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PREDICTING ENERGY-BASED ACOUSTIC PARAMETERS IN CHURCHES: AN ATTEMPT TO GENERALIZE THE μ-MODEL

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Abstract

The paper describes the application of an energy model, already tested on Spanish churches, to a different and larger group. Its simplicity allows fast prediction of every energy parameter, provided that its corrective parameter μ is known. The results of an acoustic survey carried out in more than thirty Italian churches are used in order to try to generalize the model. Different values of the μ-parameter are calculated by means of a semiempirical prediction of clarity. The study investigates in greater detail how the acoustic energy varies inside the churches. In fact, chapels, columns, trussed roofs or vaults scatter the reflections, resulting in weaker early reflections as the complexity of the church grows. The reduction observed is greater in large Italian churches than in small Mudejar-Gothic churches in Seville, showing the need to classify different values of the μ-parameter. Predicted values of some energy parameters calculated according to μ values show good agreement with experimental data. The proposed classification suggests a wider use of the model for churches of different typologies.

Keywords: Room acoustics, Acoustics of churches, Energy propagation, Energy prediction.

1 Introduction

The study of the sound field in places of worship, in any country, has recently aroused great interest within the general field of architectural acoustics. This interest rises from a practical nature, being connected with the growing demand for acoustical comfort in public spaces. Churches represent particular places where speech and music must cohexist both for liturgical and performing purposes. In addition, the studies on the acoustic of these complex and heterogeneous spaces aid the general understanding of room acoustics [1].

One of the most important topics of the acoustical research is the analysis and interpretation of the energy propagation in the space. Early analysis in churches have shown that these are complex spaces, in which architectural aspects, such as chapels, columns, trussed roofs or vaults determine a scattering of sound energy, and consequently a delay in the beginning of a purely diffuse exponential sound decay [2,3], possibly related to asymmetrical conditions of absorption [4]. In the last ten years different models have been proposed to interpret the energy decay in churches. A semiempirical one was proposed by Sendra *et al.* [5,6] according to regression of the measurements data in Mudejar-Gothic churches, then Cirillo *et al.* [7] has proposed a different model, originally conceived on Romanesque churches and recently, tested successfully on a wider type of churches [8].

This paper rises from the publication of a new model by Zamarreno *et al.* [9]. This last formulation, simpler than the previous, were tested on some Mudejar-Gothic churches located in Seville only [10], so in order to generalize its usage, an application to a wider sample is required. In particular the present paper aims at investigating the values assumed by the coefficient in the model, trying to define rules to assign it in different conditions.

2 Outline of the μ-model

The first model that provided mathematical relations to predict spatial variations of energy based parameters was proposed by Barron and Lee [11] who assumed that the reflected sound cannot arrive earlier than direct sound. Sendra *et al.* found some inaccuracies when predicting the acoustics of churches by means of this model, and ten years ago, proposed an alternative model, known as β-model [5,6], which reduced both the energy of early and late reflections, proportionally to a β coefficient which fictitiously increased source receiver distance. However, this uniform treatment led to an improved prediction accuracy for strength (G) but not for clarity (C80). So a further model, named μ-model, was proposed by Zamarreno *et al.* [9], who proposed to apply the fictitious distance increase (now represented by coefficient μ) only to the early reflections (from 0 to 80 ms). This assumption, aiming at improving the agreement between predicted and measured values, accepts a discontinuity in the decay curve. The authors justify this discontinuity, i.e. a step in the continuous loss of energy, with the discrete nature of the first reflections so that it would not be necessary to estimate a continuous ratio.

The μ-model requires a regression on the measured values of clarity (C80), in order to minimize the errors between estimation and prediction and maximize the correlation. The choice to perform the regression on this parameter, among the other energy ones, can be justified considering that it shows the largest variations inside a room, mostly depending on the arbitrary integration limit of 80ms. The resulting expressions to calculate sound strength, clarity and centre time according to the model are:

$$G_{\mu}\left(r\right)=10\log\left(d+e_{\mu}+l_{B}\right)=10\log\left\{\frac{100}{r^{2}}+31200\frac{T}{V}\cdot\left[e^{-\frac{\mu r}{T}}+e^{-\frac{1.11}{T}}\left(e^{-\frac{0.04r}{T}}-e^{-\frac{\mu r}{T}}\right)\right]\right\} \tag{1}$$

$$C_{80\mu}\left(r\right)=10\log\left(\frac{d+e_{\mu}}{l_{B}}\right)_{\tau=0.08}=10\log\left\{\frac{\dfrac{100}{r^{2}}+31200\dfrac{T}{V}\cdot e^{-\frac{\mu r}{T}}(1-e^{-1.11/T})}{31200\dfrac{T}{V}\cdot e^{-\frac{1.11+0.04r}{T}}}\right\} \tag{2}$$

