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Noise Pollution Challenges in University Classrooms: An Empirical Analysis of Acoustic Performance Standards

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ABSTRACT

This work analyzes and studies the characteristics of three enclosures on a university Campus, which present similar challenges in terms of noise pollution. To carry out an empirical and objective assessment on their acoustic performance, current regulations, and standards, are being used. Theoretical calculations are considered to calculate reverberation time parameters. In order to calculate reverberation time by using the Sabine formula, it is necessary to measure the classrooms, together with the specification of the surface occupied by each of the materials that make up the walls in the rooms under study, resulting in a T60 of between 3.6 s to 6.2 s for classrooms 11 and 12, and between 4.1 s to 7.1 s for classroom 15. To obtain the parameters that define the acoustic capacities of reverberation of the rooms, the guidelines for both measurement and calculation conditions specified in the regulations are followed. Graphical representation and mathematical calculation software are used to achieve the desired results, obtaining a T60 of between 1.8 s to 2.2 s for classroom 11, 2.0 s to 3.0 s for classroom 12, and 1.7 s to 2.7 s for classroom 15. Once the acoustic conditions of the reverberation of the room are defined, it is concluded that none of the rooms has the proper characteristics to carry out the best teaching activities in them, since they exceed the recommended 0.7 s of reverberation time, since they hinder the understanding of speech and the clarity of the word. As a conclusion, the study has served as an analysis of a challenging task in the Miguelete Campus of the Universidad Nacional de San Martin, always based on parameters commonly used in the world of acoustic pollution, both scientifically and legislatively.

1. INTRODUCTION

The object of study and solution approach of this project is the unfavorable acoustic situation found at the Universidad Nacional de San Martín (UNSAM) specifically, at the Miguelete Campus, in the old Tornavías building.

The objective problem of the study is the acoustic conflict that occurs in the classrooms called Classroom 11, Classroom 12 and Classroom 15, which share the central corridor of the Tornavías building. As the corridor is the place where students enjoy their recess, these classrooms suffer from noise at times when teaching activities are being carried out [1, 2]. The aim of the study is to obtain an accurate specification of the acoustic characteristics of these rooms, and how they behave in relation to the acoustic noise source of the building and its organization. The analysis and obtaining of these characteristics will be carried out following what the current regulations stipulate, thus simulating a situation that could well occur in the working world, in a field of acoustic inspection and/or request by a certain client for an improvement of the acoustic conditions of the place to comply with current regulations.

The campus is situated between the railway line and a main road, yet the noise generated by these sources does not significantly contribute to the acoustic pollution of the classrooms in question [3]. Previous studies have highlighted the importance of indoor acoustic conditions [1] on speech intelligibility and learning outcomes, as well as the importance of good classroom conditions in general [4]. While significant research has been conducted on urban noise and its impact on educational environments, there is limited focus on the specific challenges posed by internal acoustic factors within university classrooms. This work aims to bridge that gap, providing an empirical evaluation of the acoustic conditions of the Tornavías building and offering practical insights into improving these spaces for effective teaching and learning.

2. REVERBERATION STUDY

Reverberation plays a critical role in the acoustics of classrooms, significantly impacting speech intelligibility and the overall learning environment. Understanding reverberation is essential for creating spaces that facilitate effective communication and learning.

The reverberation in a room depends mainly on two factors:

the volume of the room, and the material of the room elements where the acoustic signals bounce [5].

The direct signal, a short burst of sound that provides a clear reflection of how sound decays in the room, is the first to arrive at the destination, and it is the one that does not undergo any temporal or frequency modification caused by a bounce. The primary and late bounces are the ones that will make up the reverberant character of the room, and on which we must concentrate to find an acoustic improvement [6].

When the direct signal encounters an obstacle, part is absorbed by it, part is transmitted through it and part is reflected. It is the latter that will influence the reverberation time. The nature of the material of the obstacle defines the ratio and proportion of these three signals to the direct signal.

A suitable reverberation can have different values or levels depending on the use of the room in question. In our case, it is necessary that the reverberation be minimal, so that the echoes, or reflections of the direct signal, do not cause incomprehension in the listening, or poor clarity. In classrooms, an optimal reverberation time is 0.7 s [7, 8] for speech clarity.

The main parameter that defines the reverberation time in a room is the T60, which is defined as the time for the average acoustic energy density in a room to decrease by 60dB once the source emission has ceased [9].

To ensure the most accurate measurement of the reverberation time of the room under study, a variety of methods will be employed to obtain different parameters [10].

