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ACOUSTIC of UNIVERSITY LECTURE HALLS:
a Design Proposal for Palazzo Malvezzi - Campeggi

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Abstract

An aspect often overlooked although essential for the learning process is a good speech intelligibility and the acoustic comfort of school classrooms in general. The other design issues, such as lighting, temperature control, environmental appeal, usually take precedence because they are more visible and closer to a tactile sensitivity. But it should be noted how the lack of a single comfort factor substantially affects the feeling of overall discomfort by nullifying the success of the other instances.
A good acoustics becomes particularly hard to achieve in the context of the Italian historical heritage rehabilitated for educational purposes. Thanks to the opening of the restoration site of Palazzo Malvezzi-Campeggi, seat of the Law School in the historic city center of Bologna, it was possible to inquire this aspect and to actively contribute in the renewal proposal. From acoustic measurements of nine lecture halls the inadequacy of the present state has been proven. It follows how passive and active acoustic treatments are essential to ensure a good comfort for students, in order to encourage learning and consequently increase school performance. The proposals was developed in collaboration with the lighting design, not treated here.
Laboratory measurements carried out in a controlled environment were conducted to support the effectiveness of the passive treatments, while predictive methods allowed to verify design performances.

Sommario

Un aspetto spesso trascurato, sebbene fondamentale per il processo di apprendimento, è una buona intelligibilità del parlato e il comfort acustico delle aule scolastiche in generale. Gli altri problemi di progettazione, come l'illuminazione, il comfort termico, la qualità degli spazi, hanno di solito la precedenza in quanto sono osservabili e più vicini a una sensibilità tattile. Va però ricordato come la mancanza di un singolo fattore di comfort influisca sostanzialmente sulla sensazione di malessere complessivo annullando il successo delle altre istanze.
Una buona acustica diventa particolarmente difficile da raggiungere nel contesto del patrimonio storico italiano riutilizzato a scopi educativi. Grazie all'apertura del cantiere di restauro a Palazzo Malvezzi-Campeggi, sede della Facoltà di Giurisprudenza nel centro storico di Bologna, è stato possibile indagare questo aspetto e contribuire attivamente alla proposta di rinnovo. Dalle misurazioni acustiche di nove aule è stata comprovata l'inadeguatezza della condizione attuale. Ne consegue come trattamenti acustici passivi e attivi siano essenziali al fine di garantire un buon comfort agli studenti, in modo da favorire l'apprendimento e incrementando di conseguenza il rendimento scolastico. Le proposte sono state sviluppate in collaborazione con il progetto illuminotecnico, qui non trattato.
Misurazioni di laboratorio eseguite in un ambiente controllato sono state condotte per supportare l'efficacia dei trattamenti passivi, mentre metodi previsionali hanno permesso di verificare le prestazioni del progetto.

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Introduction

Communication is the most important aspect of the learning process, and a good acoustics is essential for this purpose. While for new buildings a design in compliance to acoustic requirements can bring inherent benefits, in environments that are not designed with this provision, inadequate situations are easily found. The use of the historical building heritage for educational purposes is frequent in Italian universities. The results is the low quality of acoustic performance in many university lecture halls. This work concerns the acoustic characterization and the subsequent intervention proposals of nine classrooms in Palazzo Malvezzi-Campeggi, seat of the Law School, in occasion of the restoration site opening.
An introduction to room acoustics and the presentation of the basic definitions is reported in Chapter 1: the propagation of sound in a confined environment is expressed starting from the differentiation between modal and statistical domains; the concept of sound density derives the reverberation time, declined in some of its different configurations, to give the notion of sound absorption and absorbent systems; the diffuse sound field hypothesis is introduced with the implications it entails for the acoustic response of the environment; the contribution of an element to the sound insulation of a room is explicited from a theoretical point of view.
The acoustic istance is addressed in Chapter 2 from a regulatory point of view. This discussion mainly concerns the new UNI 11532 released in March 2020, which constitutes the Italian technical reference standard for schoolalstic room acoustics. It provides parameters and limits to be respected pared with forecast formulas to determin them, as well as design criteria and hints. The different arrangement configurations of passive acoustic treatments the standard provides were the starting point to study different sound-absorbing material mountings. After a study on the standard ISO 354 about sound absorption measurements in the reverberation room, currently under revision, some laboratory tests carried out in a reverberation room are described in Chapter 3. Thanks to the reverberant room at the Department of Industrial Engineering, it has been possible to verify how the same sample of sound-absorbing material develops different performances according to how it is arranged. Suitability of the room characteristics have been verified in accordance with current standard.

The acoustic characterization measures of the lecture halls under study, carried out in compliance with ISO 3382, are showed in Chapter 4 through the suggested room acoustic parameters. Furthermore, the results of the background noise measurements of some target classrooms are reported. This way it is possible to intervene at the root on the external disturbing component of speech intelligibility, as well as providing useful data for predictive formulas. With the aid of a previsional calculation model, acoustic design proposals were developed for the nine lecture halls. The treatments are differentiated for each individual scenario, highlighting how the peculiarity of spaces requires punctual attention far from a standardizing attitude unlikely achievable. It was possible to develop the acoustic design in consultation with the lighting project in order to avoid contrasts and with performance gain of both instances.
The effectiveness of the proposals is verified in Chapter 5 with both previsonal model and forecast formulas provided in UNI 11532, regarding Reverberation Time, Sound Clarity Index and STI values. The quality of enhanced acoustic comfort is examined from a perceptual point of view in Chapter 6 through the just noticeable difference of the considered parameters. Used data are taken from the standards, but further studies which provide alternative opinions are also presented. Cross-reflections on the statistical measurement error make the uncertainty field more explicit.

Chapter 1

Room Acoustics

The behavior of sound field in a room is quite different from the free field scenario due to the boundary conditions that inevitably make the problem complex. Sound propagation theory in enclosures is here briefly introduced. Basic notions like sound density and reverberation time are explained. The implication of the different formulations for the current normative are highlighted to get knowledge of the hypotheses that must be verified in order to apply the notions correctly.
Sound absorption and sound absoption systems are presented to ensure the appropriate use of them in the acoustic design. This subject will be studied in the next chapter with practical advice provided by the standards.
The problem of sound insulation of a partition between two adjacent spaces is adressed to provide some basic tools to fix situations that do not comply with regulatory limits.

1.1 Physical acoustics

Inside a room the sound field is influenced by surfaces acoustic impedance and form factors. It is possible to express this acoustic field throught Helmholtz equation [46]:

$$\nabla^2 p + k^2 \cdot p = 0 \tag{1.1}$$

Modal theory provide a closed form solution to the sound wave propagation problem in enclosed spaces: setting the boundary conditions is possible to find solutions as a function of the wave number k (eigenvalues solutions). The different equations which determine k are eigenfunctions of the eigenmodes (steady waves).
According to M. Schröeder [50], a cut off frequency for the modal region from the diffuse region can be defined by assuming that, on average, three eigenfrequencies fall into one resonance half-bandwidth. This characteristic frenquency, named *Schröeder frequency*, as in equation (1.2), is the upper

limit where the modal theory isn't worth and the stocastic theory is preferable .

$$f_c \approx 2000 \cdot \sqrt{\frac{T}{V}} \quad (Hz) \tag{1.2}$$

Under the *Schröeder frequency* eigenmodes are discernible and the sound density is not uniform; above f_c there is an overlapping of the eigenmodes and the sound field is uniform.
The stocastic theory has the following assumptions:

- waves are represented by the geometric spaces of their axises (rays);
- a source is a set of rays;
- sound field is perfectly diffused, which means rays hit a generic surface from all directions with equal odds (Sabinian hypothesis).

This theory makes possible to study the reverberant sound field, evaluating the contribution of multiple riflections and diffractions. This way the acoustic behavior of a room is characterizable through sound density and reverberation time.

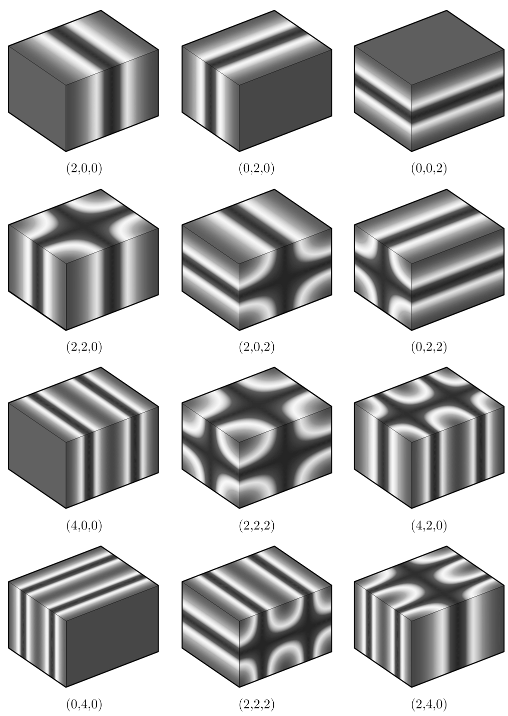


Figure 1.1: Eigenmodes of a 5.02x4.15x3.36 meter room sample under 100 Hz. This choice of dimensions guarantees the absence of degenerate or quasi-degenerate modes under that frequency. (*Made with COMSOL Multiphysics 5.4*).

1.2 Acoustic basics

The main entities related to acoustics of an enclosed space are here introduced. These are the theoretical basis from which the subject was born and which provided the basis for the subsequent regulatory developments. A clear knowledge of these notions allows a critical analysis on acoustic standards.

1.2.1 Sound density

It is called sound density D in a medium, in joules per cubic meter, the sound energy in the volume unit [46]:

$$D = \frac{dE}{dV} = \frac{I}{c} = \frac{p^2}{\rho c^2} \tag{1.3}$$

Where p is the effective sound pressure, ρ is the medium density and c is the propagation speed of sound in the medium; I is the sound intensity, in watts per square meter, defined as the sound power through a surface unit orthogonal to the wave propagation direction. Notice that ρc is the acustic impedance z, in kilograms per square meter second, a characteristic of the medium; for the air at a temperature of 20°C, z=413 kg/m^{2}s.

In an enclosed space with an emitting sound source, under the effect of direct and reflected signals, regime sound density D_r is gradually achieved when the energy emitted is equal to the energy absorpted by the boundaries. When the sound source stops emitting, the sound density gradually decreases (sound reverberation). So the regime sound density can be written like the sum of direct and reverberated contributions:

$$D_r = D_{dir} + D_{riv} \tag{1.4}$$

For a point source the direct contribution is given by the definition of sound intensity:

$$D_{dir} = \frac{WQ}{4\pi r^2 c} \tag{1.5}$$

Where Q is the direction factor equal to the ratio I/I_{is} between real sound intensity and the value for the isotropous sound sorce; r is the considered distance from the sound source; α_m is the mean sound absorption coefficient of the room given in equation (1.14).