$$T_{s\mu}\left(r\right)=\frac{\int_{0}^{0.08}t\cdot g_{\mu}(t,r)dt+\int_{0.08}^{\infty}t\cdot g_{\mu}(t,r)dt}{d+e_{\mu}+l_{B}} \tag{3}$$

where d, e_{μ}, l_B are respectively the direct sound, the integrated early reflected and late reflected energy, r is the distance between source and receiver, T is the reverberation time, V is the volume and g_{μ} is the energy density. As it can be observed, the volume of the room (V), the reverberation time (T), and the value of coefficient μ, are needed in order to determine every energy parameter in a given room.

The authors of μ-model expressed the wish to generalize "this methodology so that it can be applied to a wide range of architectural typologies whereby a range of values of μ capable of predicting the acoustic energy parameters from basic geometric and acoustic data of the space are provided". This is the main objective of the present paper. As observed in Fig. 1, using different μ values leads to larger variations in C80 than in G. In particular, it can be observed that above 0.35 no significant variation in both parameters takes place as a function of distance.

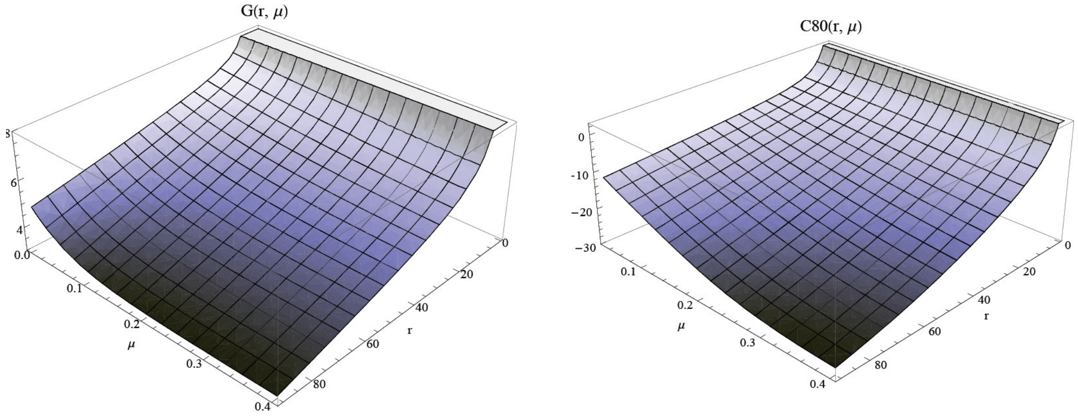


Figure 1 – Surfaces of strength (left) and clarity (right) according to μ model as a function of distance and μ-values. Room with volume of 30000m^3 and reverberation time of 5s.

