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Proposal of a simplified methodology for reverberation time prediction in standard medium size rooms with non-uniformly distributed sound absorption

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Abstract – Sabine, Eyring and Millington formulas are commonly used for reverberation time prediction, mainly, as a calculation tool in building acoustics design. These classical theories are valid only for rooms with diffuse sound fields, in which the energy density is constant throughout the enclosure, an acoustic condition that is achieved only when using surfaces with low sound absorption. Despite these limitations, Sabine's formula is still the most widely used in the prediction of the reverberation time, when spaces such as classrooms or offices are addressed. However, for these rooms, after the construction works are completed, it is quite often verified that the implemented sound-absorbent surface area is manifestly insufficient to fulfill the reverberation time requirement. In this technical note a simplified approach for reverberation time prediction, based on the use of Sabine's formula, is proposed, that can be useful in acoustic design of classrooms or offices, due to its simplicity. A previous correction to the sound absorption coefficient of the lining materials declared by the manufacturer is here proposed, making use of an empirical correction that was achieved from *in situ* experimental results and through geometrical room acoustic modelling. The empirical correction can be employed for room conditions where diffuse sound field is not met, composed of small or medium volumes (volume below 300 m^3), with regular geometry, approaching parallelepipedal shapes, where the average height is below 4.0 m.

Keywords: Reverberation time, Sabine's formula, Sound absorption, Non-diffuse sound field

1 Introduction

In medium size rooms where natural speech is the main type of use, e.g. classrooms and offices, it is essential to control reverberation, which usually involves the application of linings, with high sound absorption in medium and high frequencies, therefore creating conditions of non-uniformity in the sound distribution throughout the surrounding space. In the acoustics design of these rooms, Sabine's formula is usually used, however it can lead to results that do not correspond to the ones found in situ, especially, for rooms with uneven distribution of sound absorption. This formula was derived from Sabine's classical theory, in 1922 [1], valid for situations with perfectly diffuse sound fields. Following this theory, emerged two other classical approaches, based on the same assumptions: Eyring's theory in 1930 [2] and Millington's theory in 1932 [3]. More recently, specifically in the last 60 years, new theories, adapted to rooms, with non-uniform sound distribution, emerged, such as the methodology proposed by Fitzroy in 1959, which inspired later, in 1988, Arau-Puchades [4–6] to develop a new calculation model assuming that the reverberation decay is a hyperbolic process. This author demonstrates that the reverberation time for a non-diffuse field can be expressed as the geometric average of three reverberation times in each direction, weighted by the fraction of the area. Other methodologies have been emerging, such as that referenced in Kuttruff (see Chapter 5 in [7]), and more recently some developments to improve previous models [4].

Most of these prediction methods also display limitations and their application can be more complex and time consuming and may require knowledge of other acoustic parameters ([8, 9]), therefore when analyzing medium size rooms where only the verification of the reverberation time is intended, Sabine's formula continues to be widely used.

Assuming current design layouts (with shapes approaching parallelepiped rectangular rooms) where it is essential to control reverberation, a simple proposal, based on the use of Sabine's formula, can be very useful for acoustic designers, allowing to approach the prediction values to those obtained from *in situ* measurements and be also simple and low time consuming.

As mentioned, Sabine's formula is not valid for spaces with high sound absorption (in particular for sound absorption coefficients greater than 0.2, according to [4]) and it can even lead to significant unfavorable deviations. Usually,

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these deviations rise with the increase of the sound absorption coefficients of the linings employed and if greater asymmetries in sound absorption distribution are employed (see e.g. [10–12]).

In the present work, a simple strategy is proposed that allows to use Sabine's formula but with more accurate results. In Section 2 of this technical note, detailed explanation on the approach used is provided, consisting on the use of an empirical correction to adjust the sound absorption coefficients of lining materials employed in a room. In Section 2.1 a comparison between predicted reverberation time using Sabine's formula and an extended set of experimental results is performed, allowing to achieve a first trendline. A comparison with results obtained through 3D geometric acoustic modeling is then carried out in Section 2.2, allowing to extend the sampling by evaluating a broader range of absorption coefficients. From these results a second trendline is further developed. In Section 3, an empirical correction for adjusting the sound absorption coefficients is provided by taking into account the previous analysis and then, in Section 4, validation of the method is performed for different scenarios.

It should be noted that this methodology is not intended for large spaces or situations in need of high acoustic performance, such as auditoriums or concert halls, but rather to rooms, of regular shape (approaching parallelepiped, with average height below 4 m) and medium volume, below 300 m^3, where it is necessary to verify a reverberation time requirement and where more complex calculation methodologies would require excessive resources.

2 Methodology

The reverberation time is defined by the time taken for the sound pressure level to decay by 60 dB when a sound stops. Sabine showed that the reverberation time could be calculated from the room volume and absorption by the following expression (see Eq. 5.25 on page 140 of reference [7]):

$$T = \frac{0.161V}{A + 4\mathrm{m}V}, \tag{1}$$

where V is the volume of the space (in m^3); m is the air attenuation coefficient obtained according with the standard ISO 9613-1 (in Neper/m) and A is the sound absorption area (in m^2).

The total absorption area, A, can be calculated from the individual absorption coefficients of the room surfaces, using the following expression:

$$A = \sum S_i \alpha_i + A_0, \tag{2}$$

in which S_i is the area of the surface i (in m^2); α_i is the sound absorption coefficient of the surface i (usually given by the manufacturers of sound absorbent solutions) and A_0 corresponds to the sound absorption area of objects inside the rooms (e.g. furniture).

The strategy proposed in this technical note to evaluate the reverberation time consists of applying expressions (1) and (2) to obtain this parameter but making use of adjusted sound absorption coefficients of linings in relation to the ones given by the manufacturer, which are obtained from an empirical correction that is here proposed.

