Acoustics of a Chamber Music Hall Inside a Former Church by Means of Sound Energy Distribution

Dario D'Orazio *1, **Giulia Fratoni** †1, **and Massimo Garai** ‡1
[1]Department of Industrial Engineering, University of Bologna, Italy

Abstract

The present work concerns the acoustic design for a former church converted into a chamber music hall. The current status of the hall was classified with an acoustic measurements campaign according to technical standards requirements. Focusing on literature theories, an accurate sound energy spatial distribution analysis led to the development of an acoustic intervention, not-invasive from a volumetric point of view. An array of hanging reflecting panels over the musicians positions improves sound clarity C_{80} and sound strength G trends giving to the church an acoustic quality worthy of a concert hall. All the acoustic treatments were validated using a Geometrical Acoustic (GA) numerical model, calibrated through the measured values, in order to estimate the effect of the whole improvement proposal.

Keywords: Sound energy distribution, worship acoustics, geometric acoustic simulation.

Résumé

La présente étude concerne la transformation acoustique d'une ancienne église en salle de musique de chambre. L'acoustique actuelle de la salle a été caractérisée au moyen d'une campagne de mesures acoustiques selon les exigences des normes techniques. En se basant sur l'état de l'art, une analyse précise de la distribution spatiale de l'énergie sonore a conduit au développement d'une intervention acoustique non invasive du point de vue volumétrique. Un ensemble de panneaux réfléchissants suspendus au-dessus des positionnements des musiciens améliore la clarité C_{80} et les tendances de la force sonore G en apportant à l'église une qualité acoustique comparable à celle d'une salle de concert. Tous les traitements acoustiques ont été validés en utilisant un modèle numérique, calibré avec les valeurs mesurées, et un logiciel de simulation acoustique afin d'estimer l'effet global de la proposition d'amélioration de la conception acoustique.

Mots clefs: Distribution de l'énergie sonore, acoustique des lieux de culte, simulation acoustique géométrique

1 Introduction

The acoustics in churches is the result of several factors and certainly it represents a complex phenomenon largely analyzed in literature. Ancient Christian churches generally present a geometrical complexity that makes it difficult to delineate exactly a single scheme but there are some characteristcs they share, such as large volumes, reflecting coatings, articulated space distributions, domes, vaults, high ceilings, aisles, chapels and flat rear wall. All these recurring aspects contribute to create phehomena as long reverberation times, coupled volume effects, echoes, sound focusing defects, weak early reflections and insufficient sound clarity [1–3]. The diversity of worship buildings can lead to different source-receiver setups during an acoustic measurements campaign, making the results hardly comparable. Spanish and italian researchers have performed several acoustic surveys to propose some common guidelines [4–6]. Only a proper comparison among results allows to improve the knowledge of sound propagation inside this kind of buildings. The case study of this paper is a former church in Budrio, near Bologna (Italy), that was converted into an auditorium around 40 years ago, as frequently occurs given the large number of unused worship spaces on Italian territory [7, 8]. Now the hall is used as concert hall due to the presence of a historical piano ; nevertheless people's complaints and musicians' opinions raised the issue about a bad acoustics. The aim of the present work is the acoustic design of a chamber music hall inside the former church. Target parameters provided by previous studies were used as the reference point for the acoustic improvement [9, 10]. The sound energy distribution both of initial conditions and the design setting were analyzed and discussed, according to predictive models of literature [11–16].

2 Sound energy distribution in churches

According to the semi-reverberant theory, in a room the sound field is a combination of a direct component and a reverberant one. Strength parameter G, that is the difference between the sound pressure level at a certain distance r and the reference chosen, is expressed as :

$$G(r) = 10 \log \left(d + 31200 \frac{T}{V} \right) \quad (\mathrm{dB}) \tag{1}$$

where

- d is the sound energy of the direct sound, (Equation 4) ;

∗. dario.dorazio@unibo.it
†. giulia.fratoni2@unibo.it
‡. massimo.garai@unibo.it

- r is the source-receiver distance, in meters ;
- T is the reverberation time, in seconds ;
- V is the volume of the room, in m^3.

In their studies on concert halls, Barron and Lee observed that the total reflected sound level is affected by source-receiver distance and is not constant as the classical principles assume. In particular, it decreases moving towards the farthest rows of the audience. Their *revised theory* assumes that the total sound is composed of a direct sound component and a linearly decaying reflected component which starts when the direct sound arrives. The fact that the early energy weakens moving away from the source determines the main gap between the results pointed out by Barron and those values estimated using the semi-reverberant method. Barron and Lee's model takes into account three energy components : direct field (d), early reflections energy (e_r) and late reflections energy (l) assuming a threshold of 80 ms as the limit between early and late reflections. In Barron and Lee's revised theory the total sound pressure level G_{BL} and the early-to-late sound index $C_{80,\mathrm{BL}}$ expressions are [11] :

$$G_{\mathrm{BL}}(r) = 10\log\Big(d + e_r + l\Big) \quad (\mathrm{dB}) \tag{2}$$

$$C_{80,\mathrm{BL}}(r) = 10\log\Big(\frac{d + e_r}{l}\Big) \quad (\mathrm{dB}) \tag{3}$$

where

$$d = \frac{100}{r^2} \tag{4}$$

$$e_r = \Big(31200\frac{T}{V}\Big)e^{-0.04r/T}\big(1 - e^{-1.11/T}\big) \tag{5}$$

$$l = \Big(31200\frac{T}{V}\Big)e^{-0.04r/T}e^{-1.11/T} \tag{6}$$

The architecture of a church may be more articulated than an auditorium and thus, early reflections are even weaker than the predicted by the revised theory. Infact, the presence of elements such as chapels, aisles, apses and columns, contributes to a considerably attenuation of the early reflected energy by increasing the source–receiver distance.

Applying Barron's revised theory to churches Sendra *et al.* [12] proposed the introduction of a β factor in the negative exponential attenuation of reflected sound energies of equations 5 and 6. An empirical evaluation led to a range of $\beta = 0.06 \div 0.12$, where β values increasing with the complexity of the building. Nevertheless, this prediction model's weakest point is that β coefficient affects both early and late reflected energies without any distinction.