3 Application of the model

3.1 Measurement technique

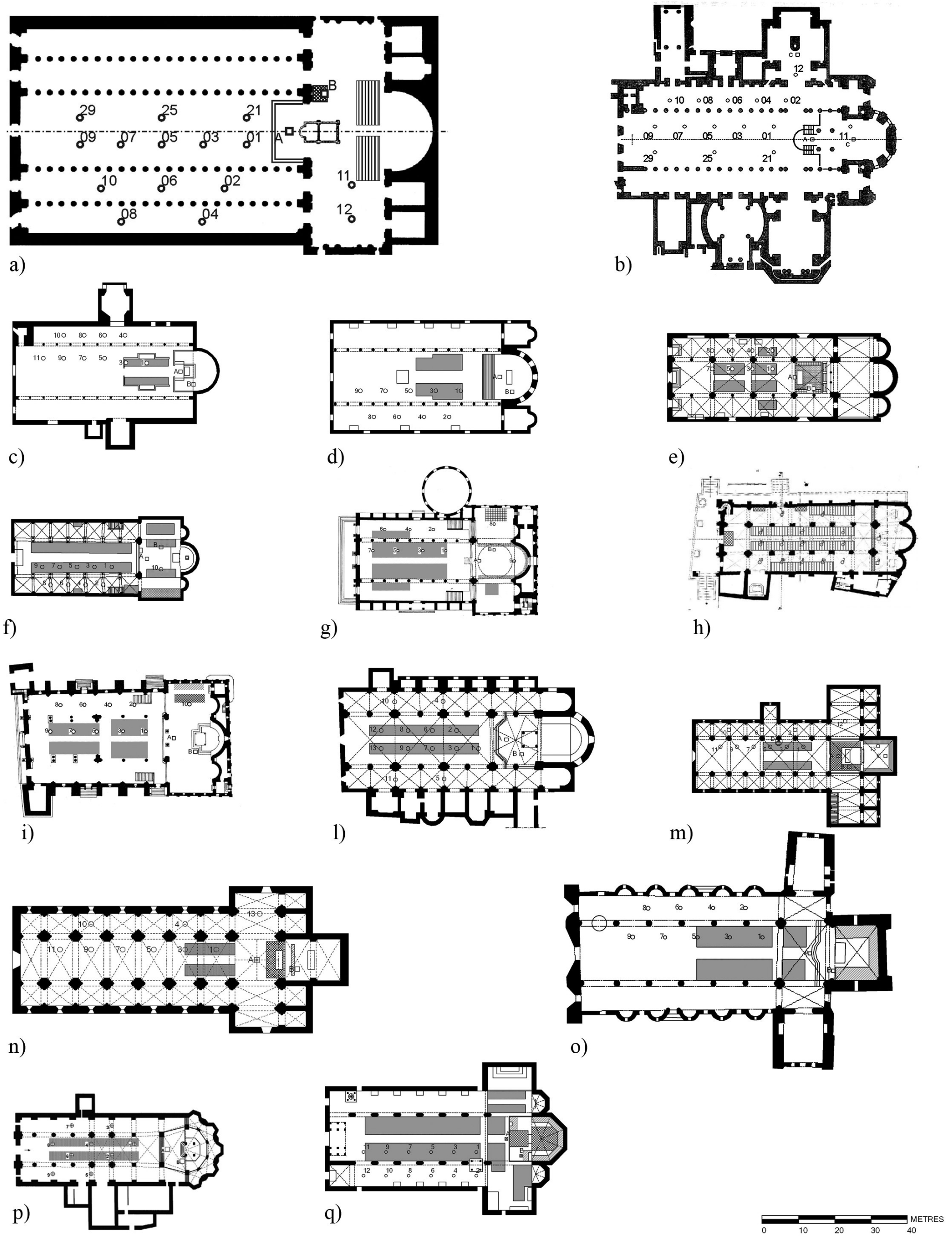
The measurements were carried out using an omni-directional sound source made of twelve 120mm loudspeakers, with a flat response up to 16 kHz, mounted on a dodecahedron, together with an additional sub-woofer to cover the lower frequencies, from 40 to 100 Hz. A calibrated measurement chain made by a GRAS 40-AR omni-directional microphone together with a 01 dB Symphonie system was used to measure the sound pressure levels. An MLS signal was used to get the calibrated impulse responses to obtain the strength values. The other acoustic parameters were obtained using high-quality impulse responses collected using a Soundfield Mk-V microphone, an Echo Audio Layla 24 sound card, and using a constant envelope equalized sine sweep to excite the room. In each church at least two source positions were used, one on the axis of symmetry and one off the axis, both placed 1.5m above the floor. Eleven receiver positions were used on average. In very large but symmetrical churches the receivers were only placed in one half of the floor, otherwise they were spread to cover the whole floor area uniformly. The microphone was placed 1.2m from the floor surface. All the measurements and the calculations of the indices were carried out according to ISO-3382 standard [12]. For the measurement of the sound strength, the sound power of the source was calibrated in a reverberation chamber, employing the same measurement chain and the same settings used during the on site survey.

3.2 Churches analyzed

Extensive acoustical measurements were carried out in thirty two churches located in Italy, chosen in order to analyze different typologies of buidings according to age, style, dimensions, volume, and interior finishing. The number of the churches makes impossible any extensive description of acoustical and architectonic aspects, which can be found in [13]. Table 1 reports only the mean geometrical data, while fig.2a-2b show the plans of the churches.

Table 1 – Basic geometric details of the thirty-one churches surveyed.