2.1 Experimental results vs. Sabine's prediction

The experimental results used in this work were obtained through measurements following the procedure prescribed in the standard ISO 3382-2:2008 [13], by employing the integrated impulsive response method. Reverberation time parameter T_{20} was obtained from the measured decay curves, after checking that the sound pressure levels as a function of time, approached a a single slope curve, within the evaluation range. The rooms analyzed display standard geometries, approaching a parallelepipedal shape and can be found in school and office buildings. In these spaces, only one surface was coated with a sound absorption material, being in most cases the ceiling, but also acoustic treatment in one of the walls was found. Different types of sound absorbing coatings, with medium or high sound absorption were adopted, with values of α declared by the manufacturers, varying between 0.2 and 0.95 ([14, 15, 16]). In the remaining surfaces, the linings exhibit low sound absorption, such as plaster, mortar or plasterboards. Wood furniture and chairs not upholstered and without occupancy were employed. The average absorption coefficients of low sound absorbing linings, also including the furniture, ranged from minimum values of 0.06 to maximum values of 0.12 ([17, 18]). A total of 16 rooms, being eight new and eight rehabilitated, were used, with volumes ranging from 77 to 260 m^3.

During the design stage of medium size rooms it is common to consider an average value of T, obtained from the arithmetic average of the results in octave bands, being the middle frequencies usually taken into account. For instance, in Portugal and Great Britain, the frequency bands used are 500, 1000 and 2000 Hz ([19, 20]), and in other countries just the bands of 500 and 1000 Hz. Taking into account these acoustic code requirements, the authors selected the results obtained for the three middle frequency octave band, for evaluation. It is, however, important to bear in mind that for low frequencies, responses are strongly conditioned by the acoustic modes of the room [21], and, on the other hand, for frequencies above 2000 Hz, air absorption may also be relevant.

Table 1 displays the reverberation time obtained from in situ measurements (labeled T_{20}), for the 16 rooms (all rooms display a geometry close to a parallelepiped), where one the surfaces was lined with absorbent material. For these rooms, the predicted reverberation time was also obtained, using direct application of Sabine's formula, according to expression (1), assuming air absorption for a temperature of 20°C and moisture of 50%, which leads to a value of $4\ \mathrm{m} = 0.002$, according to the standard EN 12354-6 [9] and also disregarding air absorption. These results are also included in Table 1, being labeled as $T-$ Sabine.

From the analysis of Table 1 it is possible to verify that there is a tendency towards predicted reverberation time values (determined based on Sabine's formula, considering

Table 1. Experimental and prediction (Sabine's formula) results obtained for the 16 rooms.

Space ID	Volume (m^3)	Octave band 500 Hz			Octave band 1000 Hz			Octave band 2000 Hz		
		T_{20}	T – Sabine		T_{20}	T – Sabine		T_{20}	T – Sabine	
			4 m = 0	4 m = 0.002		4 m = 0	4 m = 0.004		4 m = 0	4 m = 0.007
1	124	0.51	0.53	0.53	0.38	0.33	0.33	0.52	0.34	0.34
2	260	2.33	1.48	1.45	1.85	1.14	1.11	1.49	0.78	0.75
3	88	0.61	0.59	0.59	0.44	0.36	0.36	0.43	0.36	0.35
4	210	0.59	0.62	0.62	0.66	0.39	0.39	0.66	0.39	0.38
5	158	0.75	0.59	0.59	0.72	0.36	0.36	0.65	0.36	0.35
6	176	1.12	0.77	0.76	0.98	0.59	0.58	0.87	0.54	0.53
7	156	0.56	0.60	0.60	0.57	0.37	0.37	0.62	0.38	0.37
8	130	0.61	0.53	0.53	0.50	0.33	0.33	0.51	0.34	0.34
9	117	0.66	0.38	0.38	0.77	0.44	0.44	0.78	0.45	0.44
10	240	1.20	0.65	0.64	1.21	0.63	0.62	1.14	0.65	0.63
11	77	0.52	0.40	0.40	0.81	0.46	0.45	0.69	0.48	0.47
12	220	0.73	0.44	0.44	0.79	0.48	0.47	0.82	0.50	0.49
13	144	0.62	0.40	0.40	0.64	0.46	0.45	0.69	0.48	0.47
14	168	0.86	0.50	0.50	0.80	0.47	0.46	0.73	0.48	0.47
15	150	0.68	0.43	0.43	0.83	0.49	0.48	0.87	0.51	0.50
16	120	0.57	0.38	0.38	0.56	0.44	0.44	0.55	0.45	0.44

the absorption coefficients declared by the manufacturer), being lower than those obtained experimentally. In general, as expected, the differences increase for rooms with higher sound absorption.

On the other hand, the values of the Sabine reverberation time obtained with and without assuming air absorption are very similar for most of the frequencies analyzed and in few cases the differences introduce a greater discrepancy between experimental and theoretical results, if assuming air absorption. The major difference that was found, although small, occur in the 2000 Hz frequency and for the case with greater volume and higher reverberation time (Space ID 2). From this analysis we may conclude that the effect of air absorption can be neglected for the analyzed cases, which was the condition assumed for further analysis.

Figure 1 plots the deviation in the estimated reverberation time (for 4 m = 0) in relation to measured value for the 16 rooms and for the three analyzed frequency bands. From the analysis of this figure the previous conclusions are evidenced, being in a total of 48 results, only three values positive. The average deviations for the three analysed frequency bands vary between −24% (500 Hz) and −36% (1000 Hz and 2000 Hz).

In order to obtain an adjusted value of α, the results displayed in Table 1 were used to define a relation between the sound absorption coefficient provided by the manufacturer (indicated in the plot as "α declared") and the one that should be considered to predict a reverberation time similar to the measured value (indicated in the plot "α adjusted"). The responses for the sixteen rooms were used to perform the plot that is displayed in Figure 2, where for each room, the absorption coefficients for the octave bands of 500, 1000 and 2000 Hz were considered separately, leading to a total number of 48 different points.