Zamarreño *et al.* [13] tried to balance this lack of accuracy suggesting a predictive formulation known as μ–model. The coefficient μ, as the β factor, was empirically derived in order to minimize the difference between measured and simulated values and it was determined specifically for a sample of Mudejar–Gothic churches, located in the South of the Spain : a factor $\mu = 0.13$ proved suitable for this particular kind of worship spaces. According to Zamarreño *et al.* the formulation of G_μ and $C_{80,\mu}$ may be rewritten as :

$$G_\mu(r) = 10\log\left(d + e_\mu + l\right) \quad (\mathrm{dB}) \tag{7}$$

$$C_{80\mu}(r) = 10\log\Big(\frac{d + e_\mu}{l}\Big) \quad (\mathrm{dB}) \tag{8}$$

where

$$e_\mu = 31200\frac{T}{V}e^{-\mu r/T}(1 - e^{-13.82\tau/T}) \tag{9}$$

and l is the late energy of Barron's revised theory (Equation 6).

The *modified theory* suggested by Cirillo and Martellotta outlines sound energy distribution inside churches defining G_{CM} and $C_{80,\mathrm{CM}}$ [14] :

$$G_{\mathrm{CM}}(r) = 10\log\left(d + E_0^{80} + l\right) \quad (\mathrm{dB}) \tag{10}$$

$$C_{80,\mathrm{CM}}(r) = 10\log\Big(\frac{d + E_0^{80}}{l}\Big) \quad (\mathrm{dB}) \tag{11}$$

where

$$E_0^{80}(r) = i_E + i_L - l \tag{12}$$

$$i_E(r) = t_R\Big(\frac{\gamma d + g_R}{2}\Big) \tag{13}$$

$$i_L(r) = \Big(31200\frac{T}{V}\Big)e^{-(0.04+13.8\rho)r/T} \tag{14}$$

$$g_R(r) = \Big(31200\frac{13.8}{V}\Big)e^{-(0.04+13.8\rho)r/T} \tag{15}$$

where $t_R(r)$ is the time delay in which the early reflected energy linearly decreases according to this theoretical model. The interval $t_R(r)$ depends on both the source-receiver distance r and the church typology factor ρ :

$$t_R(r) = \rho r \quad (\mathrm{s}). \tag{16}$$

The factor γ is expressed as :

$$\gamma \;=\; \frac{(1-\alpha)(1-s)}{\Delta\tau} \quad (\mathrm{s}^{-1}) \tag{17}$$

with α and s as the mean absorption and scattering coefficients, $\Delta\tau$ as the time gap between the direct sound and the first reflection, assumed as the ratio of mean free path and sound speed :

$$\Delta\tau = \frac{4V}{cS} \quad (\mathrm{ms}). \tag{18}$$

Successively, Martellotta refines the formulation of the *modified theory* by replacing the previous linear model with a double–rate decay as a linear combination of two exponential decay functions [15]. This model, which may be called *refined*, provides a simpler mathematical formulation without significantly affecting the prediction accuracy of the energy–based acoustic parameters. According to the refined model, the reflected energy function is expressed as follows :

$$g'(t) = A_1 e^{-13.8t/T_1} + A_2 e^{-13.8t/T_2} \tag{19}$$

where

- $T_1 = T$ and $A_1(r) = (13.8\ 31200/V)e^{-0.04r/T}$ so the first decay coincides with the exponential decay of Barron and Lee's revised theory ;
- $T_2 = 6.9\ t_R = 6.9\ \rho r$ is a convenient value because the centre of gravity of the second exponential falls in the middle of the t_R interval ;
- $A_2(r) = 100\gamma/r^2 - (13.8{\cdot}31200/V)e^{-0.04r/T}$ is the linear parameter defined in order to obtain the initial value of g' equal to γd.

Consequently, the early reflected sound and the late reflected sound are given by :

$$E_0^{\prime 80}(r) = E_0^{80} + (A_2 \rho r/2)(1 - e^{-0.16/\rho r}) \qquad (20)$$

$$E_{80}^{\prime \infty}(r) = E_{80}^{\infty} + (A_2 \rho r/2)e^{-0.16/\rho r} \qquad (21)$$

allowing to calculate G and C_{80} by means of eq. 10 and 11.

Berardi *et al.* [16] compared the different models mentioned above and provided a unified treatment to choose the models' parameters. With the premise of similar μ parameters expected for churches with similar characteristics, a scale of μ–values was proposed according to typological features, starting from $\mu = 0.08$ for compact spaces with an increment of 0.08 corresponding to any additional structural complexity. Berardi *et al.* validated the generalized μ–model using a second set of churches, comparing the revised theory, the refined theory and the generalized μ–model. They found on one hand that the refined theory confirmed to be the most accurate prediction model but also the one that needs more input data. On the other hand, the generalized μ–model requires less parameters to know, proving to be the ideal prediction model when limited data are available.

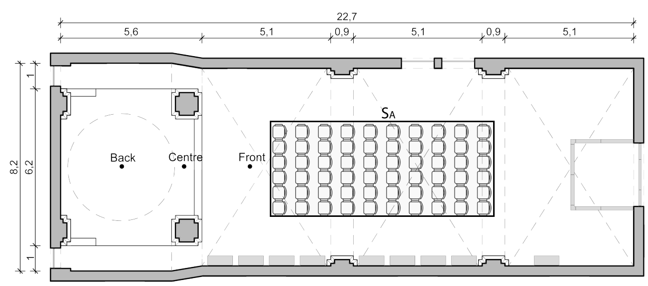
3 The case study

The auditorium is a former Catholic church, built between 1510 and 1517 and located in the centre of Budrio, a town near Bologna (Italy). It had been used in different ways over the years and finally, in 1970s, a considerable refurbishment led the architecture to the current status. The aspect of the hall is that of a small-sized single nave church. The auditorium is divided in two differents volumes, the vaulted nave and the dome volume, as shown in figure 1. Even if walls and ceilings plastered surfaces have the same physical properties of a typical traditional European chamber hall, the audience area $S_A = 30\ (\mathrm{m}^2)$ gives a ratio $\dfrac{V}{S_A} = 50\ (\mathrm{m})$ that is higher than chamber music halls studied by Hidaka and Nishihara [9]. In 2011 a Érard piano - France, 1878 - was donated to the auditorium ; there are very few similar exemplars and thus it's quite rare to have the chance to play an old piano like this. Nevertheless, complaints by people and musicians raised the issue of an insufficient sound clarity during the concerts.

