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Prediction of acoustical measurements in churches

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Simple architectural features can be used to estimate acoustical measurements.

After the changes in the Catholic liturgy decided by the Second Vatican Council in 1965, the hierarchy of the Roman Catholic Church accepts that it is essential to shape an appropriate environment for worship: "An acoustical consultant who recognizes the unique demands of liturgical space should be employed in the design and construction process" (NCCB, 1979). To comply with this goal, there must be enough knowledge, supported by sufficient data and reliable rules, to help the acoustical designer.

This article presents prediction equations to estimate acoustical measurements using simple architectural parameters. With this set of equations, designers and researchers have the basic information and tools to predict several acoustical measurements in churches at the early stages of design or in existing buildings without the need of measurements *in loco*.

In this article, we will analyze the relationships of eight objective acoustical measurements with 15 architectural parameters of churches. These relationships are based on acoustical field measurements in a major survey of Catholic churches in Portugal built in the last 14 centuries, where a series of monaural acoustical measurements were taken at several source and receiver locations. The measurements included reverberation time, early decay time, early-to-late sound index, early-to-total energy ratio, center time, loudness and two bass ratios.

Table 1
Statistics of main architectural parameters in 41 churches tested

Arch parameter	Minimum	Median	Mean	Maximum
Volume (m^3)	299	3,918	5,772	18,674
Area (m^2)	56	427	450	1,031
Max. height (m)	7	13	15	39
Max. length (m)	12	31	33	62
Width of nave (m)	4	11	13	38
Total absorption (m^2)	14	131	170	962

Table 2
Architectural parameters used

Term	Definition
Vol_{tot}	Volume total (m^3)
Vol_{nave}	Volume of nave (m^3)
$Area_{tot}$	Area total (m^2)
$Area_{nave}$	Area of nave (m^2)
L_{max}	Maximum length (m)
L_{nave}	Length of nave (m)
H_{max}	Maximum height (m)
H_{nave}	Height of nave (m)
VTO_{ATO}	Total height average (m): total volume/total area
W_{nave}	Average width of nave (m)
W_{avg}	Average width of entire church (m)
Seats	Number of seats
Alpha	Absorption coefficient — average value for all surfaces, α_{avg}
$Abso_{tot}$	Total Absorption, A (m^2)
R_{local}	Constant of the room [$R=A/(1-\alpha_{avg})$]

Note: Nave stands for the entire church, excluding lateral chapels and main altar. Total stands for the entire church, including the lateral chapels and main altar.

The study

This article is based on data collected on acoustical field measurements in a survey of 41 Catholic churches in Portugal built from the sixth century until 1993 (Carvalho, 1994b). The churches were chosen to represent the evolution of the architectural styles in church construction in Portugal.

Because Portugal is one of the oldest European countries, it can be considered a representative example of Catholic churches, making it an almost perfect location to trace the history of Catholic church buildings in the world. Therefore, measurements were taken in 12 churches from the 6th-13th centuries, 16 churches from the 13th-16th centuries, 13 churches from the 16th-19th centuries and four churches from the 20th century. Extremely large churches (a total volume of more than 1,9000m^3) were not included in this study. Table 1 displays the data for the main architectural features of these churches; Table

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2 presents the 15 architectural parameters used in this study.

Acoustical measurements

Because of the specific characteristics of acoustics in churches (different speech and music requirements), a small group of six monaural acoustical measurements was chosen to be the most significant for the purpose of this research. Acoustics in churches is basically an interaction between speech and music enjoyment. Therefore, monaural acoustical measurements were chosen among those hypothesized to better assess the characteristics of these two requirements: definition (D) for speech and C80 (clarity) and center time (TS) for music. Reverberation time (RT) and loudness (L) were chosen because of their hypothesized role in characterizing the overall acoustical impression in a room. Reverberation time was also included because it remains the single most used and valuable measurement to characterize a large room (Barron, 1994). Loudness was included because of its hypothesized strong relation with the sense of loudness and intimacy (Cremer and Müller, 1972; Barron, 1988; Barron, 1994). This later one (to feel involved or detached from the sound performed) is, in a church, an important subjective quality and perhaps plays a role giving a church a sense of mystique or dignity. The acoustical measurements are:

- *RT (reverberation time):* The time it takes for sound to decay 60dB. This measurement was proposed by W.C. Sabine (Sabine, 1927). RT$_{30}$ (from -5dB to -35dB) is often measured from a decay of 30dB and then multiplied for a factor of 2: RT = $2[SD^{-1}(35) - SD^{-1}(5)]$ where $SD(t)$ is the sound decay as a function of time and $SD^{-1}(t)$ is the inverse function of $SD(t)$.