Seven different types of coatings, with medium or high sound absorption were employed (with values of α declared by the manufacturers, varying between 0.2 and 0.95). For each room, the "adjusted" α value was determined so that, when applying Sabine's formula, it would lead to the same reverberation time measured in situ (according to Tab. 1), allowing to obtain three points of the plot. If using case ID 5, the procedure employed to obtain the three points, consisted of: i) performing in situ measurements in the room without applying the absorbent lining which allowed to obtain reverberation times of $T_{500\text{Hz}} = 2.13$ s, $T_{1000\text{Hz}} = 1.51$ s and $T_{2000\text{Hz}} = 1.51$ s; ii) using these results to obtain an average absorption coefficient of reflective existing surfaces and furniture; iii) applying an absorbent lining with "declared" absorption coefficients of $\alpha_{500}^{\text{declared}} = 0.85$, $\alpha_{1000}^{\text{declared}} = 0.68$ and $\alpha_{2000}^{\text{declared}} = 0.55$ and perform measurements which allowed to obtain reverberation times of $T_{500\text{Hz}} = 0.75$ s; $T_{1000\text{Hz}} = 0.72$ s and $T_{2000\text{Hz}} = 0.65$ s; iv) using these results to calculate the "adjusted" α so as the reverberation time using Sabine would be the same as the experimental result, allowing to reach values of $\alpha_{500}^{\text{adjusted}} = 0.44$; $\alpha_{1000}^{\text{adjusted}} = 0.38$; $\alpha_{2000}^{\text{adjusted}} = 0.35$ (see Figure 2). For the other cases the same procedure was employed. It should be noted that, for different rooms, with a similar absorbing lining two slightly different values were obtained, for example, when using one absorbing lining with a declared value of α equal to 0.8 (corresponding to a perforated plasterboard, with a mineral wool in the air gap, for the octave frequency band of 500 Hz) a corrected coefficient of 0.42 and of 0.44 was obtained in two different rooms, respectively.

Using the obtained "adjusted" α values, corresponding to 48 results (divided by the 500 Hz, 1000 Hz and 2000 Hz frequency bands), a trendline was drawn, based on a prescribed quadratic function, resulting in the dashed curve indicated in Figure 2.

It is important to bear in mind that absorption coefficients obtained by manufacturers in laboratory can vary

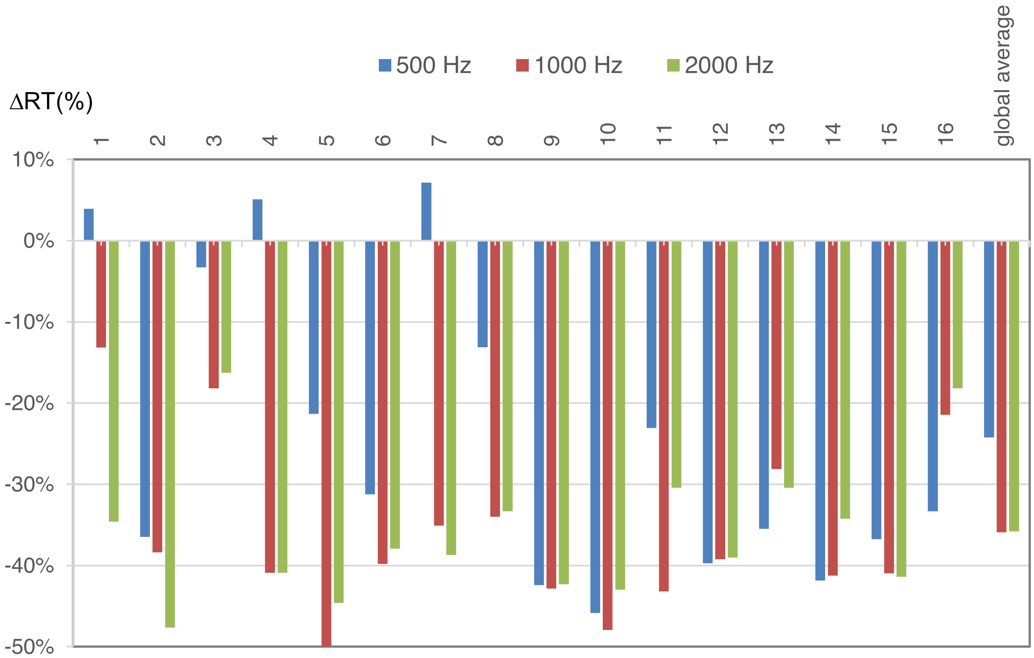


Figure 1. Deviation in the estimated reverberation time (for 4 m = 0) in relation to measured value for the 16 rooms.

