Proposals and analysis of the effects of acoustic corrections in a modern church

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Abstract

It is rather common experience to observe that many contemporary churches, in contrast with the effort to achieve refined architectonic shapes and finishes, exhibit poor acoustic quality, such as high reverberation times and low speech intelligibility. The causes of such deficiencies are ordinarily generated by the smooth and hard surfaces of walls, floor and ceiling that focus most of sound energy in late reflections, diminishing the effectiveness of direct and early reflected sound.

Recently, the authors have been involved for analyzing the acoustic behavior of a modern church situated in Ragusa, (Italy), with the aim to individuate suitable interventions for improving the acoustic quality of that church.

Preliminarily, a measurement survey was conducted to evaluate the main acoustic indices proposed by ISO 3382 (T_{30}, STI, EDT, C_{80}, D_{50}) and portray the current acoustic climate. After that, the Authors developed a simulation on a 3D model of the church, in order to calibrate the model comparing measured and simulated acoustic parameters.

The previously described activities are necessary for testing the reliability and accuracy of the prediction of the acoustic simulations. The subsequent step of the work consists in the choice of suitable interventions for the acoustic corrections; three different typologies of materials were evaluated. Globally, the acoustic corrections allow to obtain noteworthy improvements of the acoustic quality of the church, e.g. the T_{30} decrease from 7.3 to 2.5 s and the STI increase from 33% to 40%, at 1000 Hz.

Further, the influence of the variation of the audience presence was analyzed, finding out a strict correlation between occupancy percentage and the law of variation of T_{30}. Finally, after the realizations of one of the suggested interventions of acoustic corrections, the Authors conducted a second survey to evaluate the effects of the refurbishment interventions on the acoustic climate. Since the obtained results do not match very well with the design previsions, some hypotheses that can justify such discrepancy are illustrated.

Keywords: Church Acoustics, Acoustic Measurements, Computer simulation, Modern Churches;

1. Introduction

Buildings as churches are built around communication (verbal, musical, and emotional) as well as worship. The minister communicates with the congregation by preaching, leading prayers, and announcing church activities. Moreover, music attempts to communicate ideas and concepts while it simultaneously enhances the worship experience through emotional involvement. Therefore, the acoustics of the church have a profound impact on all of these functions.

In recent years, some studies conducted by F. Martellotta [1,2] deepened in this topic with the proposal to improve the knowledge of the sound propagation inside this typology of buildings, to preserve the original features in case of restoration and to determine optimal approaches to improve the acoustic conditions inside existing buildings. These works led to determine some guidelines in acoustic measurements within churches to standardize the choice of sources and receivers locations in function of church geometry. It was given more importance to the three basic aspects of the measurement procedure: the choice of the source positions, the choice of the receiver positions, and the equipment to be used. Moreover, the studies focused on the effect of different architectural elements on sound propagation such as side chapels, columns, and trussed roofs. Those elements appeared to scatter the reflections, so that the purely diffuse exponential sound decay begins after a time interval which grows with the source–receiver distance and with the complexity of the church. Consequently, the reflections create very attractive sounds effects but they are difficult to evaluate with theoretical models [1,2].

It is usual that the acoustics of ancient churches has always been a very attractive part of this type of buildings, contributing to the development of both choral and organ music. But, starting from the second part of the 20th century, the way to build churches underwent important changes, especially about shapes, materials and finishes. Architects gave more importance to the iconographic message, without investigating the acoustic behavior of these buildings. So, irregular shapes, the use of smooth and hard materials and the lack of complex finishes within the halls often lead to deal with unsuitable absorption and diffusion coefficients, which result is a poor acoustic quality (high reverberation time, low speech intelligibility).

Contemporary churches have been involved in many recent studies in different countries, such as Italy [3,4], Portugal [5], Germany [6], Spain [7], in which the aim is to assess the acoustic quality for studied churches and propose corrective solutions to improve reverberation time and speech intelligibility. Particularly, C. Buratti et al. [8] used Ramsete software to evaluate acoustic indices after the introduction of a special acoustic plaster over the walls and resonant panels on ceiling in a modern church in Perugia.

Also, D.Q. de Sant'Ana et al [9] carried out an acoustic survey and computer simulation to evaluate its acoustic quality with regard to speech intelligibility in a modern catholic church. They investigated the acoustic behavior of a modern church in Brazil because the liturgical reforms introduced by the Second Ecumenical Council of the Vatican in 1965 involved the adoption of vernacular languages in place of Latin, and this meant a higher requirement for good speech intelligibility respect to the high reverberations requirements.

This paper presents the results of an experimental investigation on the acoustic performance of a contemporary Catholic Church located in Ragusa (Italy). With the aim to characterize the distribution of the sound energy and the room acoustic quality, the authors have proceeded through the following steps:

- measurements of the acoustic indices (T_{30}, STI, EDT, C_{80}, D_{50}, STI).
- modelling the geometrical and acoustic features of the church using the CATT-Acoustic software.
- validation and calibration of the computer model.
- proposal of suitable interventions for the acoustic corrections.
- evaluation of the effects of audience presence in the hall.
- measurements of the acoustic indices (T_{30}, STI, EDT, C_{80}, D_{50}, STI) after interventions.

2. Methodology

In order to get good acoustic quality, it is important to satisfy the requirements of the acoustic parameters that define the quality of the sound field and the listener sensations [10,11,12,13]. These parameters, according to ISO 3382 [14], include the Sabine's Reverberation Time (T_{30}), the Definition Index (D_{50}), the Clarity (C_{80}), the Early Decay Time (EDT) and the STI Index.

The Reverberation Time is defined as the time it takes for a signal to drop by 60 dB from its initial stationary level. In accord with ISO 3382, the measurements can be made between -5 and -35 dB or between -5 e -25 dB. The reverberation time is then obtained by mathematical extrapolation, assuming a purely linear decay; RT is called T_{30} and T_{20}, if deduced from the first or the second approach [14].