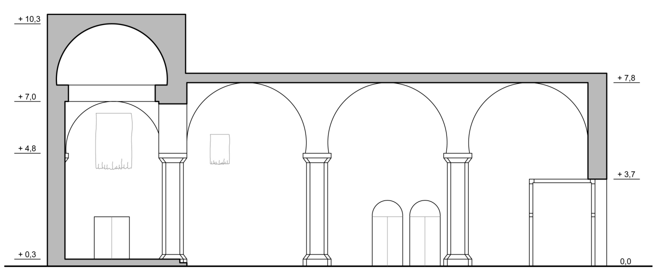
On March 2016 a measurement campaign was carried out in order to investigate the acoustical characterization of the hall. Both monoaural and binaural techniques were employed to define all necessary room criteria. Impulse responses (IRs) were acquired in an unoccupied state according to ISO 3382 [17]. The equipment was made up of a MacBook that launched the Exponential Sine Sweep signal (256K length at 48 kHz) [18] and performed the post processing work, an audio interface as signal converter (RME fireface 800), an high SPL dodecahedron [21] powered with Crown 2500 W, three monoaural half inch free-field microphones (Bruel&Kjaer 4190) and a spherical microphone (Schoeps KFM6). Complying with the guidelines provided by previous studies [4], one source position was placed in the nave, another one under the dome and the last one in the middle of these areas, in order to study the behavior changes depending on the volume the source is placed in. Due to the intended purpose as chamber music hall, the aim is to consider different kinds of possible instrumental setup, spanning from a

Table 1: Auditorium general characteristics. Subscripts "hall" and "dome" mean that respectively the nave or the dome volume is considered (see section in figure 1(b)).

Feature	ID	Value
Length (m)	L	23
Width (m)	W	8
Hall's height (m)	H_{hall}	8
Dome's height (m)	H_{dome}	10
Hall's volume (m^3)	$V' = V_{hall}$	1100
Dome's volume (m^3)	V_{dome}	400
Total volume (m^3)	$V = V_{hall} + V_{dome}$	1500
Total surface (m^2)	S	850
Floor surface (m^2)	S_{floor}	184
Number of seats	N	60
Audience area (m^2)	S_A	30



(a) Plan of the church. Sound source positions.



(b) Longitudinal section of the church. Proportions between the dome volume and the hall volume are shown.

Figure 1: The case study : plan and section layouts.

Table 2: Measured room criteria. Results are provided for *Front*, *Centre* and *Back* source positions, averaged over all the receivers points. "M" and "3" subscripts identify those values averaged over the central octave bands, respectively $500 \div 1000$ Hz and $500 \div 2000$ Hz. "E" and "L" (standing for Early and Late) indicate integration extremes : from 0 to 80 ms or from 80 ms to ∞. The occupied values are simulated according to absorption coefficients reported in studies concerning the occupancy within concert halls [19]. LEV was calculated according to Beranek formulation [20].

Source	$T_{30,M,occ}$ (s)	$EDT_{M,unocc}$ (s)	$C_{80,3}$ (dB)	BR_{occ}	$T_{S,3}$ (ms)	$G_{E,M,unocc}$ (dB)	1-$IACC_{E,3}$	*LEV* (dB)
Front	1.93	2.32	-1.2	1.4	151	14.3	0.68	7.1
Centre	1.94	2.38	-2.1	1.4	163	12.9	0.72	6.9
Back	1.94	2.44	-3.4	1.4	180	11.1	0.72	6.6

piano concert to a quintet (Figure 1(a)) :

- *Back* in the barycentre of the domed zone, corresponding to the piano in concert configuration ;
- *Centre* along the same longitudinal axis and between the columns, representing a singer or woodwinds position ;
- *Front* closer to the audience area, in the place of the strings.

Thirty positions were chosen alternating seats and creating a receivers grid. According to ISO 3382-1 [17] the dodecahedron and all the receivers were placed at 1.5 m and at 1.2 m above the floor. The impulse responses were treated with an octave-band filtering process and all the final results were extracted with Matlab software [22–24]. Data thus gained were averaged over all receivers points and they are provided in table 2.

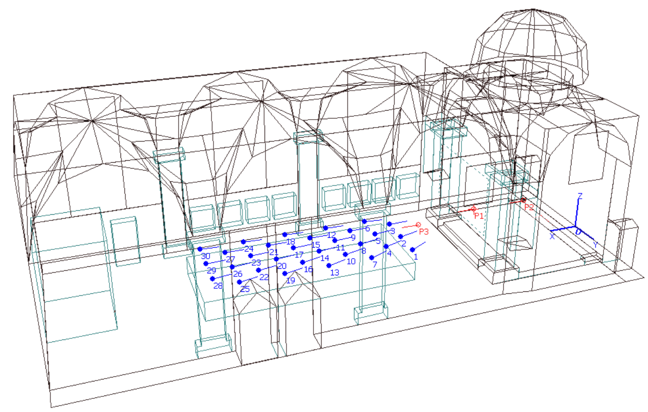


Figure 2: Calibration layout in Geometrical Acoustics (GA) simulation. View of sources and receivers inside the 3D model.

