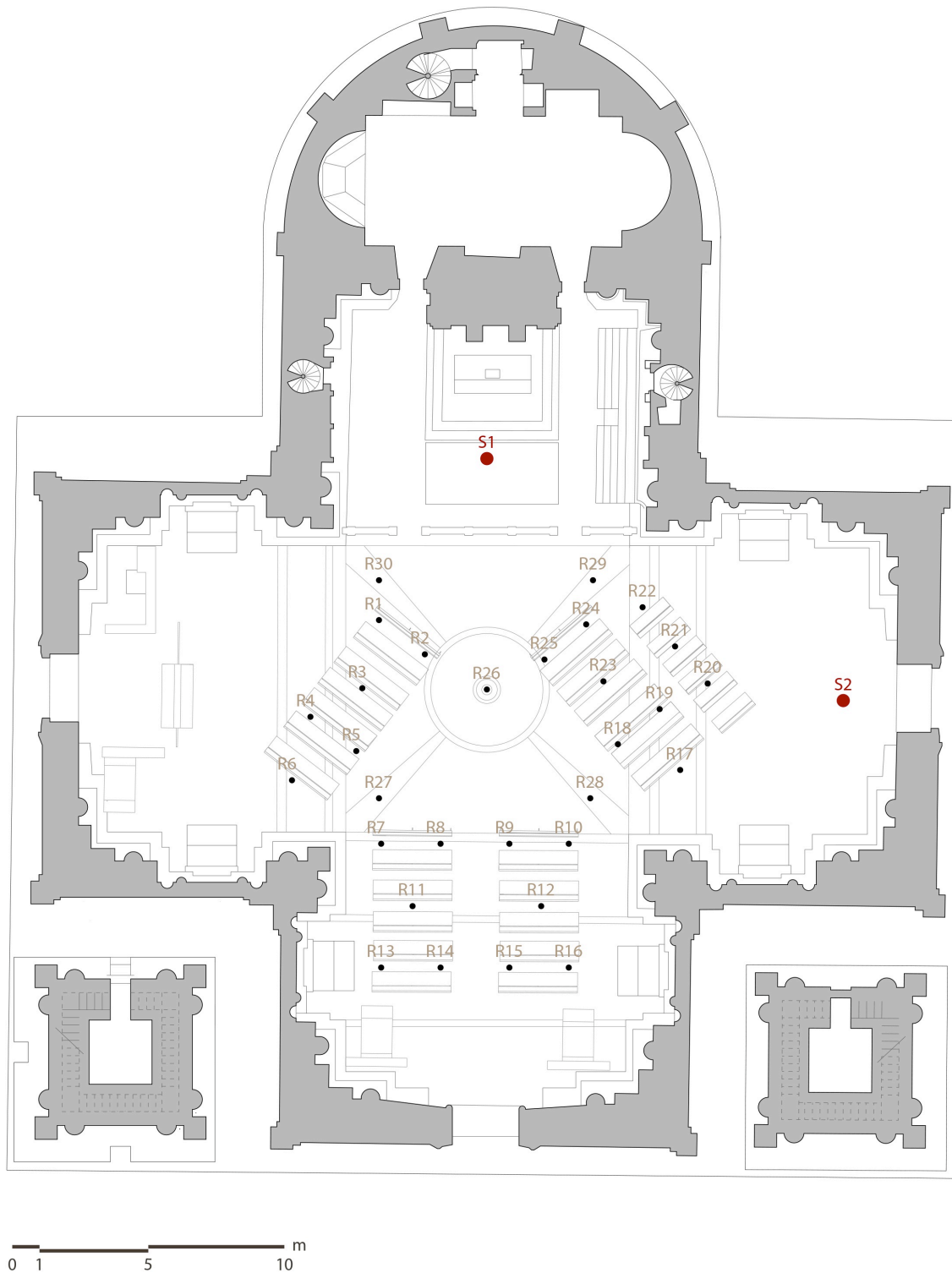


Figure 4, Acoustic measurement positions (S for Stations, R for Receivers);

Twenty-five receivers were placed taking into account the position of the church users along the pews (Fig.4). The remaining five were located for taking into account the geometry of the church and, in particular, its dome.