The reverberated contribution is caused by the power $W(1-\alpha_m)$ remaining after the first reflexion:

$$D_{riv} = \frac{4W(1-\alpha_m)}{cA^*} = \frac{4W}{cR^*} \tag{1.6}$$

Where R^*, in square meters, is an environmental constant used to simplify further results. From the consideration concerning equation (1.4) the analog for the sound pressure is:

$$p^2 = p_{dir}^2 + p_{riv}^2 \tag{1.7}$$

From equations (1.3), (1.5), (1.6) and (1.7) the total sound pressure in each point of the room is:

$$p^2 = \rho c W \left(\frac{Q}{4\pi r^2} + \frac{4}{R^*} \right) \tag{1.8}$$

The sound pressure level is:

$$\begin{aligned} L_p = 10 \log \frac{p^2}{p_{rif}^2} &= 10 \log \left[\frac{\rho c W}{p_{rif}^2} \left(\frac{Q}{4\pi r^2} + \frac{4}{R^*} \right) \right] = \\ &= 10 \log \frac{W}{W_{rif}} + 10 \log \left(\frac{Q}{4\pi r^2} + \frac{4}{R^*} \right) \end{aligned} \tag{1.9}$$

By the definition of sound power level Hopkins-Stryker relation is [46]:

$$L_p = L_W + 10 \log \left(\frac{Q}{4\pi r^2} + \frac{4}{R^*} \right) \tag{1.10}$$

The sound pressure level for reverberating field can now be compared to sound pressure level for free field condition:

$$L_p = L_W + 10 \log \left(\frac{Q}{4\pi r^2} \right) = L_W - 20 \log r - 11 + 10 \log Q \tag{1.11}$$

The reflexions caused by the enclosure boundaries amplify the sound pressure level.
By setting D_{dir} equal D_{riv} the critical radius is given. It is the distance from the source at which direct sound and the first reflection arrives at the same time. From equations (1.5) and (1.6) it can be written like:

$$r_c = \sqrt{\frac{QR^*}{16\pi}} \quad (m) \tag{1.12}$$

1.2.2 Reverberation time

The reverberetion time T_{60}, in seconds, is defined by the time the sound pressure level needs to obtain a decay of 60 dB (Fig.1.2). If the sound-to-noise ratio is not enough to obtain the full 60 dB decay, it is possible to use the decay curve slope of lower decays and to extrapolate the 60 dB decay corresponding time. The value obtained from 20 dB and 30 dB decays, named respectevely T_{20} and T_{30}, are commonly used. All these decays start from 5 dB below the initial level to avoid direct sound and reach full speed sound field.
The decay curve is obtained in practise through the integrated imupulse response method. The impulse response is the temporal evolution of the

sound pressure level at a point in a room as a result of the emission of a Dirac impulse at another point in the room. Due to the impossibility in practice to recreate a true Dirac delta function, short transient sound (shots), a period of maximum-lenght sequence type signal (MLS) or another deterministic, flat-spectrum signal used; then it is possible to transform the measured response back to an impulse response.
To evaluate the reverberation time both Sabine's (1.15) and Norris-Eyring's (1.20) formulations are possible. The differences between the two equations are in their assumptions. Sabine assumes that the sound wave in a room impacts the surfaces one after another, while Norris-Eyring that all the surfaces are simultaneously hit by the initial sound and the successive waves are separated by mean free paths impacting the surfaces diminishing their energy with the average room absorption coeffcient [46].
Despite the lack of math sense accuracy, the Sabine's equation is largely used for the evaluation of reverberation time in rooms with various usage.

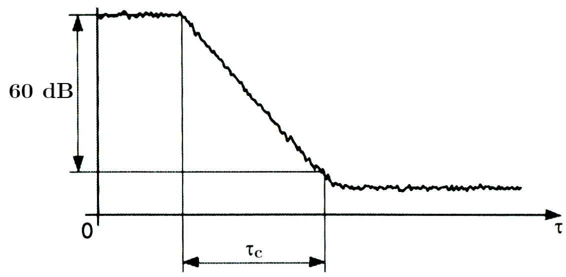


Figure 1.2: Generic decay curve inside a an enclosed space. The 60 dB decay time is spotlighted.

Sabine's formulation

Sabine Wallace Clement theorized his formulation for the reverberation time after his studies on Harvard University lecture halls. The hypothesis of this theory are [46]:

- Reverberation time (T_{60}) value, in seconds, is the same for every point in the room, wich means the sound field is perfectly diffuse;
- Sound energy is influenced by the mean free path (l) value, in meters, that is the mean distance between two consecutive hits

$$l = 4\frac{V}{S} \quad (m) \tag{1.13}$$

- All the walls absorb in a similar way, so they have near the same absorption coefficient (α_m)

$$\alpha_m = \frac{\sum \alpha_i S_i}{S} \tag{1.14}$$

- Air sound absoportion is negligible;
- It is acceptable to approximate a discontinuous phenomenon with continue relations.

Sabine's formula is given considering the energy conservation between power emitted and the power absorbed by the walls or stored in the room:

$$T_{60} = 0.16 \frac{V}{S \cdot \alpha_m} \quad (s) \tag{1.15}$$

Where V is the volume of the room in m^3, S is the total surface in m^2 and α_m is the mean absorption coefficient of the room given above in equation (1.14). Notice that $S{\cdot}\alpha_m$ gives the equivalent sound absorption area A^*. The value 0.16, in seconds on meter, is given assuming default physical values to ease the problem, for example the sound propagation speed of sound in the air (c) is considered equal 344 m/s. A more accurate approach considers the depending on temperature, which can be calculated in the range of 15°C to 30°C from the following formula:

$$c = 331 + 0.6t \quad (m/s) \tag{1.16}$$

The reverberation time, like the sound absorption coefficient, is function of the frequency.
Sabine's formula can not be applied to high absorbing rooms, in fact if the room has α value equal 1, T_{60} is not equal 0; instead when α is equal 0, T_{60} is correctily equal infinity:

$$T_{60}(\alpha_m = 1) = 0.16 \frac{V}{S \cdot 1} \neq 0; T_{60}(\alpha_m = 0) = 0.16 \frac{V}{S \cdot 1} = +\infty \tag{1.17}$$

Furthermore, reverting the formula, there are values of T_{60} that gives $\alpha > 1$ when the ambient is very absorbent. Being $\alpha = a + t = 1 - r$ the ostensible absoprtion coefficient, where a, t and r are respectively absorption, transmission and reflection coefficients, and assured that $r < 1$, it is possible to see that a value of α grater than 1 makes no physical sense.
When sound absorption coefficent is equal 0, the reverberation time is equal infinity:

Norris-Eyring's formulation

This inaccuracy is solved by Norris-Eyring's theory denying the diffuse field condition and the continuos formulation of the problem.
A mean reflection coefficent $\overline{r}$ is introduced, so it is possible to write the energy W reflected after n hits of a single ray from a full speed power W_{reg}:

$$W = \overline{r}^n W_{reg} \tag{1.18}$$

The total path of energy for T_{60} is:

$$c \cdot T_{60} = ml = m4\frac{V}{S} \quad (1.19)$$

Where m is the number of hits happened until the 60 dB decay and the free mean path l is given by the equation (1.13). By the definition of reverberation time the corresponding value of $\overline{r}^m$ is 10^{-6}.
Norris-Eyring's formula can be written [46]:

$$T_{60} = -0.16\frac{V}{S \cdot \ln(1-\alpha_m)} \quad (s) \quad (1.20)$$

The overestimation of the Sabine's result (measured in the reverberant room) can be corrected by the Norris-Eyring's result:

$$\ln(1-\alpha_E) = \alpha_S \Rightarrow \alpha_E = \alpha_{corr} = 1 - e^{-\alpha_S} \quad (1.21)$$

The correction is proportional to the magnitude: a high value is drastically reduced while a low value remains almost the same. Notice that for environment with a low mean sound absorption coefficient Sabine's and Norris-Eyring's reverberation time are almost the same.

1.2.3 Diffusion of the sound field

The diffuse sound field hypothesis has to be achieved in order to allow the Sabine formulation use and, by extension, to validate the results seen before. The diffusion of the sound field is linked with the shape of the enclosure. At low frequencies is possible to explain this behavior through the spatial patterns of the modes [53]. Taken two room with the same volume, one rectangular and one asymmetrical, the modald density is the same, because it depends on the chamber volume, not on its shape. However, the spatial patterns of the modes are not the same.

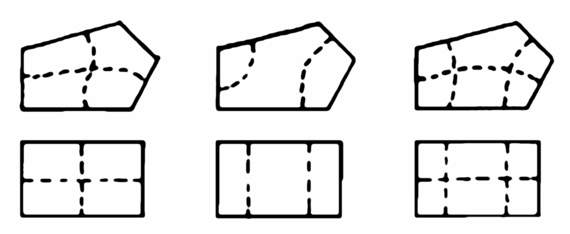


Figure 1.3: Nodal lines measured experimentally for some low modes in two model reverberant enclosures, a rectangular one and an asymmetrical one.