4 Acoustic design

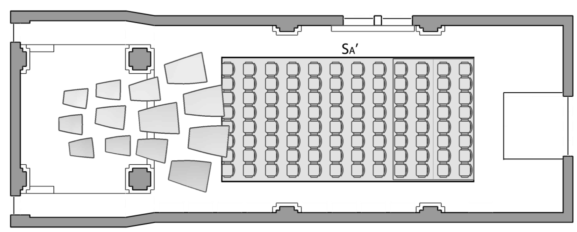
Results found out through measurements campaign show reverberation values inappropriate for the purpose of the hall, both the EDT, linked with sound perception, and the objective T_{30} index. The aim is to modify the current room criteria in order to bring them closer to the target values, considering both the parameters for chamber music halls and the optimal values for churches as reference points (see table 3).

Measured values of C_{80} show negative values and a strong fluctuation throughout the space : values obtained in *Back* source position are the lowest because of the greater source-receiver distance while *Front* source position records the highest values, the only ones within an acceptable range. The whole analysis leads to define the acoustic quality of the hall as unsuitable, consequently an intervention design was elaborated to enhance it. Strengthening the early reflected energy, especially in the farthest rows, is one of the main tasks in this work.

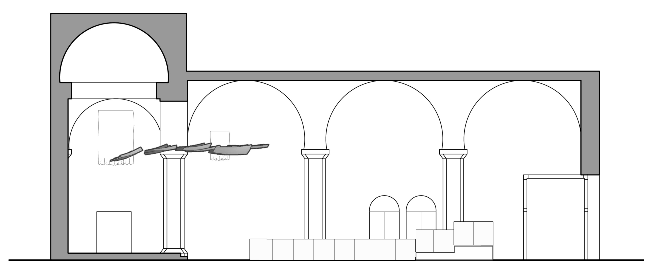
According to guidelines [25, 26] a numerical model was realized (Figure 2). The calibration was considered completed when simulated room criteria were within the Just Noticeable Difference (*JND*) of each index evaluated (see table 4) [27]. Scattering and absorption coefficients applied to the surfaces are provided in table 5.

The acoustic correction includes the introduction of :

1. an array of hanging reflecting panels ;
2. a carpet all over the floor ;



(a) Proposal layout : plan.



(b) Proposal layout : longitudinal section.

Figure 3: Acoustic treatment : additional audience area from $S_A = 30$ (m^2) to $S'_A = 50$ (m^2) and reflectors array, wooden platform and carpet all over the floor.

3. an additional audience area, increasing from $S_A = 30\ \mathrm{m}^2$ for 60 seats to $S'_A = 50\ \mathrm{m}^2$ for 96 seats ;
4. two wooden steps under the last four rows of seats.

The design proposal aims to enhance early reflections [28], avoiding echo–flutter phenomena and decrease re-

Table 3: Target values taken as reference point for the acoustic design. The first line provides the optimal values for chamber music halls parameters according to studies by Hidaka and Nishihara [9]. The second and the third lines respectively provide the optimal values for music and speech indices inside a worship space when used as multi–purpose hall according to studies by Berardi [10]. "M" and "3" subscripts identify those values averaged over the central octave bands, respectively 500 ÷ 1000 Hz and 500 ÷ 2000 Hz. "E" and "L" (standing for early and late) indicate integration extremes : from 0 to 80 ms or from 80 ms to ∞.

$T_{30,M,occ}$ (s)	$EDT_{M,unocc}$ (s)	$C_{80,3}$ (dB)	$C_{50,M}$ (dB)	BR_{occ}	$T_{S,3}$ (ms)	$G_{E,M}$ (dB)	G_M (dB)	LF	$1\text{-}IACC_{E,3}$	LEV (dB)	Ref.
< 1.6	1.5÷1.7	0÷2	–	1.0÷1.2	< 120	> 4	–	–	> 0.6	> 7	[9]
–	2.1÷4.2	–	> -6	1.1	< 300	–	> 3	> 0.25	0.65	–	[10]^1
–	0.8÷1.0	–	> 0	1.05	< 150	–	> 0	> 0.20	0.65	–	[10]^2

^{1} Music, ^{2} Speech.

Table 4: Model calibration : all the differences between measured and simulated values are within the JND provided by ISO 3382 (T_{30} and EDT=5 %, C_{80}=±1 dB) [17]. All the values are considered in unoccupied state. "M" and "3" subscripts identify those values averaged over the central octave bands, respectively 500 ÷ 1000 Hz and 500 ÷ 2000 Hz.

Source	Measured			Simulated			Differences		
	$T_{30,M}$ (s)	EDT_M (s)	$C_{80,3}$ (dB)	$T_{30,M}$ (s)	EDT_M (s)	$C_{80,3}$ (dB)	$T_{30,M}$ (s)	EDT_M (s)	$C_{80,3}$ (dB)
Front	2.35	2.32	-1.2	2.40	2.37	-0.4	0.05	0.05	0.8
Centre	2.37	2.38	-2.1	2.36	2.44	-2.3	0.01	0.06	0.2
Back	2.36	2.44	-3.4	2.35	2.51	-3.1	0.01	0.07	0.3

verberation time. The increase of audience area, beside removing a part of reverberant field by absorbing at medium–high frequencies, allows to increase the ratio $\frac{V}{S'_A} = 30\,(\mathrm{m})$ instead of the initial value $\frac{V}{S_A} = 50\,(\mathrm{m})$, getting closer to values that are typical of chamber music halls [9]. The wooden platform behave like a low frequencies absorber and at the same time it improves perceived sound in the farthest seats by putting them into a raised position. Sound absorbing surfaces, such as the carpet, were conceived on the lower part of the hall and on the floor, in order to not affect side walls of the nave that give good results in terms of spaciousness criteria, such as $1 - IACC_{E,3}$ and LEV.