S1

S2

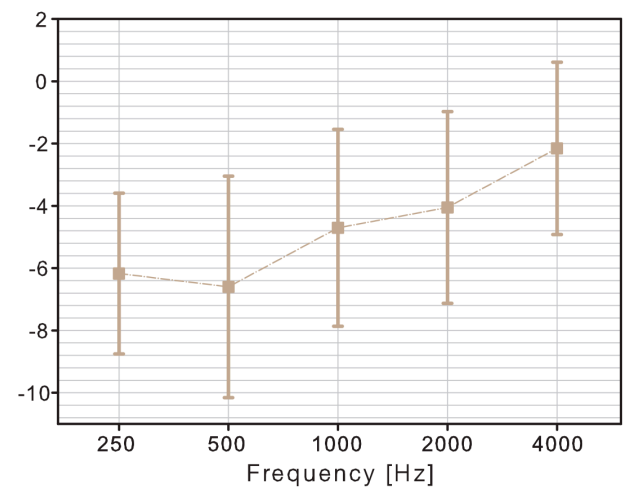
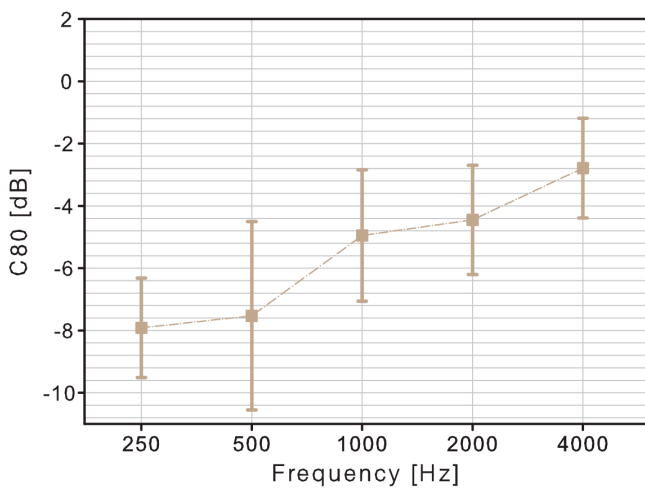
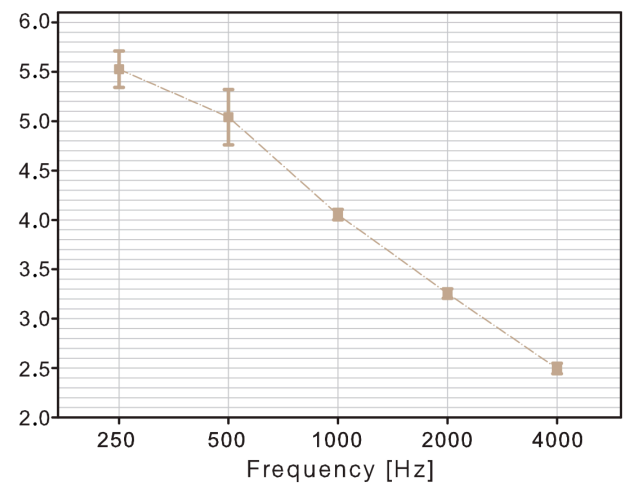
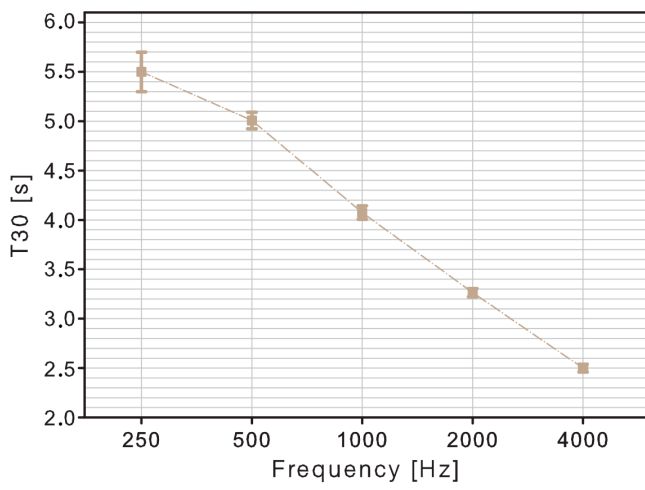
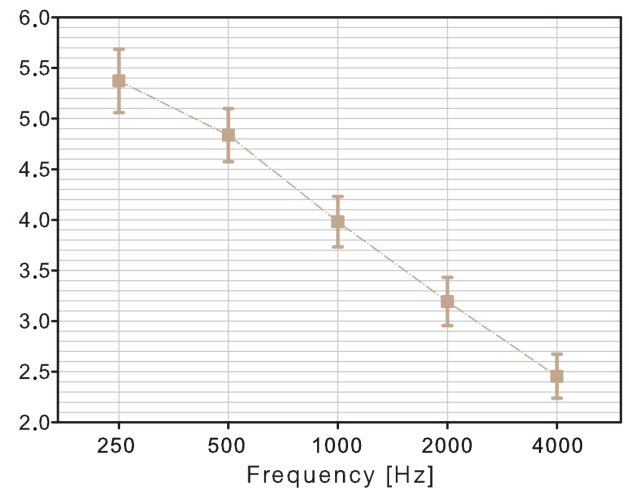
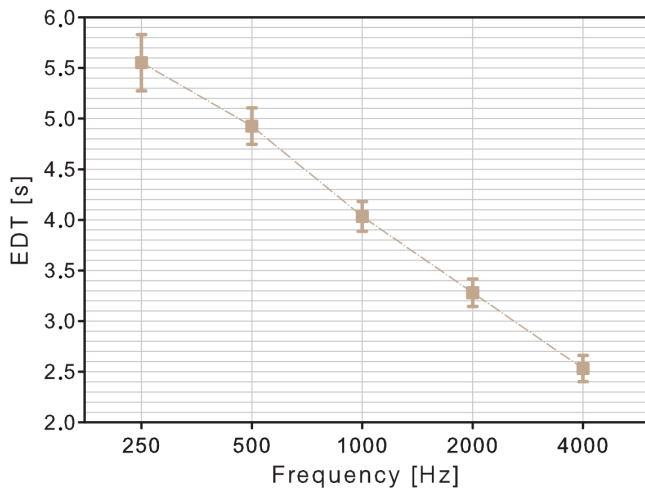


Figure 5 measured EDT, T30, and C80 average values for S1 and S2

Despite the symmetrical plan of the church, an asymmetrical distribution of the receivers was selected to better reveal unexpected anomalies in the spatial sound distribution.

The survey was carried out by adopting an impulse response technique that reproduces a sine sweep through an omnidirectional dodecahedral source (BKS type 4292-1) and an amplifier (BKS type 2716-c) and records the results throughout a sound level meter (BKS 2250). For the impulse response acquisition and to calculate acoustic parameters the Dirac Room Acoustic software was used, combined with the soundcard Edirol Fa-101.

During the survey, temperature and relative humidity, which are valuable data for the numerical modelling, were measured using a multi-functional instrument (Lutron LM-8000A). **The values obtained were a temperature of 32°C and 38% of relative humidity.**

The values were subsequently collected and processed to obtain the parameters EDT, T30, C80, and D50.

These indexes represent respectively:

EDT (Early Decay Time) is an acoustic parameter connected to the reverberation phenomena and it is descriptive of the early reflections. It is defined as the time needed for the sound level to decrease by the first 10 dB.

T30 (Reverberation Time) is an acoustic parameter that defines the reverberation phenomena in its entirety. This parameter is an interpolation of T60 (1), which is defined as the time necessary for the sound level in the room to decrease by 60 dB after the sound source ceases to emit sound.

$$Eq. (1) T_{60} = 0.16 \cdot \frac{V}{A_s}$$

V= Volume

A_s= Total absorption

C80 (Clarity) is an acoustic parameter used mostly to define the music clarity of the space. It is defined as the ratio between the sound energy in the first 80 milliseconds and the sound energy after 80 milliseconds (2).

$$Eq. (2) C_{80} = 10 \log \frac{\int_0^{80} p^2(t) dt}{\int_{80}^{\infty} p^2(t) dt}$$

p= Sound pressure

t= Time

D50 (Definition) is an acoustic parameter often adopted to define the speech intelligibility and definition of the space. It is calculated as the ratio between the sound energy received in the first 50 milliseconds and the total sound energy received (3).

$$Eq. (3) D_{50} = \frac{\int_0^{0.050s} p^2(t)dt}{\int_0^{\infty} p^2(t)dt}$$

The values presented below indicate the average of all receiver-source pairs for the experimental measurements for both source number one and source number two.