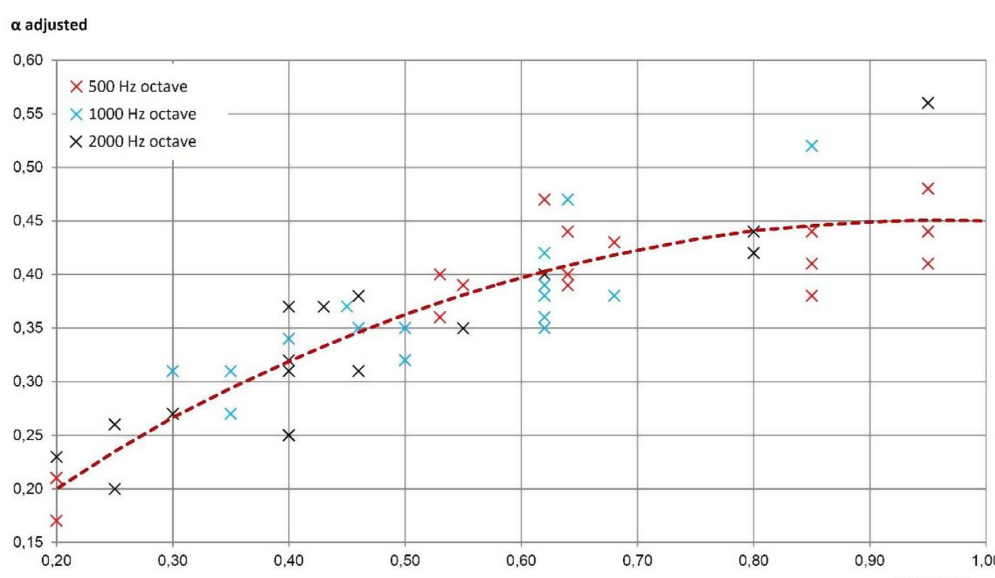


Figure 2. Sound absorption coefficients declared by the manufacturers vs the adjusted values that would be necessary to use in the Sabine formula to have similar results to those obtained in experimental tests and trendline (in red) that provides a good agreement to these results.

according to the set-up conditions. The uncertainty of sound absorption coefficients for measurements according to the ISO 354 [22] (reproducibility and repeatability), has been found to be frequency dependent ([23, 24]), being the lowest values of standard deviation situated within the frequency bands where the evaluations were performed. Reprodutibility also varies with the amplitude of sound absorption coefficient, being the standard deviation higher for increasing values.

From the analysis of Figure 2, although the number of results is small, a greater dispersion for higher sound absorption coefficients is found in relation to the lower values.

2.2 Numerical results vs. Sabine's prediction

In order to extend the samples and allow a more robust definition of a simplified methodology, a similar procedure

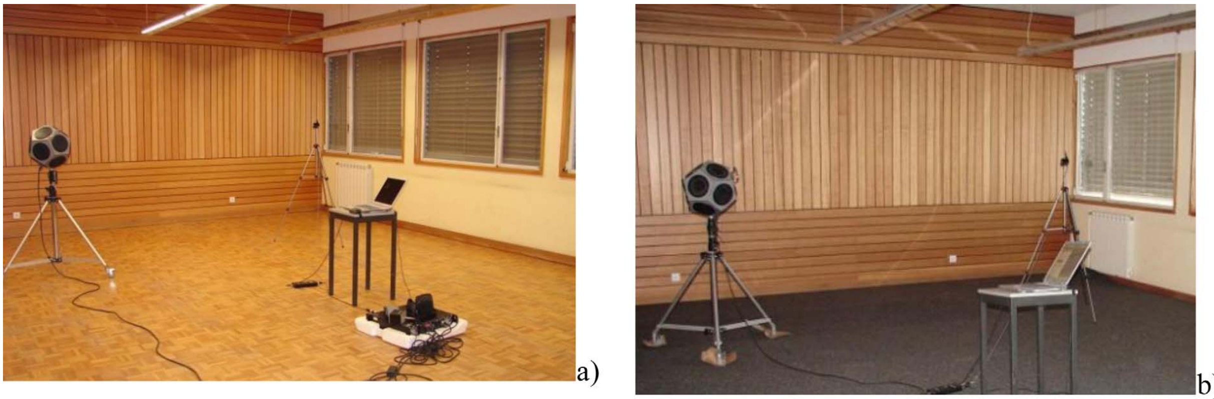


Figure 3. Images of room CR, during measurements without the polyurethane foam (a) and with the polyurethane foam (b) on the floor.

to that defined in the previous section was employed but results of numerical modeling were assumed as reference. For this propose, a model, using ray tracing ([17, 18, 25]), of a classroom existing in the Department of Civil Engineering of the University of Coimbra (referenced as CR), with dimensions 8.8 m by 6.2 m with 3.2 m high ($V = 175$ m^3) and geometry approaching a parallelepiped one, was initially developed, where experimental tests were also performed. The Schroeder's frequency of this room, regarded as the frequency between the zone of modal and statistical behavior is 250 Hz for the most unfavorable case, thus the frequencies of interest (500 Hz, 1000 Hz and 2000 Hz) are well above this limit and the calculation using ray tracing is assumed reliable. Originally, the existing surfaces of this room were lined with low sound absorption coatings (walls and ceilings are plastered, windows without curtains and floor in parquet), providing high reverberation and poor intelligibility. Therefore, to improve sound quality, acoustic rehabilitation was performed, inserting on the opposite wall in relation to the speaker's position, a lining composed of grooved wood panels with mineral wool in the air gap (see Fig. 3a). The sound absorption coefficient of this solution was previously evaluated by measurements performed in a reverberation chamber existing in the Department of Civil Engineering of the University of Coimbra, according to the procedure of the standard ISO 354 [22], allowing to obtain an NRC of 0.57.

In order to have a third situation an additional lining, composed of a "temporary" floor covering, in flexible polyurethane foam with 30 mm thickness (with a NRC of 0.69) was also evaluated (see Fig. 3b). The experimental results were obtained for the room without furniture, allowing to perform an accurate calibration of the sound absorption coefficients of linings used in the numerical model, by disregarding the contribution of furniture.

Figure 4 shows the results of the frequency domain reverberation time, assuming the original empty room (without furniture or occupancy), obtained from in situ measurements, numerical modelling, and Sabine's formula. Note that the absorption coefficients used in numerical modelling and Sabine's prediction were obtained so as an approximation of numerical results to in situ measurements could be attained, whereas standard values for scattering coefficients were used (10% according to references [26, 27]). This figure also displays the frequency domain results for the two types of configurations previously indicated (see images in Fig. 3). In Figure 4, the differences obtained for the two prediction methods in relation to the experimental results expressed in terms of percentage were also included.