The array of hanging reflecting panels was introduced to shorten early reflections paths increasing early-to-late indicators. Moreover, reflectors are able to break the unwanted focussing effect due to vaults, to interrupt normal modes paths (changing the wave theory boundaries conditions) and vibrate at their own resonance frequency (absorbing sound energy in that octave band). In a reflectors array the relative density $RD = \frac{S_{panels}}{S_{tot}}$ (Eq. 25 in A-appendix), the number of panels N and their size S, in square meters, are peculiar factors to consider. The position chosen for the installation is above the three source positions *Front*, *Centre* and *Back*, comprising half of the dome volume and half of the first vault in the nave (Figure 3). The height of the whole reflectors system was settled at 5 meters above the floor according to musicians' requirements [29]. For panels material, the choice fell on a poly methyl methacrylate panel because it's a light and cheap material. In addition, each panel proved to be enough deformable to bend owing to its weight. Distinct configurations of the array were investigated to found out the best set up. Comparisons conducted among their behaviors show that :

- given a panel size S, the most efficient setting could be that one with the highest relative density RD ;
- given a relative density RD, the most efficient setting could be that one with the smallest size panel S.

The layout consisting of 13 panels ($RD = 50\%$ and $S < 2\,\mathrm{m}^2$) was selected as the optimal investigated configuration. In view of the central position of seats throughout the nave, lateral surfaces within the array are tilted, in order to direct sound precisely towards the listeners and curved surfaces were chosen to better diffuse sound throughout the area concerned (see figure 3 for the array final layout and table 6 for simulated results of the whole acoustic intervention).

Simulated post-operam results are in line with Rindel's theory about arrays of reflectors (see A–appendix) [32]. The fact that small panels give better effects is confirmed by calculations of f_g values (see equation 22 in A–appendix) for the panel size selected. Choosing small panels (see figure 3) only the octave band of 4000 Hz may be affected by the dependence on the single panel contribution, while in the remaining frequency range there is not difference whether the sound ray hits the single reflector or not. At the same time, the relative density value as $RD = 50\%$, an optimal value found in previous references, may allow to obtain a reflected amount of energy that is only 6 dB weaker than an ideal reflection [32].

5 Discussion

Literature about sound energy predictive models generally considers the whole volume of the enclosed space V [11–16]. Concerning the opera houses, Hidaka [9] and Prodi *et al.* [33] suggested the use of the main hall volume only without the

Table 5: Scattering and absorption coefficients chosen for the simulation are selected from scientific literature. In the first group of elements there are the pre–existing materials, in the second group there are the new elements introduced with the acoustic design proposal, in the third group there are the conditions to simulate the occupied state. Scattering values are provided at the mid–frequency 707 Hz, according to Odeon's algorithm.

Material	Scattering	Absorption						Ref.
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	
Floor	0.05	0.01	0.01	0.02	0.02	0.03	0.03	[26]
Seats	0.70	0.35	0.40	0.41	0.38	0.33	0.27	[19]
Plaster	0.10	0.01	0.02	0.03	0.04	0.03	0.02	[30]
Curtains	0.05	0.10	0.15	0.25	0.30	0.30	0.30	[31]
Reflectors	0.50	0.08	0.08	0.03	0.01	0.01	0.01	[30]
Carpet	0.05	0.10	0.15	0.20	0.30	0.40	0.45	[30]
Wooden steps	0.20	0.40	0.40	0.30	0.15	0.15	0.15	[31]
Occupied seats	0.70	0.47	0.59	0.67	0.70	0.72	0.76	[19]

Table 6: Comparison between ante–operam measured values and post–operam simulated values for acoustic criteria. Results are averaged over all the sources and receivers positions. "M" and "3" subscripts identify those values averaged over the central octave bands, respectively 500 - 1000 Hz and 500 - 1000 - 2000 Hz. "E" and "L" (standing for early and late) indicate integration's extremes : from 0 to 80 ms or from 80 ms to ∞. The occupied values are simulated according to absorption coefficients reported in studies concerning the occupancy within concert halls [19]. Post–operam simulated values satisfy the target values of table 3 [9].

	$T_{30,M,occ}$ (s)	$EDT_{M,unocc}$ (s)	$C_{80,3}$ (dB)	BR_{occ}	$T_{S,3}$ (ms)	$G_{E,M}$ (dB)	$1\text{-}IACC_{E,3}$	*LEV* (dB)
Ante-operam	1.9	2.4	-2.2	1.4	165	13	0.7	7
Post–operam	1.4	1.6	0.9	1.2	102	14	0.7	7

flytower volume. Garai *et al.* proposed on an experimental basis the use of an "effective" acoustic volume of the hall "seen" by the sound source [34]. In other words in case of coupled spaces the spatial distribution of G may depend on the sound source position and consequently on the total volume of the coupled volumes excited.

The analysis of EDT/V vs G diagrams led to the hyphotesis that each source position is affected by its own part of the total volume.

Measured values tend to fit the theoretical curves only when the "effective" acoustic volume is taken into account for each sound source. For instance, with reference to figure 4, assigning the value of $V' = V_{hall}$ (see table 1) for *Front* source, $V'' = V_{hall} + \frac{V_{dome}}{2}$ for *Centre* source and $V = V_{hall} + V_{dome}$ (see table 1) for *Back* source, ante–operam measured values distribution fit better the slope of theoretical Beranek's trend [35] and the Hidaka and Nishihara's experimental one [9].

Therefore, in the below assessment on the accuracy of prediction models, compared with measured values and simulated ones, two "effective" values are taken into account, the total volume V and the partial volume of the hall V_{hall}.