In this study, this measurement was calculated from reverse integration of the logarithmic decay curve obtained from an impulse response (Schroeder, 1965). RT is suggested to be a measure of the subjective sense of reverberance (Beranek, 1962; Barron, 1988; Chiang, 1991; Müller, 1992). However, it is not as important as EDT.

- *EDT (early decay time):* The time it takes for sound to decay 60dB. It was proposed by Jordan based on research made by Cremer and Müller. EDT10 (from 0 to -10dB) is an adaptation of the reverberation time measured from a decay of 10dB multiplied for a factor of 6: EDT = $6[SD^{-1}(10) - SD^{-1}(0)]$

In this study, this measurement was calculated the same way RT was calculated. EDT is suggested to be a measurement of the subjective sense of reverberance (Cremer and Müller, 1978; Barron, 1988; Chiang, 1991/94), clarity (Chiang, 1994) and overall acoustical impression (Cervone *et al.*, 1991).

- *C80:* Early-to-late sound index or clarity with a time window of 80ms. It is one type of ratio of arriving early-to-late sound energy or early-to-reverberant sound energy; the ratio in decibels between the energy received in the first 80ms of the received signal and the energy received afterward. It was proposed by Reichardt *et al.* in 1975 with a limit of 80ms because that is the limit of perceptibility for music. This figure is calculated by using 10 log of the ratio of the integrated squared pressure arriving before the time 80ms to that arriving after 80ms. In concert halls, it usually lies between -2dB and 2dB. It is suggested to be a measure of the sense of clarity (Chiang, 1991/94). Use the following equation:

$$C80=10\log\frac{\int_0^{80} p^2(t)dt}{\int_{80}^{\infty} p^2(t)dt}$$

where $p(t)$ is the sound pressure measured using a microphone at a certain location. The notation t designates time where t at the arrival of the wide-band direct pulse equals 0.

- *D:* Definition or early-to-total energy ratio with a time window of 50ms. It is the ratio between the energy received in the first 50ms and the total energy received. It lies between 0 and 1. Proposed by Thiele in 1953, the measurement has a duration of 50ms because that was called the limit of perceptibility (regarding speech). It is hypothesized to be a measure of how clear a sound appears to a listener — the higher the D, the clearer the sound.

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

- *TS (center time):* The point in time where the energy received before this point is equal to the energy received after this point. This measurement, which was proposed by Cremer and Müller in 1978, is also hypothesized to be a measurement of how clear a sound appears to a listener — the lower the TS, the clearer the sound. It usually lies between 140ms and 180ms in concert halls.

$$TS=\frac{\int_0^{\infty} t,p^2(t)dt}{\int_0^{\infty} p^2(t)dt}$$

- *L:* The loudness, total sound level or overall level or strength of arriving energy. It is the ratio, in decibels, of the total energy received at a particular position in the enclosure and the energy received because of the direct sound alone (measured at a distance of 10m from the source in an anechoic environment). It was first used by Gade and Rindel (Gade, 1985; Chiang, 1994) following ideas introduced in earlier studies (Yamagushi, 1972; Lehmann, 1976; Cremer and Müller, 1978). L is a measurement of the room's ability to amplify sound from the source position. It is also used to verify the room's sound-field uniformity and to analyze whether the transmitted energy to the room is deficient at some frequencies. This figure usually lies between 3dB and 9dB in concert halls. L is also denoted as G in literature. It is suggested to be a measure of the sense of loudness (Cremer and Müller, 1978; Barron, 1988; Chiang, 1994) and intimacy (Barron, 1988).

$$L=10\log\frac{\int_0^{\infty} p^2(t)dt}{\int_0^{\infty} p_A^2(t)dt}$$

Table 3
Statistics of acoustical measurements in the 41 churches tested (all source and receiver positions)

Measurement	Minimum	Mean	Maximum
RT(sec)	0.8	3.2	9.3
EDT (sec)	0.6	3.1	10.8
C80 (dB)	-14.2	-3.0	11.2
D	0.01	0.24	0.88
TS (ms)	33	226	670
L (dB)	1.0	13.3	27.9

Table 4
Seven options of frequency averaging methods tested

Code	Definition
41_{all}	Average of all six frequencies (125Hz to 4,000Hz octave bands)
41_{W24}	Average of the four lowest frequencies (125Hz to 1,000Hz octave bands)
41_{4H}	Average of the four highest frequencies (500Hz to 4,000Hz octave bands)
41_{4M}	Average of four middle frequencies (250Hz to 2,000Hz octave bands)
41_{3F}	Average of three medium frequencies (500Hz, 1,000Hz and 2,000Hz octave bands)
41_{O24}	Average of the two highest frequencies (2,000Hz and 4,000Hz octave bands
41_{2F}	Average of two medium frequencies (500Hz and 1,000Hz octave bands)

where $p_A(t)$ is the sound pressure measured in a anechoic chamber corrected to a distance of 10m.