From the analysis of this figure, it is possible to verify that for reduced surface areas of linings displaying a high sound absorption, Sabine's formula leads to results slightly below the experimental values (varying between −1% and −13%), but for larger areas the differences become relevant (differences varying between −34% and −47% were found). From the comparison of results between modeling and experiments, a reasonable agreement is found, but with a tendency towards simulation values being slightly higher than experimental ones, especially when the absorption area increases (differences varying between 5 and 6% for the case with higher equivalent sound absorption area were found). One possible way of approaching numerical to experimental results consists of changing scattering coefficients and assume slightly higher values than those usually employed.

For this room, numerical simulations were then performed to obtain the reverberation time, using a sound absorbent floor covering in one surface (on the floor), and theoretical values of α ranging from 0.10 to 0.95, with steps of 0.05 (with constant values in frequency bands of 500, 1000 and 2000 Hz). Since it is not feasible to consider a coefficient of 1.0, coefficients of 0.98 and 0.99 were considered. Notice that the floor was used for placing the sound absorbent material, and not the ceiling, to enable later comparison with experimental results, but if simulation would have been performed on the ceiling, similar results are expected since the room has no furniture. Subsequently, for each value α of the mentioned range ("declared" α), the "adjusted" sound absorption coefficient was taken from Sabine's formula assuming the same reverberation time as numerical modelling. An average in the octave bands of 500, 1000 and 2000 Hz has been chosen to evaluate the

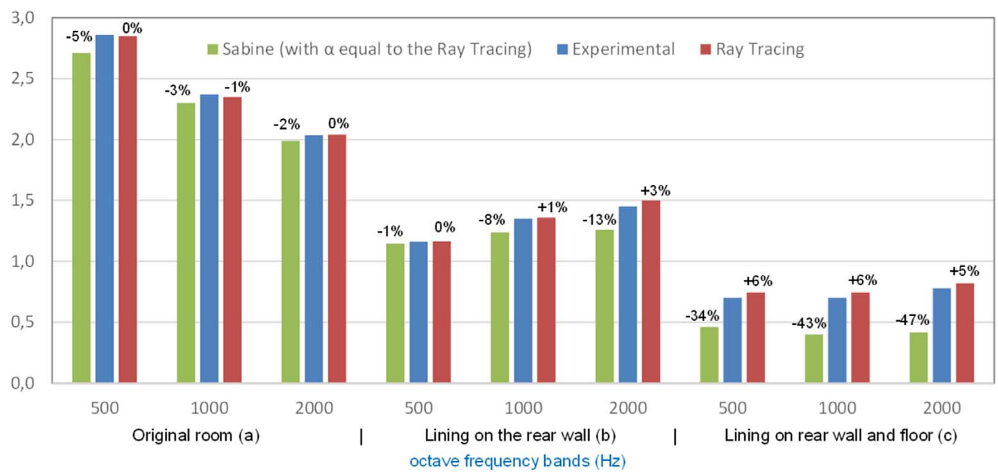
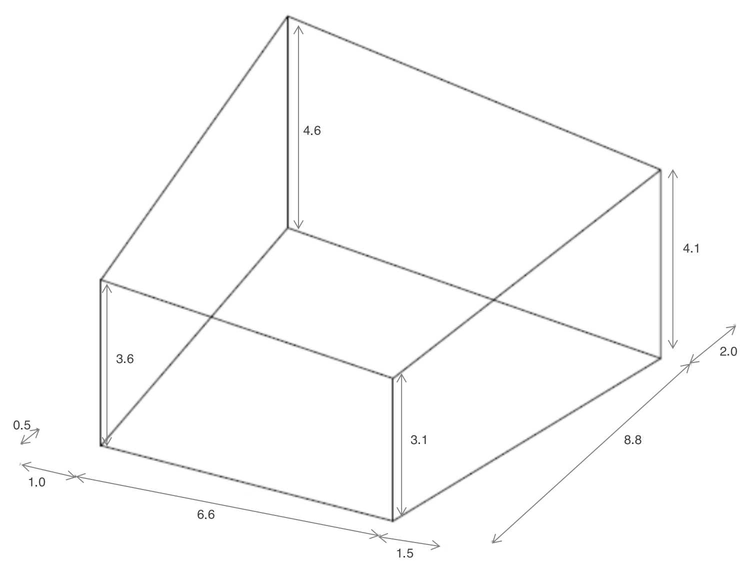
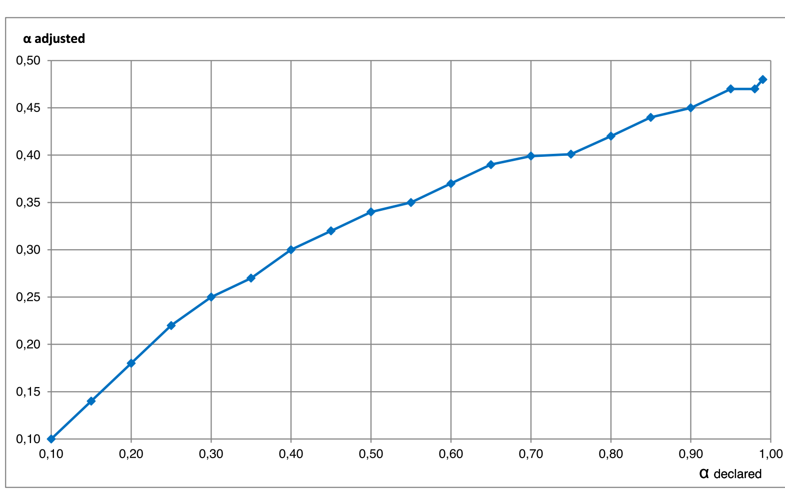


Figure 4. Frequency domain average reverberation times measured and predicted in room CR assuming the original room (a); with lining placed on the rear wall (b), and simultaneously on rear wall and floor (c).



a)



b)

Figure 5. a) Configuration of the asymmetric geometry of the room (dimensions in m) used as reference in geometric room acoustic modeling; b) Relationship between the sound absorption coefficients given by the manufacturer and their adjusted values that should be used in Sabine's formula so as the reverberation time would be similar to the modelling scenario.