It should be noted that the reverberation time measurements were taken in an empty classroom. Therefore, when the classroom is occupied, the time will be shorter, due to the clothing of students and teachers being more absorbent than reflective, among other factors. This is not an error in the process of finding the solution, as it implies that our measurements define the worst-case scenario, which we are attempting to resolve. Subsequently, the presence of people in a classroom will only enhance the room's acoustic quality.

3 THE SABINE FORMULA

This method allows us to obtain the T60 from the volume of the room, and the material of which the surface where the sound bounces off is made up [11]. The value obtained with this method is purely theoretical and is applied to make a comparison of values with other methods based on 'in situ' measurements. It is useful to know the certainty offered by this method, as it does not imply the need for certain material (microphones, sound sources, sound analysis equipment, among others), and the process is simpler. The formula to obtain the T60 is as follows:

$$T60[s] = k\left(\frac{V}{A}\right) \tag{1}$$

where, V is the volume of the room, and A is the equivalent sound absorption area.

The k-factor was calculated empirically by Sabine and follows the following expression:

$$k[\mathrm{s/m}] = \frac{24\ln(10)}{C_{20}} = 0.161 \tag{2}$$

where, C_{20} is the speed of sound at 20 degrees (343 m/s).

The sound absorption area is defined as:

$$A[\mathrm{m}^2] = \sum_{n=1}^{i} \alpha_i \cdot S_i \tag{3}$$

where α_i is the absorption coefficient of a given surface at a given frequency (normally, this value is usually given for the frequency of 1,000 Hz), and S_i is the m^2 of that surface.

To carry out the calculation, the room must be divided according to the type of material of each surface, the surface must be measured, and the calculation carried out. The more rigorous the division of the surfaces, the more accurate the calculation of the reverberation time will be.

The materials found in the classrooms analysed are as follows: glass for the windows, plaster covering most of the walls, exposed brick walls, terrazzo flooring, varnished wood for the doors, and melamine for the blackboards (Table 1).

Table 1. Material's sound absorbing coefficients in classroom [12]

Frequency [Hz]	500	1,000	2,000
(exposed) Brick	0.032	0.042	0.05
Glass	0.027	0.03	0.02
Plaster	0.02	0.028	0.04
Ground	0.01	0.01	0.02
Whiteboard	0.14	0.08	0.13
Painted Wood	0.06	0.08	0.10

3.1 T60 calculations for classrooms 11, 12

Both classrooms share similar measurements, so the process of generating plans, and calculating their volume, equivalent absorption area and consequent T60, has been carried out only once. To calculate the volume of the classroom, we make use of the Autocad software with which the plans have been drawn, and which offers the surface measurement function [12]. We proceed to measure the surface area of the classroom floor, and multiply by the height to obtain the total volume.

The value obtained in Autocad is in mm^2, we convert it to m^2 and then we multiply it by 2,85 m which is the height in the whole classroom:

$$V[\mathrm{m}^3] = 58.3288 * 2.85 = 166.2371 \tag{4}$$

The process of calculating the surfaces of each material is continued. The surfaces are divided by type of material.

Glass

Glass has a refractive index for the model frequency of 1,000 Hz of 0.03. Calculations for the 500 Hz, 1,000 Hz and 2,000 Hz frequencies of the glass are shown below.

$$A_{\text{glass}}(500\mathrm{Hz}) = 0.027 * (6.4555 + 6.006) = 0.33646\mathrm{m}^2 \tag{5}$$

$$A_{\text{glass}}(1000\mathrm{Hz}) = 0.03 * (6.4555 + 6.006) = 0.3738\mathrm{m}^2 \tag{6}$$

$$A_{\text{glass}}(2000\mathrm{Hz}) = 0.02 * (6.4555 + 6.006) = 0.2492\mathrm{m}^2 \tag{7}$$

Brick

The brick has a refractive index for the model frequency of

1,000 Hz of 0.042. Calculations for the 500 Hz, 1,000 Hz and 2,000 Hz frequencies of the seen brick are shown below:

$$A_{\text{brick}}(500\text{Hz}) = 0.032 * (17.1075 + 0.684 * 2) = 0.5912\text{m}^2 \tag{8}$$

$$A_{\text{brick}}(1000\text{Hz}) = 0.042 * (17.1075 + 0.684 * 2) = 0.7815\text{m}^2 \tag{9}$$

$$A_{\text{brick}}(2000\text{Hz}) = 0.05 * (17.1075 + 0.684 * 2) = 0.9237\text{m}^2 \tag{10}$$

