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Proposal of a Simplified Tool for Early Acoustics Design Stage of Classrooms in Compliance with Speech Intelligibility Thresholds

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Abstract: The speech intelligibility properties of classrooms greatly influence the learning process of students. Proper acoustics can promote the inclusion of foreign students and children with learning or hearing impairments. While awareness of the topic is increasing, there is still no parameter that can describe all aspects of speech transmission inside a room. This complicates the design of classrooms and requires designers to have extensive knowledge of theory and experience. In the scientific and technical literature, there is a lack of predictive tools, easy to use by designers, which can guide the choices in the early design stages in order to move towards technical solutions able to ensure adequate levels of speech intelligibility. For this reason, in this paper, the most relevant speech intelligibility parameters found in the literature were collected and discussed. Among these, the Clarity index and Speech Transmission Index were singled out as the most effective ones, whose prediction can be made with relatively simple methods. They were then analyzed through their prediction formulas, and a tool was proposed to allow an easy estimation of the minimum total equivalent sound absorption area needed in a classroom. This tool greatly simplifies the early acoustics design stage, allowing the intelligibility of speech within a classroom to be increased without requiring much theoretical effort on the part of the designers.

Keywords: room acoustics; classroom acoustics; students learning; speech intelligibility; clarity index; prediction diagram

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1. Introduction

Classroom acoustics is one of the main goals in classroom design to ensure a fruitful learning environment. Neglecting sound in design can easily lead teachers to vocal diseases [1] due to high phonation times and high sound pressure levels of speech [2] and can worsen students' performance and create annoyance [3]. The increase in sound levels of speech under conditions of high background noise, as described in ISO 9921:2003 [4], is due to what is now known as the Lombard effect [5], an unconscious vocal change that leads to an increase in pitch and lengthening of word duration [6]. At the same time, noise in classrooms has a dual origin: it can come from the external environment or students' activity [7] and consequently from an untreated decay of sound in the environment. For this reason, Reverberation Time (*RT*) has often been considered one of the indispensable parameters in proper acoustic design [8,9], although not directly correlated with student performance [10,11].

Parameters of greater relevance are those that consider the contribution of early reflections related to the listening experience [12], such as the Clarity index C_{50} (ISO 3382-1:2009 [13]), or parameters that include both room acoustics and speech-to-noise-ratios measurements, such as the Speech Transmission Index *STI* (IEC 60268-16:2020 [14]) or the Useful-to-detrimental sound ratio U_{50} [15]. Describing these parameters in international [13,16] and national acoustic standards [17,18], it has become necessary to unambiguously establish which of these is needed as the main parameter of the acoustic quality of learning environments, even considering the expensive instrumentation required for proper in situ measurement. The lack of adequate instrumentation and the presence of several parameters complicate the design of these environments for those who do not specialize in the acoustics of learning environments.

To minimize the number of measurement points, Astolfi et al. [19] proposed to characterize classrooms with the Clarity index in a central location and a spatial average of Reverberation Time (T20), while a global indicator of classroom acoustics was proposed by Chetoni et al. [20]. These parameters, however, can and should be able to be predicted at the early acoustics design stage so that materials and their arrangement can be consciously chosen to ensure speech intelligibility within the school environment. This can be achieved through acoustic simulation of the classroom [21,22] and through prediction formulas [23], of which those that allow the estimation of Reverberation Time [24], Clarity index [25,26], and Speech Transmission Index [27–29] were considered in this article, as conducted in previous research by the same authors [30]. However, the advantages associated with being able to predict the acoustic behavior of the environment are not obtainable without effort. Simulations require knowledge of specific software that are not always freeware, with high modeling times of the environment and calculation times highly dependent on the type of simulation and the required accuracy. Prediction formulas, on the other hand, are many, and their choice is not always obvious. They also, in some cases, require a nontrivial amount of hand calculations, often having to consider different variables. These difficulties prevent a simple preliminary assessment and do not directly address the main objective of acoustic design: the choice and arrangement of materials.