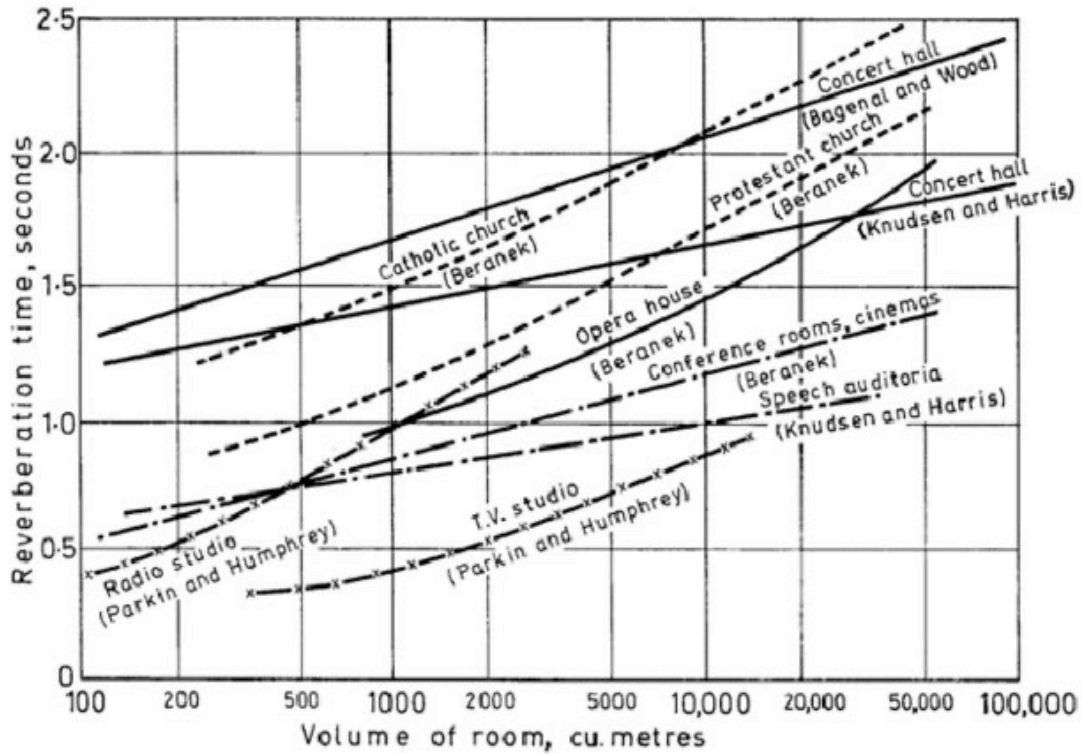


Figure 6, Reverberation time on Volume from various sources (Harris 1979)

Paying attention to the data regarding EDT and T30, it is possible to see that the values are very similar to each other, both in the case of source one and source two (Fig.5). This highlights how the dimensions of the church and its geometrical characteristics, both in plan and in elevation, make the first reflections almost indistinguishable from the entire reverberation tail. It's also possible to see that, with a total volume of 14207 m³, the reverberation time is higher than the suggested values (Fig.6) both from Beranek's and Bagenal and Wood's values (Harris 1979).

A further possible observation of the obtained data concerns the value of the index C80. From the octave band relative to 500 Hz onwards, the clarity is very similar both for the measurements of source one and for those of source two. This indicates that the symmetry of the church can also be found in its acoustic qualities, meaning that the position of musical reproduction within the church could be changed without finding a significant variation in the clarity of the performance.

6. Numerical Analysis

In the present research, Odeon Room Acoustics 14 was used for performing numerical analyses. The selection of this software was mainly related to the presence of a genetic algorithm in it that allows the calibration of the acoustic absorption coefficients of materials. Based on the geometric surveys, a detailed 3D model was created, and, in it, the surfaces were grouped according to their materials. Once the mesh surface model was prepared, it was imported into Odeon Room Acoustics with the ".3ds" file extension. Sources and receivers were subsequently introduced in the same number and position adopted during the experimental survey. As for the absorption coefficients, we initially referred to materials such as those included in other commercial software databases - like Ramsete - which have been selected considering the historical analysis conducted on them. These values were then calibrated (Table 2) regarding the outputs of T60, EDT, and C80 of the experimental measurements (Fig. 7).

At the end of the calibration, a job list was created to calculate the indices for each source-receiver pair and a Grid type calculation. In order to verify the reliability of the numerical model, the experimental measurements and the numerical simulations were compared in accordance with the limens specified in ISO3382 (Ref. Table 1).

ISO 3382 Parameter	Symbol	Subjective Limen
Early Decay Time	EDT [s]	5%
Reverberation Time 20	T_{20} [s]	5%
Reverberation Time 30	T_{30} [s]	5%
Clarity	C_{50} [dB]	1 dB
Clarity	C_{80} [dB]	1 dB
Definition	D_{50}	0.05
Gravity Time	T_s [s]	10 ms
Sound Strength	G [dB]	1 dB

Table 1, ISO3382 JND subjective limen values table

Material	Absorption coefficient							
	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
Carrara's Marble	0.01	0.01	0.01	0.02	0.03	0.03	0.04	0.05
Wood	0.11	0.11	0.12	0.12	0.12	0.1	0.1	0.1
Travertine	0.05	0.05	0.05	0.05	0.05	0.05	0.03	0.03
North facing door	0.11	0.11	0.12	0.12	0.12	0.1	0.1	0.1
East facing door	1	1	1	1	1	1	1	1
Plaster	0.02	0.03	0.04	0.04	0.06	0.07	0.07	0.09
Pavement	0.018	0.021	0.025	0.028	0.03	0.03	0.036	0.045
Statues	0.01	0.01	0.01	0.02	0.03	0.03	0.04	0.05
Glass	0.42	0.35	0.25	0.18	0.12	0.07	0.04	0.03
Organ	0.24	0.13	0.07	0.03	0.02	0.01	0	0
plasterboard	0.28	0.28	0.22	0.17	0.09	0.1	0.11	0.11

Table 2, Calibrated material's absorption coefficient's list

It is verified that the difference between the value of the simulated and the measured indexes did not exceed the "Just-noticeable differences" limen.