Early Decay Time (EDT) is the reverberation time measured over the first 10 dB of the decay. Unlike late reverberation, early reverberation just comprises few primary reflections that are integrated with the direct sound, thus reinforcing it. This early reverberation can affect the clarity of sound, as well as the perception of liveliness: indeed, the greater the energy in the early reverberation, the better the clarity. On the contrary, high late reverberant energy can increase liveliness or fullness, but decreases the clarity.

Furthermore, clarity (C_{80}) is defined through the difference between the sound energy in the first 80 ms, and the late reverberation energy arriving after the first 80 msec. In some cases, a single C_{80} value is used, which averages clarity at 500, 1000 and 2000 Hz. Definition (D_{50}) or early-to-late energy ratio characterizes the speech intelligibility [15]:

$$C_{80} = 10log \int_0^{80ms} p^2(t)dt / \int_{80ms}^{\infty} p^2(t)dt \quad (1)$$

$$D = \int_0^{50ms} p^2(t)dt / \int_0^{\infty} p^2(t)dt \quad (2)$$

The speech transmission index (STI) is widely used for assessing room acoustics [16]. The scientific principle, on which the STI is based, is that information in speech is represented acoustically in the form of modulations: a loss of these modulations translates into a loss of intelligibility. The STI measures the ability of a transmission channel (the room in this case) to carry across the characteristics of a speech signal without loss of modulation. In practice, the field measurement of this parameter is based on a well-established procedure that allow calculating a value of STI ranging from 0 to 1; closer the STI value approaches zero, more information is lost. There are standardized ratings linking certain ranges of the STI to subjectively experienced intelligibility [17].

3. The studied contemporary church

This research is focalized on the acoustic analysis of a contemporary Catholic Church situated in Ragusa (Italy), built around 1980, that is featured by an asymmetric radial shape, as shown in Figure 1, which probably reminds a heart.

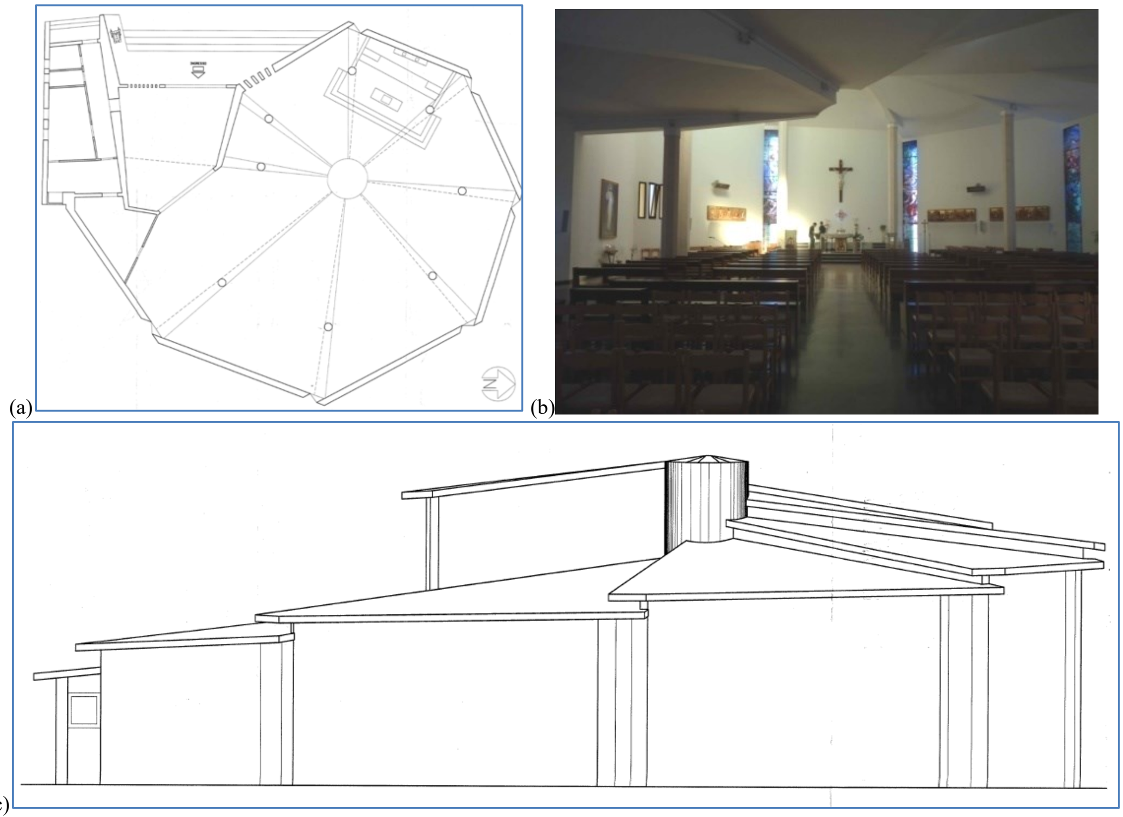


Fig. 1. (a) Floor Plan of the Church (b) View of the altar from audience area (c) East elevation of the Church

The Church's internal volume is about 3,580 m^3, with an extension in plan of 23.10 x 18.40 m and a variable height of the ceiling from 6.05 to 10.30 m. The floor and ceiling surfaces are subdivided into eight parts. Each sector of the ceiling has different slope, both in radial and tangential direction. All the sectors of the ceiling rejoin toward the skylight, which is placed almost at the center of the church at 10.80 m from the floor.

The floor finish is marble, while walls and ceiling are entirely covered by extremely smooth plaster. In addition, furniture includes only wooden pews in audience area, which cover about the 50% of whole plan area. The wide volume and smooth surfaces lead to a lack in the acoustic quality, as evidenced by high reverberation time values and poor speech intelligibility.