Plaster

The plaster has a refractive index for the model frequency of 1,000 Hz of 0.028. Calculations for the 500 Hz, 1,000 Hz and 2,000 Hz frequencies of the plaster are shown below:

$$A_{\text{plaster}}(500\text{Hz}) = 0.02 * (58.32 + 7.54 + 2 * 20.45) = 2.1358\text{m}^2 \tag{11}$$

$$A_{\text{plaster}}(1000\text{Hz}) = 0.028 * (58.32 + 7.54 + 2 * 20.45) = 2.9901\text{m}^2 \tag{12}$$

$$A_{\text{plaster}}(2000\text{Hz}) = 0.04 * (58.32 + 7.54 + 2 * 20.45) = 4.2715\text{m}^2 \tag{13}$$

Ground

The ground material has a refractive index for the model frequency of 1,000 Hz of 0.01. Calculations for the 500 Hz, 1,000 Hz and 2,000 Hz frequencies of the ground are shown below:

$$A_{\text{ground}}(500\text{Hz}) = 0.01 * (58.3288) = 0.5833\text{m}^2 \tag{14}$$

$$A_{\text{ground}}(1000\text{Hz}) = 0.01 * (58.3288) = 0.5833\text{m}^2 \tag{15}$$

$$A_{\text{ground}}(2000\text{Hz}) = 0.02 * (58.3288) = 1.1666\text{m}^2 \tag{16}$$

Whiteboard

The whiteboard has a refractive index for the model frequency of 1,000 Hz of 0.08. Calculations for the 500 Hz, 1,000 Hz and 2,000 Hz frequencies of the whiteboard are shown below:

$$A_{\text{board}}(500\text{Hz}) = 0.14 * (2.9869) = 0.4181\text{m}^2 \tag{17}$$

$$A_{\text{board}}(1000\text{Hz}) = 0.08 * (2.9869) = 0.2389\text{m}^2 \tag{18}$$

$$A_{board}(2000Hz) = 0.13 * (2.9869) = 0.3882m^2 \tag{19}$$

Painted wood

The wood has a refractive index for the model frequency of 1,000 Hz of 0.08. Calculations for the 500 Hz, 1,000 Hz and 2,000 Hz frequencies of the wood are shown below:

$$A_{\text{wood}}(500\text{Hz}) = 0.06 * (3.7199) = 0.2232\text{m}^2 \tag{20}$$

$$A_{\text{wood}}(1000\text{Hz}) = 0.08 * (3.7199) = 0.2976\text{m}^2 \tag{21}$$

$$A_{\text{wood}}(2000\text{Hz}) = 0.10 * (3.7199) = 0.3719\text{m}^2 \tag{22}$$

Final calculations for T60 classrooms 11 and 12

In this section we will make use of the previously calculated parameters to calculate the theoretical T60 according to the Sabine formula for three of the frequencies of the audible spectrum: 500 Hz, 1,000 Hz and 2,000 Hz. First, we calculate the sum to obtain the sound absorption area for each of the frequencies (the order of materials is: glass, brick, plaster, ground, board and wood):

$$A(500\text{Hz}) = 0.3365 + 0.5912 + 2.1358 + 0.5833 + 0.4181 + 0.2232 = 4.2881\text{m}^2 \tag{23}$$

$$A(1000\text{Hz}) = 0.3738 + 0.7815 + 2.9901 + 0.5833 + 0.2389 + 0.2976 = 5.2652\text{m}^2 \tag{24}$$

$$A(2000\text{Hz}) = 0.2492 + 0.9237 + 4.2715 + 1.1666 + 0.3882 + 0.3719 = 7.3711\text{m}^2 \tag{25}$$

Once the calculation has been completed, the relevance of each material at each frequency is evaluated. It is also noted that as the frequency increases, the absorption area is greater, which reduces the theoretical T60. This is in line with the anticipated behaviour of the room with respect to the frequency, as at lower frequencies, controlling the omnidirectionality of reverberation times is more challenging.

It is also important to analyse the influence of each of the materials, considering the surface area they occupy in the classroom. The high value of the absorption area of both board and wood (one would expect a small value with respect to the other materials due to their small relative surface area in the classroom) is due to the high refractive index with respect to the other materials. Plaster, despite having one of the lowest refractive indices of all the materials present, is the one that has the greatest weight for the three frequencies in the calculation of the equivalent sound absorption area, since it is the material that occupies the largest surface area in the classroom.