Church	Period	Style	Volume (m^3)	Total area (m^2)	Floor area (m^2)	Length (m)
S. Paolo Fuori Mura, Rome	383	Early-Christian	130000	33650	7500	130
St. Maria Maggiore, Rome	410	Early-Christian	39000	12000	2100	80
St. Sabina Basilica, Rome	432	Early-Christian	17500	6000	1290	52
St. Apollinare in Classe, Ravenna	549	Early-Christian	22500	7200	1450	57
Modena Cathedral	1099	Romanesque	20000	8000	1300	62
Trani Cathedral	1099	Romanesque	21500	8360	950	50
Bari Cathedral	1099	Romanesque	30100	9500	1260	50
SS. Sepolcro, Barletta	1178	Romanesque	7700	4050	815	49
St. Nicholas Basilica, Bari	1197	Romanesque	32000	10500	1570	59
St. Ambrogio, Milan	1197	Romanesque	23000	10200	1650	67
Abbey church of Chiaravalle	1136	Gothic	12500	7500	1250	59
Abbey church of Fossanova	1173	Gothic	17000	1000	1330	69
Barletta Cathedral	1262	Gothic	16000	6000	912	46
Duomo, Orvieto	1290	Gothic	78000	15000	2770	90
Lucera Cathedral	1301	Gothic	33100	10500	1700	64
St. Petronius Basilica, Bologna	1390	Gothic	160000	42000	7000	130
Basilica Laurentiana, Florence	1419	Renaissance	39000	18000	2750	83
Santo Spirito, Florence	1446	Renaissance	55000	19000	2900	94
Gravina Cathedral	1452	Renaissance	10500	4900	850	47
Sant'Andrea, Mantova	1472	Renaissance	78000	19000	2500	100
The Holy name of Jesus Church, Rome	1568	Renaissance	39000	13000	1450	68
St. Luke and Martina, Rome	1664	Baroque	8700	5500	450	30
Sant'Agnese in Agone	1672	Baroque	14000	5300	500	28
San Lorenzo, Turin	1680	Baroque	12000	4500	550	34
Basilica of Superga, Turin	1731	Baroque	22000	8000	650	46
Giovinazzo Cathedral	1747	Baroque	7900	3800	700	41
St. Martin Basilica, Martina Franca	1763	Baroque	16400	6500	830	45
Church Carmine, Bari	1964	Modern	9700	3000	760	46
Concattedrale, Taranto	1970	Modern	9000	6200	1300	58
S. Maria Assunta church, Riola	1978	Modern	5500	3700	650	34
Dives in Misericordia, Rome	2003	Modern	10500	4800	580	27
Padre Pio Pilgrimage church, San Giovanni	2004	Modern	50000	15600	4300	56



a) b) c) d) e) f) g) h) i) l) m) n) o) p) q)

Figure 2a – Plans of the churches surveyed: a) S. Paolo Fuori le Mura in Rome, b) St. Maria Maggiore in Rome, c) St. Sabina Basilica in Rome, d) St. Apollinare in Classe in Ravenna, e) Modena Cathedral, f) Trani Cathedral, g) Bari Cathedral, h) SS. Sepolcro in Barletta, i) St. Nicholas Basilica in Bari, l) St. Ambrogio, Milan, m) Abbey church of Chiaravalle, n) Abbey church of Fossanova, o) Duomo of Orvieto, p) Barletta Cathedral, q) Lucera Cathedral. (Same scale for all the churches).