For these reasons, the authors found it useful to propose a simplified tool to be used in the early acoustics design stage. The tool would allow for the rapid estimation of the total equivalent sound absorption area (A) required to ensure compliance with the thresholds of speech intelligibility parameters necessary for the construction of fruitful learning environments. Firstly, the parameters of interest were selected based on their importance in describing the acoustics of classrooms. Secondly, the prediction formulas of the respective parameters were selected according to the criterion of effectiveness versus simplicity of use. Thirdly, the chosen prediction formulas were made a function of the same variables (volume V and total equivalent sound absorption area A) so that they could be easily calculated and compared. Finally, in the same prediction A–V diagram, the contour lines of the parameter thresholds suggested by standards and the technical literature for classrooms were drawn in order to divide the total sound absorption area (A) into different zones with different speech intelligibility ratings. The result was then compared with measurements taken in two medium-sized university classrooms at the University of Pisa ($300 < V < 800$ m^3) and with data from four small-sized classrooms of first-grade schools ($V < 300$ m^3) taken from Astolfi et al. [19].

2. Materials and Methods

In creating a simplified tool for the estimation of speech intelligibility parameters, the first part of the research focused on trying to determine which parameters best represent speech intelligibility and their relationship to actual student learning. Of those set out in the literature, they cannot all be taken indiscriminately, but the parameters must also be selected on the basis of the most recognized and widespread prediction models, adhering to the study's objective of creating a simplified tool that is a shortcut in the use of different prediction theories.

Taking for granted the need to consider RT as a predictive parameter for classroom design, it must be evaluated what else to consider. For the contribution of the first reflections, C_{50} was considered the best parameter, which is solely dependent on classroom characteristics and not affected by external noise, which is difficult to estimate. At the same time, STI and U_{50} can be considered complete predictors of speech intelligibility because they both include a measure of room acoustic quality and a measure of speech-to-noise ratio [31]. Since STI is easier to predict with formulas found in the literature and easier to measure in situ, it was chosen as the parameter of interest. These considerations, and thus the choice of selecting *RT*, *STI*, and C_{50} as characteristic parameters. The choices made agree with what was suggested by Astolfi et al. [19], who also suggested the possibility of considering the C_{50} in the center of the room instead of the average C_{50}, recommending threshold values for both.

Reverberation Time (*RT*) can be easily estimated from classical theory with the equation:

$$RT(A, V) = 0.161\frac{V}{A} \tag{1}$$

where V is the volume of the room (m^3) and A is the total equivalent sound absorption area (m^2). A was intentionally chosen as a variable so that one could indiscriminately choose whether to use Sabine's ($A = S\overline{\alpha}$) or Eyring's ($A = -S\ln(1-\overline{\alpha})$) formula. S is the total area of the room (m^2), and the equation is considered to neglect the air absorption contribution under the assumption of small and medium-sized room conditions.

The clarity index (C_{50}) can be estimated with Barron's revised theory [32], also in the Italian standard UNI 11532-1:2018 [33]:

$$C_{50}(RT,\ V,\ r) = 10\log\left(\frac{\frac{100}{r^2} + \left(\frac{31200RT}{V}\right)\left(1 - e^{\frac{-0.691}{RT}}\right)e^{\frac{-0.04r}{RT}}}{e^{\frac{-0.04r}{RT}}\left(\frac{31200RT}{V}\right)\left(e^{\frac{-0.691}{RT}}\right)}\right), \tag{2}$$

where r (m) is the source-receiver distance, this theory was first developed for concert halls and has been tested under reasonably diffuse room conditions [25]. In the case of no-uniform absorption, Barron's revised theory could be corrected by including the reverberation radius proposed by Arau-Puchades and Berardi [34] within the formula. Berardi expanded his studies to look at the sound energy decay in space with no uniform absorption and proposed several new models to take in account this circumstance in highly reverberant rooms like churches [35,36]. The use of Equation (2) involves two problems: the presence of three variables and the fact that, among them, *RT* and r are unknown at the early acoustics design stage. In accordance with the criterion of effectiveness versus simplicity, a change of variables is deemed necessary so that the choice of variables is consistent with what is made explicit in the choice of the *RT* prediction formula. In addition, V and A are the designer's starting and target information, respectively, placing the choice of materials as the first necessity and their layout at a later stage.