Next, the theoretical T_{60} is obtained for each of the three frequencies:

$$T_{60}(500\text{Hz}) = 0.161 \frac{166.2371}{4.2881} = 6.2414\text{s} \tag{26}$$

$$T_{60}(1000\text{Hz}) = 0.161 \frac{166.23715}{5.2652} = 5.0832\text{s} \tag{27}$$

$$T_{60}(2000\text{Hz}) = 0.161 \frac{166.2371}{7.3711} = 3.6309\text{s} \tag{28}$$

3.2 T60 calculations for classroom 15

The calculation for volume for classroom 15 is shown. As previously, the surface is multiplied by the height (2.85 m):

$$V = 70.5451 \cdot 2.85 = 201.0535\text{m}^3 \tag{29}$$

The process of calculating the surfaces of each material is continued. The surfaces measurements obtained by Autocad [13] are multiplied by the refraction factor of each material:

Glass

$$A_{\text{glass}}(500\text{Hz}) = 0.027 * (3.948 + 15.84) = 0.5343\text{m}^2 \tag{30}$$

$$A_{\text{glass}}(1000\text{Hz}) = 0.03 * (3.948 + 15.84) = 0.5936\text{m}^2 \tag{31}$$

$$A_{\text{glass}}(2000\text{Hz}) = 0.02 * (3.948 + 15.84) = 0.3958\text{m}^2 \quad (32)$$

Plaster

$$A_{\text{plaster}}(500\text{Hz}) = 0.02 * (70.545 + 12.63 + 19.95 + 20.89 + 10.152) = 2.6833\text{m}^2 \quad (33)$$

$$A_{\text{plaster}}(1000\text{Hz}) = 0.028 * (70.545 + 12.63 + 19.95 + 20.89 + 10.152) = 3.7566\text{m}^2 \quad (34)$$

$$A_{\text{plaster}}(2000\text{Hz}) = 0.04 * (70.545 + 12.63 + 19.95 + 20.89 + 10.152) = 5.3667\text{m}^2 \quad (35)$$

Ground

$$A_{\text{ground}}(500\text{Hz}) = 0.01 * (70.545) = 0.7055\text{m}^2 \quad (36)$$

$$A_{\text{ground}}(1000\text{Hz}) = 0.01 * (70.545) = 0.7055\text{m}^2 \quad (37)$$

$$A_{\text{ground}}(2000\text{Hz}) = 0.02 * (70.545) = 1.4109\text{m}^2 \quad (38)$$

Whiteboard

$$A_{\text{board}}(500\text{Hz}) = 0.14 * (7.32) = 1.0248\text{m}^2 \quad (39)$$

$$A_{\text{board}}(1000\text{Hz}) = 0.08 * (7.32) = 0.5856\text{m}^2 \quad (40)$$

$$A_{\text{board}}(2000\text{Hz}) = 0.13 * (7.32) = 0.9516\text{m}^2 \quad (41)$$

Painted wood

$$A_{\text{wood}}(500\text{Hz}) = 0.06 * (7.2924) = 0.4375\text{m}^2 \quad (42)$$

$$A_{\text{wood}}(1000\text{Hz}) = 0.08 * (7.2924) = 0.5834\text{m}^2 \quad (43)$$

$$A_{\text{wood}}(2000\text{Hz}) = 0.10 * (7.2924) = 0.7292\text{m}^2 \quad (44)$$

Final calculations for T60 classroom 15

In this section we will make use of the previously calculated parameters to calculate the theoretical T60 according to the Sabine formula for three of the frequencies of the audible spectrum: 500 Hz, 1,000 Hz and 2,000 Hz. First the sum was calculated to obtain the sound absorption area for each of the frequencies (the order of materials is: glass, brick, plaster, ground, board and wood):

$$A(500\text{Hz}) = 0.5343 + 2.6833 + 0.7055 + 0.4181 + 0.2232 = 4.5644\text{m}^2 \quad (45)$$

$$A(1000\text{Hz}) = 0.5936 + 3.7566 + 0.7055 + 0.2389 + 0.2976 = 5.5922\text{m}^2 \quad (46)$$

$$A(2000\text{Hz}) = 0.2492 + 0.9237 + 4.2715 + 1.1666 + 0.3882 + 0.3719 = 7.9335\text{m}^2 \quad (47)$$

As in classroom A12, the higher the frequency, the greater the sound absorption area, resulting in a shorter reverberation time. In comparison with classroom A12, the sound absorption area values are higher for all frequencies, since it has more surface area, and does not have a material such as exposed brick that has a higher refractive index than the rest of the common surface materials.

Next, the theoretical T_{60} is obtained for each of the three frequencies:

$$T_{60}(500\text{Hz}) = 0.161 \frac{201.0535}{4.5644} = 7.0917\text{s} \quad (48)$$

$$T_{60}(1000\text{Hz}) = 0.161 \frac{201.0535}{5.5922} = 5.7884\text{s} \quad (49)$$

$$T_{60}(2000\text{Hz}) = 0.161 \frac{201.0535}{7.9335} = 4.0801\text{s} \quad (50)$$

4. FOLLOW-UP TO ISO3382 STANDARD

This standard [8] presents the basis to obtain measurements at three levels of accuracy (from lowest to highest: control, engineering and precision) of the T60 reverberation time [14]. In our case we will use the engineering method.