When a few modes are exited simultaneously, the nodal lines tend to coincide for the rectangular enclosure, giving a kind of spatial degeneracy. But for the asymmetrical enclosure, the nodal lines do not tend to coincide and a more uniform distributiom of sound energy results; thus, the sound field is more diffuse in this case.
A related point concerns the directions of the particle-displacement vectors that pertain to these modes. The vectors are at right angles to the contours of pressure, so for the asymmetric enclosure a whole range of directions are present, whereas for the rectangular one, only one is represented. Since the same effect occurs for the three-dimensional modes, it possible to see that the angular diffusion of the sound field of the asymmetrical enclosure is much better than that for the rectangular one.
It is necessary to have some indicators to validate the sound field diffusion condition: the lack of viable metrics for diffuseness is still a research topic to date [41][42]. The definition of diffuse sound field means the behavior have to be the same for every point in the field, so the reverberation time measured from every receiver when the same source emits has to be near equal. The stationary sound field in a room is not costant, but fluctuates with time and place resulting in a statistical variation of reverberation time for different positions in the room. This considerations start showing the link between diffusion of the sound field and reproducibility of the measure. One possible parameter to investigate is the spatial standard deviation of the T, calculated for each source for all the receivers at each octave or 1/3 octave band frequency. The measured spatial standard deviation $\sigma_{s,m}$ at the i-th one-third-octave band for N receivers is:

$$\sigma_{s,m} = \sqrt{\frac{\sum_{i=1}^{N}(T_i - \overline{T})^2}{N}} \tag{1.22}$$

Dividing $\sigma_{s,m}$ by the mean reverberation time $\overline{T}$, the relative standard deviation ε is given:

$$\varepsilon = \frac{\sigma_{s,m}}{\overline{T}} \tag{1.23}$$

The standard ISO 354 [2] gives a stocastic relative standard deviation reference for T_{20}, in equation (1.24), but it does not provide a real limit value (Fig.1.4.a):

$$\varepsilon_{20,ref} = \sqrt{\frac{2,42 + 3,59/N}{f \cdot T}} \tag{1.24}$$

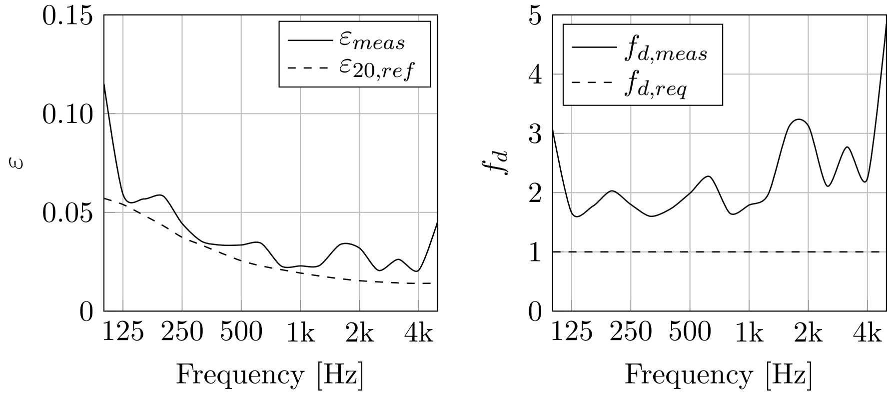
The Draft ISO 354:2018 [3] presents a way to determine if the diffusion is satisfactory. The theoretical spatial standard deviation of the reverberation time is given:

$$\sigma_{s,t} = \sqrt{1,09 \cdot \frac{\overline{T}}{f}} \tag{1.25}$$

Where f is the one-third-octave mid band frequency.

The ratio between measured and theoretical spatial standard deviation, also named sound field factor f_d, avereged over the one-third octave band from 250 Hz to 3150 Hz, shall not be larger than the unit for a good sound diffusion (Fig.1.4.b):

$$f_d = \frac{\sigma_{s,m}}{\sigma_{s,t}} < 1 \tag{1.26}$$



(a) Spatial Relative Standard Deviation - ε. (b) Diffuse sound field factor - f_d.

Figure 1.4: Diffuse sound field indicators referred to measures in the empty reverberation room at Department of Industrial Engineering laboratories: (a) Spatial relative standard deviation ε_{meas} determined in one-third octave bands (continuos) compared with the standard reference $\varepsilon_{20,ref}$ (dashed). The obtained values follow the trend given by the standard with minor deviations; (b) Diffuse sound field factor f_d values in one-third octave bands for an empty room (continuos) compared with the maximum allowed value 1.0 (dashed). The room behavior is far from the reccomended one of the Draft [3].

1.2.4 Sound absorption coefficient

The main factor to evaluate the acoustic properties of a given material is the sound absoprtion coefficient, already seen in the previous pages. On the basis of the measurement method and the incidence of the sound wave on the sample, two values can be distinguished: direct sound absorption coefficient is measured with standing wave tube, also named Kundt tube; random sound absorption coefficient is measured in a reverberation room with ISO 354 [2]. The two values can be related through the acoustic impedance of the material. However, for room acoustics purposes the random sound absorption coefficient is used. It can be evaluated from reverberation time measure equation (1.15):

$$\alpha_m = 0.16\frac{V}{ST} \tag{1.27}$$

The result is the value of the mean sound absorption coefficient for the room. The measure of T is made in a reverberant room with (subscript 2) and without (subscript 1) the test material, so the equation became [21]:

$$\alpha_s = 0.16\frac{V}{S}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{1.28}$$

This solution is correct only for steady values of temperature, relative umidity and pressure for the two measurement sessions. Otherwise is necessary to consider the different air sound absorption in both scenarios.

In some cases it is possible to find a sound absorption coefficient greater than unit. Cox and D'Antonio summarised the reasons why the sound absorption coefficient α_s can exceed unit [23]:

- *Edge diffraction*: the diffraction from the edges at low frequencies causes the reflected wave to no longer be planar, and so diffraction produces the edge effect whereby substantially more absorption happens near the edges of an absorber than at its center;

- *Non-diffuseness*: in order to apply Sabine's theory a statistical approach must be assumed. Therefore it can be supposed that the time and space distribution of the sound pressure level is even across the room, which is typically not the case in real situations;

- *Sabine formulation*: Sabine's formulation should not be applied when the mean absorption value is higher than 0.4.

From the sound absorption coefficient in one-third octave bands, practical sound absorption coefficient α_p can be calculated like the mean between the values obtained for the three one-third octave bands included in that i-octave band [10]:

$$\alpha_{pi} = \frac{\alpha_{i1} + \alpha_{i2} + \alpha_{i3}}{3} \tag{1.29}$$

The weighted sound absorption coefficient α_w is a single value that assigns a sound absorption class from A to E (under class E the sample is not classifiable):

Table 1.1: Sound absorption classes according to α_w value. The frequency response is not explicit.

Class	α_w
A	$\alpha_w \geqslant 0.90$
B	$0.80 \leqslant \alpha_w < 0.90$
C	$0.60 \leqslant \alpha_w < 0.80$
D	$0.30 \leqslant \alpha_w < 0.60$
E	$0.15 \leqslant \alpha_w < 0.30$
NC	$\alpha_w < 0.15$

It is obtained from α_p curve compared to a reference curve. The reference curve must be iteratively shifted to the measured curve by steps of 0.05 s until the sum of the unfavorable deviations between the two curve is lower or equal than 0.1 s. Unfavorable deviations occure when the curve value is higher than the measured one. The value of α_w is the value of the reference curve at 500 Hz after the last shift [10].

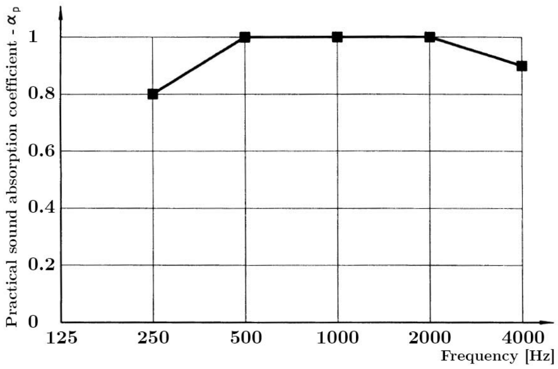


Figure 1.5: Reference curve for evaluation of weighted sound absorption coefficient α_w, from ISO 11654 [10].

1.3 Sound absorption systems

Sound absorption works thanks to sound energy conversion into friction heat. Sound absorbent materials provide a good sound absorption coefficient within a sufficiently extended frequency range.
Three different sound absorption systems can be considered:

- *Porous materials*: sound absorption given by material porosity;
- *Perforated panels*: sound absorption given by cavity resonance;
- *Vibrating panels*: sound absorption given by panel resonance or a tense membrane;

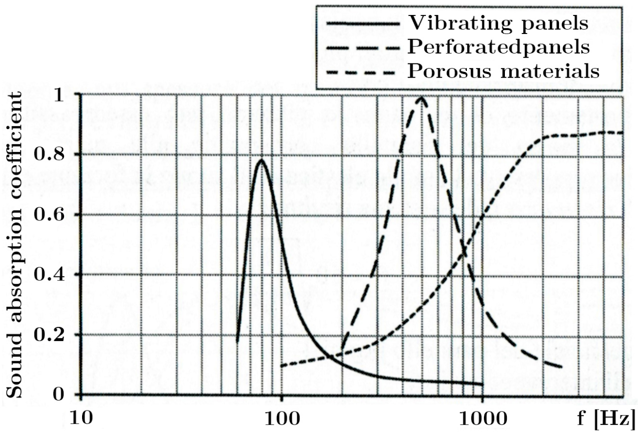


Figure 1.6: Quality comparison between the absorption coefficients of the three types of sound absorbing systems: vibrating panels (Fig.1.10), perforated panels (Fig.1.9) and porous materials (Fig.1.7).

1.3.1 Porous materials

Porous material samples are often mounted on a stiff support. The sound wave makes the air inside pores linked with the outside moving. This way the air kinetics energy is transformed into friction heat on the solid walls of the material. This type of absorption is function of porosity (air volume to total volume ratio), flow resistivity (difficulty of the air flow to pass through the material) and a structure factor (quantity of space not taking part in sound absorption).
In order to obtain an high sound absorption, high porosity and low structure factor and flow resistivity are needed. Moreover high thickness is needed to deny sound reflection on the stiff support given by low flow resistivity. The higher the thickness the larger is the frequency range with and higher the

sound absorption coefficient. The proper working range of porous material is above 500 Hz (mid to high frequencies); by increasing the thickness of the panel an improvement for the low frequencies is possibile. Also a distancing of the panel from the wall can give the same results, giving the best performance for a distance of $\lambda/4$ depending on the target frequency.

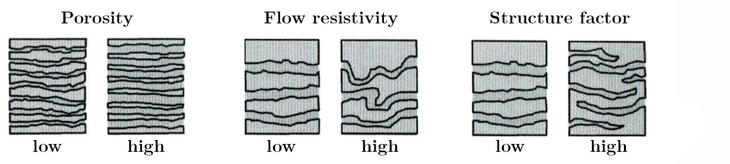


Figure 1.7: Parameters of a porous sound absorbing material.

1.3.2 Perforated panels

A simple acoustic resonator is formed by a cavity linked with the outside by an hole substantially smaller than the cavity itself. Under the effect of the sound wave the air mass in the bottleneck swings thanks the spring effect given by the air in the cavity. This mass-spring mechanism has a resonance frequency where the motion amplitude is the highest. Given the geometry of the resonator this frequency can be founded:

$$f_r = 55\sqrt{\frac{S}{VL}} \quad (Hz) \tag{1.30}$$

Where S, in square meters, is the area of the hole cross section, V, in cubic meters, is the volume of the cavity and L, in meters, is the hole length.

Figure 1.8: Resonance absorption of a cavity: simple acoustic resonator and mass-spring system.