In accordance with the revised theory and substituting *RT* into Equation (2) using Equation (1), the following is obtained:

$$C_{50}(A,\ \mathrm{V},\ r) = 10\log\left(\frac{\frac{100}{r^2} + \frac{1600\pi}{A}e^{-\frac{rA}{4V}}\left(1 - e^{-\frac{4.29A}{V}}\right)}{\frac{1600\pi}{A}e^{-\frac{rA}{4V}}e^{-\frac{4.29A}{V}}}\right) \tag{3}$$

The only remaining problem is to be able to somehow correlate the volume V to the source-receiver distance r so that all formulas can be considered within the same graph. In this regard, the proposal of Astolfi et al. [19] was considered, according to which both the mean value C_{50M} and the value measured at the center of the classroom C_{50C} can be chosen.

Considering the C_{50C} helps to significantly reduce the range of source-receiver distances that can be considered within a classroom of fixed volume. For example, if the position of the teacher (source) within a regular-shaped classroom is fixed on a symmetry axis 1.5 m away from the wall, the distance to the center of the classroom (receiver) can easily be calculated as a function of area (Figure 1). Following this intuition, two different situations of regular-shaped classrooms were assumed: in the first case (Figure 1a), a square-shaped classroom; in the second case (Figure 1b), a rectangular-shaped classroom with sides in golden ratio (ca. 1.61), with the source-receiver distance parallel to the short side.

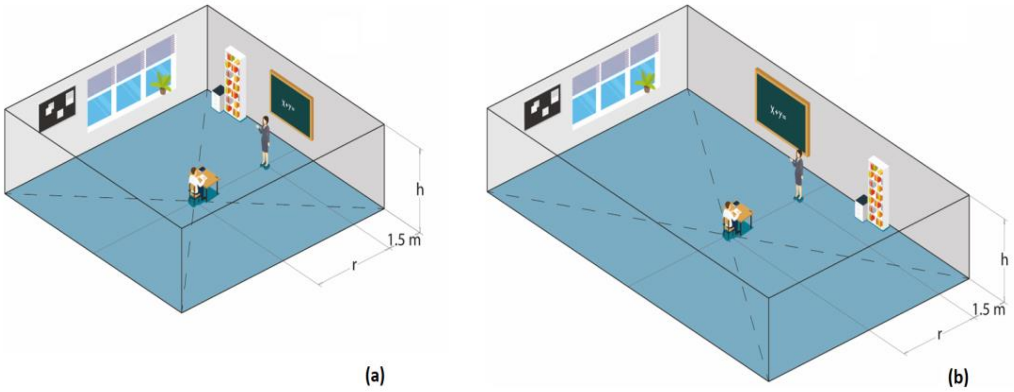

Figure 1. Axonometric diagram of the assumed arrangement of the location of the source and the receiver within a: (**a**) Square-shaped classroom; (**b**) Rectangular-shaped classroom.

Then, consider the following:

- a volume for classrooms ranging from 150 to 300 m^3;
- a net height varying from 3 to 4 m (3 is the minimum by law in Italy according to Ministerial Decree 18/12/1975 for newly built classrooms);

Plausible r ranges can be easily found (Figure 2).