To obtain the T60, measurements in ranges below 60 dB decay are used, with subsequent extrapolation to 60 dB. The ranges chosen in this standard are 20 dB and 30 dB, with a preference for the 20 dB decay range. These values, while still referring to the same phenomenon (time required for a 60 dB decrease in energy density), will have a different abbreviation than T60, and will be T20 (measurement in the 20 dB range) and T30 (measurement in the 30 dB range).

We will measure empty classrooms to understand the inherent acoustic properties of the room itself, being important that this standard accepts the presence of two people in the room to take a picture of the empty room.

It defines a large volume room as a room whose volume is greater than 300 m^2. This is a relevant definition because in rooms that meet this requirement, air attenuation is a factor that influences the results obtained for reverberation time. However, it is also specified in the standard that this attenuation is low in the following cases:

-At the 2 kHz frequency, if the reverberation time is less than 1.5 s.

-At the 4 kHz frequency, if the reverberation time is less than 0.8 s.

Two positions will be provided for the sound source to excite the room, the teacher's desk and the center of the classroom, considering the possible sound sources. However, the engineering and control measurement methods do not specify requirements for the sound source, other than that it shall be capable of generating sufficient sound pressure to generate decay curves of at least 20 dB (the range necessary to obtain T20). The source shall be as omnidirectional as possible.

Measurements shall be made at times when background noise is minimal, to ensure that the source we use (both for the interrupted noise method and the impulsive response method) generates enough dynamic range to draw a suitable decay curve to analyze. These moments will be those in which academic activity is minimal in the analyzed space. This is especially true on weekends when there is no teaching-learning activity.

The signal reception will be done with an omnidirectional microphone as small as possible (maximum diaphragm of 14mm), which will be connected to one of the following two options:

-Filters and equipment where the decreasing curve is visible.

-Recording equipment for further analysis. We will make use of the latter option.

The devices and software that have been used are the ones that follow:

-Behringer ECM8000 microphone [15].

-Focusrite 18i20 Generation 3 audio interface [16].

-JBL EON610 self-powered loudspeaker [17].

-DELL Latitude E6540 computer for recording and analysis [18].

-REW (Room Acoustic Software) [19].

The measurement positions of both the source and the microphone, and the number of measurements is defined by Table 2.

Table 2. Positions and number of measurements

Positions	Control	Engineering[1]	Precision
Source-microphone	2	6	12
Source position[2]	≥ 1	≥ 2	≥ 2
Microphone position[3]	≥ 2	≥ 2	≥ 3
Number of decrements in each position (Interrupted sound method)	1	2	3

[1]When the result is used for a correction term in other engineering level measurements, only one source position and three microphone positions are required. [2]For the interrupted noise method, non-correlated sources can be used simultaneously. [3]For the interrupted noise method and when the result is used for a correction term, a rotating microphone hanger can be used instead of multiple microphone positions.

Since our measurement method is the engineering method, we have the following conditions:

-There must be 6 source-microphone combinations.

-Minimum 2 source positions.

-Minimum 2 microphone positions.

-For the interrupted noise method, two decrements must be measured at each combination of positions.

To meet these conditions, we will use two source positions, and in each of them, 3 microphone positions, which will be along the area where the students will be located, trying to cover as much area as possible, to generate two decrements at each position combination, generating a total of 6 positions. The standard, with respect to the distances in the microphone positionings, imposes the following conditions:

-The position of the source must be the normal position in the room. In our case, it is advisable to place the source in places where the teacher usually teaches his or her class.

-The positions of the microphones should be at least half a wavelength apart. The maximum wavelength occurs at lower frequencies. In our case, the lowest frequency we will be measuring is 100 Hz, so the minimum distance is:

$$\lambda = cF = \frac{340 \text{ m}/s}{100 \text{ Hz}} = 3.4 \text{ m} \quad (51)$$

$$Dmin = \frac{3{,}4}{2} = 1.7 \text{ m} \quad (52)$$

where C is the speed of sound and F is the lowest frequency (100 Hz). To make the measurement simpler, we take the minimum distance as 2 m.

-The distance between the microphone and any obstacle or wall shall be at least one quarter of the wave distance, i.e. $Dmin \cong 1\text{m}$.

-Avoiding symmetrical positions.

-The minimum distance between any position of the microphone and the source shall be such that:

$$Dmin = 2\sqrt{\frac{V}{cT}} \quad (53)$$

where V is the volume of the room, c is the speed of sound and T is an estimate of the expected reverberation time. The estimated reverberation time is 5s (approximately) and has been obtained by using the Sabine calculation method in the previous section.