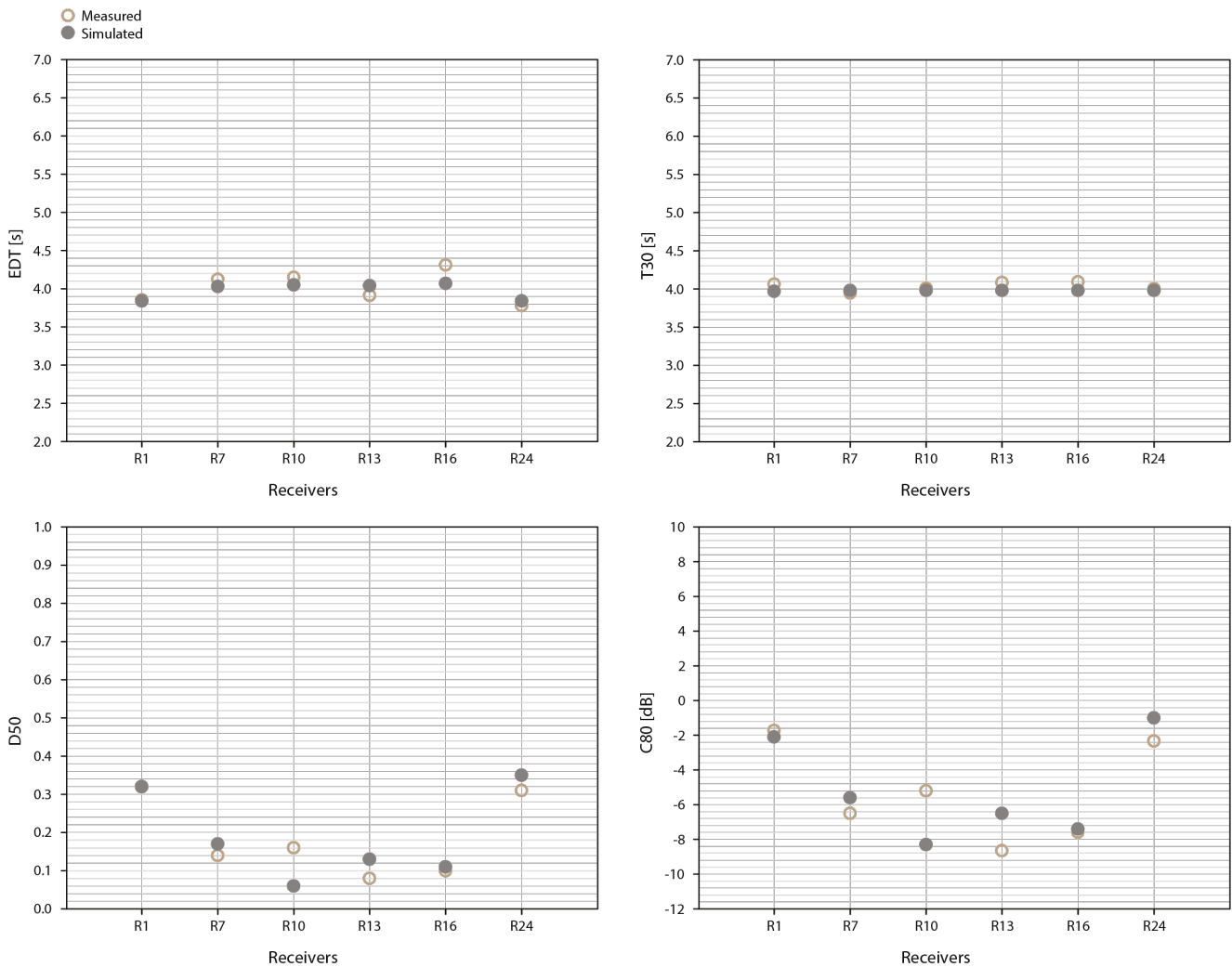
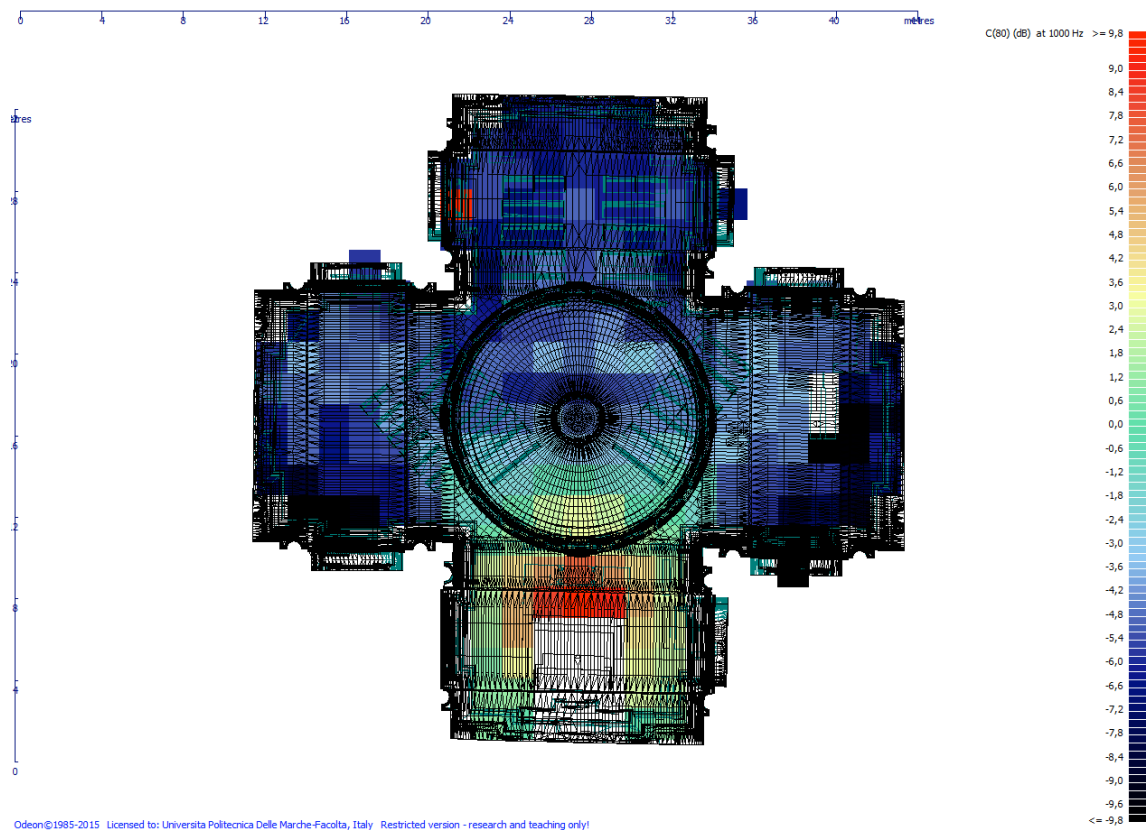


Figure 7, S1 measured vs. simulated results

Figure 7 reports 6 measurement points out of the twenty-five analyzed in order to compare the reliability of the calibrated numerical values with respect to experimental ones; the showed points represent more significant position inside the church.