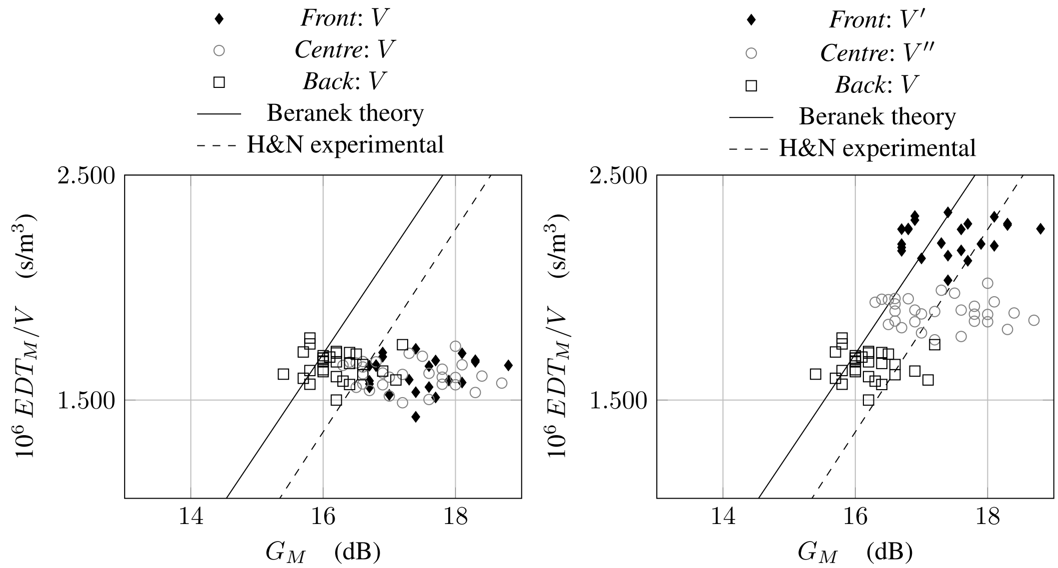
Applying the refined theory and the generalized μ–model to the case study, the chosen parameters are :

- $k = 0.7$ and $\mu = 0.08$ (see table VI in ref. [16]) ;
- $\rho = 0.002$ as a consequence of the choice made for k ($\rho = k/c$ according to table III in ref. [14] ;
- $\Delta\tau = 21$ ms (see eq. 18 and table 1) ;
- $s = 0.2$ (see table IV in ref. [14]) ;
- $\bar{\alpha} = 0.12$ (given the data provided in table 1 and $T_{30,M,unocc} = 2.36$ (s) as measured reverberation time) ;
- $\gamma = 34$ (s^{-1}) as a consequence of the parameters mentioned before (see eq. 17).

The performances of predictive models were compared by RMS errors according to Berardi *et al.*'s studies [16]. Figure 7 provides differences both with ante–operam measured values and post–operam simulated ones.

Results show that the generalized μ–model proved the most reliable for predicting the acoustic initial conditions of the church ante–operam (gray bars in figures 7(a) and 7(c)). A simplified model like this one probably is the ideal one to consider in case of a quite regular volume, such as the church in study. RMS errors analysis revealed also a general different trend between G_M and $C_{80,3}$: sound strength values are affected by the volume chosen in the calculations while clarity values are not, possibly because the sound field is so reverberant that the volume considered is not significant in the whole energy behaviour. Moreover, taking into account only G_M values, Barron's revised theory proves more sensible to the volume selected than the other two predictive models, that are specifically conceived for articulated spaces with complex coupled volumes, like churches are.

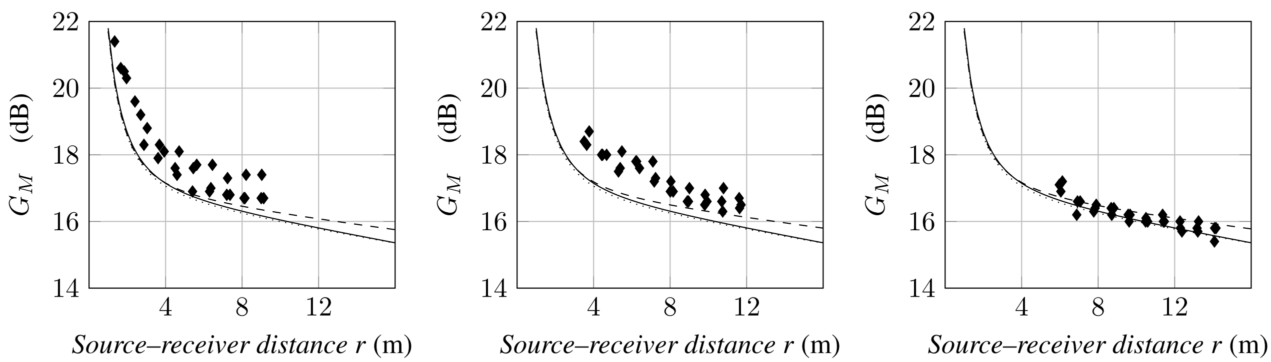
About chamber music halls in former churches a further evaluation is on the simulated effects of the acoustic intervention. The reflectors array, designed following Rindel's guidelines, makes the sound energy distribution much similar to that one of a chamber music hall (white bars in figure 7(b),



(a) Constant volume value V.

(b) "Effective" volume values V', V'' and V.

Figure 4: EDT_M/V vs G_M ante–operam measured values compared with Beranek's theoretical curve [35] and Hidaka and Nishihara's (H&N) experimental one [9]. In figure 4(a) total V was used for all the sources positions. In figure 4(b) values were derived considering the "effective" volume for each sound source position : V' (see table 1) for *Front* position, V'' for *Centre* position, V (see table 1) for *Back* position.

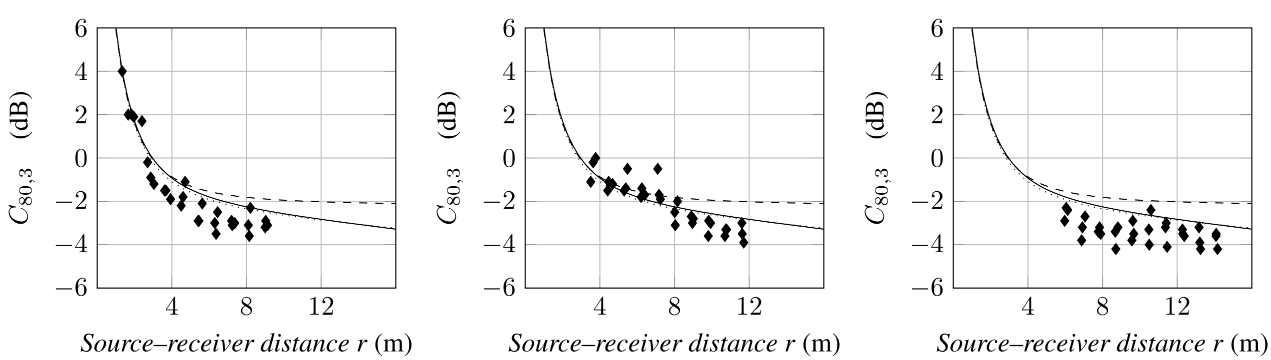


(a) *Front* sound source position

(b) *Centre* sound source position

(c) *Back* sound source position

Figure 5: Comparison between Barron and Lee's revised theory curve (dashed line, see eq. 2), Martellotta's refined theory curve (solid line, see eq. 10), Berardi *et al.*'s generalized μ–model when $\mu = 0.08$ (dotted line, see eq. 7) and ante–operam measured G_M values considering the sound source in *Front*, *Centre* and *Back* positions (see the plan in figure 1(a)).