3.1. Acoustic Measurements

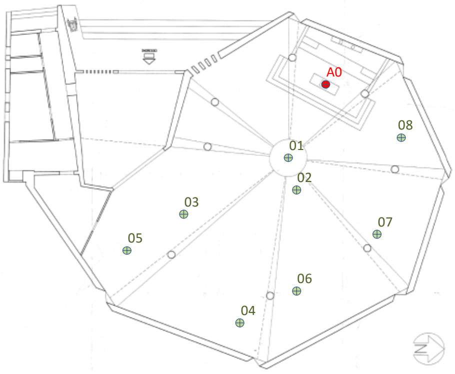
In order to evaluate the acoustic indices defined by ISO 3382 and identifying the causes of the lacks in acoustic quality, a measurement survey was conducted. The position of the sound sources (A_i in red color) and the receivers (0_j in green color) are depicted in Figure 2a.

Microphones were placed at the height of 1.20 m (ears height in sitting position), aiming to the altar.

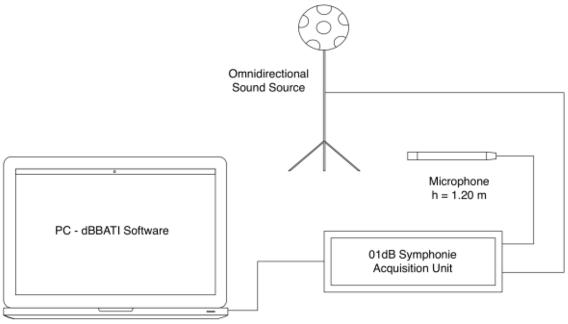
Measurements were carried out using a 01dB-Stell Symphonie precision audio-acquisition unit, powered by *dBBati32* software. Multiple sound sources were used: an omnidirectional dodecahedral loudspeaker (fig. 2c), a commercial two-ways directional loudspeaker (fig. 2d) and the public amplification (PA) audio system already operating within the Church. The second source was used with the aim to replicate the audience coverage of PA audio system, because of the poor frequency response of PA loudspeakers, which do not work properly below 500 Hz.

The procedures employed are those established in the ISO 3382-1 and IEC 60268-16 standards, and all measurements were accomplished in the unoccupied room.

The signal used to excite the rooms was an MLS (Maximum Length Sequence) signal with following parameters: 18th order; response length 10.2 s; averages number 4.



(a)



(b)

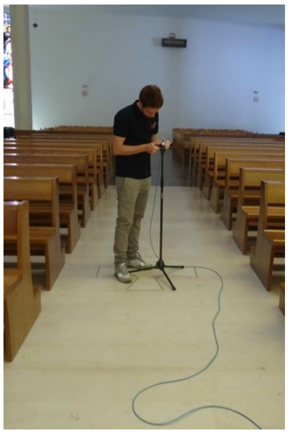
(c)  (d)  (e) 

Fig. 2. (a) Source and receivers position map (b) Measurement chain (c) Omnidirectional Sound Source (d) Directional Sound Source (e) Receiver 01

The room responses were recorded and used to determine the acoustic parameters at each octave band from 125 Hz to 4000 Hz for all the receivers.

Figure 3 illustrates the average indices values and respective standard deviation calculated over the eight receivers, referred to the omnidirectional sound source. It is possible to notice that the acoustic parameters do not significantly vary at the different receiver positions, as confirmed by the low standard deviation values. Such result is probably generated by the late reflections that create an almost diffuse acoustic field. Moreover, there are no significant differences between T_{30} and EDT values in the overall frequency spectrum.

The values of C_{80} and D_{50} are very low if they are compared with the threshold values specifically suggested for speech halls. Anyway, considering that Churches can host circumstances that foresee the listening of religious songs or sing choral songs, the acoustic behavior of such buildings must be calibrated taking in account also these possible applications. Overall, acoustic treatment should certainly make the church be attractive for both possible purposes.

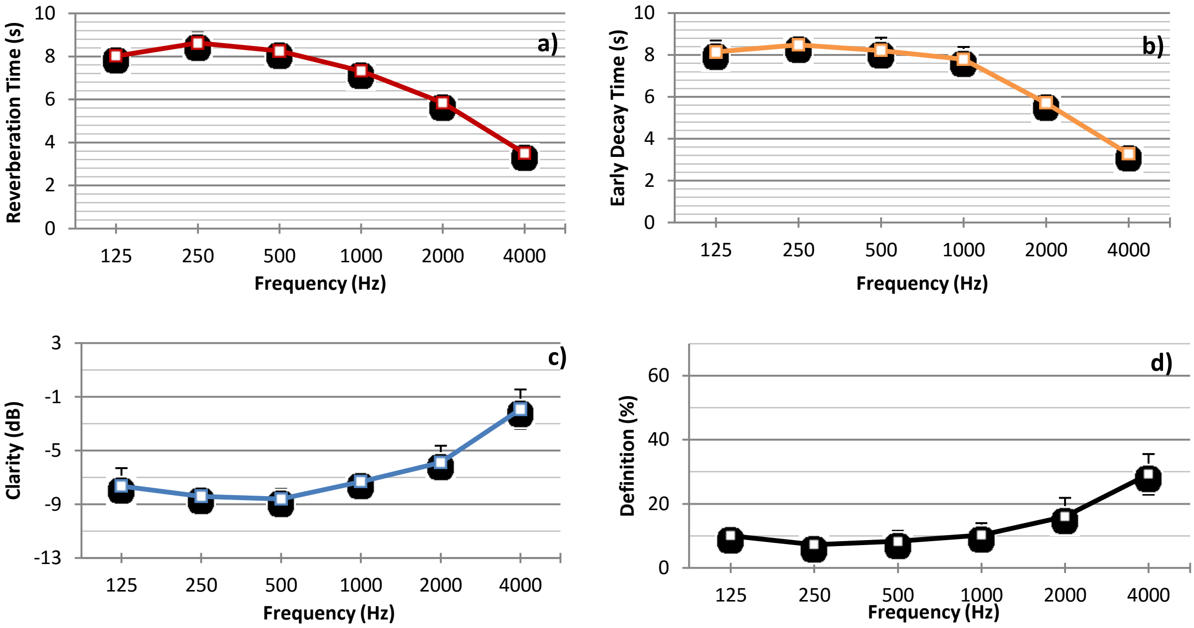


Fig. 3. Average indices values with standard deviation (error bars).
(a) Reverberation Time T_{30} (b) Early Decay Time EDT (c) Clarity C_{80} (d) Definition D_{50}.