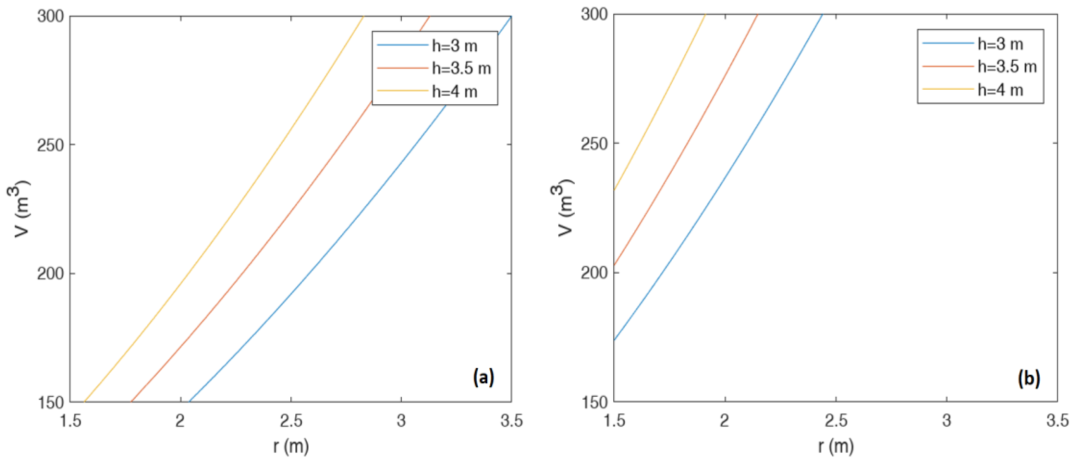

Figure 2. Graph of the correlation between volume (V) and source-receiver distance (r), for different heights of the classrooms, within a: (**a**) Square-shaped classroom; (**b**) Rectangular-shaped classroom.

With these considerations, it seems reasonable to consider a value of r = 2 m as the source-receiver distance. This assumption is also made in view of the fact that the aim of the study is to find plausible A-value zones that can meet the threshold requirements of speech intelligibility values. Otherwise, in cases where it is necessary to carry out detailed calculations, it will be necessary to use Equation (2) or Equation (3).

STI can be quickly estimated with several equations proposed in the literature using *RT* [28,29]. Among the various models, the logarithmic equation proposed by Leccese et al. [27], and obtained by regression analysis, is considered here as the reference equation. However, nothing prohibits the use of another model among those proposed. To easily compare the results with data found in the literature, it was chosen to correlate the *STI* with the mean *RT* values of the 0.5–1 kHz frequencies, resulting in the Formula:

$$STI\ (RT_{0.5-1\ \mathrm{kHz}}) = 0.6158 - 0.2106\ln(RT_{0.5-1\ \mathrm{kHz}}) \quad (4)$$

The same expedient should also be considered in the evaluation of A and C_{50}. Similarly to what was performed with C_{50}, *STI* is made a function of the variables V and A as well, substituting Equation (1) in Equation (4):

$$STI(A,V) = 0.6158 - 0.2106\ln\left(0.161\frac{V}{A}\right) \quad (5)$$

The found equations can thus be easily plotted as a function of the same variables and easily compared.

3. Results

The proposed simplified tool for estimating speech intelligibility parameters is based on Barron's revised theory [25] and the logarithmic equation by regression analysis proposed by Leccese et al. [27] on the assumption that r can be set as a plausible value and on considering conditions under which the acoustics of the classroom depend primarily on its physical characteristics. This was to highlight the fact that background noise from external noise sources was not considered. In fact, in order to ensure the reliability of the proposed tool, it is taken for granted that the lowering of background noise, predominantly from outside, requires the correct design of façade sound insulation, which is not the subject of this study, although it is of relevant importance.

3.1. Graph of STI and C_{50} as a Function of A and V

STI (calculated with Equation (5)) and C_{50} (calculated with Equation (3)) predictive graphs can be plotted as a function of A and V (Figure 3), considering for C_{50} (A, V, r) a fixed r = 2 m value. As can be easily seen from the graphs, the two parameters show similar trends, demonstrating some correlation. By also plotting the graph of *RT*, the strong negative correlation of *RT* values with C_{50} and speech intelligibility parameters [19,37] can also be confirmed.