The standard describes two measurement methods, the interrupted noise method and the integrated impulsive response method. For both, certain generalities are defined with respect to the frequency spectrum to be measured in the engineering method:

-The measured frequency range in octave bands shall be from 125 Hz to 4 kHz. The nominal accuracy with this choice of measurement is assumed to be better than 2.5%.

-The frequency range measured in thirds of an octave shall be from 100 Hz to 5 kHz. Nominal accuracy is assumed to be better than 5%.

4.1 Interrupted noise method

The source, by means of random noise, must be able to generate a sound intensity level at least 35 dB above the background noise that exists in the room for the selected third of the band. This is to obtain a decay curve with which to analyse and clearly see the T20. The bandwidth of the excitation signal must be greater than one third of an octave, being a flat signal in the octave third to be measured [20].

Since our software, by means of the Fourier transform of the signal picked up by the microphone, can plot the level in all octave thirds simultaneously, it is not necessary to make a measurement for each of the octave thirds to be measured. The standard gives as an example of excitation a pink noise comprising frequencies between 88 Hz and 5,657 Hz. The limiting frequencies of this excitation correspond to the lower frequency of the first third of the octave (centre frequency of 100Hz), and to the upper frequency of the last third of the octave (centre frequency of 5 Khz). This is the excitation to be used [21].

To obtain the final reverberation time, we follow one of the two methods offered by the standard:

-By finding the individual reverberation times for all the decay curves and taking the mean value. This is the method chosen in our case.

-By calculating an average of all the squared sound pressure decays and finding the reverberation time of the resulting decay curve. The individual decays are superimposed by synchronising their origins. The sampled values of the squared discrete sound pressure are summed for each increment of the time interval of the decays and the sequence of these sums is used as a single decay of the set from which T is evaluated. It is important that the source sound power is identical for all measurements.

4.2 Results obtained

The results obtained for the reverberation time for each of the classrooms are shown below. The main objective of the measurements is to obtain the value of T30 or T20, although other relevant values are also included, such as the clarity C50, which expresses the clarity especially in cases where the source is a human voice.

According to the Basic noise protection document [7], the reverberation time in classrooms with a volume of less than 350 m^3 shall not exceed 0.7 s. This is information that gives us a prerequisite on which to conclude the adequacy of the reverberation time data obtained.

The frequency spectrum in which human voices are found is also a key piece of information. Typical adult male speech will have a fundamental frequency of 85 to 180 Hz, and typical adult female speech will have a fundamental frequency of 165 to 255 Hz. Then the most critical frequencies will be between 86 Hz and 255 Hz.

4.2.1 Classroom 11

The reverberation time in room 11 ranges from 2.2 s (maximum value) to 555 ms (minimum value). The tendency of the T60 is to decrease with increasing frequency. At the frequencies of a typical speech by a male person, the reverberation time obtained ranges from 1.8 s to 2.2 s, always above the maximum values for adequate intelligibility. For the speech frequencies of a female person, the result, although improved, is still above the desired 0.7 s. The range is small, with minimum values of 1.7 s and maximum values of 1.8 s (Figure 1).

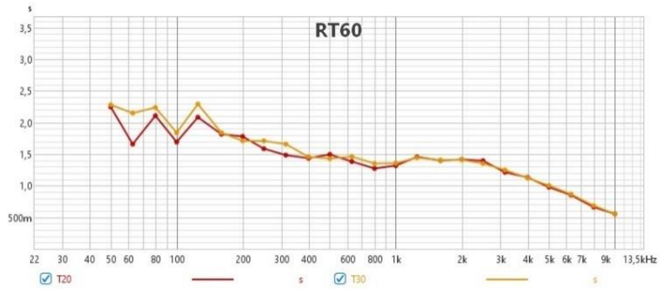

Figure 1. Classroom 11, reverberation time T60 (or RT60)

The difference between T30 and T20 values are small and are more variable at low frequencies. The T30 value is more explanatory of the T60 than the T20 value, since the extrapolation carried out to obtain the T60 is smaller and implies less error.

Figure 2 shows the sound intensity level decay in frequency and time, with a photograph at 1 kHz frequency value.