The comparisons underline the reliability of the obtained values. More significant discrepancies can be noticed in the low frequencies. These discrepancies can be explained by the use of Raytracing. In fact, the lower range of frequencies can hardly be simulated by the adopted numerical model (Siltanen, Lokki, and Savioja 2010; Funkhouser et al. 2002).

Among the discrepancies, it can also be noted that in the C80 and D50 indexes, there is just over 1 JND of difference, which should not influence the general results.



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Figure 8, S1 C80 grid results at 1000Hz

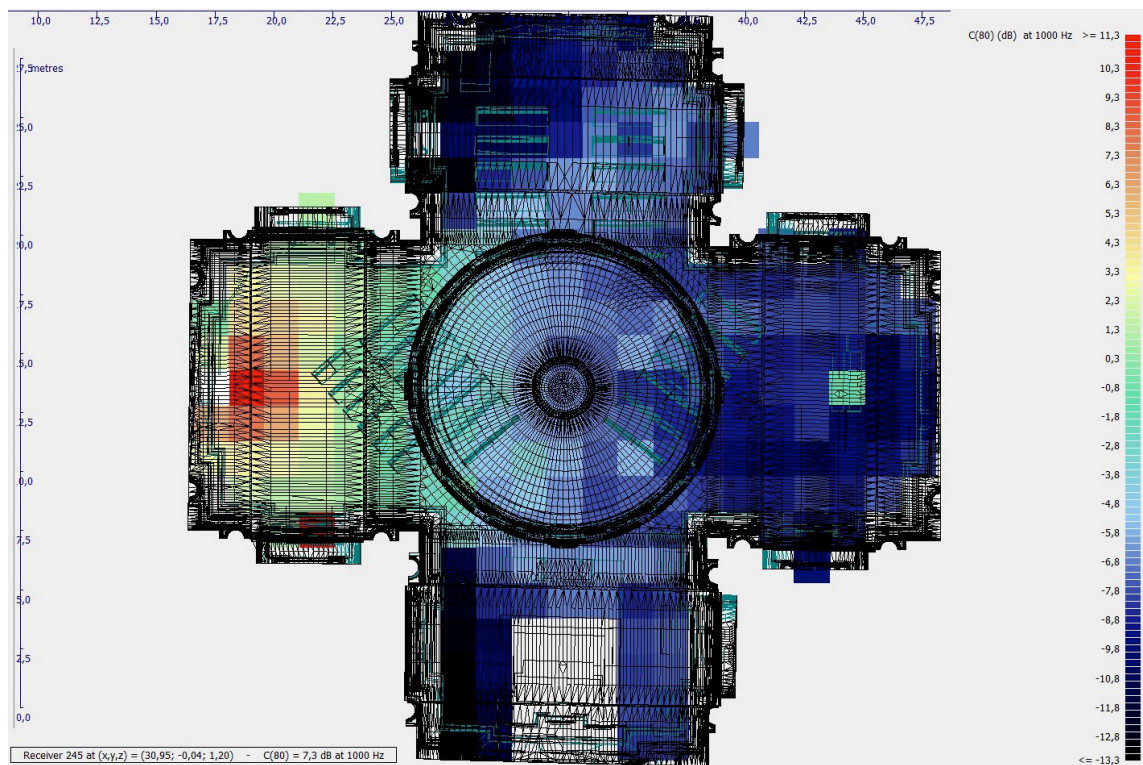


Figure 9, S2 C80 grid results at 1000Hz

Regarding the outputs of grid calculations, we can see that the data obtained from the experimental measurements are confirmed. In fact, it is possible to notice the presence of shadow zones in the estimation of the C80 index and how these change with the geometry variation (Fig.8, 9). This type of calculation allows us to deepen the results obtained

during the experimental campaign and analyze the values concerning the geometry of the case study.

It also confirms what has already been reported about the indices EDT and T30, their similarity, and the reflections' spatial distribution (Fig. 10, 11, 12, 13).