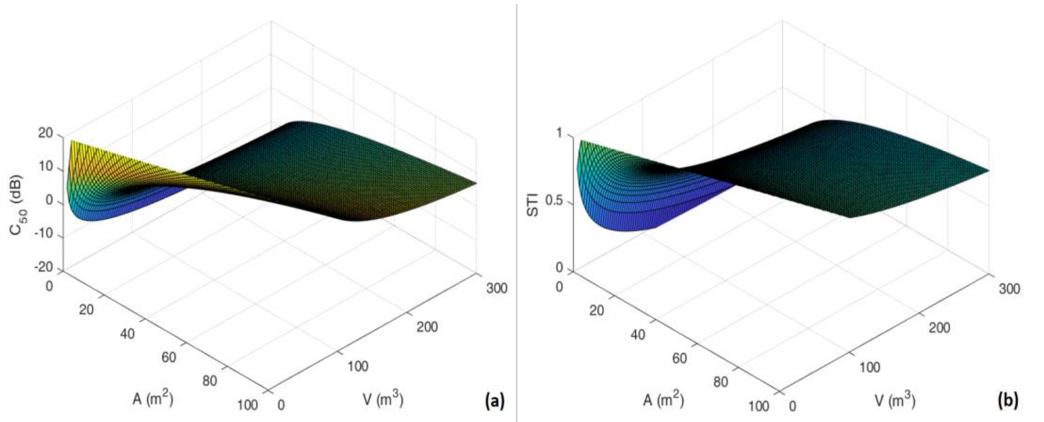

Figure 3. Graphs of two-variable functions of (**a**) Clarity index C_{50} (dB) for a fixed r = 2 m value; (**b**) Speech Transmission Index *STI*.

Given the trend of the functions, contour lines can be plotted for significant values, dividing the graph into two areas: one where the value will be less than the value of the contour line and one where it will be greater (Figure 4). Thus, given a certain volume V, a range of A values for which the speech intelligibility parameters are met can easily be found on the graph. Another thing that can be noticed from this type of graph is that by plotting different contour lines at the same C_{50}, and changing the source-receiver distance, the curves flatten out after about 4.5 m, making the difference in values after that distance more negligible.

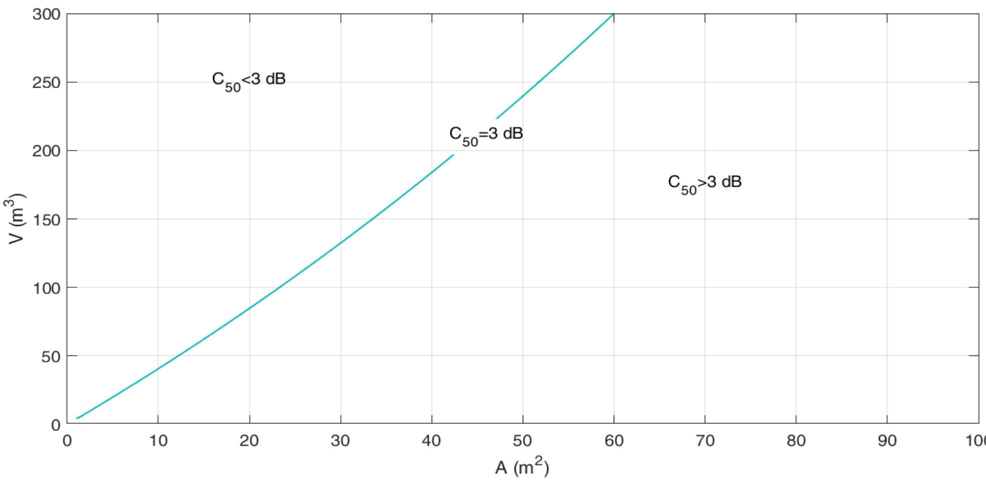

Figure 4. Prediction *A*–*V* Diagram: contour line for C_{50} = 3 dB, which divides the graph into two zones, one for C_{50} < 3 dB and the other for C_{50} > 3 dB.

3.2. Prediction *A*–*V* Diagram of Speech Intelligibility Parameters in Small-Medium Classrooms

Now the question remains as to what values the contour lines (Figure 4) should be drawn. Not considering *RT*, for which reference values have been repeatedly proposed in national standards [9,18], it is considered necessary to establish limit values for C_{50} and *STI*. For example, the Italian standard UNI 11367:2010 [38] recommends values for speech rooms of $C_{50} \geq 0$ dB and $STI \geq 0.6$; values are generally accepted as a minimum threshold.

Referring again to the proposal by Astolfi et al. [19], the C_{50} threshold (both as spatial average and as a single central value) for *moderate requirements* should be 3 dB, while the C_{50C} threshold (single value in the central position) for *severe requirements* should be 6 dB, thus ensuring a high component of first reflections on late sound, necessary for good speech intelligibility [39].