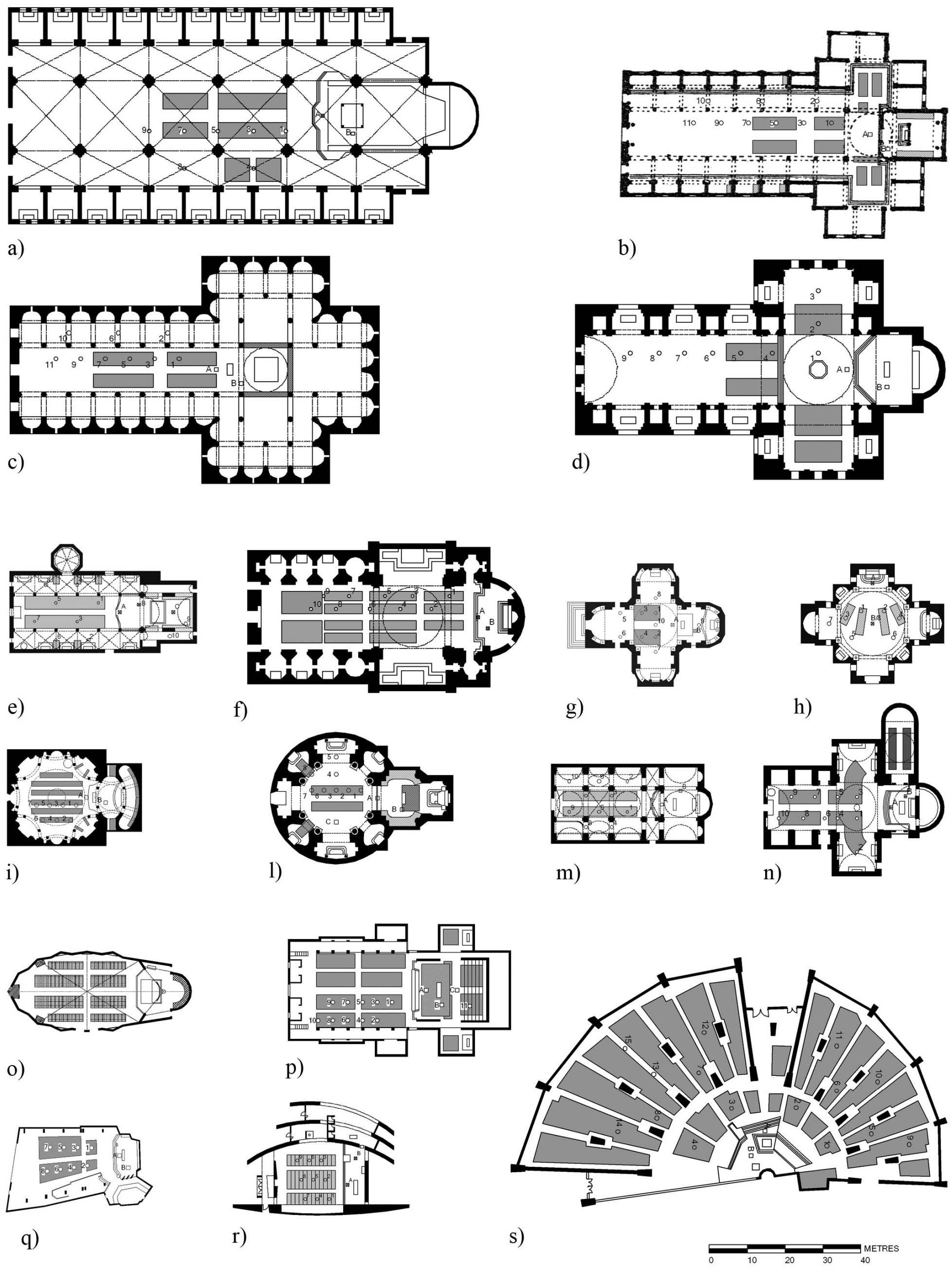


Figure 2b – Plans of the churches surveyed: a) St. Petronius Basilica in Bologna, b) Basilica Laurentiana in Florence, c) Santo Spirito in Florence, d) Sant'Andrea in Mantova, e) Gravina Cathedral, f) The Holy name of Jesus Church in Rome, g) St. Luke and Martina in Rome, h) Sant'Agnese in Agone, i) San Lorenzo in Turin, l) Basilica of Superga in Turin, m) Giovinazzo Cathedral, n) St. Martin Basilica in Martina Franca, o) Church Carmine in Bari, p) Concattedrale in Taranto, q) S. Maria Assunta church in Riola, r) Dives in Misericordia in Rome, s) Padre Pio Pilgrimage church in San Giovanni Rotondo. (Same scale for all the churches).

3.3 Generalization of the model

The original application of the μ model was to ten Mudejar-Gothic churches in Seville, to which corresponded a mean μ value of 0.13, with negligible difference among different churches (standard deviation σ equal to 0.02).

The first step was the application of μ model to the present survey. The analysis consisted in calculating the μ-value for each church by minimizing the rms error between measured and predicted values of C80 at 1 kHz as a function of source-receiver distance. The results are reported in table 2, together with the corresponding parameters required to apply the model. Coherently with the octave band chosen for C80, also T was referred to the same band.

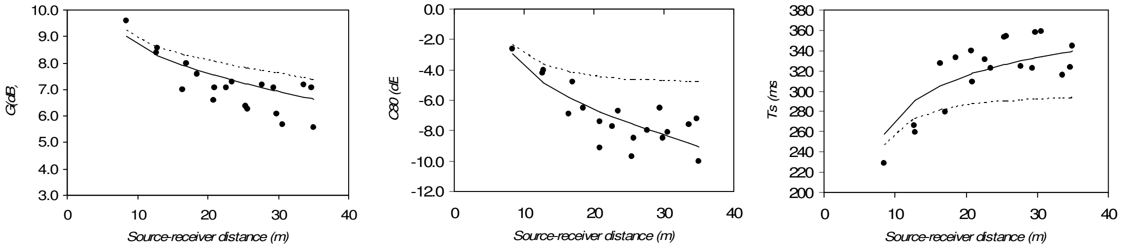
Table 2 – Input parameters required to implement the Spanish model and corresponding errors