The working range of a resonator is condensed at this resonance frequency, but it can be extend by inserting porous material inside the cavity. Nevertheless this method decreases the maximum absorbing power because the air motion is damped by the friction between air and pores walls.
A single perforated panel consists in multiple acoustic resonators. The panel is usually positioned keeping an air gap filled with porous material from a stiff support. If all the holes are the same and equally distanced they can be

considered like n simple resonators each one working with $1/n$ of the total gap volume. The maximum absorption frequency is given by:

$$f_r = 5.4\sqrt{\frac{p}{H(L+0.8D)}} \quad (Hz) \tag{1.31}$$

Where p, as a percentage, is the share of porous surface; H, in meters, is the depth of the air gap; L, in meters, is the panel thickness; D, in meters, is the holes diameter.

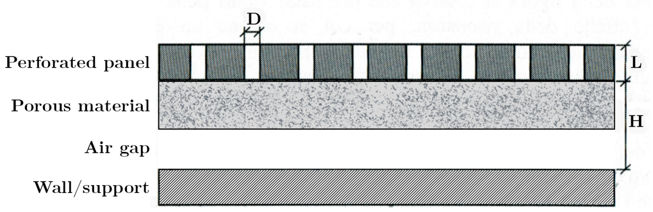


Figure 1.9: Multiple cavity resonator.

Perforated panels are used usually for mid frequencies absorption.

1.3.3 Vibrating panels

Non-porous panels are mounted on frames keeping a gap from the wall. The panel mass and the air in the gap form a mass-spring mechanism. The absorption is maximum at the system resonance frequency:

$$f_r = 60\sqrt{\frac{1}{M_s H}} \quad (Hz) \tag{1.32}$$

Where M_s, kilograms on square meter, is the surface mass of the panel and H, in meters, is the thickness of the gap.
Vibrating panels work at low frequencies, but like for perforated panels it is possibile to fill the gap with porous material to extend the effective frequency domain with a loss in the absorption power.

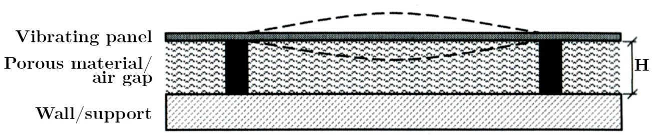


Figure 1.10: Vibrating panel.

1.4 Sound insulation

Sound source and the listener can be in adjacent locations divided by a partition. In this scenario the sound insulation properties of the partition should be verified. Sound propagation takes place in two different ways: aerial transmission, if air is the sound medium, and structural transmission, when the mediums are solid elastic vibrating parts. Furthermore direct transmission throught the partition must be distinguished by flanking transmission throught the nearby structures.

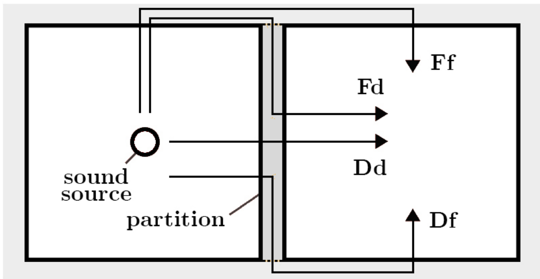


Figure 1.11: Different path of sound transmission: D=direct, F=flanking. Dd is the only direct transmission, while Df, Ff and Fd are all flanking transmissions.

The transmission factor t can be used to define transmission capability of a partition:

$$t = \frac{W_t}{W} \tag{1.33}$$

Where W is the total sound power transmitted and W_t is the sound power transmitted directly by the partition. However the wide range of t makes the sound reduction index R preferable:

$$R = 10 \log \frac{1}{t} \quad (dB) \tag{1.34}$$

Also named *sound transmission loss*, it represents the attutide of a partition to damp direct transmission.
Considering a generic thin planar partition, with a thickness much lower than wavelength of incident sound, comparable to a simple oscillator and made by a homogeneous isotropic material, for perpendicular planar waves the transmission factor is:

$$t_n = \left[1 + \left(\frac{\pi M_s f}{\rho c}\right)^2\right] \tag{1.35}$$

Where M_s, in kilograms on square meter, is the surface mass of the partion; f, in hertz, is the sound frequency and $\rho c = 412$ kg/m^{2}s is the air acoustic impedance.

Given $(\pi M_s f/\rho c)^2 >> 1$ and $20\log(\pi/\rho c) \cong 42.3$, replacing equation (1.35) in (1.34), sound reduction index for perpendicular incidence R_n is determined [46]:

$$R_n = 20\log(M_s f) - 42.3 \quad (dB) \tag{1.36}$$

From the (1.36) (commonly named "mass law") it is possible to see that doubling the surface mass or the sound frequency, R_n increase of 6 dB.
For perfectly diffuse sound field, the sound reduction index is:

$$R = R_n - 10\log(0.23R_n) \quad (dB) \tag{1.37}$$

With medium diffuse sound field hypothesis the following definition can be used:

$$R = 20\log(M_s f) - 47.2 \quad (dB) \tag{1.38}$$

In practise the real behavior of a partition is better represented by Fig.1.12.

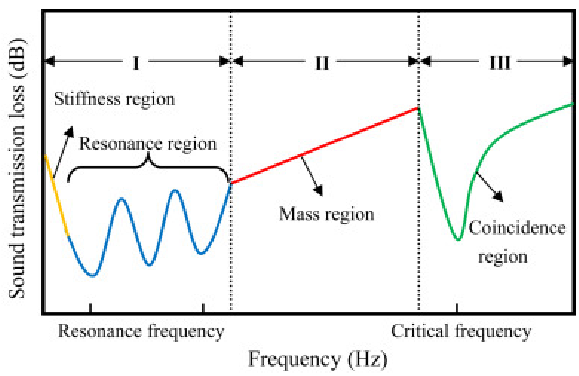


Figure 1.12: Qualitative trend of the transmission loss of a homogeneous thin partition: deviation from the "mass law".

Three regions can be determined:

- ***1st Region***. At the lower vibration frequency, also named *fundamental frequency* or *resonance frequency* f_r , there is a minimum; after that a series of maximums and minimums follow, given by the vibration modes of the partition (*resonance effect*). Below f_r the transmission loss decreases, controlled by the stiffness .

- ***2nd Region***. The "mass law" can be used with good approximation to describe the partition behavior, so an increase of 6 dB/oct is expected.

- ***3rd Region***. At high frenqencies the transmission loss reach a minimum at the *critical frequency* f_c (*coincidence effect*). Above that value the damping properties of the partition control the transmission loss and an increas greater than 6 dB/oct can be verified. The coincidence effect happens when the wavelength λ of the incident sound wave at an angle θ is equal to the projection on θ direction of the flexural vibration wavelength λ_F:

$$\lambda = \lambda_F \cos\theta \quad (m) \tag{1.39}$$

Each sound wave with $\lambda \leqslant \lambda_F$ can coincide with flexural wave when $\theta \leqslant \pi/2$. The critical frenquency f_c is the lowest coincidence frequency, corresponding to an incidence angle $\theta = \pi/2$.

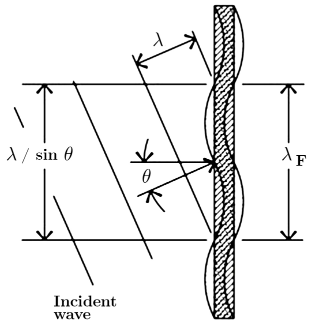


Figure 1.13: Coincidence effect on a thin vibrating panel.

Notice that the lower is the damping of the material, the higher is the drop at low frequencies given by the resonance effect and at high frequencies for coincidence effect.
The resonance frequency of a panel is function of its dimensions (here named a and b) and thickness (h), in addition to the material properties (density ρ, Young's modulus E and Poisson's modulus ν):

$$f_r = \left(\frac{1}{a^2} + \frac{1}{b^2}\right)\frac{\pi}{4}h\sqrt{\frac{E}{3\rho(1-\nu^2)}} \quad (Hz) \tag{1.40}$$

The coincidence frequency is not function of the partition dimensions:

$$f_c = \frac{c^2}{\pi h}\sqrt{\frac{3\rho(1-\nu^2)}{E}} \quad (Hz) \tag{1.41}$$

The measurement of the transmission loss on a specific partition can be conducted in laboratory with standard ISO 10140 [9]. The test specimen is positioned between two structurally decoupled reverberation rooms to consider only direct transmission. If the perfectly diffuse sound field is effective, the transmission loss is given by the following relation:

$$R = L_1 - L_2 + 10\log\frac{S}{A_2^*} = L_1 - L_2 + 10\log\frac{T_2 S}{0.16 V_2} \quad (dB) \tag{1.42}$$

Where L_1 and L_2 are respectively the mean sound pressure levels of the source room and the receiving room, in decibels; S is the frontal surface of the partition, in square meters; A_2^* is the equivalent sound absorption area of the receiving room, in Sabine's square meters, given by the volume V_2, in cubic meters, and the reverberation time T_2, in seconds, by Sabine's formula (1.15).

In situ measurements can not avoid flanking transmission, so the result will be an apparent sound reduction index:

$$R' = 10 \log \frac{W}{W_t + W_f} \quad (dB) \tag{1.43}$$

Where W_f is the sound power transmitted by flanking elements, in watts. The value can be obtained following the standard ISO 140 [1] in a way formally equal to the one for laboratory measurements:

$$R' = L_1 - L_2 + 10 \log \frac{S}{A_2^*} = L_1 - L_2 + 10 \log \frac{T_2 S}{0.16 V_2} \quad (dB) \tag{1.44}$$

For field measurements the airborne sound insulation D, in decibels, can be described in terms of the sound pressure level difference between the source and receiving rooms:

$$D = L_1 - L_2 = R' - 10 \log \frac{S}{A_2^*} = R' - 10 \log \frac{T_2 S}{0.16 V_2} \quad (dB) \tag{1.45}$$

While R and R' are both functions of the partition tested, depending on the stratigraphy and on the mounting method with other structures, sound insulation D is also a funtion of the acoustic characteristics of the perturbed environment. This can cause problems when setting sound insulation requirements for regulatory purposes, because adding or removing sound absorptive material from the receiving room will change the measured sound pressure level, and hence change the level difference. So it is necessary to measure the reverberation time in the receiving room and to 'standardize' or 'normalize' the level difference. This provides a fairer basis on which to set performance standards for sound insulation.

The level difference D is 'standardized' in equation (1.47) using a reference value for the reverberation time $T_0 = 0.5$ s and is 'normalized' in equation (1.46) using a reference value for the absorption area $A_0^* = 10$ m^2 Sabine:

$$D_n = D - 10 \log \frac{A_2^*}{A_0^*} = R' - 10 \log \frac{S}{A_0^*} \quad (dB) \tag{1.46}$$

$$D_{nT} = D + 10 \log \frac{T_2}{T_0} = R' - 10 \log \frac{T_0 S}{0.16 V_2} \quad (dB) \tag{1.47}$$

Chapter 2

Acoustics of lecture halls

A first taxonomic classification of lecture halls according to standards is given. Acoustic descriptors for indoor spaces are illustrated referring to normative definitions. Each parameter is explained in depth through technical literature. The described room criteria concern the acoustic performance of rooms and speech intelligibility. Design proposals provided by the standards are presented and discussed.