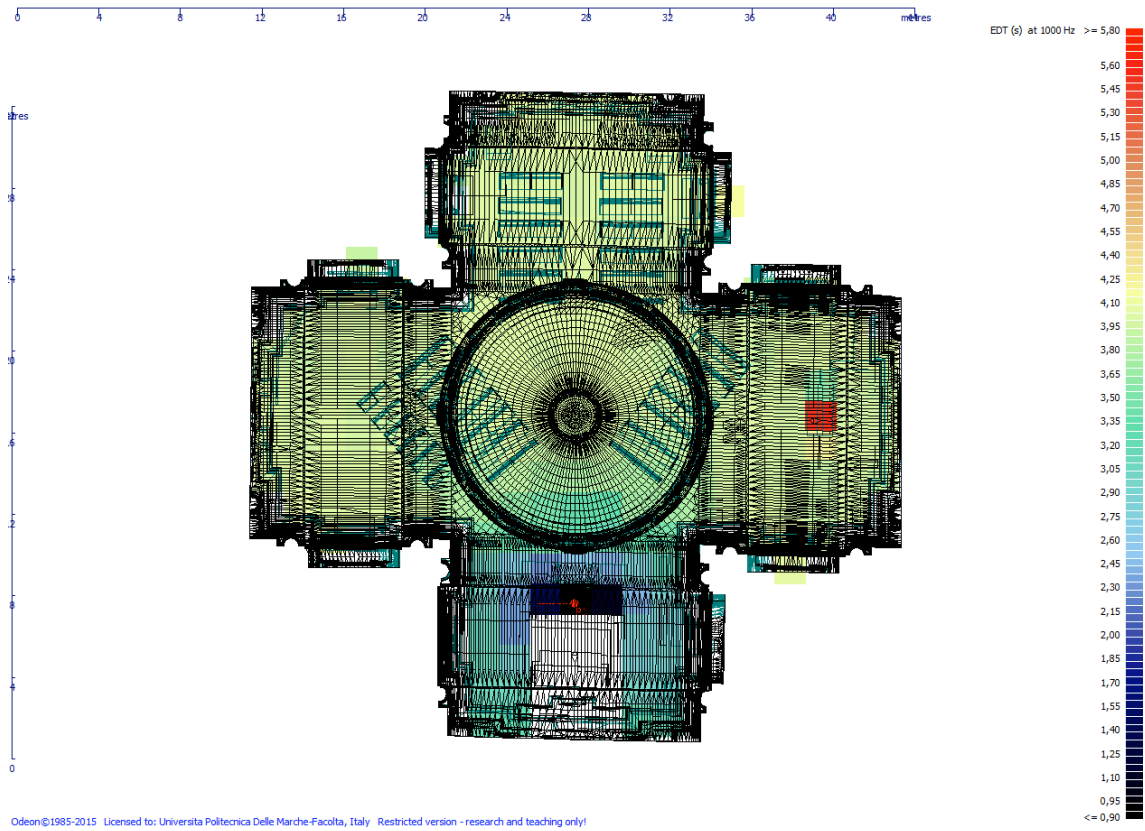


Figure 10, EDT grid results at 1000Hz for S1

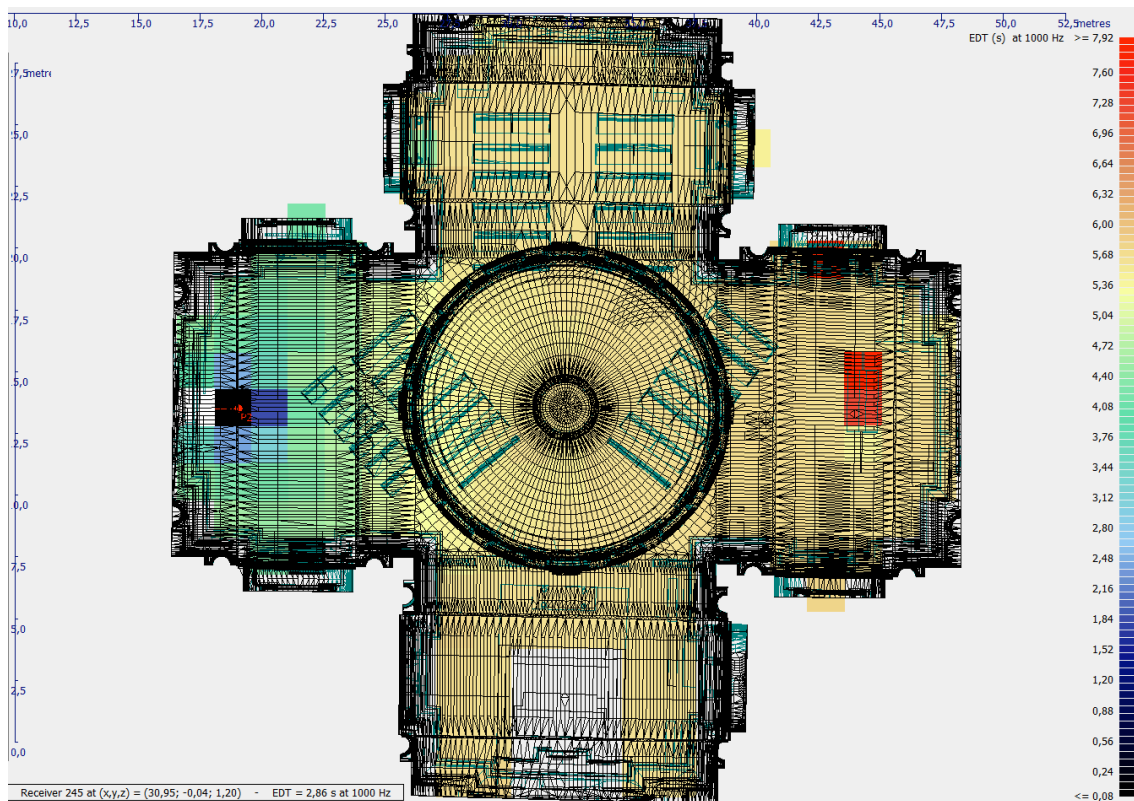


Figure 11, EDT grid results at 1000Hz for S2

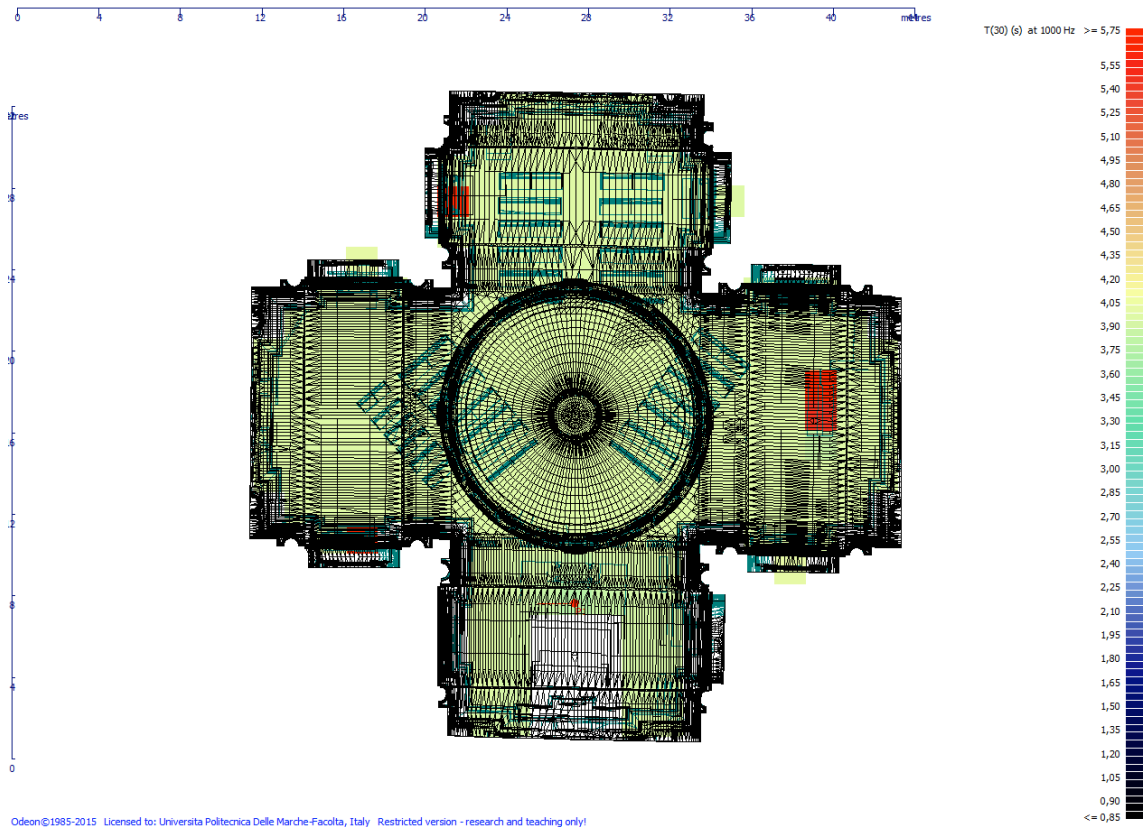


Figure 12, T30 grid results at 1000Hz for S1

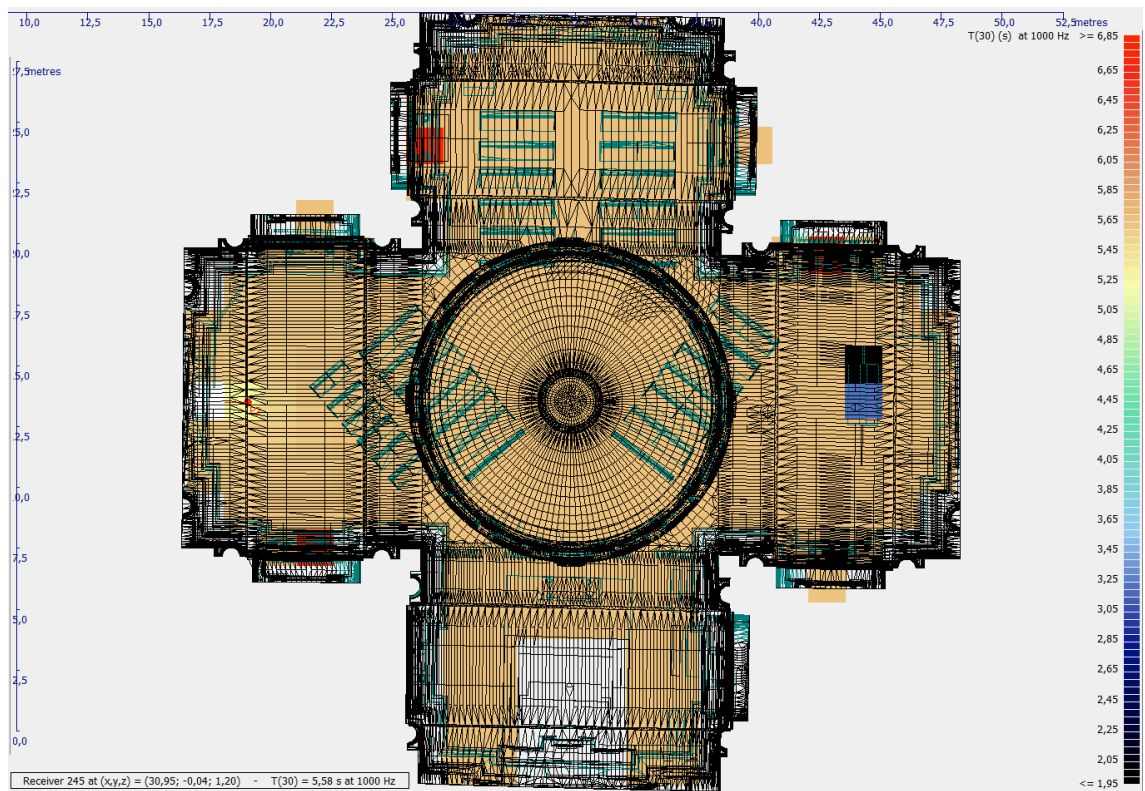


Figure 13, T30 grid results at 1000Hz for S2

6.1. The influence of the mesh definition in the raytracing calculation

In the case of the Temple of San Biagio, the differences between the choice of a realistic model and a scattering-calibrated one are analyzed to quantify the variation of the estimations according to the selected geometry.

To this end, two models (Fig.14) were analyzed in the same modes, setting a single material and a unique acoustic scattering coefficient and using the same options for the simulations. The choice of adopting only one material and