Church	Volume (m^3)	T_{1kHz} (s)	μ (s/m)	μ_{mid}	σ_{mid}	rms G (dB)	rms C80 (dB)	rms Ts (ms)
St. Paolo Fuori le Mura, Roma	130000	7.5	0.16	**0.17**	**0.03**	1.07	1.70	65
St Maria Maggiore, Roma	39000	4.1	0.20			0.84	2.10	31
St. Sabina Basilica, Rome	17500	4.1	0.17			0.65	1.14	21
St. Apollinare in Classe, Ravenna	22500	3.6	0.13			0.51	0.83	15
Modena Cathedral	20000	5.0	0.28	**0.25**	**0.05**	0.81	1.32	38
Trani Cathedral	21500	5.2	0.30			1.05	1.17	45
Bari Cathedral	30100	5.3	0.22			0.58	1.12	24
SS. Sepolcro, Barletta	7700	3.9	0.17			1.20	1.40	57
St. Nicholas Basilica, Bari	32000	4.4	0.23			0.87	0.98	40
St. Ambrogio, Milano	23000	6.0	0.29			0.81	1.45	39
Abbey church of Chiaravalle	12500	5.6	0.29	**0.35**	**0.06**	1.71	1.21	71
Abbey church of Fossanova	17000	6.3	0.33			1.71	2.03	94
Barletta Cathedral	16000	6.8	0.42			1.20	0.77	63
Duomo, Orvieto	78000	7.2	0.36			1.71	1.21	72
Lucera Cathedral	33100	5.3	0.29			0.79	1.50	53
St. Petronius Basilica, Bologna	160000	9.8	0.42			0.96	1.49	66
Basilica Laurentiana, Florence	39000	7.9	0.22	**0.26**	**0.07**	0.59	1.14	62
Santo Spirito, Florence	55000	10.7	0.31			1.26	1.73	54
Gravina Cathedral	10500	4.1	0.18			0.32	0.59	13
Sant'Andrea, Mantova	78000	8.8	0.28			1.08	1.90	102
The Holy name of Jesus Church, Rome	39000	5.1	0.34			1.32	1.52	50
St. Luke and Martina, Rome	8700	3.1	0.23	**0.26**	**0.07**	0.71	1.12	20
Sant'Agnese in Agone	14000	5.0	0.24			1.06	1.39	46
San Lorenzo, Torino	12000	4.1	0.21			0.85	1.25	26
Basilica of Superga, Torino	22000	5.0	0.19			0.99	1.37	29
Giovinazzo Cathedral	7900	4.8	0.35			0.69	0.90	41
St. Martin Basilica, Martina Franca	16400	6.9	0.33			2.22	1.39	114
Church Carmine, Bari	9700	4.2	0.13	**0.13*****	**0.05*****	0.62	0.90	25
Concattedrale, Taranto	9000	4.2	0.17			1.94	0.95	48
S. Maria Assunta church, Riola	5500	6.1	0.16			0.58	1.01	26
Dives in Misericordia, Roma	10500	7.3	0.66			0.84	1.4	41.6
Padre Pio Pilgrimage church, San Giovanni	50000	5.5	0.06			1.09	1.33	44
mean	*32721*	*5.7*	*0.25**			*1.02*	*1.29*	*48*
*Values calculated excluding Dives in Misericordia church								

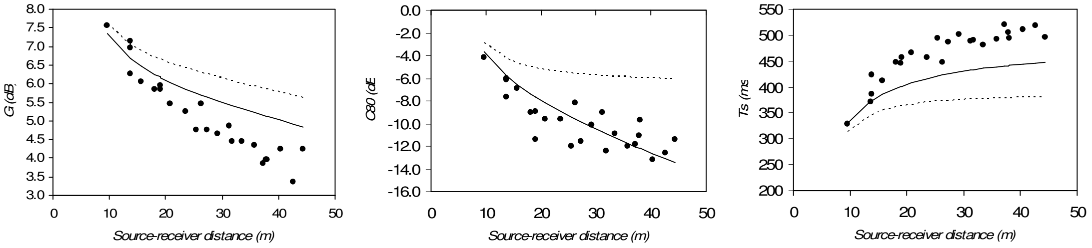
The values assumed by μ in the analyzed churches vary in the interval from 0.06 to 0.42, respectively belonging to the church of Padre Pio Pilgrimage (San Giovanni Rotondo) and St. Petronius Basilica (Bologna), showing much greater variations in comparison with Mudejar-Gothic churches, justifying, once more, the need for the present extension.

As the μ coefficient affects the early energy by increasing the actual source-receiver distance (to which corresponds the original value of 0.04 as defined in [11]), observed values as high as 0.42 suggest that the energy of the early part corresponds to that predicted by Barron and Lee at much farter points.