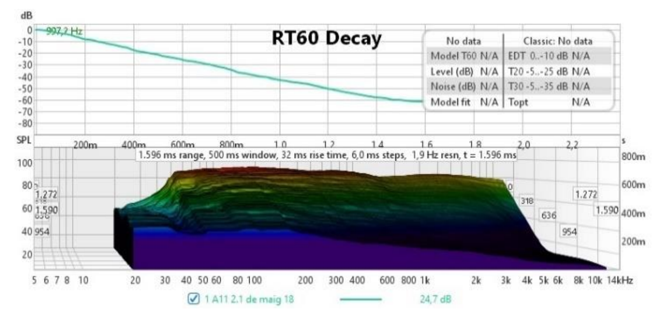

Figure 2. Level decay at 1 kHz for classroom11

The C50 compares the energy of the early reflections (up to 50ms) with the late reflections. It is expressed in dB. The higher the C50, the clearer the speech. The C80 parameter responds to the same definition, but with 80 ms as the limit of the first reflections with respect to the late ones.

It can be seen in the graph that the values of C50 and even C80 are low, being always in negative values, and only exceeding the value of 0dB (in the case of C50) at frequencies from 2 kHz onwards.

A summary of the acoustic reverberation capabilities of Classroom 11 is that it does not meet the requirements for acceptable listening quality at the frequencies at which human speech moves. The reverberation time is too high for a clear perception of direct signals, as can be seen in the RT60, C50 and C80 clarity graphs (Figure 3).

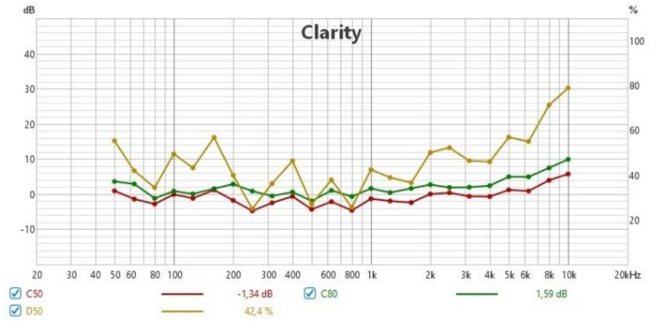

Figure 3. Classroom 11 clarity

4.2.2 Classroom 12

The results obtained in classroom 12 for the acoustic parameters relating to reverberation time are presented below:

As shown in the Figure 4, the T60 reverberation time is, for most of the frequency range, greater than 1.5 s. This indicates the poor acoustic quality of the room, or at least that its capabilities do not match the intended use of the room.

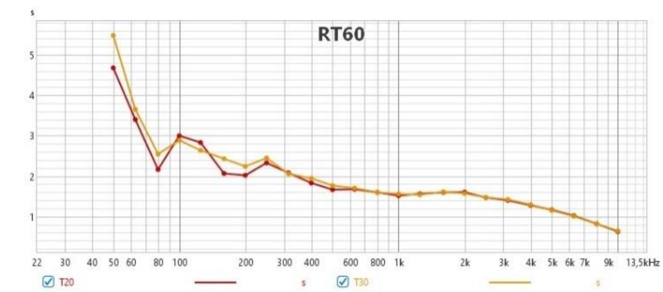

Figure 4. Reverberation time for classroom 12, T60 (or RT60)

As in classroom 11, the reverberation time is longer at low frequencies, since sounds of this type tend to be more omnidirectional and more difficult to contain and control.

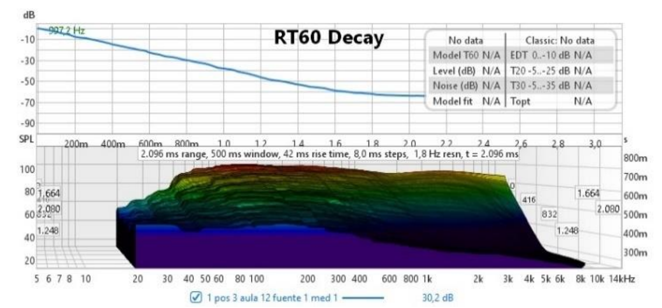

Figure 5. Level decay at 1kHz for classroom 12

For the frequencies that conceive of human speech, both male and female, the reverberation times we found oscillate between 2 s and 3 s.

The curve showing the sound intensity level in time and frequency is presented in Figure 5.

Figure 6 shows the clarity values C50 and C80, with specific values in the legend for the 1 kHz frequency.

Figure 6. Classroom 12 clarity

Although the values from the mid-low frequencies of C50 are slightly better than in classroom 11, the values especially for the frequencies of interest (50-250 Hz) are negative, ranging between -10 dB and -4 dB.

Classroom 12, in terms of reverberation time and speech clarity, does not meet the requirements to be considered an optimal classroom for the activities for which it has been built. The reverberation time is too high especially at the frequencies of interest, and the first reflections do not have a noticeably higher energy than the later reflections.

4.2.3 Classroom 15

The results obtained by acoustically analysing the values related to reverberation time and clarity in room 15 are presented below. Figure 7 shows contain information on T60 measured at T30 and T20.