2.1 Lecture halls

A lecture hall is a room designed for teaching at university. While a high-school classroom has an occupancy of maximum thirty people, a lecture room can contain hundreds of people. Some lecture halls may be structured as an amphitheater both for a comfortable view and for acoustic reasons.
In the Italian context it often happens that the historical cultural heritage is converted into educational use. This implies a great variety of shapes, dimensions, occupancy capacity and boundary conditions. The actual states are often far from those for good acoustics, and therefore an adequate design is particularly necessary. On the other hand, the cultural value of these environments makes the type of intervention more complex and delicate. Designs must be calibrated and customized on a case-by-case basis, and often it cannot lead to full compliance with the regulations conceived for new construction buildings. Modern lectures hall required audio-visual equipments and thus a specific acoustic design is needed to make a lecture more effcient. A Public Address (PA) system is not enough to increase the speech intelligibility if in the room there are not the proper acoustic conditions.
The UNI 11532 [15] (like the prior German standard DIN 18041) distinguishes the small spaces (with a volume lower than 250 m^3) from the medium room (with a volume between 250 m^3 and 5000 m_3). The ISO 3382-2 [4] considers 'large' a space with a volume greater than 300 m^3.
The most important aspect concerning the acoustics of these spaces is the

verbal communication. Its efficiency can be evaluates with objective parameters like Speech Transmission Index (STI) that takes into account considerations about the room's acoustic characteristics and background noise due to systems and student activity, but also the behavior of the human auditory system and how it differs based on sex and auditory stimulus.

2.2 Acoustic requirements

Starting from these theoretical assumptions, sector-based standards give acoustic requirements for the specific application also introducing the used parameter definitions. UNI 11532 [15] is the standard reference for scholastic rooms, while ISO 3382 [4] gives parameter definitions and guidelines for room acoustic measurements in performance spaces.

2.2.1 Reverberation time T

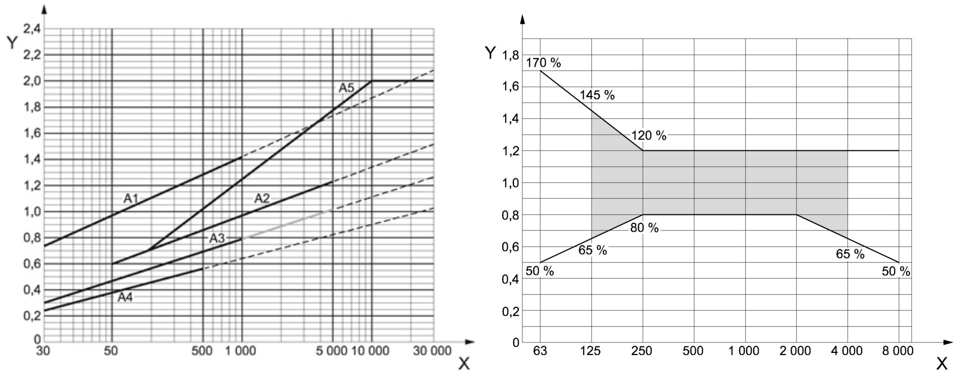
The Sabine's formula for the reverberation time can be rewrited as:

$$T = 0.16 \frac{V}{\sum_i \alpha_i S_i \sum_j A_{obj,j}} \quad (s) \tag{2.1}$$

Instead of the mean sound absorption coefficient of the room α_m, every α_i coefficient related to the S_i surface is considered, in addition to the equivalent sound absorption area of each mobile object $A_{obj,j}$. This way the formulation is easier for fast estimations and simulation purposes.
The standard UNI 11532 [15] provides the optimal value of reverberation time in function of the volume and the room category for activity performed: A1 - music rooms; A2 - lecture rooms with one speaker; A3 - lecture rooms with two speakers; A4 - special lesson rooms; A5 - sport halls; A6 - not educational areas and libraries.
The following table reports the optimal values given for A1 to A5 classes.

Category	T_{opt} [s]	V [m^3]
A1	$0.45 \log V + 0.07$	30 m^3 $\leqslant$V<1000 m^3
A2	$0.37 \log V - 0.14$	50 m^3 $\leqslant$V<5000 m^3
A3	$0.32 \log V - 0.17$	30 m^3 $\leqslant$V<5000 m^3
A4	$0.26 \log V - 0.14$	30 m^3 $\leqslant$V<500 m^3
A5	$0.75 \log V - 1.00$	200 m^3 $\leqslant$V<10000 m^3
	2.00	V$\geq$10000 m^3

Table 2.1: Optimal reverberation time for scholastic rooms. For categories A1 to A4 the value is intended for 80% occupation, while for A5 two values for volume below or above related to the unoccupied circumstance.



(a) (b)

Figure 2.1: (a) Optimal reverberation time for categories from A1 to A5 in function of the room volume. (b) Compliance range of reverberation time for categories from A1 to A4 in the frequency domain, given proportionally to the optimal value. On X-axis the frenquency octave bands; on Y-axis the T-to-T_{opt} ratio.

Starting from this single value the optimal range for the reverberation time is given in the frequency domain following simple proportional rules (Fig.2.1). As already said the compliance range is referred to the 80% of the total occupation condition, but usually the measurements are executed in unoccupied condition. So the standard gives the relation between occupied and unoccupied measured reverberation time (known the volume V of the room, in cubic meters):

$$T_{occ} = \frac{T_{inocc}}{1 + T_{inocc}\dfrac{\Delta A_{pers}}{0.16V}} \quad (s) \tag{2.2}$$

The equivalent sound absorption area of the audience is given in octave-band frequency from 125 Hz to 4000 Hz for many options of seat models and people density or composition. The values of a sitting person for three stuffed seat type are reported in Table 2.2.

Table 2.2: Equivalent sound absorption area ΔA_{1pers}, in Sabine's quare meters, of a single person for three seat type in octave-band frequency from 125 to 4000 Hz. The values are taken from Table C.1 of UNI 11532-2 [15].

Description	Frequency [Hz]					
	125	250	500	1000	2000	4000
Person on not upholstered seat	0.15	0.30	0.40	0.45	0.55	0.55
Person on lightly uph. seat	0.10	0.15	0.20	0.25	0.25	0.25
Person on heavily uph. seat	0.05	0.05	0.05	0.10	0.10	0.15

From this additional sound absorption areas, in Sabine's quare meters, the corresponding value for the audience is:

$$\Delta A_{pers} = N \cdot \Delta A_{1pers} \quad (m^2) \tag{2.3}$$

Where N is the number of people corresponding to %80 of the occupacy. It is possible to consider a precautionary value equal the %30 of the total auditory to ensure an appropriate behavior in worse occupancy conditions. To determine the compliance range in inoccupied state the standard give the equation (2.2) reverse formula:

$$T_{inocc} = \frac{T_{occ}}{1 - T_{occ}\frac{\Delta A_{pers}}{0.16V}} \quad (s) \tag{2.4}$$

2.2.2 Sound clarity index C_{te}

The clarity index C_{te} is defined as an early-to-late arriving sound energy ratio. In ISO 3382-1 [5] the formula for C_{te} is given:

$$C_{te} = 10 \log \frac{\int_0^{t_e} p^2(t)dt}{\int_{t_e}^{\infty} p^2(t)dt} \quad (dB) \tag{2.5}$$

Where p, in pascals, is the instantaneous sound pressure measured at the measurement point. The time interval t_e represents the early reflections limit can be assumed 50 ms or 80 ms, respectively for speech or music. After that time the late reverberations are considered detrimental energy. Given these extremes the formula becomes:

$$C_{50} = 10 \log \frac{\int_0^{50ms} p^2(t)dt}{\int_{50ms}^{\infty} p^2(t)dt} \quad (dB) \tag{2.6}$$

$$C_{80} = 10 \log \frac{\int_0^{80ms} p^2(t)dt}{\int_{80ms}^{\infty} p^2(t)dt} \quad (dB) \tag{2.7}$$

Requirement for the clarity index is provided by UNI 11367 [14] which suggests as suitable value $C_{50} > 0$ dB in spaces designed for speech.
For scholastic environments UNI 11532 [15] states C_{50} can be applied as a meaningful parameter for category from A1 to A4 when the room volume is below 250 m^3. The measured value, related for the furnished room with at most two people inside, shall be $C_{50} \geqslant +2$ dB. The value is gained by the arithmetic mean over all sources and receivers measured values in octave-band range of 500÷1000÷2000 Hz.

A predictive value of the sound clarity index can be expressed in function of reverberation time and the source-receiver distance r by Barron&Lee's formula:

$$C_{50}(r) = 10 \log \frac{\frac{100}{r^2} + \left(\frac{31200T}{V}\right)\left(1 - e^{-0.691/T}\right) e^{-0.04r/T}}{e^{-0.04r/T}\left(\frac{31200T}{V}\right) e^{-0.691/T}} \quad (dB) \quad (2.8)$$

The same standard presents also a simplified expression of it:

$$C_{50} \approx 10 \log(e^{0.691/T} - 1) \quad (dB) \quad (2.9)$$

2.2.3 Speech Transmission Index STI

Speech is made up of fluctuations in the signal intensity which correspond, depending on their speed, to the subdivision of sentences and individual words if they are slow or to individual phonemes within words if they are fast. These fluctuations are affected by a transmission channel with a Modulation Transfer Function (MTF). A good intelligibility can be obtained if the envelope intensity is preserved as much as possible. The MTF highlights how much the signal is degraded by distortions like noise, reverberation and echo representing the decrease of modulation depth in function of the modulation frequency. The Speech Transmission Index (STI) is an objective measure between 0 and 1 representing the quantity of speech understood from a listener to evaluate the sound quality. This parameter has been developed since the 1970s and today is defined by IEC 60268-16 [17]. It depends on the reverberation time, the sound pressure level and the background noise.
The STI measurement can be achieved through a direct method using a suitably modulated test signal, or indirect methods based on the system's impulse response using the Schoroeder's integral, wich is applicable in case of linear and invariant transmission systems.
The STI index is based on the concept of modulation of a carrier assuming that the human speech is simulated in this way: a complex signal consisting of 98 combination (14 one-third octave band modulation frequencies f_m from 0.63 to 12.5 Hz x 7 octave band frequencies k from 125 to 8000 Hz) is used with a speaker of the size of a human mouth, acting as a person speaking. The method associates the characteristics of the environment with the transfer function comparing the input (the modulated signal) and the output (the microphone signal at the location where the STI is to be determined). So STI is evaluated on the basis of two parameters: the acoustic characteristics of the room through the reverberation time, and the signal-to-noise ratio.
Given the modulation index m_i of the test signal played into a room or through a communication channel, it will be received at a listener position

with a modulation index m_o (i=input; o=output). The reduction of each modulation frequency f_m is quantified by the modulation transfer ratio wich is determined, for each octave band k, by:

$$m_k(f_m) = \frac{m_{o,k}(f_m)}{m_{i,k}(f_m)} \tag{2.10}$$

In standard UNI 11532-1 Annex A [15] three methods to evaluate $m_k(f_m)$ are described:

- A Method: with the aid of simulation software, the impulse response can be determined at the different points of a room. This way it is possible to change the shape and materials of the environment in order to optimize speech intelligibility by the relation:

$$m_k(f_m) = \frac{|\int_0^\infty \exp^{-j2\pi f_m t} p_k^2(t)dt|}{\int_0^\infty p_k^2(t)dt} \cdot \frac{1}{1 + 10^{-(S/N)_k/10}} \tag{2.11}$$

  Where $p_k^2(t)$ is the impulse response for the receiver-source path in the octave band k and $(S/N)_k$ is the signal-to-noise ratio, i.e. the difference between the signal level (the speech level) and noise level in the listener position, for the octave band considered, in decibels.
  The numerator of the first term of the equation is the Fourier transform of the impulse response square, while the denominator is the total energy of the impulse response;

- B Method: assuming the hypothesis of a perfectly diffused reverberated field and disrupting the contribution of direct sound, i.e. considering the receiver at a distance far beyond the critical distance (consider a distance greater than at least 5 times the critical distance), the 98 values of modulation depth reduction factor can be determined by the relation:

$$m_k(f_m) = \frac{1}{\sqrt{1 + \left(\frac{2\pi f_m T_k}{13.8}\right)^2}} \cdot \frac{1}{1 + 10^{-(L_{sr,k} - L_{n,k})/10}} \tag{2.12}$$

  Where T_k is the reverberation time for the octave band k, in seconds; $L_{sr,k}$ is the speech level in the reverberated field for the octave band k, in decibels; $L_{n,k}$ is the noise level for the octave band k, in decibels. Both are referred in the position of the listener.
  The speech level in the reverberated field can be obtained with:

$$L_{sr,k} = L_{s,1m,k} - ID_k - 10 \log r_{c,k}^2 \quad (dB) \tag{2.13}$$

  $L_{s,1m,k}$ is the speech level at 1 m from the speaker's mouth in a free field, in decibels. It can be assessed considering the A-weighted sound

pressure level at 1 m in front of the speaker's mouth $L_{s,A,1m}$ provided in relation to the A-weighted background noise level (Fig.2.2) and depending on the actual foregone vocal effort (Tab.2.3). Then, adding the values in Tab.2.4 to $L_{s,A,1m}$, the speech level $L_{s,1m,k}$ is given.
ID_k is the directivity index, in decibels, obtained from the directivity factor Q_k for the octave band k by the:

$$ID_k = 10 \log Q_k \quad (dB) \tag{2.14}$$

$r_{c,k}$ is the critical distance, in meters, in the octave band k. It can be evaluated from the volume of the room V, in cubic meters, and the the reverberation time for the octave band k T_k:

$$r_{c,k}^2 \approx 0.0032 \frac{V}{T_k} \quad (m^2) \tag{2.15}$$

- C Method: assuming the hypothesis of a perfectly diffused reverberant field and considering the contribution of direct sound, the 98 values of modulation depth reduction factor can be determined by the relation:

$$m_k(f_m) = \frac{\sqrt{A^2 + B^2}}{C} \tag{2.16}$$

Expressions for A, B and C are:

$$A = \frac{Q_k}{r^2} + \frac{1}{r_{c,k}^2} + \left[1 + \left(\frac{2\pi f_m T_k}{13.8}\right)^2\right]^{-1} \tag{2.17}$$

$$B = \frac{2\pi f_m T_k}{13.8 \cdot r_{c,k}^2} \left[1 + \left(\frac{2\pi f_m T_k}{13.8}\right)^2\right]^{-1} \tag{2.18}$$

$$C = \frac{Q_k}{r^2} + \frac{1}{r_{c,k}^2} + Q_k \cdot 10^{(-L_{s,k} + L_{n,k})/10} \tag{2.19}$$

The terms already seen are the same as for Method B, while r is the distance between speaker and listener, in meters, and $L_{s,k}$ is the level of speech in the listener's position, in decibels, for each octave band k. It can be obtained from the logarithmic sum of the speech level in the direct field $L_{sd,k}$ and in the reverberated field $L_{sr,k}$, both in decibels. The level of speech in the direct field is calculated with the following equation:

$$L_{sd,k} = L_{s,1m,k} - 20 \log r \quad (dB) \tag{2.20}$$

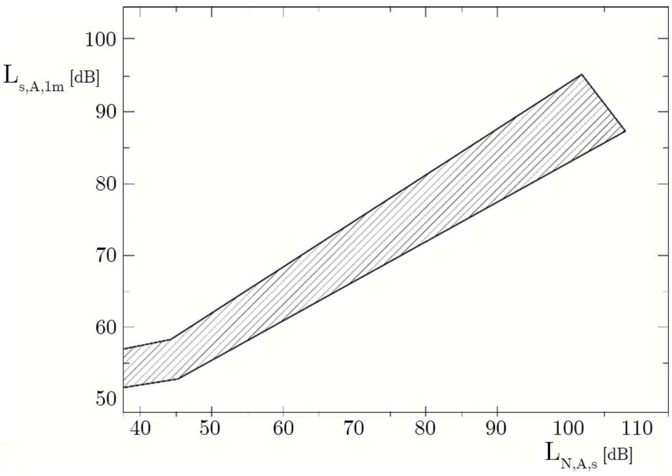


Figure 2.2: Relationship between vocal effort $L_{s,A,1m}$ and background noise level in the speaker position $L_{N,A,s}$, adapted from ISO 9921 [8]. The marked area represents the variability of the Lombard effect between different speakers.

Table 2.3: Vocal effort of a speaker and related A-weighted sound pressure levels at 1 m in front of the mouth $L_{s,A,1m}$, from ISO 9921 [8].

Vocal effort	$L_{s,A,1m}$ [dB(A)]
Relaxed	54
Normal	60
High	66
Strong	72
Very strong	78

Table 2.4: Speech sound pressure levels at 1 m from the speaker's mouth $L_{s,1m,k}$, relative to the A-weighted global level $L_{s,A,1m}$, for each octave band.

Speaker sex	Octave band [Hz]						
	125	250	500	1000	2000	4000	8000
males	2.9	2.9	-0.8	-6.8	-12.8	-18.8	-24.8
males	-	5.3	-1.9	-9.1	-15.8	-16.7	-18

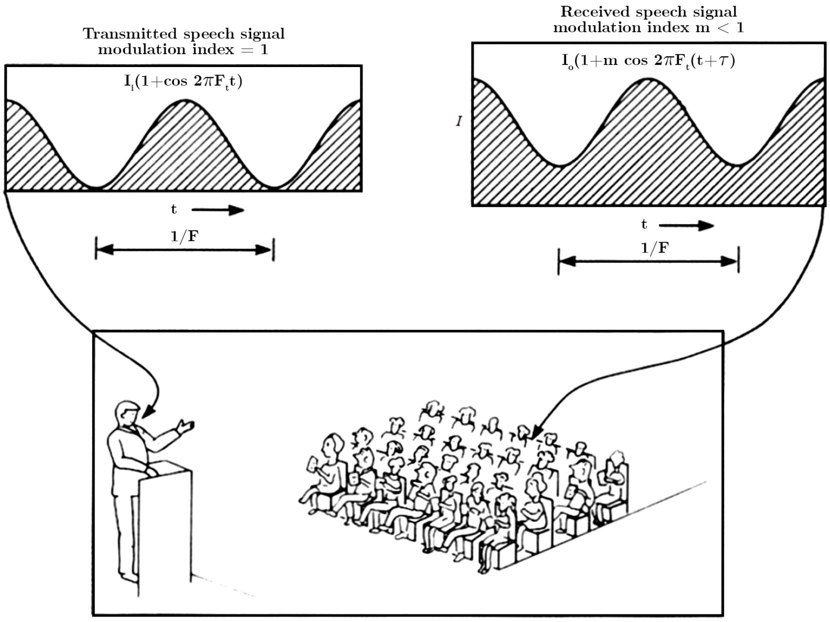


Figure 2.3: Concept of the reduction of modulation due to a transmission channel. The received signal suffers a detrimental modulation (m<1) of the sound intensity amplitude.

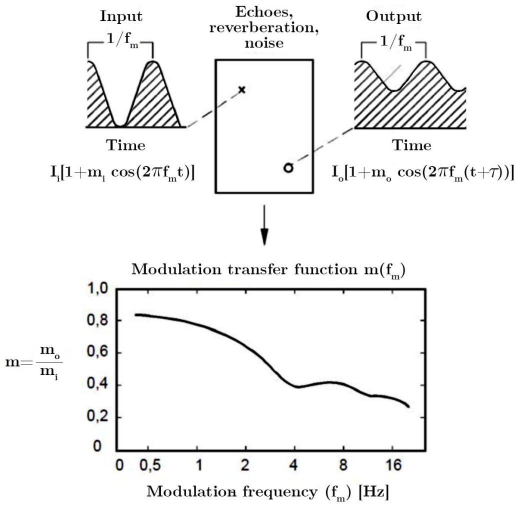


Figure 2.4: Input and output signal comparison gives the MTF. m_i and m_o are input and output modulation indices respectively, while I_i and I_o are input and output sound intensities respectively.

Table 2.5: MTI octave band weight (α) and redundancy (β) factors in function of speaker's sex.