The STI values are quite constant in whole the hall, with an average value of 33%. Such value is associated with "POOR" speech intelligibility, according to ISO 3382, therefore the hall does not guarantee a sufficient quality for speech.

Finally, MLS signal was also sent through the Church's PA audio system, but values for main acoustic indices were not so accurate at low frequencies because loudspeaker have a flat frequency response only in 500-10000 Hz. Anyway, it was possible to evaluate the STI perceived when this system is used, which confirms the 33% amount.

3.2. Computer modeling

The software CATT-Acoustic was used for simulating the acoustic behavior of the Church under study. Sound sources and receivers were implemented in the same way of measurement process. The hall was modeled taking in account all dimension above 30 cm, in order to improve calculation speed and not to have too many surface to deal with. For this reason, proper scattering coefficient were used for all surfaces, especially for wooden pews (modeled as one-block geometry) to get the most realistic effect of diffusion, as suggested by CATT-Acoustic user manual.

Simulations in CATT-Acoustic were conducted through Randomized Tail Corrected Cone-Tracing algorithm, setting a number of rays of 28740 and a ray truncation time of 9000 ms. Measurements of the acoustic indices were used for validation and calibration the 3D acoustic model of the Church.

First, the virtual model was validated through an iterative procedure, based on the adjustment of absorption coefficients for cladding materials, in order to obtain average values of simulated T_{30} comparable with measured ones. No spatial distribution of T_{30} was considered in calibration process because of standard deviation of measured values, which is smaller than 5% for each octave band.

At the end of the calibration process, simulated and measured values differ by no more than 5% at each frequency (Figure 4).

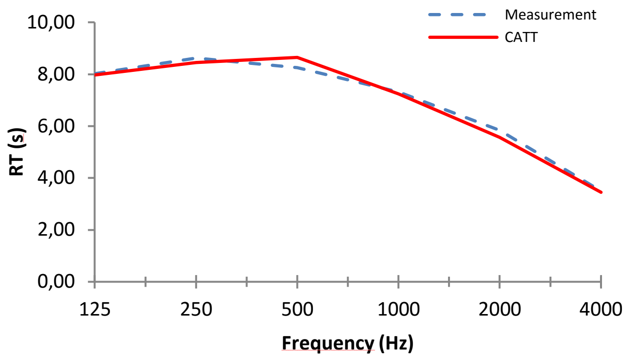


Fig. 4. Validation for CATT-Acoustic model

4. Proposal of Acoustic corrections

The choice of the interventions of acoustic correction must consider different perspective beyond the merely physical parameters. Indeed, in place like churches, the aesthetic point of view plays a fundamental role about any kind of intervention that involves walls or ceiling, especially if a large amount of area needs to be treated.

However, the chosen interventions have to yearn to achieve the highest possible acoustic quality of the hall, having as reference the threshold values of the acoustic descriptors suggested by the scientific literature.

4.1. Threshold values of the acoustic descriptors

The optimum reverberation time T_{30} is usually defined as a function of the volume and the hall purpose. For churches, the threshold value of T_{30} at 500 Hz octave band for a 3,500 m^3 hall is 2.6 s [18].

For speech auditoria, Clarity and Definition have to be respectively larger than 2.0 dB and 50%. Considering that within churches, for the reasons previously mentioned, is not sufficient optimize only speech listening but it is necessary to choose values of Clarity and Definition that must lead to a sufficient acoustic quality of the hall for both purposes: speech and music [19]. Finally, a value of STI higher than 45% was considered sufficient [20].

The reference values of the acoustic descriptors are listed in table 1.

Table 1. Summary for target values

Parameter	Target Value
T_{30} at 500 Hz	2.6 s
C_{80}	-4.0 ÷ 2.0 dB
D_{50}	≥ 25%
STI	≥ 45%

4.2. Interventions of acoustic correction

The choice of the surfaces to treat was led by the following consideration. The upper part of each wall was chosen since it allows attenuating late reflections spread in the wide volume of the hall without strongly affecting the aesthetic of the church (see Figure 5). That area has an extension of about 230 m^2, which corresponds to 46% of the whole surface of the walls.

Therefore, we have investigated three different acoustic treatments that can be applied on such surfaces [21,22].

- Wood Wool panels, operating as porous absorbers (figure 6a);
- Micro-Perforated panels, operating as viscous absorber / Helmholtz resonator (figure 6b);
- Acoustic Plaster, containing cork particles (figure 6c).

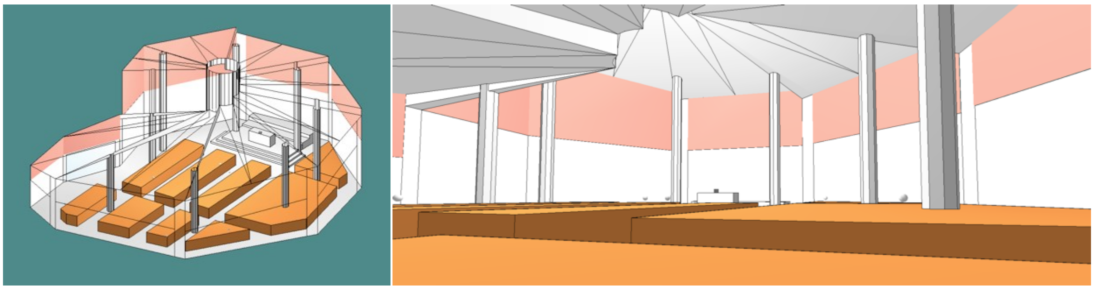


Fig. 5. Area of intervention for acoustic correction (pink)

The main features for the above-mentioned acoustic treatments are shown in Table 2. Absorption coefficient values were obtained from the manufacturer data sheet, except for MPPT ones calculated using the equation proposed in [23].