- *BR_{RT} (bass ratio based on reverberation time) and BR_L (bass ratio based on loudness):* Proposed by Beranek and Gade (Beranek, 1962; Gade, 1989). These ratios are usually used to evaluate balance by comparing the loudness and reverberation times for the low frequencies to the loudness and reverberation times for the high frequencies. They are usually used to evaluate the subjective sense of timbre, tonal balance or warmth. They are defined by the following equations:

$$BR_{RT}=\frac{RT(125Hz)+RT(250Hz)}{RT(500Hz)+RT(1kHz)}$$

$$BR_L=\frac{L(125Hz)+L(250Hz)-L(500Hz)-L(1k)}{2}$$

where RT is the reverberation time and L is the overall level for the specified octave bands.

Much in the available literature regarding concert halls and auditoria suggests that some of these acoustical measurements are highly correlated (Wilkens, 1975; Lehmann, 1976; Gade, 1990; Siebein *et al.*, 1992). The author used those measurements separately because of the different conditions that are hypothesized to be present in churches regarding diffusion and the shape of the decay curve, which is not perfectly exponential; these factors permit more differences in those values within the room and more variability among them. The measurements are used separately also to test the relationships among these acoustical measurements (Carvalho 1994a). Table 3 presents simple statistics of the values obtained in the sample used.

The method used to calculate the acoustical measurements is based on the integrated impulse-response method (Schroeder, 1965). A limited-bandwidth noise burst is generated and transmitted into the church by a loudspeaker via an amplifier. The room's response to the noise burst (called the impulse response) is then sampled from the rms detector output of the sound-level meter (Brüel, 1990). A loudspeaker emitting noise (short noise-pulse bursts) in $^3/_2$-octave frequency bands (to ensure that the received noise-burst is of $^1/_1$-octave bandwidth) was used as sound source. The receiving section consisted of one half-inch-diameter microphone (which changed position throughout the room) and a sound-level meter with a $^1/_1$-octave filter set. (A filter centered on the same frequency as the filter in the transmitting section reduces the influence of background noise.)

The procedure was controlled by a specific software using, *in loco*, a notebook computer. In each church, two sound-source locations were used for

Table 5
Prediction equations for acoustical measures using architectural parameters (simple models)

Equations	Standard error of estimate	R^2 (variance explained)
$RT=0.785+0.176H_{max}$	1.1s	0.54
$EDT=0.754+0.171H_{max}$	1.1s	0.54
$C80=8.950-4.887\log_n(H_{max})$	2.1dB	0.49
$D=0.685-0.083\log_n(Area_{tot})$	0.068	0.50
$TS=60.835+12.634H_{max}$	79ms	0.55
$L=36.101-7.219\log_n(L_{nave})$	1.7dB	0.78
$BR_{RT}=1.358-0.019Lmax+0.00021(L_{max})^2$	0.16	0.16
$BR_L=5.264-1.094\log_n(L_{max})$	0.79	0.25

Table 6
Prediction equations for acoustical measures using architectural parameters (general linear models)

Equations	Standard error of estimate	R^2
RT$=1.148+0.149\,H_{max}+0.078\,W_{nave}-13.383\,Alpha$	0.91s	0.71
EDT$=1.075+0.145\,H_{max}+0.077\,W_{nave}-12.756\,Alpha$	0.90s	0.71
C80$=0.864-0.217\,W_{nave}-0.404\,VTO_{ATO}+35.121\,Alpha$	1.2dB	0.85
D$=0.452+0.000014\,Vol_{tot}-0.007\,L_{nave}-0.008\,W_{nave}-0.014\,VTO_{ATO}+1.364\,Alpha$	0.042	0.84
TS$=85.448+10.603\,H_{max}+5.941\,W_{nave}-983.356Alpha$	61ms	0.74
L$=22.918-0.306\,L_{nave}-24.520Alpha$	1.5dB	0.82
BR$_{RT}=1.279+0.00045\,Seats-0.008L_{max}-1.867Alpha$	0.14	0.35
BR$_L=2.663-0.047\,L_{nave}$	0.80	0.25

the loudspeaker, one in front of the altar to standardize the measurements and to allow comparison of the results among churches and another in the center of the main floor to simulate the sound of the congregation. The sound source was positioned at 0.8m above the floor and at a 45° angle with the horizontal plane. Each measurement was calculated from an ensemble of three or four pulse responses in each position. Five receiver positions were used on average, depending on the width of the church. The microphone at each location was placed 1.3m above the floor. In total, nearly 8,000 values were determined (all combinations of the six octave-frequency bands, 125Hz to 4kHz, and the source and receiver locations).