scattering coefficient is made for reducing the number of variables that could affect the results. Thus, the geometric aspects become the unique parameters capable of affecting the estimations.

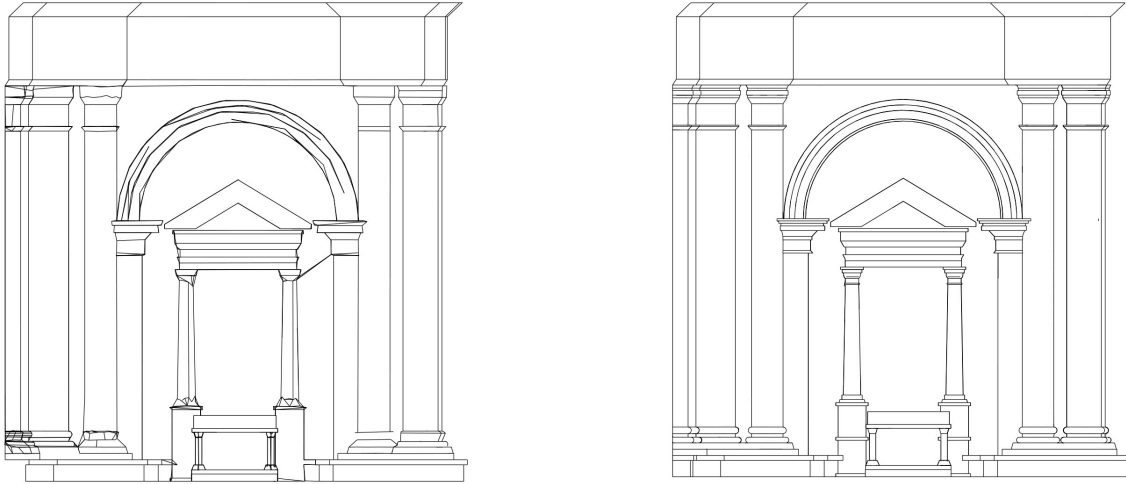


Figure 14, Left: low-resolution model; Right: high-resolution model

The first model to be generated presents a simplification in the number of the adopted meshes, reduced to 66254 meshes, whereas the second configuration is chosen to maintain a high and reasonable complexity degree, discretizing the model into 230005 meshes. According to the obtained results (Fig.15), a few discrepancies can be noticed only in the indices C80 and D50 and, even if present, they can be considered negligible. The same observation can be made by looking at the GRID calculation results, where the difference between the two models is furthermore negligible.