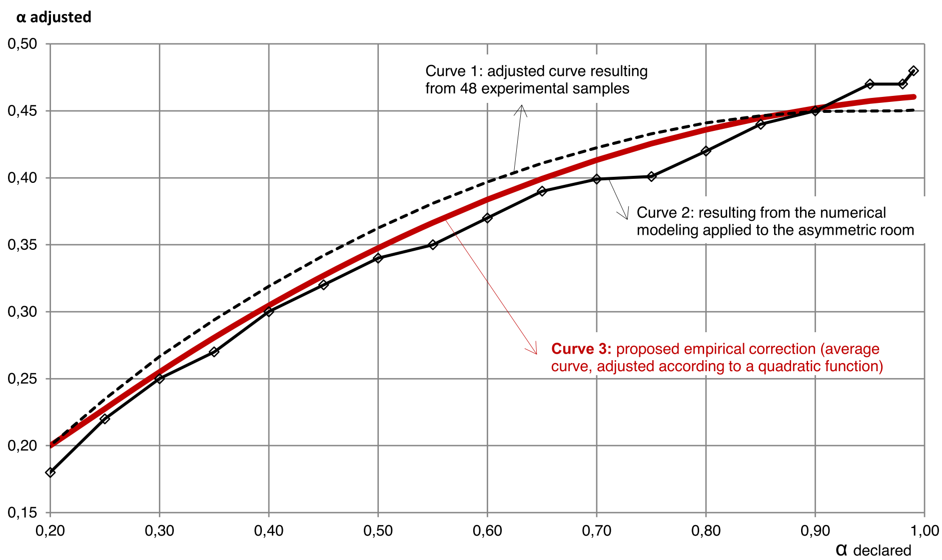


Figure 6. Empirical correction for the correction of the declared sound absorption coefficients, for subsequent determination of reverberation times, through Sabine's formula.

"adjusted" values of α. The curve is provided in Appendix has it will not be used for further analysis (Curve 1 in Fig. A1). Analysis of the sensitivity of the model in relation to the scattering coefficients of the reflective linings was performed and is also provided in Appendix, evidencing that the scattering coefficients used for modeling the low absorption surfaces influence the obtained curves. In order to remove the influence of the scattering effect provided by flat surfaces, a fictitious second asymmetric room was also assumed, in order to create a more diffuse field and reduce dependency on the surface scattering coefficients (see Fig. 4a). The rigid smooth surfaces were modelled with absorption coefficients similar to those defined for room CR and standard scattering properties were employed (10%). For this geometry an analysis of sensibility regarding scattering coefficients was also performed and no significant changes in the results were found (not lustrated here for sake of brevity). Figure 5b displays the corresponding curve. Analysis of curve provided in Figure 5b, evidences a similar trend to the curve obtained in the previous section (see Fig. 2) and will be therefore considered, in the next section, for proposal of an empirical correction.

3 Proposal of an empirical correction for adjusting values of *a*

In this section a proposal to provide a correction of the sound absorption coefficients provided by the manufacturer, for the lining materials employed in a room is addressed. The empirical correction should be applied in cases that do not meet diffuse sound field conditions, when using linings with high sound absorption in one or two main surfaces of the room. Figure 6 shows the two correction curves resulting from the two different approaches, described in the previous sections: the one presented in Section 2, based on experimental results (Curve 1); and the one presented in Section 3 (Curve 2), based on the results of numerical modeling. In this figure a third curve (indicated as Curve 3 in the plot) is also displayed corresponding to an adjustment following a quadratic function, between the two previous curves and setting the coefficient in a starting a value of 0.2. This third curve corresponds to the proposal of an empirical correction for adjusting the declared α values. For values below 0.20 (0.10 and 0.15) no results are displayed, since predictions using Sabine and numerical simulations match without any kind of correction. Curve 3, shown in Figure 6, which corresponds to the methodology proposed in this technical note, can be expressed as follows:

$$\alpha_{\text{declared}} \leq 0.2 => \alpha_{\text{adjusted}} = \alpha_{\text{declared}}$$
$$0.2 < \alpha_{\text{declared}} < 1.0 => \alpha_{\text{adjusted}} =$$
$$-0.338\alpha_{\text{declared}}^2 + 0.734\alpha_{\text{declared}} + 0.0651$$
$$\alpha_{\text{declared}} \geq 1.0 => \alpha_{\text{adjusted}} = 0.46. \quad (3)$$

4 Validation

In order to perform a validation of the proposed empirical correction, experimental results were obtained as well as an estimation of reverberation time (T) according to the present proposal. Table 2 displays a description of the eight different classrooms (four rooms in the Department of Civil Engineering of the University of Coimbra and four in two secondary schools in Porto, in Portugal). These eight rooms correspond to spaces not included in Sections 2 and 3, some of them displaying a more irregular geometry, where it was possible to measure reverberation times before and after the application of medium or high absorption coatings. In

Table 2. Description of the case studies.