On the other hand, the *STI* thresholds for *good* (0.6–0.75) and *excellent* (>0.75) ratings can simply be taken in IEC 60268-16:2020 [14]. It should be mentioned here, however, that in the case of non-native listeners, the thresholds should be increased to 0.68 and 0.86 for the two ratings, according to the same standard.

Then, set the thresholds of speech intelligibility parameters at:

- C_{50} = 0, 3, and 6 dB;
- *STI* = 0.6, and 0.75;

The contour lines can be plotted. The prediction *A*–*V* diagram shown in Figure 5 thus divides the plane into areas with greater or lesser values than the selected thresholds. This makes it easy to determine which combinations of volume *V* and total equivalent sound absorption area *A* allow a greater chance of achieving desired levels of speech intelligibility. Considering, for example, a room volume of V = 150 m^3, a total equivalent sound absorption area greater than A = 50 m^3 is considered necessary to facilitate the condition that C_{50} > 6 dB occurs. Clearly, this consideration must be supported by the material layout provisions in the standards or by considerations based on experience. Figure 5 is, therefore, the prediction *A*–*V* diagram of the speech intelligibility parameters underlying the simplified tool and can be used in the early acoustics design stage to have a starting point on which to choose the materials with which to furnish a classroom in order to improve its speech intelligibility. It could also be used to improve the speech intelligibility of an existing classroom by finding its position within the prediction *A*–*V* diagram and moving on the *x*-axis to find the minimum difference in the *A* values required to reach the next threshold. To perform this in a simple way, the geometric and material survey of the room can be bypassed, and the *A* values of the room can be obtained directly using the inverse Sabine formula while always making sure that the room is in diffuse field conditions.

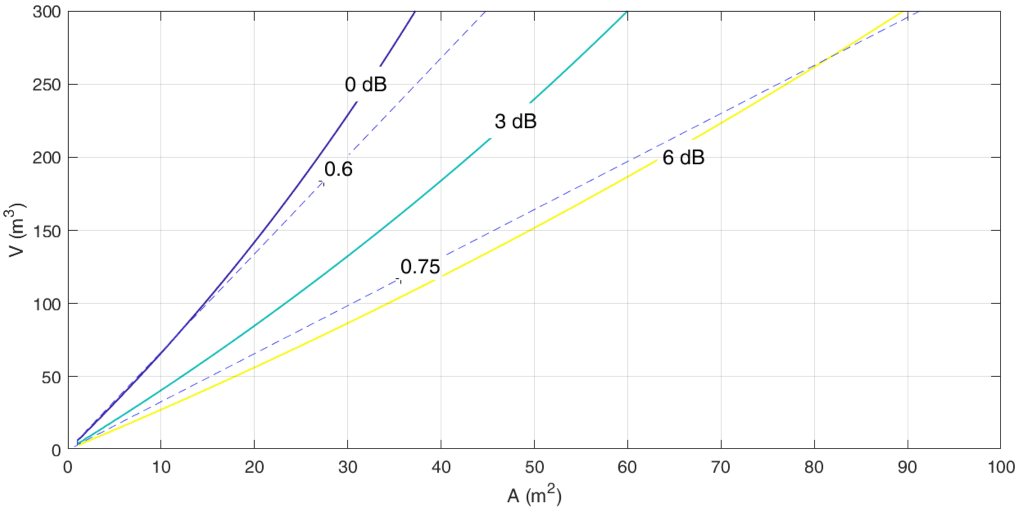

Figure 5. Prediction *V*–*A* diagram of speech intelligibility parameters in small-medium classrooms. C_{50} contour lines are continuous; *STI* contour lines are dashed.

3.3. Notes on the Applicability of the Model

For the proposed simplified tool here to be applicable, notes on the geometric and material characteristics of the classrooms must be considered. Some of these are due to the applicability of the theories on which the method is based, while others are due to the choices made within this paper on the definition of the problem.

The characteristic of the classrooms for which this method is reputed to be valid is summarized as follow.