If we consider the difference in the computational time between the two variants, the best option suggested by this test is to simplify the mesh and insert an adequate scattering coefficient. This solution improves computational time optimization even more in the GRID calculation, which is even more time-consuming.

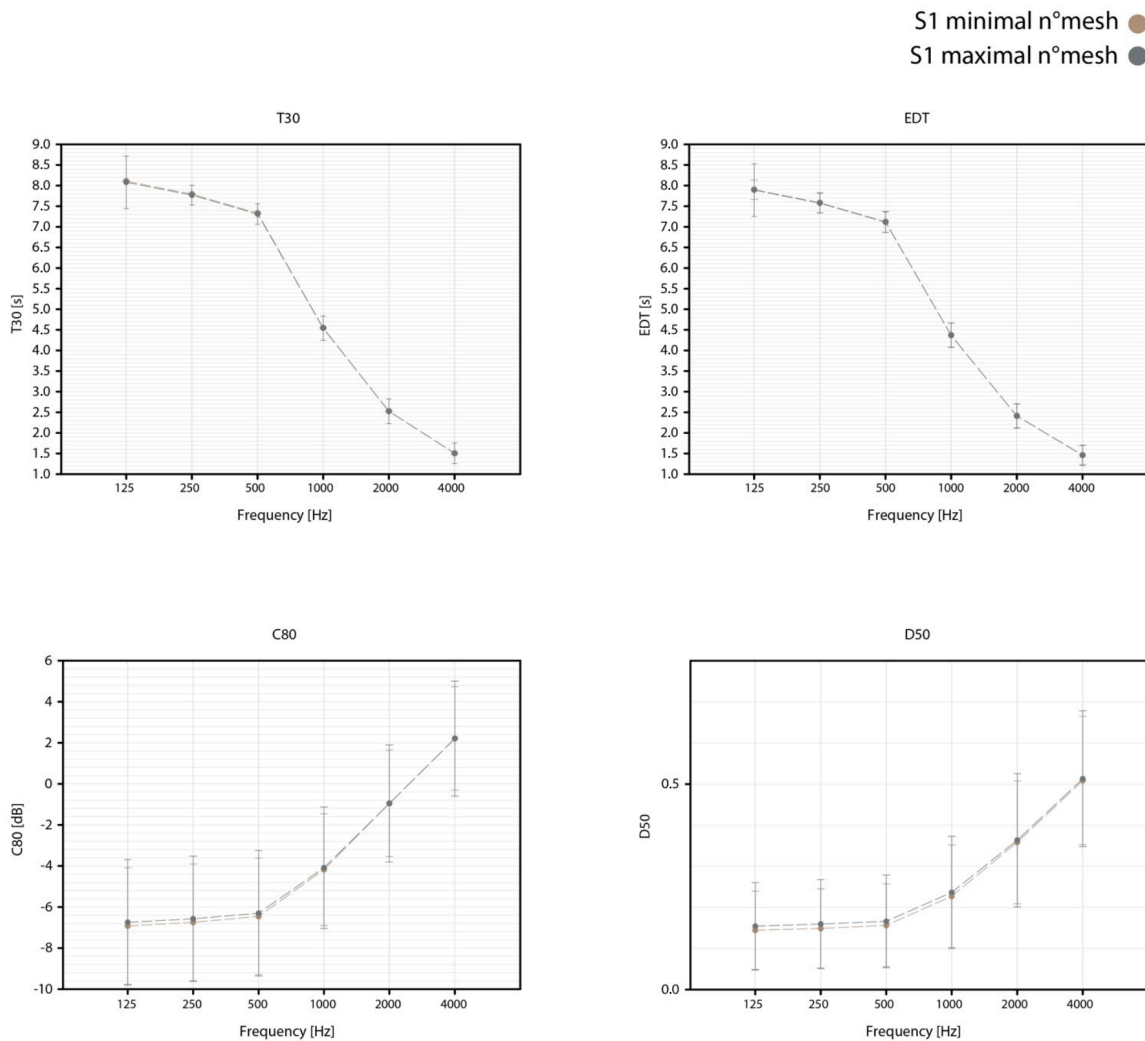


Figure 15, The mean and standard deviation for Source 1;

8. Conclusions

This paper aims to describe a methodology for the acoustic characterization of CHs, by analyzing and studying the case study of the San Biagio's Temple. The definition of a numerical model capable of analyzing and interpretate the acoustic characteristics of the ancient church is fundamental to preserve, disseminate and promote the intangible cultural asset as recognized by the UNESCO convention of 2003.

The results obtained from the surveys and the presented analyses led to the creation of the digital numerical model and allowed the validation of the methodology.

This kind of model digitally represents the acoustic phenomenon within the cultural heritage and can be compared to the role that the laser scanning survey technique has acquired over the years. From this model it is also possible to obtain an important array of information and data, including the possibility of making the auralization of the acoustic characteristics in order to be able to use them digitally. This is because, unlike an experimental survey, the data are not only latched to the acoustic indices related to

individual points of responses, but to the geometry and characteristics of the materials of which the asset is composed.

The procedure for obtaining such results, which is repeatable and applicable to other types of architectural bodies as well, starts with the historical study of the property, the materials with which it was made, and the techniques used to design and build it. The investigations subsequently carried out are photographic, geometric and acoustic surveys. This is the core part of the methodology used to obtain the numerical model, which is strongly based on the gathering of such information.

The data obtained from the selected procedure showed how the Temple of San Biagio performs from the acoustic point of view. The symmetry in the plan is also found in the propagation of sound, making the 4 naves similar points of reproduction for both music and speech. The space is highly reverberant and presents a standing wave phenomenon below the dome. These qualities are reflected in the C80 and D50 indexes, which show that both clarity and definition are affected by the lengths and dimensions of the church. In conclusion, such a procedure is a more advanced method than simple experimental surveying and is more suitable for the tools being developed today for CH digitalization, management and promotion, such as heritage BIM.

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