Table 2. Main features for absorbing materials chosen for acoustic correction

Treatment Name	Material	Description	Absorption Coefficients α					
			125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
WWPT	Wood Wool Panel	Porous absorber Panel thickness 25 mm Distance from wall ≥ 24 mm	0.12	0.11	0.48	0.72	0.51	0.82
MPPT	Micro-Perforated Panel	Panel thickness 2.0 mm Hole diameter 0.2 mm Hole repeat distance 1.0 mm Distance from wall 70 mm	0.21	0.54	0.84	0.74	0.29	0.19
APT	Acoustic Plaster	Plaster thickness 25 mm Cork Particles	0.14	0.25	0.57	0.67	0.60	0.64

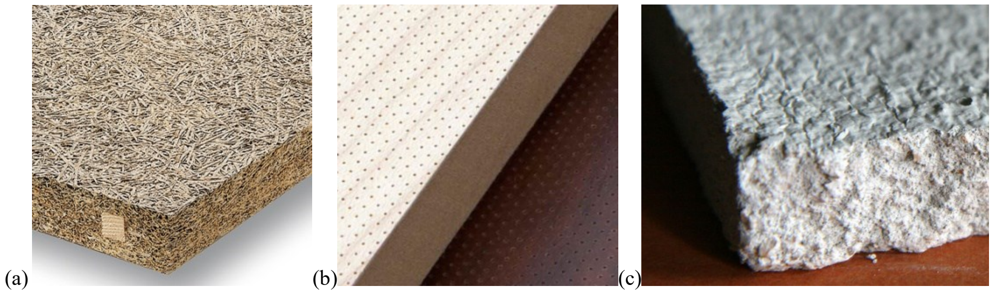


Fig. 6. (a) Wood Wool Panel (b) Micro-Perforated Panel (c) Acoustic Plaster

4.3. Simulations Results

The results of simulations carried out through CATT-Acoustic are plotted in figure 7. Four different scenarios were simulated: NT scenario that is based on the no-treatment condition, MPPT scenario that is based on the performances of the Micro-Perforated Panel treatment, WWPT scenario that is based on the performances of the Wood Wool Panel treatment, APT scenario that is based on the performances of the Acoustic Plaster treatment.

It is possible to notice that the T_{30} and EDT values are improved mainly at mid and high frequencies for all the treatments in accord with the values of the absorption coefficients of the three treatment materials. Moreover, even if this hall cannot be considered as a Sabinian one, it is possible to highlight a good linearity between absorption coefficients and T_{30} attenuation.

The results of simulations underline the equality between T_{30} (Randomized Tail Corrected Cone-Tracing algorithm) and EyrT (reverberation time based on rays mean free path and arithmetic mean of all absorption values encountered by the rays).

All scenarios allow achieving the target values requested for the reverberation time at 500 Hz. The MPPT treatment achieves the best performance at low frequencies.

The noteworthy improvement of the values of C_{80} and D_{50} indicate that the amount of energy in the early reflections is higher than the amount of energy contained in the late reflections. Even in this case, it is possible to notice differences in the spectrum balance: WWPT and APT improve mostly high frequencies (speech), while MPPT allows to obtain a more balanced frequency spectrum.

The proposed treatments increase the speech intelligibility, but are not sufficient for reaching the expected objectives (at least 50%). Average values of STI, reported in table 3, are 42% for MPPT and APT treatments, while little bit worse when the WPPT treatment is chosen (40%): this is probably due to the higher reverberation at low-mid frequencies.

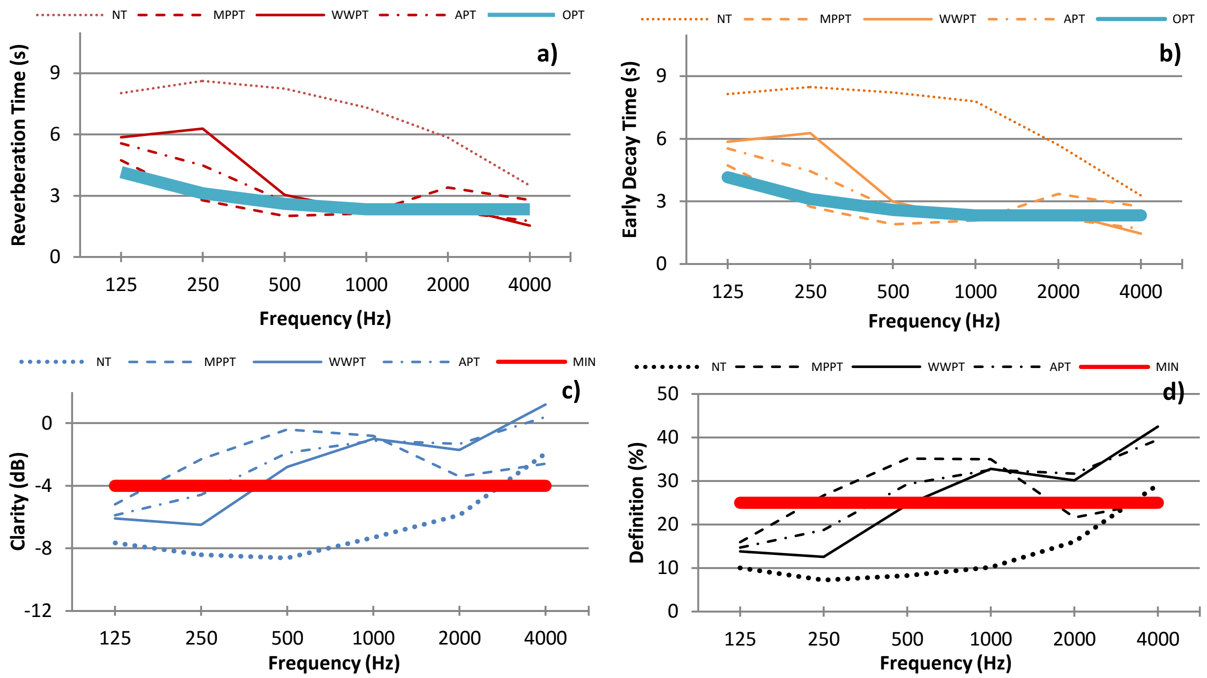


Fig. 7. Average indices values after acoustic correction. OPT indicates for optimum values ranges, MIN for minimum values. (a) Reverberation Time T_{30}; (b) Early Decay Time *EDT*; (c) Clarity C_{80}; (d) Definition D_{50}.