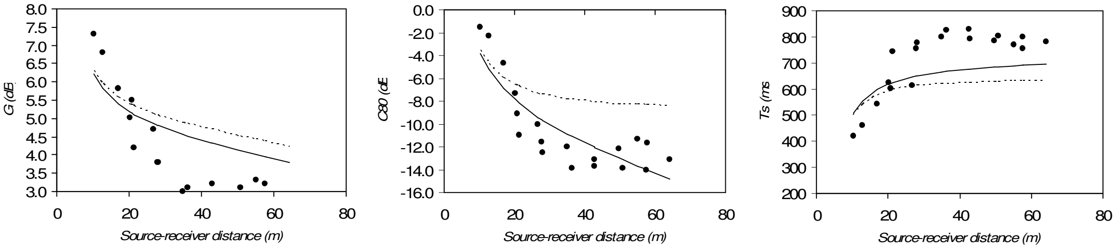
The application of the model suggests some reflections, mostly related to the "blind" exptrapolation of μ from clarity values. In fact, a clearly unrealistic μ value of 0.66 was observed in the church Dives in Misericordia in Rome, where abnormally low values of C80 appear at a distance of about 15 m from the source as a consequence of the lack of early reflections and, conversely, strong reflections arriving after the 80 ms limit, emphasized by curved walls. Such behaviour results in G and Ts predictions which are worse than those obtained by applying Barron model. However, the interesting aspect is that assuming a μ value of 0.13 (corresponding to the average of the period, calculated excluding the outlyer), leads to rms errors for G, C80, and Ts respectively of 0.6 dB, 2.6 dB, 35 ms.



Early-Christian style - St. Sabina Basilica, Romanesque style -Trani Cathedral

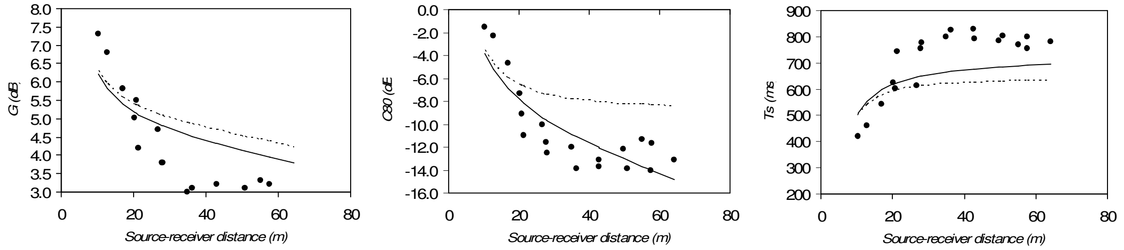


Gothic style - Lucera Cathedral

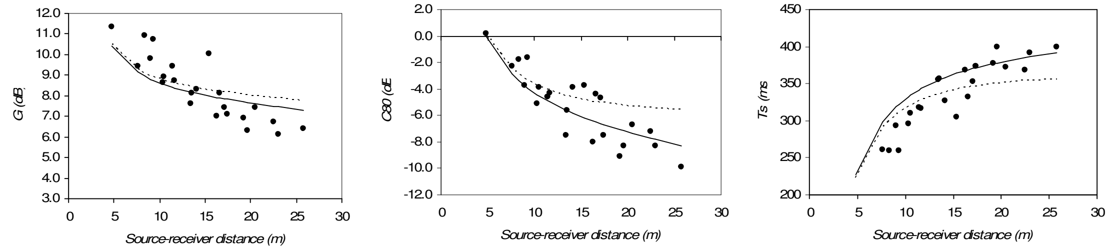


Renaissance style - Sant'Andrea, Mantova

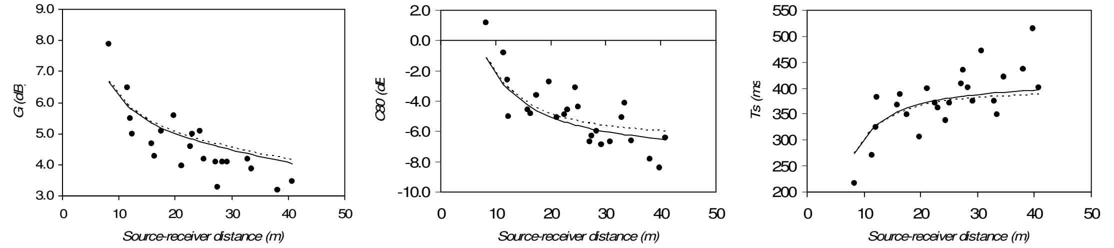
Figure 3a – Measured (•) and predicted values of strength (left), clarity (centre), and centre time (right) according to Barron theory (- -) and μ model (—), for three churches representative of different styles.