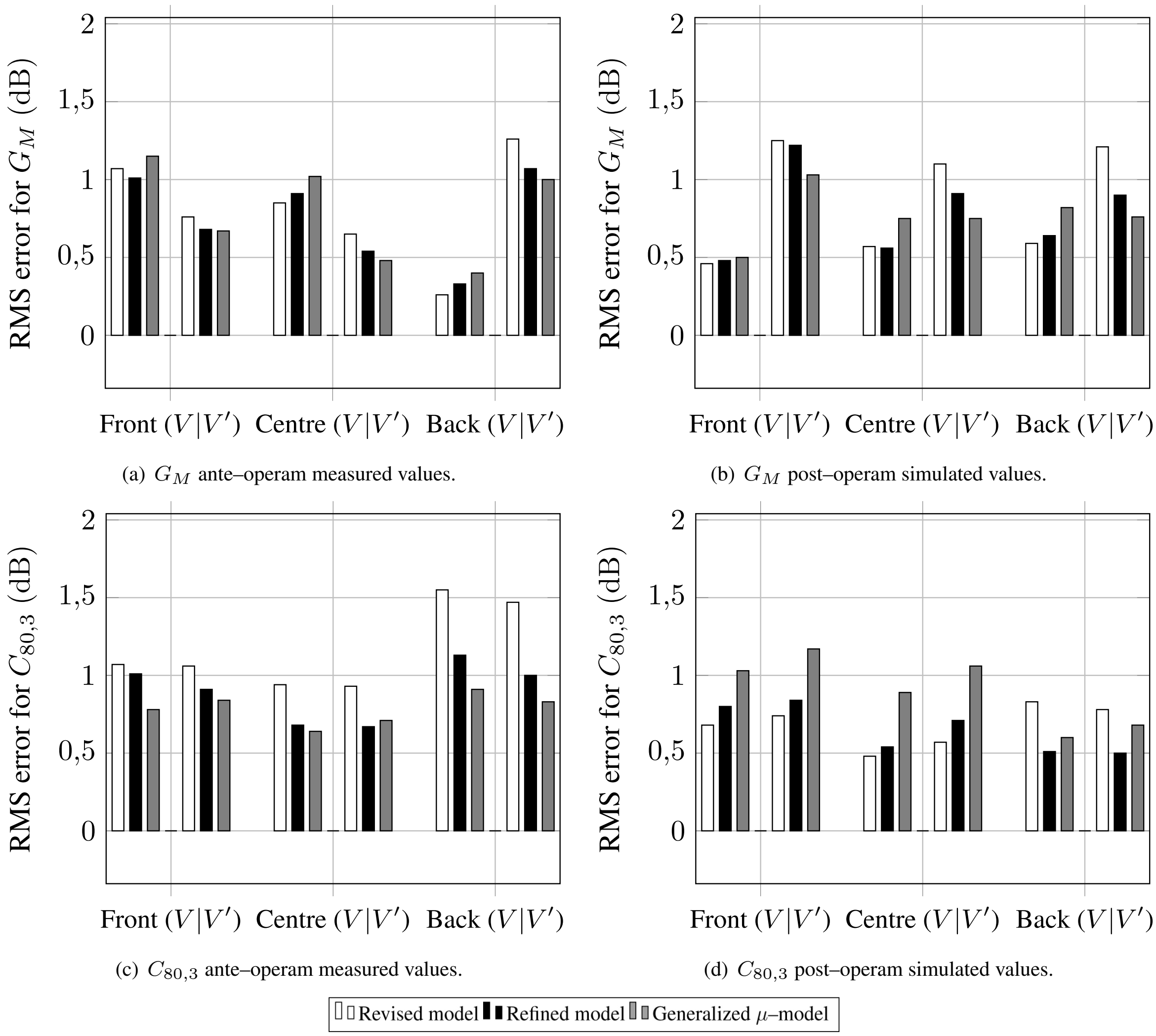


(a) *Front* sound source position

(b) *Centre* sound source position

(c) *Back* sound source position

Figure 6: Comparison between Barron and Lee's revised theory curve (dashed line, see eq. 3), Martellotta's refined theory curve (solid line, see eq. 11), Berardi *et al.*'s generalized μ–model when $\mu = 0.08$ (dotted line, see eq. 8) and ante–operam measured C_{80} values considering the sound source in *Front*, *Centre* and *Back* positions (see the plan in figure 1(a)).



(a) G_M ante–operam measured values.

(b) G_M post–operam simulated values.

(c) $C_{80,3}$ ante–operam measured values.

(d) $C_{80,3}$ post–operam simulated values.

Figure 7: Comparison among RMS errors for G_M and $C_{80,3}$ derived from the revised theory (see eqs. 2, 3), refined theory (see eqs. 10, 11) and generalized μ–model (see eqs. 7, 8) with ante–operam measured values and post–operam simulated values. Theoretical values are calculated using the total volume (V) and the volume of the hall (V').