Case study	Type of use	Dimensions	Volume (m^3)	Description of absorbing linings and seats
C1	Classroom	8.8 m × 6.2 m × 3.2 m	$V = 175$ m^3	Polyurethane foam agglomerate boards with 60 mm, in about 60% of the floor area without chairs
C2	Classroom	8.7 m × 6.1 m × 3.1 m	$V = 165$ m^3	Perforated plasterboard suspended ceiling and without chairs
C3	Classroom	8.8 m × 6.5 m × 3.2 m	$V = 183$ m^3	Grooved wood panels with mineral wool in the air gap, low upholstered chairs (30 seats) and PVC curtains
C4	Auditorium	≈ 15.4 m × 8.8 m × (from 2.5 to 4.5 m)	$V = 470$ m^3	Perforated plasterboard, in about 50% of the ceiling area and grooved wood panels with mineral wool in the air gap, in about 40% of the wall area and wooden chairs (150 seats)
C5	Classroom	7.0 m × 5.7 m × 3.0 m	$V = 120$ m^3	Perforated plasterboard ceiling and wooden chairs (20 seats)
C6	Classroom	9.6 m × 7.3 m × 3.0 m	$V = 210$ m^3	Perforated plasterboard ceiling and wooden chairs (40 seats)
C7	Computer room	8.2 m × 6.1 m × 5.2 m	$V = 260$ m^3	Wood wool bonded with cement and wood chairs (25 seats)
C8	Music room	5.0 m × 5.5 m × 2.9 m	$V = 80$ m^3	Perforated plasterboard on the ceiling and perforated wood panels on a wall without chairs

this table, there are two cases C4 and C7, which are not within the limits that were set for the proposed method, C4 because it provides non-standard geometry and high volume and C7 due to double-height.

Table 3 shows the obtained reverberation times and deviations, between theoretical and experimental results (in percentage) being the positive values on the safety side (i.e. estimated values above measured ones) and the negative values, the unfavorable ones. For the predicted reverberation times, absorption data for linings and chairs available in the literature and manufacturers technical documentation were used ([14–18]). From these eight rooms, two of them, which correspond to the cases that are not within the limits that were set for the proposed method, have a geometry assumed "non-common": Case 4 (C4) refers to a small auditorium and Case 7 (C7) with double height, where the effect of parallelism between walls significantly amplifies the reverberation of the room. In terms of distribution of sound absorption, from the eight rooms, six of them have a high sound absorption coating only on one of the surfaces while in two of them this high sound absorption coating is applied on both the ceiling and in part of the walls.

From the analysis of the results presented in Table 3 it is possible to verify that in the calculation of reverberation times through Sabine's formula, the use of absorption coefficients declared by the manufacturer for the surfaces of high sound absorption, leads to results significantly different from the experimental ones, with clearly unfavorable tendencies. On the other hand, if adjusted sound absorption coefficients are used, according to the empirical correction proposed in Figure 6, for regular geometries, there is a good approximation with experimental results, even if occasionally there are some deviations in frequency. In general, there is a slight tendency towards obtaining conservative predictions (when the requirement is to provide an upper limit for the reverberation time). In a frequency band analysis, this trend remains, even if occasionally, higher deviations may occur. In case C7, probably because of its sound "unfavorable" geometry (with a height of 5.2 m) and where the medium/high absorption coating was employed only on the ceiling (being less effective than in standard situations with heights around 3 m), even considering the adjusted sound absorption coefficients, the predicted result using the empirical correction remains significantly unfavorable. The higher deviation confirms the need to restrict the range of applicability of the method. For this type of enclosure or in others displaying more complex geometries, numerical modeling should be used. However, in relation to case C4, with high volume, the obtained deviations were small and favorable.

5 Conclusions

In the present work, a proposal of an empirical correction to adjust the values of the sound absorption coefficients provided by lining materials, declared by the manufacturers (obtained in the laboratory according to ISO 354:2003) was presented, allowing for a more accurate prediction using Sabine's formula in the cases where at least one surface has significantly higher absorption than the others, when applying linings with higher sound absorptions in one or two main surfaces of the room. This empirical correction was achieved from previous analysis using two types of approaches: one attained from the comparison between experimental reverberation times (using 48 samples) and

Table 3. Comparison between experimental and theoretical results, obtained using the proposed empirical correction, for eight case studies (corresponding to eight classrooms).

Case study		500 Hz		1000 Hz		2000 Hz		Average
		Value	Deviation in the estimated T (%)	Value	Deviation in the estimated T (%)	Value	Deviation in the estimated T (%)	Deviation in the estimated T (%)
C1: Classroom	α without correction	0.99		0.99		0.95		
	α with correction	0.46		0.46		0.46		
	T without correction	0.74	−40%	0.70	−39%	0.69	−35%	−38%
	T with correction	1.34	9%	1.20	6%	1.11	4%	6%
	T experimental	1.23		1.13		1.07		
C2: Classroom	α without correction	0.69		0.62		0.37		
	α with correction	0.41		0.39		0.29		
	T without correction	0.59	−28%	0.63	−24%	0.89	−6%	−19%
	T with correction	0.88	7%	0.90	7%	1.04	10%	8%
	T experimental	0.82		0.84		0.95		
C3: Classroom	α without correction	0.74		0.54		0.42		
	α with correction	0.42		0.36		0.31		
	T without correction	0.72	−3%	0.74	−10%	0.75	−14%	−9%
	T with correction	0.78	5%	0.85	4%	0.87	0%	3%
	T experimental	0.74		0.82		0.87		
C4: Auditorium	α_1 without correction	0.94		0.65		0.48		
	α_2 without correction	0.74		0.54		0.42		
	α_1 with correction	0.46		0.40		0.34		
	α_2 with correction	0.42		0.36		0.31		
	T without correction	0.56	−32%	0.69	−17%	0.80	−15%	−21%
	T with correction	0.88	7%	0.93	11%	0.97	3%	7%
	T experimental	0.82		0.84		0.95		
C5: Classroom	α without correction	0.85		0.70		0.55		
	α with correction	0.44		0.41		0.37		
	T without correction	0.34	−33%	0.38	−33%	0.44	−21%	−29%
	T with correction	0.53	4%	0.53	−7%	0.55	−2%	−2%
	T experimental	0.51		0.57		0.56		
C6: Classroom	α without correction	0.85		0.80		0.70		
	α with correction	0.44		0.43		0.41		
	T without correction	0.39	−34%	0.40	−37%	0.42	−28%	−33%
	T with correction	0.60	2%	0.59	−6%	0.57	−2%	−2%
	T experimental	0.59		0.63		0.58		
C7: Computer room	α without correction	0.30		0.45		0.70		
	α with correction	0.25		0.33		0.41		
	T without correction	0.96	−36%	0.78	−28%	0.58	−51%	−38%
	T with correctiono	1.04	−30%	0.91	−16%	0.80	−33%	−27%
	T experimental	1.49		1.08		1.19		
C8: Music room	α_1 without correction	0.85		0.70		0.55		
	α_2 without correction	0.80		0.60		0.45		
	α_1 with correction	0.44		0.41		0.37		
	α_2 with correction	0.43		0.38		0.33		
	T without correction	0.28	−30%	0.34	−35%	0.43	−25%	−30%
	T with correction	0.47	18%	0.52	0%	0.57	0%	5%
	T experimental	0.40		0.52		0.57		