1. The floor plan should be as regular as possible (square or rectangular).
2. Side surfaces should not be excessively absorbent.
3. Side walls should have elements that allow the avoidance of the occurrence of standing waves.
4. Ceilings should not be shaped in such a way as to create significant sound focus.
5. Ceilings should not be excessively diffuse.
6. Dimensions of the classrooms should be proportionate (comparable height, width, and depth).
7. Source-receiver distance (receiver placed in the center of the room) should be comparable to 2 m.
8. The environment should be properly isolated from external noise sources.

These notes mostly represent the well-known diffuse field conditions. Considering the aim of making the proposed tool as simple as possible, it was considered useful to be able to easily distinguish which environments are not suitable to be estimated with the models used. It is, in any case, considered that these notes exclude only a small percentage of the real classrooms and that the proposed simplified tool can be used extensively.

4. Discussion

In order to verify that the component models of the proposed simplified tool were plotted correctly, data obtained from measurements of classrooms were inserted into the prediction *A*–*V* diagram. The data chosen do not serve to verify the reliability of the prediction models of the C_{50} and *STI*, which have already been discussed and recognized, but only as counter-evidence of the ease and reliability of using the prediction *A*–*V* diagram to find the total equivalent sound absorption area of a classroom required to ensure speech intelligibility. As can be seen in Minelli et al. [40], it is not easy to find data from measurements of classrooms in the literature that present at the same time *V*, *A*, *RT*, C_{50}, and *STI* values. In this regard, to validate the proposed simplified tool and consequently verify the reliability of the prediction *A*–*V* diagram of the speech intelligibility parameters, the values of six different classrooms were considered (Table 1). In particular, measurements of two university classrooms were taken from an earlier work by the authors [30] (larger in size but relevant to the required characteristics) and four primary school classrooms from the work by Astolfi et al. [19].

Table 1. Classroom data taken from the authors' previous work and found in the literature.

ID	Ref.	V (m^3)	RT (s)	A_H (m^2)	A_C (m^2)	C_{50M} (dB)	C_{50C} (dB)	STI
C1	[30]	773	2.3 (^{1})	51.5	53.1	−3.83	—	0.45
C4	[30]	438	1.6 (^{1})	42.7	43.4	−2.09	—	0.52
A4	[19]	233	0.7 (*)	—	53.6	4.7	4.4	—
B2	[19]	201	0.5 (*)	—	64.7	7	8.1	—
F2	[19]	261	1.7 (*)	—	24.7	−0.1	−1.1	—
G3	[19]	138	0.8 (*)	—	27.8	4.4	4.7	—

Note: V (m^3) indicates the volume of the classroom. RT (s) the measured Reverberation Time (T30 or T20) for frequencies between 0.5 and 1 kHz; the values with apex (^{1}) are T30 measured in unoccupied condition; the values with apex (*) are T20 measured in unoccupied condition. A_H (m^2) is the total equivalent sound absorption area assumed from the geometric survey and estimation of absorption coefficients by tables of known values. A_C (m^2) is the total equivalent sound absorption area calculated by inverse formula from the measured RT value. C_{50M} (dB) is the spatial average of measured Clarity index values for frequencies between 0.5 and 1 kHz. C_{50C} (dB) is the single measured Clarity index value at the room center position for frequencies between 0.5 and 1 kHz. STI is the measured Speech Transmission Index value. To use the data of the last four classrooms, the A values were found by inverse formula.

The proposed simplified tool assumes that the classroom can be approximated by the prediction formulas of classical theory and, most frequently, by Sabine's own theory. Consequently, it was seen that the prediction A–V diagram had only a little match with classrooms whose assumed values of A did not meet Sabine's prediction of RT, in accordance with what has already been presented in Section 3.3.

The classroom data entered within the prediction A–V diagram show more than acceptable agreement with the measured results, as can be seen in Figure 6. The only classroom discordant with the thresholds represented in the prediction A–V diagram is G3, the smallest, whose C_{50C} is 4.7 dB, although it is in the region between 0 and 3 dB. While the discordance is acceptable because it was underestimated, it is believed that this is probably due to the small size, which results in the lower accuracy of Barron's revised theory formulated for much larger environments [25]. In smaller classrooms, less reliance can be placed on the diffuse field hypothesis, and additional arrangements are required. However, using this prediction A–V diagram only at an early acoustics design stage to choose a value of A and verify the speech intelligibility afterward during construction, the proposed tool can still be considered reliable. Once the total equivalent sound absorption area A of the room has been established, materials can then be selected based on their random incidence absorption coefficients.