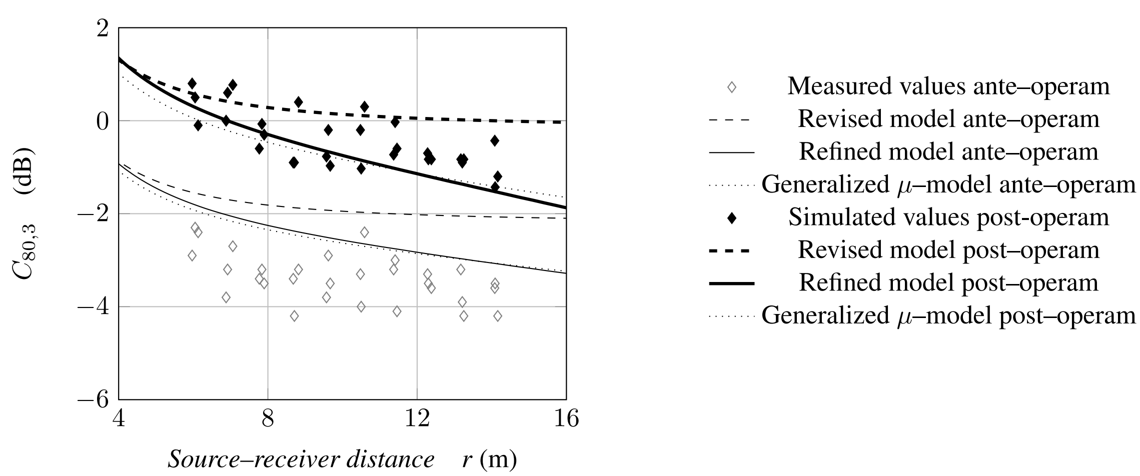


Figure 8: $C_{80,3}$ trends changes before and after treatments for *Back* source position (see the plan figure 1(a)), compared with Barron and Lee's revised theory (see eq. 3), Martellotta's refined theory (see eq. 11) and Berardi *et al.*'s generalized μ–model curves (see eq. 8). Predictive curves are calculated with appropriate reverberation time values : ante–operam $T_{30,M,unocc} = 2,36$ s and post–operam $T_{30,M,unocc} = 1,65$ s.

considering V). For the same reason, in figure 7(d), predictive values derived from the generalized μ–model for churches show the biggest difference with post–operam simulated values.

Figure 8 compares the behaviours of spatial distributions of C_{80} before and after the treatment : ante–operam values are closer to the refined theory curve, while post–operam values raise towards the curve of revised theory (from 1.5 dB to 0.8 dB as RMS error, as shown in figure 7).

6 Conclusions

The paper concerns the renovation of a former church used as a chamber music hall. A preliminar measurements campaign was performed in the case study according to ISO 3382–1 confirming inadequate reverberation times and an insufficient sound clarity, peculiar traits inside worship buildings.

In addition to the achievement of target values for chamber music halls, the validation of the acoustic intervention was carried out with a methodology based on sound energy distribution analysis. This approach led to a design proposal able to give the space the appropriate acoustic conditions for the purpose. Post–operam simulated results show how the acoustic treatments, above all the reflectors array, could change the global behavior of sound distribution throughout the space : from typical church acoustic features (refined theory and generalized μ–model prediction curves) to an acoustic quality worthy of a chamber music hall, in line with Barron and Lee's revised theory.

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Appendix A. Diffraction from a reflectors array

Reflectors are devices specifically designed for fortifying the early reflected sound energy, which plays a crucial role in affecting sound perception. A system of more components separated from each other by gaps is more effective rather than an entire continuous surface because it could happen that "strong directional reflections may cause the specularity effect of comb filtering and image shifting, because the specular reflections contain the same frequency content as the direct sound and are displaced in time" [32]. An array solution allows to avoid these undesired effects thanks to the gaps among the panels. The amount of open area, i.e. the relative density RD of panels, is a property able to optimize reflectors performance. Rindel investigated the case of five rows of rectangular flat reflectors, placed at the same height above the floor in a x-y plane, in order to found out how diffraction phenomena reduce reflected energy at the different frequencies. A sound wave is emitted from a source S and it arrives to a receiver R after being reflected on the overhead canopy.

Frequency response is divided in two fields, determined by f_g :

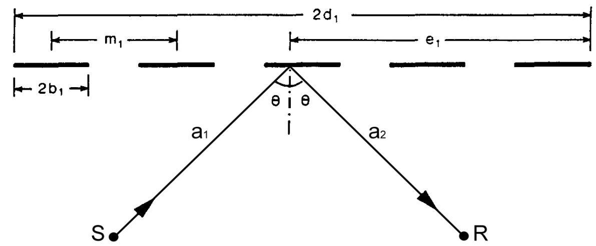

Figure 9: Specular reflection from an array of reflectors with five rows of panels [32].

$$f_g = \frac{ca^*}{2Scos\theta} \quad \text{(Hz)} \tag{22}$$

where

- c is the sound velocity in the air at 20° C, assumed as $343\ \mathrm{m/s}$;
- S is the surface area, in m^2 ;
- $a^* = \dfrac{2a_1 \cdot a_2}{a_1 + a_2}$ is the characteristic distance in meters, a sort of average between source-panel and panel-receiver paths (see fig. 9) ;
- θ is the angle of incidence (see fig. 9).

Above f_g, it's significant the contribution of the single reflector because at high frequencies there are strong local variations whether the sound ray geometrically hits the surface or not. Below f_g, instead, the role played by the single component becomes less relevant because at low frequencies what it's significant is just the relative density RD of the whole array system. The attenuation due to diffraction has the following expression :

$$\Delta L_{diffr} = 10 \log K = 10 \log K_1 K_2 \quad \text{(dB)} \tag{23}$$

where

- K is a quantity less than 1 that reduces the energy reflected from an ideal infinite surface, which is taken as reference point ;
- K_1 and K_2 respectively correspond to x and y direction sections of reflectors system.

In view of the difference between high and low frequencies, Rindel proposed this approximation :

$$K = RD^2 \qquad \text{for } f \leq f_g \tag{24}$$

Here RD is the relative density, defined as

$$RD = \frac{S_{panels}}{S_{tot}} \tag{25}$$

where S_{panels} is the area of all the reflectors and S_{tot} is the total area covered by the array. This model was convalidated by Rindel with experimental measurements.

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