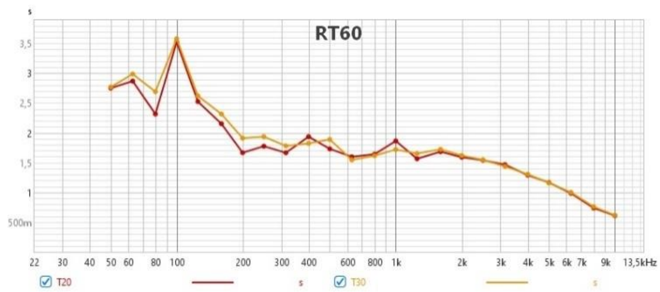

Figure 7. Classroom 15 reverberation time

As in the previous cases, the reverberation time continues to decrease in value as the frequency increases. At frequencies of interest, values ranging between 1.7 s and 2.7 s are observed, with the exception of a peak at the 100 Hz frequency, which may be due to a mode specific to the classroom. From 300 Hz onwards, the T60 remains constant, oscillating between 1.7 s and 1.9 s until it reaches the frequency of 2 kHz, after which the reverberation time begins to fall steadily to a value of 600 ms at 10 kHz.

The graph of the sound level drop in time and frequency is shown in Figure 8, with the curve drawn for the frequency value of 1 kHz:

Figure 9 presents the clarity values in the classroom, with specific values for the 1 kHz frequency.

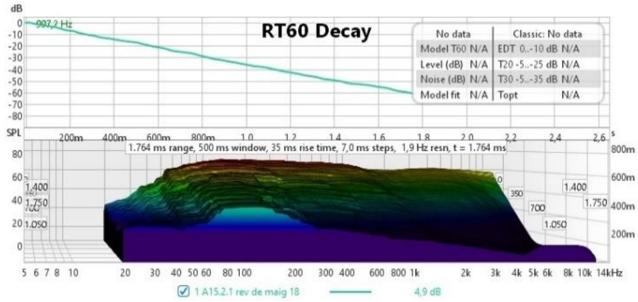

Figure 8. Sound pressure level decay of classroom 15

Figure 9. Classroom 15 clarity

As can be seen in the figure, the C50 values are negative in a large part of the captured spectrum. For the frequencies of interest (80 to 250 Hz), except for the peak at 250 Hz, the values oscillate between -8 and -3dB. At frequencies higher than 250 Hz, stable values are maintained around -2 dB up to 4 kHz, a frequency from which the sound clarity value increases.

Summarizing, according to the values obtained in classroom 15, it can be stated that although it has slightly better values compared to classrooms 11 and 12, it does not meet the minimum requirements to obtain a quality of listening and speech in accordance with the teaching activity.

4.2.4 Result comparing

Sabine predictions were higher than measured values at low frequencies, indicating limitations in accounting for specific material characteristics. This discrepancy arises because the Sabine formula assumes diffuse sound fields and uniform material absorption, which may not be fully applicable in real-world conditions like those present in classrooms with irregular geometries and non-uniform material distributions.

At low frequencies, room modes often dominate the acoustic behavior, leading to uneven sound absorption and distribution, which the Sabine formula cannot accurately predict. In contrast, at higher frequencies, where the sound field is more diffuse, the measured values align more closely with theoretical predictions. This observation supports the notion that Sabine's approach is better suited for higher frequencies or for spaces with highly diffusive surfaces.

5. CONCLUSIONS

Once the reverberant capacities of the rooms had been measured, it was concluded that none of the classrooms complied with the requirements of the Basic Document on Noise Protection, i.e. that the reverberation time should be less than 0.7 s. Although this document does not specify at which frequency this requirement applies, it is understood that it applies to the whole frequency range. In this case, where the frequencies of interest are those where human speech is found (80-250 Hz), no classroom has the capacity to carry out the teaching activity, having among the three classrooms a T60 with values between 143% to 330% above the recommended value.

As far as speech clarity is concerned, since this is closely related to reverberation time, the results also indicate that the classrooms have acoustic conditions that are not conducive to adequate speech comprehension, which is crucial.

To address these shortcomings, measures such as installing sound-absorbing panels, using carpets, upgrading windows and doors, and incorporating diffusers can be applied. These interventions would reduce reverberation, improve speech clarity, create more suitable acoustic environments for teaching activities, as well as improving the method of sound measurement.

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NOMENCLATURE

T60	reverb time measured in 60 dB difference
T20	reverb time measured in 20 dB difference
T30	reverb time measured in 30 dB difference
C50	clarity. 50 ms reference
C80	clarity. 80 ms reference

Greek symbols

α	acoustic refraction index
Λ	wave length