The equipment used consisted of a sound level meter (Brüel & Kjær model 2231), a $^1/_3$-$^1/_1$-octave filter set (B&K 1625), a B&K BZ7109 room acoustics module, a B&K 4224 sound source, a $^1/_2$-inch microphone, a Compaq LTE notebook computer and B&K VP7155 room acoustics application software.

Simple linear and non-linear regression models were tested for each of the eight acoustical measurements.

Acoustical measurements and architectural parameters

The analyses were done with averaged data for each church. Seven averaging methods were previously tested using the average of 2-, 3-, 4- or 6-octave frequency bands to obtain a single number for each acoustical measurement and for each church. Table 4 presents the options tested.

Regression analyses were performed with all seven averaging options to check for their influences in the architectural parameters. The differences among them were found to be small. Nevertheless, the option 41_{2F} was used because it appeared to be the most suitable for this type of analysis, giving the highest percentage of variance explained for almost all situations.

Prediction equations using simple models

Using the average of 500Hz and 1,000Hz octave-band data (frequency-averaging option 41_{2F}), simple linear and non-linear regression models were tested for each of the eight acoustical measurements regarding their relationships with the 15 architectural parameters. Table 5 presents the equations for the best regression line found for each of the eight acoustical measurements. The accuracy of each model was judged by its R^2 (representing the percentage of variance explained) and the standard error of the estimate (representing the magnitude of differences between estimated and observed values). The variance of L can be largely explained with just one of the 15 architectural parameters (R^2 of approximately 0.80). For RT, EDT, C80 and TS, the percentage of variance explained by just one architectural parameter is not very significant (R^2 of aproximately 0.50). The bass ratios, with $R^2 \leq 0.25$ cannot be explained or predicted significantly with the use of just one architectural parameter.

To find a better model to explain the relationships between acoustical measurements and architectural parameters, general linear models were calculated using the forward stepwise modeling method with an α-to-enter (or -to-remove) equal to 0.05. Table 6 presents the general linear models found.

The R^2 coefficients are improved (the percentage of variance explained is greater) if the expected values for some acoustical measurements calculated by the diffuse field theory formulas (Table 7) (Chiang, 1994) are included in the models. In that case, knowing

Table 8
Revised predictions for acoustical measurements (using architectural parameters and known real RT)

General linear model equations expected values)	Standard error of estimate (STD of residuals	R² (using (variance explained)
$\mathbf{EDT} = -0.019 + 0.976\,EDT_{exp}$	0.11s	0.996
$\mathbf{TS} = 8.518 + 0.974\,TS_{exp}$	14ms	0.985
$\mathbf{C80} = 0.0576 + 1.045\,C80_{exp} - 0.025\,L_{max}$	0.70dB	0.944
$\mathbf{L} = -0.196 + 0.966\,L_{exp}$	0.76dB	0.957

the real RT (usually easily measured *in loco*) results in better predictions for EDT, TS, C80 and L, as seen in Table 8 (the same 0.05 was used for the α-to-enter and -remove). As seen, the percentage of variance explained by the use of the expected values of the acoustical measurements is significantly better than with the models using only the architectural parameters. Note that only the measurement C80 shows the inclusion of some architectural parameter in the general linear model. If a larger α-to-enter and -remove was chosen, it should be a $\alpha \geqslant 0.16$ in order to have all four of these general linear equations with at least one architectural parameter. But even then, their R^2 would not greatly improve, except in the C80 model, where a small increase of 0.03 would be found for its R^2.

Investigating the effect of 15 simple architectural parameters on eight acoustical measurements and calculating prediction equations to estimate mean acoustical measurements reveals that several acoustical measurements can be predicted by simple equations using only two to five architectural parameters with 71% (RT and EDT) to 85% (C80) of variance explained and relatively small standard error of the estimates. The use of the real measured RT in prediction equations using the diffuse field theory equations largely increased the fitness of the predictions models to R^2=0.944 (for C80) or R^2=0.996 (for EDT). Finally, the study showed that bass ratios cannot be predicted with this group of architectural parameters ($R^2 \leqslant 0.35$). S&VC

Table 7
Diffuse field theory formulas

$EDT_{exp}=RT$

$TS_{exp}=RT/0.0138$

$C80_{exp}=10\,\log_{10}\,(e^{1.104/RT}-1)$

$L_{exp}=10\,\log_{10}\,(RT/V)+45$

Note: exp is expected

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