Table 3. Summary for STI values

Treatment Name	STI
WWPT	40%
MPPT	42%
APT	42%

Furthermore, it is possible to state that acoustic treatments lead to a better distribution of SPL in the time domain: figure 8 shows a comparison between audience area maps carried out from CATT-Acoustic software, in which the SPL distribution at 1 kHz in four time windows (0 to 20 ms, 20 to 50 ms, 50 to 80 ms, 50 to 200 ms) is shown for both NT (fig. 8a) and MPPT scenarios (fig. 8b).

In the upper-left window, no difference can be found between considered scenarios, because most of sound energy in 0-20 ms time range can be assumed as direct, especially in large halls.

Having a look in the upper-right window (20-50 ms), the effect of the absorber in rear walls is highlighted by lower values of SPL in further seats, while in the hall center there is still no notable difference because most of reflection wavefronts has not reached this area yet.

The most significant result is obtained in 50-80 ms time range (lower-left window), where is possible to observe an overall attenuation of SPL values in MPPT scenario rather the NT one: indeed, if no absorber is present, the high reflected energy contributes to increase pressure levels in rear audience seats, affecting clarity and definition of direct sound. In case of treated scenario, instead, the SPL distribution seems to be homogeneous already in this time window, with no level peaks due to high reflection rate.

Finally, in 80-200 ms time range the SPL distribution appears to be even in both scenarios, featuring higher values in no treatment condition according to late reflection energy spreading.

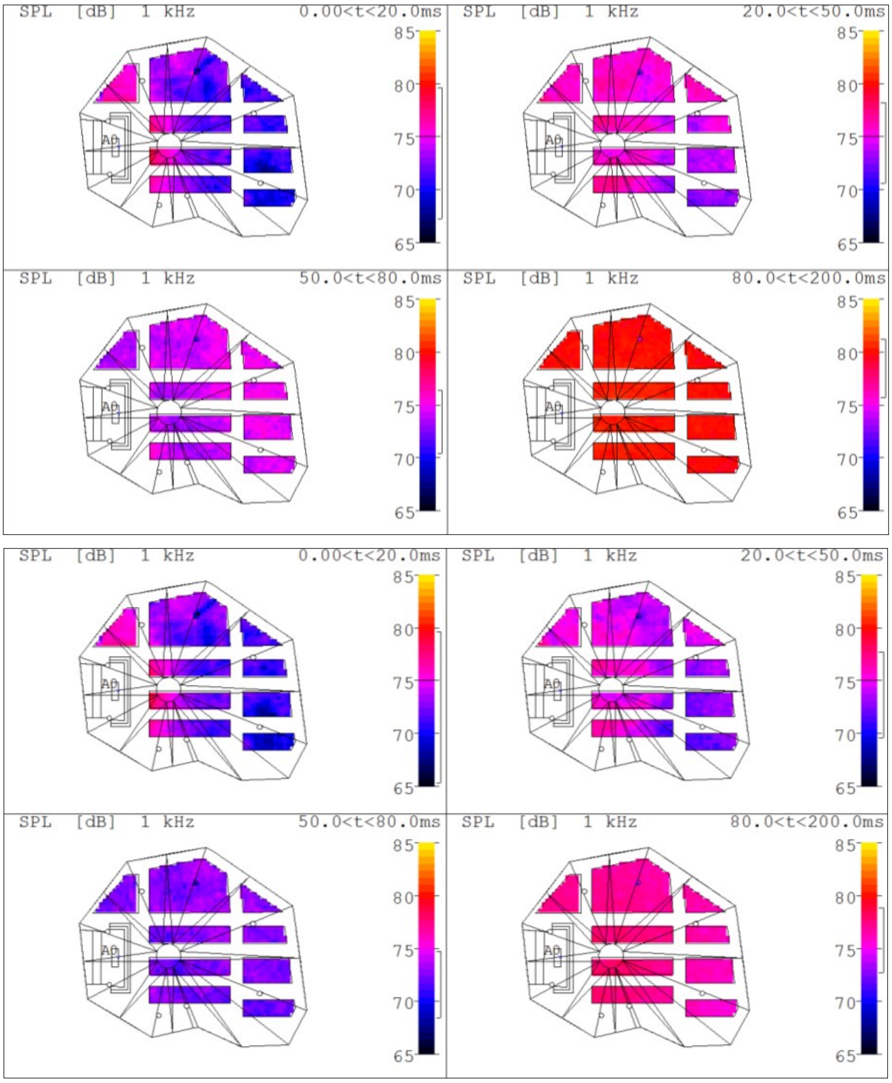


Fig. 8. SPL distribution over time domain.
(a) No Treatment scenario (b) MPPT Scenario

4.4. The effect of audience

All results reported in previous paragraph were carried out considering empty hall condition, or most exactly considering only the wooden pews.

Generally, the presence of audience causes significant changes of the acoustic behavior of the hall, because a large amount of absorbing surface reduces the reflective effect of the floor and contributes to perceive substantial improvements in speech intelligibility [24].

Therefore, the acoustic parameters were computed in occupied hall conditions too. For each treatment (MPPT, WWPT and APT, authors considered three different occupancy conditions:

- empty hall (seen in previous paragraph);
- 50% occupied hall, equivalent to 1 pers./m^2;
- 100% occupied hall, equivalent to 2 pers./m^2.

In table 4 are reported the absorption coefficients of the audience area.