In any case, it should be remembered that the propagation of sound waves within the classroom to ensure good levels of speech intelligibility depends not only on the sound absorption area but also on the arrangement of materials, for which it is advisable to follow the suggested indications in the literature or the technical standards. It is precisely because of the dependence of speech intelligibility parameters on other factors that this proposed simplified tool can be used at the early acoustics design stage and provides a considerable starting point, but it cannot replace more accurate survey methods. The obtained values should be verified by in situ measurements during construction and the final testing phase.

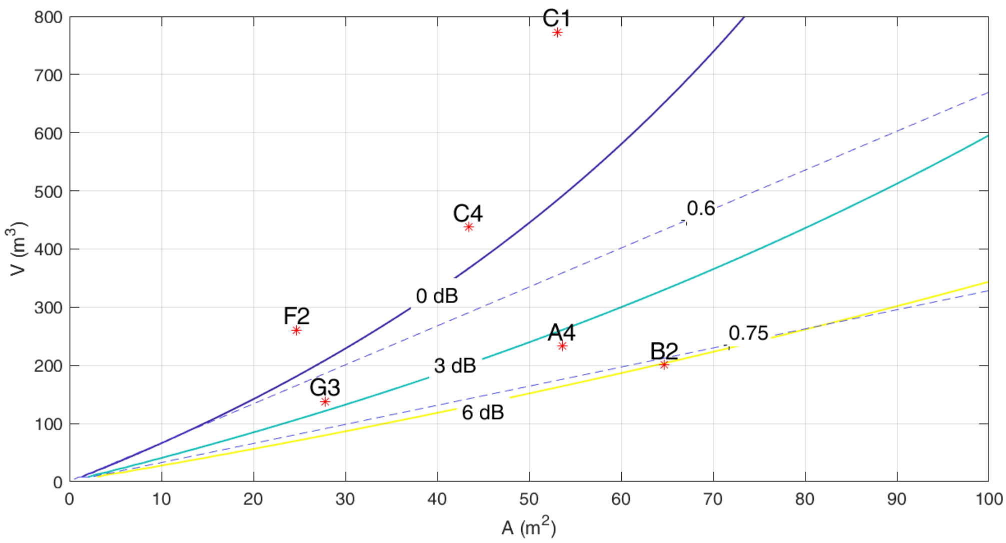

Figure 6. Prediction *A–V* diagram of speech intelligibility parameters in small-medium classrooms. C_{50} contour lines are continuous; *STI* contour lines are dashed. Classroom values taken from previous work by the authors (C1, C4) [30] and found in the literature (A4, B2, F2, G3) [19] were included.

5. Conclusions

In this paper, a simplified tool has been proposed to estimate the minimum total equivalent sound absorption area in the early acoustic design stage of a classroom. The estimate of the minimum sound absorption area, with the proposed tool, allows directing of the design solutions (from the early stages) towards those capable of ensuring compliance with the thresholds of the Clarity index and Speech Transmission Index values necessary to ensure an adequate level of speech intelligibility. The simplified tool is a prediction diagram composed of contour lines that divide the *A–V* plane into areas where speech intelligibility parameters are above or below the selected thresholds. At the early acoustics design stage, knowing the volume of the room, a starting value of the total equivalent sound absorption area can then be estimated from which materials can be chosen. Alternatively, it can be used in existing classrooms by checking how much the sound absorption area found with the inverse Sabine formula deviates from that in the diagram to achieve the desired threshold. This reliable, quick, and simple tool can be used at an early acoustics design stage, but it cannot replace more precise survey methods and does not provide an indication of the correct arrangement of materials within the environment. It also does not directly account for background noise and requires that the sound insulation of the envelope has already been treated separately.

In the future, the method can be developed by adding corrections to the prediction formulas based on considerations due to the non-uniformity of classroom sound absorption or the addition of the dependence on the signal-to-noise ratio. A version of the prediction *A–V* diagram under fully occupied room conditions could also be proposed.

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