Renaissance style - Sant'Andrea, Mantova



Baroque style - Basilica of Superga, Turin



Modern style - Padre Pio Pilgrimage church, San Giovanni Rotondo

Figure 3b – Measured (•) and predicted values of strength (left), clarity (centre), and centre time (right) according to Barron theory (- -) and μ model (—), for three churches representative of different styles.

The smallest μ value is observed in Padre Pio Pilgrimage church, 50% larger that the original value suggested by Barron in auditoriums. This circumstance verifies the hypothesis of the model; in fact this church has architectonic aspects similar to a wide space as an auditorium, without decorations or chapels.

3.4 Discussion of the results

The observed variations of μ values inside different churches suggest that given volume and reverberation time, this parameter might take into account all geometric and material characteristics of a building, therefore, representing at the same time different aspects of the church.

The results (Table 2) suggest that μ grows according to dimensions and complexity. A regression between μ and room volume shows a weak correlation coefficient (R^2=0.27), suggesting that other architectural elements may influence μ values. In particular the relationships with two architectural parameters are interesting, the ratio between volume and floor surface (R^2=0.32), and the ratio between volume and main nave length ($R^2=0.42$). The latter proved to be reasonably well correlated also in Mudejar-Gothic churches ($R^2=0.70$). This ratio expresses the mean dimension of transversal section, so it is an index of the mean cross section of the church, and it has a good influence even in heterogeneous survey of buildings as this. This allows including a “shape” factor in the model which otherwise included only the room volume which may be the same in very different places.

Another approach in the interpretation of μ values is the study of its historical evolution, according to architectonic and stylistic periods. Dividing the sample into the relative architectural style, the mean μ-value for every one was calculated. Considering the strong typological connotation that characterizes different architectural styles, and the specific use of materials or ornamentations, it would be possible to study correlations of both these aspects as already done in similar studies [14,15]. Architectural specific characters correspond to each historical period are briefly summarized here:

- Early-Christian churches have few decorations, many walled plain surfaces and basilica-plans, relatively open due to the moderate depth of the side aisles or the slenderness of the columns. Their stylistic mean value of μ is (0.17), very small in comparison to other styles;
- Romanesque churches have material characters similar to the early-Christian, for example walls made of stone, but the plan is generally more complex, with three aisles whose width has a relation of 1:2 or 1:4 with main nave. Their value of μ (0.25) falls in between the others;
- Gothic churches have considerable volumes, especially because of their height, combined with a great spatial complexity for the presence of lateral chapels and thick pillars. These elements determine a delay in the establishing of the diffuse field, in fact mean value of μ is the highest (0.35) among the other styles;
- Renaissance churches have generally three naves, and in some cases five, with some decorations. This return to simplicity after previous style takes to an intermediate mean value of 0.26;
- Baroque churches are characterized by great spatial complexity, side chapels, additional volumes and often, a cross plan. These elements determine a considerable sound diffusion but the resulting mean value of μ (0.26) falls in between the others. In this case rich decorations and complex volumes should reduce strong early reflections, leading to increased μ values. However, the smaller volume may explain the resulting mean value of the μ coefficient;
- Modern churches have often reflecting surfaces, according to the use of rigid materials as concrete or ceramics, the plans are simple, with spatial opening and a tendency towards unique volume. They show the lowest value of μ (0.13), also because of the presence of the auditorium-like Padre Pio Pilgrimage church.

Finally, the study of μ variations among different styles shows that different typological plans, together with material and architectural characteristics, may actually explain different values of this parameter.

4 Conclusions

The μ-model, originally defined on Gothic-Mudejar churches, was tested on a different sample of churches in order to investigate its generalization. The results clarified merits and limits of this model. The analysis has recognized the simplicity of μ-model that may be conveniently applied to different churches, with predicted values showing good agreement with experimental data. However, resulting μ values appeared to vary in a large interval, so in order to obtain predictions with no reference to experimental data (except obviously reverberation time), further studies are required to define rules to assign μ. The present analysis showed some relations. One of the possibilities can be a typological classification, in terms of architectural characteristics. The basic hypothesis would be the linearity among architectural characteristics and acoustic behaviour, as shown in the present paper. This assumption is confirmed by the small variations shown by μ values when calculated on homogeneous samples of churches. The possibility to obtain typological rules for religious buildings represents a difficult target to pursue, for the differences existing among this type of spaces. The peculiarities of every building appear difficult to fit to generalizations, especially modern architecture which shows a complex and non-stylistic liberty. Nonetheless, the possibility to obtain punctual values of energy parameters without using detailed and time consuming computer models encourages to further study this approach.

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