Table 4. Absorption coefficients for audience area in different occupancy conditions

Surface	Occupancy	Absorption Coefficients α					
		125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Wooden Pews	0%	0.05	0.05	0.05	0.04	0.03	0.03
1 pers./m^2	50%	0.16	0.24	0.56	0.69	0.81	0.78
2 pers./m^2	100%	0.24	0.40	0.78	0.98	0.96	0.87

The aim of this analysis is to understand how the acoustic corrections interact with the audience presence and if it can cause an excess of absorbing area or further improvements.

Authors computed, for each treatment and occupancy condition, mean reverberation times (T_{30Av}) over the central octave bands (250 to 2000 Hz). This choice allows excluding the extreme values.

Figure 9 shows the variation of the reverberation time respect to the occupancy percentage

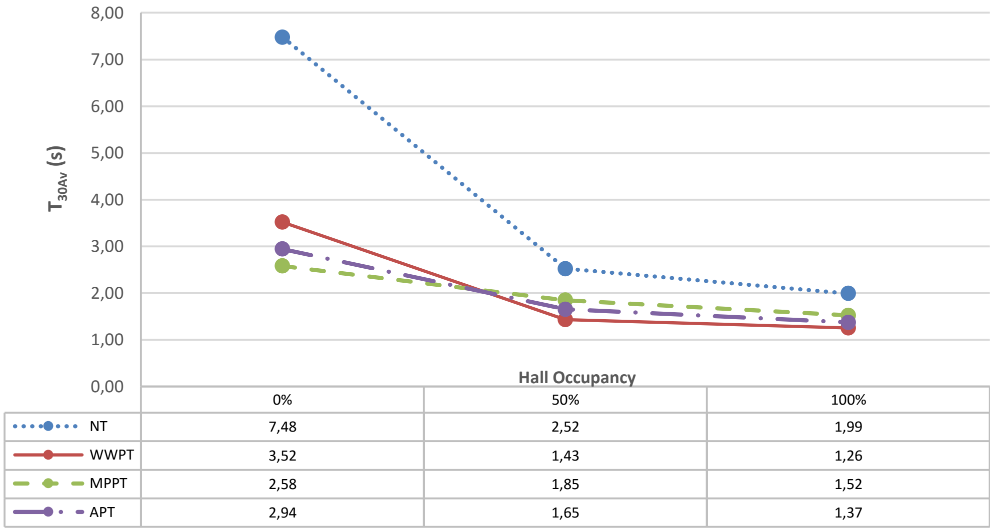


Fig. 9. Mean RT trend according to occupancy condition

For NT scenario it is highlighted a wide variation of T_{30Av} respect to the other scenarios. Indeed, for NT scenario the only absorbing area is made by audience and its density strongly affects sound reflections. While in the other scenarios, the reverberation time values are more stable to the changes in the occupancy percentage.

Further, Authors have tried to correlate the absorption of the empty hall with the standard deviation of $T30_{Av}$ (σ_{RT}) (4). As reference value of the absorption of the hall, the arithmetic mean of all absorption areas encountered by the traced rays was chosen (AbsC). AbsC parameter is directly calculated by CATT-Acoustic (3).

The mathematical equation used for calculating σ_{RT} and AbsC are reported in the follows formulae.

$$AbsC = \frac{\sum_{i=1}^{n} \alpha_i}{n} \quad (3)$$

$$\sigma_{RT} = \sqrt{\frac{\sum_{x=0\%}^{100\%} (RT_x - \overline{RT})^2}{m}} \quad (4)$$

where n is the number of surfaces encountered by the traced rays, x is the state of occupancy, m the number of occupancy condition analyzed for each treatment.

Table 5 reports, for each treatment scenario, initial (empty hall) AbsC values (average over central octave bands 250-2000 Hz) and standard deviation for RT series (function of occupancy percentage).

Table 5. Initial AbsC values and Standard Deviation for each treatment

Treatment Name	Initial AbsC (empty hall)	RT as function of occupancy percentage (x)			RT Standard Deviation
		0%	50%	100%	σ_{RT}
NT	3.05%	7.48 s	2.52 s	1.99 s	3.03 s
WWPT	8.20%	3.52 s	1.43 s	1.26 s	1.26 s
MPPT	9.98%	2.58 s	1.85 s	1.52 s	0.54 s
APT	9.00%	2.94 s	1.65 s	1.37 s	0.84 s

Plotting these values (Figure 10), a linear regression with a good fit (R^2 = 0.9976) is derived.

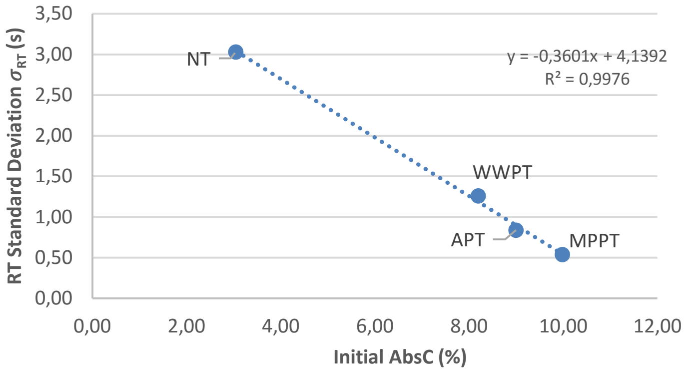


Fig. 10. Linear regression between RT Standard Deviation and Initial AbsC

The analysis of this plot indicates that little variation of the mean absorption coefficient in empty hall conditions (for example from 3% to 8%) lead to minimize the effect of "variable acoustics" in churches.

The result of this analysis can be a useful indicator for evaluating the effectiveness of a certain treatment, in order to establish how much audience presence affects the acoustic quality of the hall and its consequential effects such as PA system calibration.

5. Evaluation of acoustic correction interventions

Subsequently the acoustic survey conducted by the Author, one of the investigated refurbishment intervention was realized. More specifically, acoustic plaster treatment was chosen by the client for the following reasons:

- low aesthetic impact;
- small thickness (25 mm);
- fiber-free material, no coating required.

Sidewalls involved in these interventions are shown in Figure 11. It is highlighted that effectively treated area is quite different respect to the proposed one (see previous paragraph).