those estimated using Sabine's formula; in the second one predicted results using Sabine's formula were compared with those from numerical modeling (using Ray tracing method). Although these are different approaches, it was found that they both lead to similar trends.

From the performed analysis, it was possible to verify that the application of Sabine's expression to enclosures where surfaces of high sound absorption are employed, using the sound absorption coefficients indicated by the manufacturers (obtained in the standard laboratory conditions) can lead to highly unfavorable results with subsequent in situ non-compliance with a reverberation time requirement. Unfortunately, it is very common to verify, after the construction works are completed, that the applied sound absorbent surface area is clearly unsatisfactory.

The proposal here presented may be suitable for simple design situations, for small or medium volume spaces (with a volume below 300 m^3), with regular geometry and average height below 4 m, when the main goal is the evaluation of an average reverberation time, for later comparison with an acoustic requirement. This methodology can be very useful in the sound design practice, due to its simplicity, providing more accurate results than the classical approach. The analysis performed neglected the effect of air absorption, however, as, it was demonstrated, this assumption would lead to similar results in the cases of small and medium rooms.

It is important to bear in mind that, quite often, the source of greater uncertainty turns out to be the lack of information regarding the sound absorption of some surfaces, in particular, furniture and fillings.

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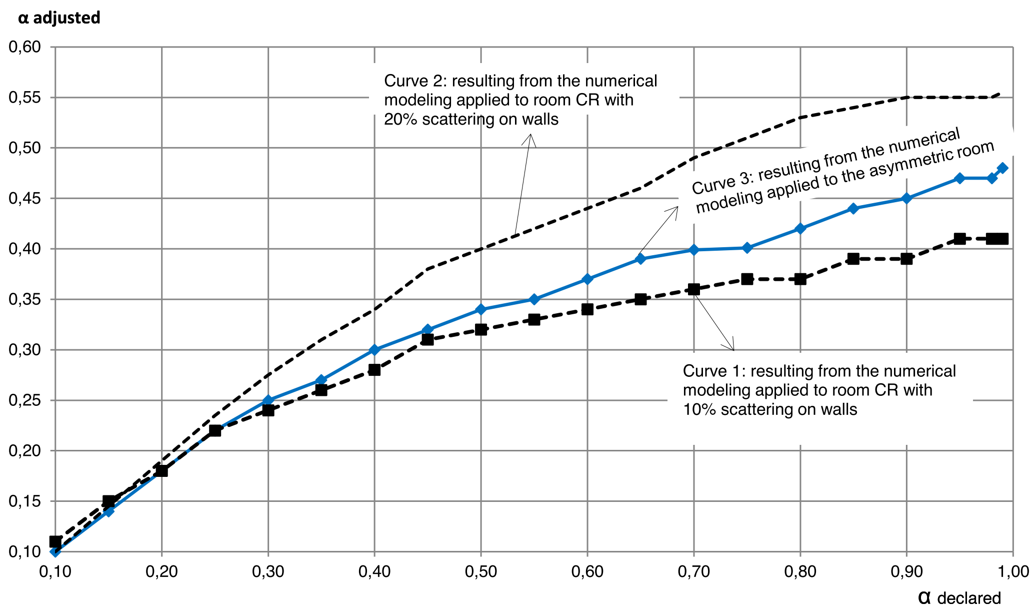

Figure A1. Relationship between the values of sound absorption coefficients given by the manufacturer and their adjusted values that should be used in Sabine's formula so as the reverberation time would be similar to those obtained in the numerical modelling scenarios.

Appendix

This appendix reports the analysis performed in what regards sensitivity of the model in relation to values of the scattering coefficients of flat surfaces used. With this purpose, two curves were obtained, one assuming the flat surfaces with a standard scattering coefficient of 10% (Curve 1) and a second where a scattering coefficient of 20% was employed (curve 2) for these surfaces. Figure A1 displays the obtained relation between the values of sound absorption coefficients declared by the manufacturers and the corrected values obtained by numerical modeling for these two simulation cases (Curves 1 and 2 respectively).

As can be seen in Figure A1, these adjusted values are similar to declared ones, for low sound absorption coefficients. However, as the absorption coefficient increases the tendency of curves one and two is to diverge, varying between 0.40 to 0.55 receptively, for declared absorption coefficients near 1, evidencing a strong influence of scattering in the simulation (this evidence was also observed by other authors ([26, 27]). In Figure A1 the response obtained for the asymmetric room modelling scenario (see Figure 5) is also included (Curve 3), being situated between Curves 1 and 2. This curve provides a better approach to the experimental one (displayed in Fig. 2) being adopted for further analysis.

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