Octave band [Hz]		125	250	500	1000	2000	4000	8000
males	α	0.085	0.127	0.230	0.233	0.309	0.224	0.173
	β	0.085	0.078	0.065	0.011	0.047	0.095	-
females	α	-	0.117	0.223	0.216	0.328	0.250	0.194
	β	-	0.099	0.066	0.062	0.025	0.076	-

The obtained value of $m_k(f_m)$ can be corrected with the auditory masking effect. However, this is interpreted as an effective signal to noise ratio:

$$SNR_{eff,k}(f_m) = 10 \log \frac{m_k(f_m)}{1 - m_k(f_m)} \quad (dB) \tag{2.21}$$

The SNR_{eff} value is limited to the range of -15 dB to 15 dB. One value can be obtained for each signal frequency-modulation frequency couple.
The transmission index can be calculated using:

$$TI_k(f_m) = \frac{SNR_{eff,k}(f_m) + 15}{30} \tag{2.22}$$

The derived transmission indices TI are avereged over all the n modulation frequencies f_m to obtain the modulation transfer index MTI per octave band:

$$MTI_k = \frac{1}{n} \sum_{m=1}^{n} TI_k(f_m) \tag{2.23}$$

The STI can now be calculated:

$$STI = \sum_{k=1}^{7} \alpha_k MTI_k - \sum_{k=1}^{6} \beta_k \sqrt{MTI_k MTI_{k+1}} \tag{2.24}$$

The weight factor α represents the different importance each octave band has in the speech intelligibility. The redundancy factor β is necessary as a subtractive term for the overlapping of the adjacent octave bands which compete in the linstening comprehension.
The result of this measurement procedure is named STI. Three simplified form of the STI, based on measurement using a lower number of modulation indicies, are STIPA, STITEL and RASTI: STIPA consist of a test signal with a predefined set of two modulation per octave band that are generated simultaneously giving a total of 14 modulation indices; STITEL consist of a test signal with a predefined set of seven modulation frequencies, one per octave band, that are generated simultaneously giving a total of 7 modulation indices; RASTI consist of a test signal with a predefined set of nine

modulation frequencies that are generated simultaneously, five for the 2000 Hz octave band and four for the 500 Hz octave band, giving a total of 9 modulation indices. STI is necessary for detaled measurements concerning for example difference between male and female voices. STIPA is generally used for assessing the suitability of room acoustics for speech communication and evaluating the PA (Public Adress) and VA (Voice Adress) systems. STITEL suits the evaluating of telecommunication channels. RASTI is a condensed version of STI, but it is now considered obsolete.

Table 2.6: Speech Transmission Index values corresponding to the intelligibility by IEC 60268-16 [17] and correctly included syllables and words percentages.

STI value	Quality index	Percentage of syllables heard correctly (%)	Percentage of words heard correctly (%)
0.00 ÷ 0.30	bad	0 ÷ 34	0 ÷ 67
0.30 ÷ 0.45	poor	34 ÷ 48	67 ÷ 78
0.45 ÷ 0.60	fair	48 ÷ 67	78 ÷ 87
0.60 ÷ 0.75	good	67 ÷ 90	87 ÷ 94
0.75 ÷ 1.00	excellent	90 ÷ 96	94 ÷ 96

Despite its definition, STIPA method could be used also for natural speech measurements and not only for public address systems. STIPA method is validated for male speech spectrum. There is a difference indeed between male and female speech spectrum: the male one is subjected to more distortions unlike the female one, that is considered more intelligible. Gender difference are expressed with different weighting and redundancy factors that influence the STI calculation as seen in (2.24).

The STI requirements are given by UNI 11532-2 [15] depending on volume of the room and PA systems presence:

Table 2.7: STI requirements according to UNI 11532-2 [15]. The standard gives different limit values in function of the room volume and specifies the SPL of the sound source used for the measurements.

public adress	Volume [m^3]	
system	<250 m^3	⩾250 m^3
not/off	⩾0.55 (60 dB at 1 m)	⩾0.50 (70 dB at 1 m)
on	⩾0.60	

2.2.4 Background noise

A fundamental aspect of speech intelligibility is background noise. The signal-to-noise ratio highlights how much the background noise is detrimental for intelligibility. In a lecture hall, during a lesson, the background noise is made by the HVAC devices, the student activity and, if the room is near the street, the external traffic. The DIN 18041 [12] suggests an optimal difference between signal level and background noise of almost 10 dB.
The determination of the overall noise that will occur in the environment, furnished but not occupied, is fundamental for a clear understanding of speech in the teacher-student communication. The overall noise in an environment is determined by:

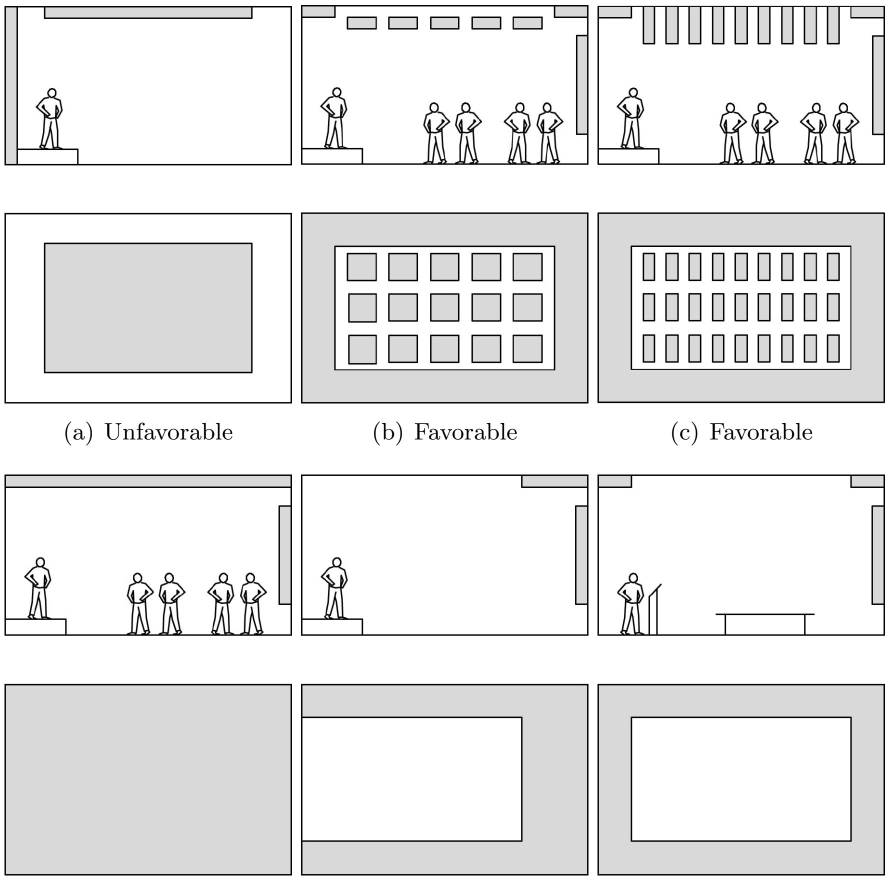
- Noise due to sources outside the school (noise from vehicular or rail traffic, noise from commercial or industrial activities, etc.);
- Noise of continuously operating systems serving the environment (mechanical ventilation systems, heating, cooling, vents, etc.).

The noise due to continuous operation systems, generated in environments other than the environment in question, is subject to compliance with passive acoustic requirements.
Standard UNI 11532-2 [15] sets the upper limits of 38 dB(A) and 41 dB(A) for libraries and classrooms with a volume respectively smaller or grater than 250 m^3.

2.3 Acoustic design hints

In order to decrease the reverberation time in a room and consequently to improve speech intelligibility, it is suitable to introduce sound-absorbing material. The acoustic design problem in an environment with poor performance is mainly composed of how much material to dispose of and how to arrange it. The first instance can be resolved by comparing the current situation with the standard target: the result is the equivalent sound absorption area to reach the required reverberation time value. The second instance needs understanding about the nature of the problem and the experience of the good practice [51]. Another aspect to take into account is what type of material to use, based on the specific needs of the case in question and at which frequencies an adjustment is required.

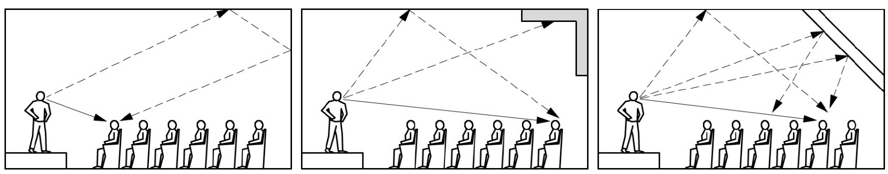
Standard UNI 11532 [15] includes (like DIN 18041 [12]) design examples of favorable and unfavorable positioning of material inside a generic lecture hall. It gives some general principles but also address some practical situations. These indications are discussed in the following pages.
The principle behind the indications is to favor the first reflections, which bring useful information, and to absorb subsequent reverberations, which lead to a deterioration of the source signal with a detrimental effect on speech intelligibility. As a good pratice it is desirable to evenly distribute the surfaces and absorbent elements on the surfaces or in the environment. In other words, the concentration of sound-absorbing material only in certain positions is generally not recommended. As it is not recommended to place sound-absorbing material on the wall behind the teacher (Fig.2.5.a). The correct placing may change according to the frequencies treated, for example low-frequency performing materials are very effective near the sound source, in the corners or in the edges of the room.
For rooms with a rectangular plan, with flat walls and in an unfurnished condition, like the majority of traditional lecture room, if you only intervene with a sound-absorbing false ceiling, you risk the occurrence of excessive delays or flutter echoes. This danger can be avoided by leaving a reflective central ceiling (Fig.2.5.c,f). As compensation for the smaller equivalent area applied, the walls should be partially treated with sound-absorbing material. An alternative is to arrange the absorbent surfaces on the ceiling according to distributions that create reflective and absorbent mixed areas (vertical/horizontal baffles) (Fig.2.5.b,c). For rooms with a volume up to about 250 m^3, in combination with an acoustically absorbing rear wall it is possible to use a completely absorbent ceiling (Fig.2.5.d).
In rooms longer than 9 m the back walls can cause delayed reflections that can lead to a reduction in the speech intelligibility, especially for the first rows (Fig.2.6.a). The surfaces must be accordingly treated with sound absorbing material (Fig.2.6.b) or with sloping reflective surfaces (Fig.2.6.c).



(a) Unfavorable (b) Favorable (c) Favorable

(d) Favorable (e) Favorable (f) Favorable

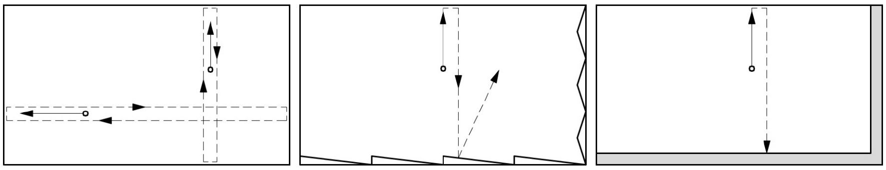
Figure 2.5: Examples of favorable and unfavorable distribution of sound absorption surfaces for small and medium-sized rooms.