The whole area covered by acoustic plaster was 96 m^2, which means about 41% respect to the area foreseen by the simulations in the previous paragraph.

Fig. 11. Walls involved in refurbishment interventions (red)

During the application phases, the Authors were not involved and they were involved just to verify the effectiveness of the interventions realized. Surprisingly, the first impression Author had during a preliminary visit were very disappointing: We did not perceive any significant change in terms of sound decays and speech intelligibility.

Figure 12 shows the comparison of reverberation times between measurement session *ex-ante* and *ex-post* refurbishment interventions. The T_{30} trend carried out from the measurement session proves a poor performance of the absorber. Are these the expected results of such treatment?

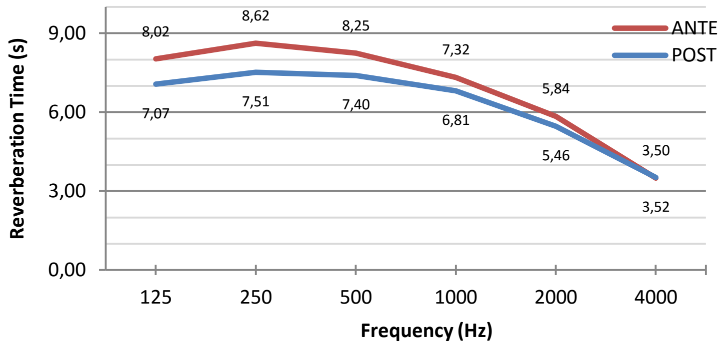


Fig. 12. Comparison between measurement ex-ante and ex-post

To answer at that question, Authors implemented the new treated area in the 3D CATT-Acoustic model and calculated the acoustic indices. This analysis should allow highlighting what did not work properly, such as the positioning of the absorbing area, mixing or installation of the plaster.

Figure 13 shows the comparisons between simulated and measured data.

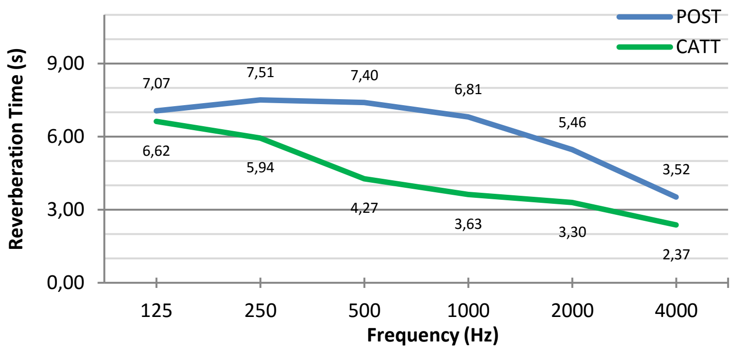


Fig. 13. Comparison between measurement ex-post and expected values (from CATT-Acoustic)

It is possible to affirm that the simulation results foresee an acceptable performance of the acoustic plaster. Therefore, as appears clearly by the measured values, the acoustic plaster not works as expected, especially at the-mid frequencies where it features the higher absorption coefficient values.

On the contrary, STI values both measured and predicted match perfectly, taking the value of 33%, which is equivalent to the no-treatment condition.

Thereby, the simulation indicates that the choice to treat the two walls in question is not improper, considering that the treatment allows achieving acceptable reverberation times, but it is not sufficient to guarantee good speech intelligibility. Therefore, the cause of this mismatch should be attributable with some fault in material preparation (plaster mixing) or installation: particularly, acoustic plasters have to be prepared and mixed according to well-defined procedures specified by the manufacturer, in order not to compromise absorbing features.

Moreover, plaster was covered with a special acoustically transparent paint provided by the manufacturer: this should not affect plaster properties, but an improper installation can act as an obstacle for sound passing through pores, attenuating cork particles absorption.

The type of installation also can have a determinant role in plaster performance: indeed, even if manufacturer suggests both hand and plastering machine application, the second one may be more suitable to preserve the mixing porosity, as well as accurate.

In conclusion, innovative materials such as acoustic plasters can be highly performing rather than classic ones for the designated purpose, but the installation/application is a critical step in treatment procedure to work properly.

Manufacturers should provide a service of skilled labor together with the product sale, in order to prevent shortcomings that would impair the performance of the same and ensure technical specifications declared.

6. Conclusions

The acoustic survey carried out on a contemporary catholic church has revealed that reverberation time, clarity, definition and speech intelligibility index values are very far from acceptable values for this kind of environments, e.g. T_{30} and EDT of about 7.3 sec at 1 kHz.

A 3D computer model was set up in CATT-Acoustic software to simulate the acoustic field within the church. This computer model was validated and calibrated, finding no more than 5% error in values matching.

Once defined the surfaces where the absorbing materials could be inserted, three different treatments were proposed for acoustic correction of the hall: the first is a porous absorber made of wood wool; the second is a micro-perforated panel, based on the principle of viscous absorber and Helmholtz resonator; the third is an acoustic plaster, mixed with cork particles. The simulations carried out revealed that the three proposed acoustic interventions allow achieving significant improvements for each acoustic index (e.g. T_{30} of about 2.5 sec at 1000 Hz and STI of about 40%).

All of the three treatments were also analyzed in occupied-hall condition: the result is that the presence of a larger absorbing area in empty hall condition contributes to minimize the effect of "variable acoustics" due to audience occupancy. Particularly, Authors found direct proportionality between the mean absorption coefficient of the hall and the standard deviation for reverberation time in function of the occupancy percentage.

Finally, Authors evaluated the efficacy of a refurbishment interventions with acoustic plaster through simulations and measurements survey. It was found out that the treatment effects do not match with the theoretical results deriving from simulations with CATT-Acoustic software. The cause of this mismatch can be attributed to some faults in plaster preparation or application, such as incorrect mixing, improper painting, wrong type of installation.

With the aim to reduce such risk and the consequential contestations, manufacturers should provide skilled labor to apply this kind of material to ensure its proper functioning.

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