(a) Unfavorable (b) Favorable (c) Favorable

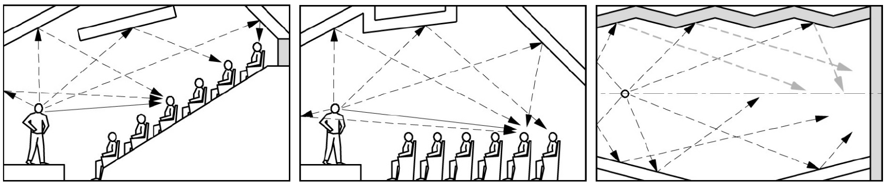
Figure 2.6: Reflections on the back wall and possible treatments.

This way that the incident sound is reflected as a positive contribution for listeners placed far from the sound source.
When there are parallel walls at least one of them must be arranged with sloping reflective elements to spread the sound (Fig.2.7.b) or with sound absorbing material (Fig.2.7.c).



(a) Unfavorable (b) Favorable (c) Favorable

Figure 2.7: Reflections on parallel walls and possible treatments.



(a) Section (b) Section (c) Plant

Figure 2.8: Useful reflections for the rear area.

This is particularly true in larger rooms without a terrace seating distribution. A slope of at least 5° can be enough.
To increase the useful sound component which reaches longer distances and to achieve better speech intelligibility, it is necessary to provide suitably inclined reflective surfaces (Fig.2.8). The wall behind the speaker and the central part of the ceiling, where the first reflections that reach the listeners are generated, shall be reflective at medium and high frequencies. If the ceiling or the surfaces of the side wall are not planar, the individual elements shall be oriented in such a way that the sound is directed in the central and rear listening areas.

Chapter 3

Mounting effects on sound absorption

As seen in the previus chapter, the standard UNI 11532 [15] gives advice on the correct positioning of sound absorption material to gain a good perfomance for acoustic comfort in a lecture hall. Several examples show as many different material arrangements (Fig.2.5-2.7).
A test carried out on a sample of sound-absorbing material in a controlled environment (reverberation chamber) allows to experimentally verify the effect of different positionings.

3.1 Sound absorption measurements

The reference standards for sound absorption measurements on furnitures or objects in general are ISO 354 [2], which provides guidelines for reverberant room measurements, and ISO 20189 [11], which supplies indications on how to operate with more complex absorbent systems than a single sample of generic material.

3.1.1 Reverberation room

The acoustic certifications regarding the performance of materials or things are carried out in the reverberation room.
The reverberation room used for this work is located in the basement of the Department of Idustrial Engineering laboratories of University of Bologna, at Via Terracini 34, Bologna.
The chamber has five non-parallel walls, a linoleum floor and a pi-shaped prefabbricated beams ceiling. All the plastered surfaces are painted with many layers of varnish to fill the porosity in the concrete, in order to reduce the sound absoportion of the chamber. The volume of the room is 280 m^3 for a total surface (including the beam convexity in the ceiling) of 350 m^2.

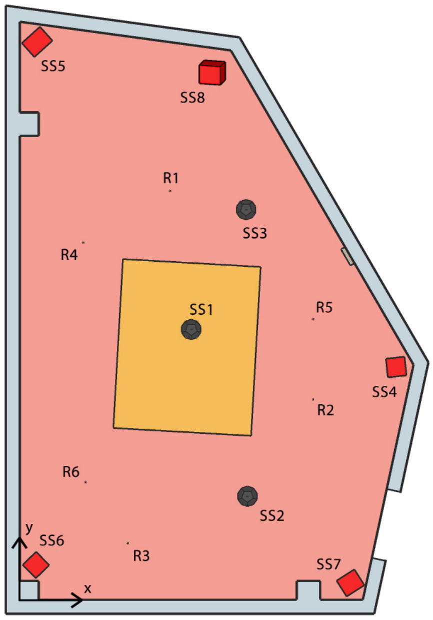


Figure 3.1: Department of Idustrial Engineering reverberation room plant.

Table 3.1: Sources and receivers positions and elevations from a x-y plane in the corner or the room. All distances are in meters.

Source/Receiver	x	y	height
SS1	3.65	5.75	2.10
SS2	4.85	2.20	1.65
SS3	4.82	8.30	1.90
R1	3.20	8.70	1.35
R2	6.25	4.26	1.35
R3	2.30	1.20	1.90
R4	1.35	7.60	2.05
R5	6.25	5.97	1.85
R6	1.40	2.50	1.75

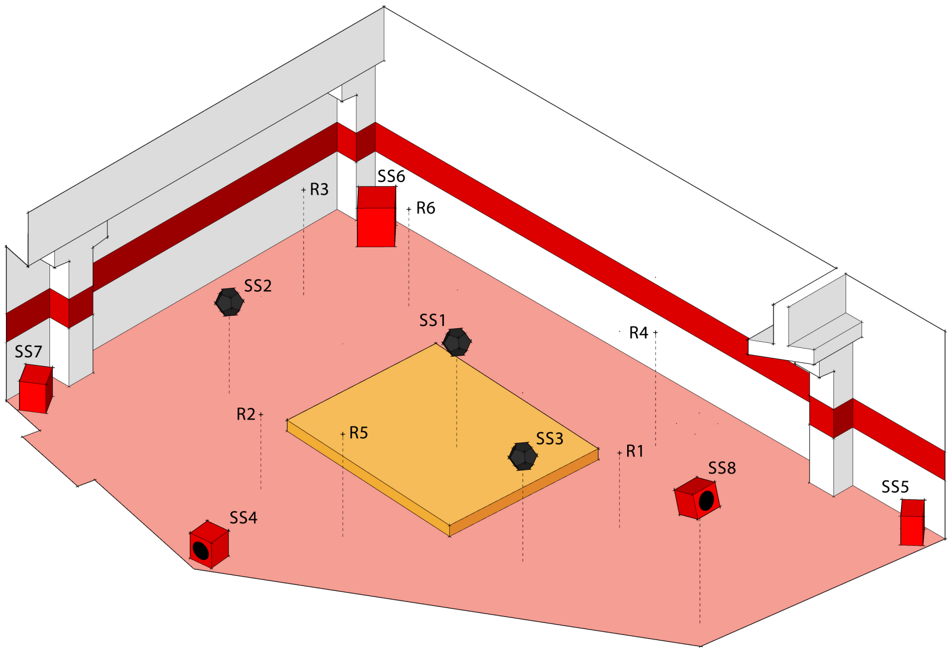


Figure 3.2: Reverberation room axonometric view.

Inside the room, seven sound sources and six receiver are positioned (Fig.3.1), for a total of fortytwo measure couples. The sources emit at different frequency band, covering all the audible spectrum. Two of them are high SPL dodecahedron hanging from the ceiling; the other four are subwoofer positioned in the corners, placed on the floor except one hanging in a slope position, each one with the emitting cone oriented towards the wall to avoid direct sound field. All sources and mics are related throught a patchpay board to the sound board, for more flexibility on the electronic configuration. Recordings are developed on the workstation placed in the adjacent chamber, where the operator can send the signal to sources in order to start the measurement procedure.

The standard ISO 354 [2] gives some advise on the correct project of the reverberation room and the sample test arrangement.

The volume of the room shall be at least 150 m^3, up to 200 m^3 for new constructions. It shall not be greater then 500 m^3 due to the inaccuracy at high frequencies because of air absorption.

The shape of the room has to fulfill the condition:

$$I_{max} < 1.9 \cdot V^{1/3} \tag{3.1}$$

Where I_{max}, in meters, is the length of the longest straight line which fits within the boundary of the room, and V, in cubic meters, is the volume of the room.

Table 3.2: Equivalent sound absorption area limit values, in Sabine's square meters, according to ISO 354 [2], for a 200 m^3 empty reverberation room determined in one-third octave bands.

Freq [Hz]	100	125	160	200	250	315	400	500	630
$A_{1,200}$	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Freq [Hz]	800	1000	1250	1600	2000	2500	3150	4000	5000
$A_{1,200}$	6.5	7.0	7.5	8.0	9.5	10.5	12.0	13.0	14.0

Table 3.3: Equivalent sound absorption area limit and meausered values, in Sabine's square meters, for a 280 m^3 empty reverberation room, according to ISO 354 [2], determined in one-third octave bands.

Freq [Hz]	100	125	160	200	250	315	400	500	630
$A_{1,280}$	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1
$A_{1,mes}$	5.9	6.6	6.8	6.8	6.4	6.4	6.2	5.9	6.0
Freq [Hz]	800	1000	1250	1600	2000	2500	3150	4000	5000
$A_{1,280}$	8.1	8.8	9.4	10.0	11.9	13.1	15.0	16.3	17.5
$A_{1,mes}$	6.4	6.8	7.2	7.8	8.7	9.9	11.7	14.2	18.3

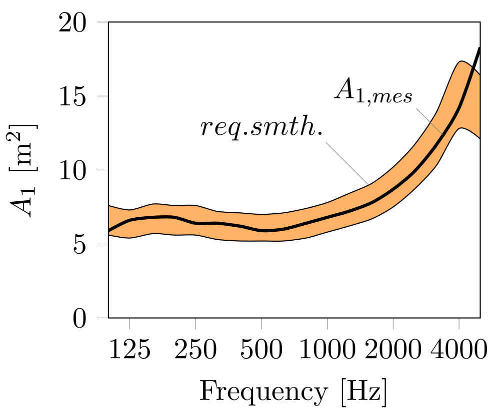


Figure 3.3: Empty reverberation room equivalent sound absorption area - A_1: on y-axis the equivalent sound absorption area, in Sabine's square meters, on x-axis one-third octave frequencies. The black line show the A_1 of the empty reverberation room, the orange range gives the required smoothness of the curve from ISO 354 [2].

In order to achieve a uniform distribution of natural frequencies, especially in the low-frequency bands, no two dimensions of the room shall be in the ratio of small whole numbers.
The equivalent sound absoption area of the empty room A_1, determined in one-third octave bands, shall not exeed the value in Tab.3.2. These value limits are for a 200 m^3 room. They shall be multiplied for $(V/200\ \text{m}^3)^{2/3}$ to give the equivalent for the room volume (Tab.3.3). It is possible to evaluate the actual limits for the 280 m^3 Department of Indutrial Engineering reverberation room and then obtain the measured value in empty room condition (Tab.3.3). The graph of the equivalent sound absorption area of the empty room versus the frequency shall be a smooth curve and shall have no dips or peaks differing by more than 15% from the mean of the values of both adjacent one-third octave bands (Fig.3.3).

3.1.2 Temperature and relative humidity

Changes in temperature and relative humidity during the course of a measurement can have a large effect on the measured reverberation time, especially at high frequencies and at low relative humidities. The changes are described quantitatively in ISO 9613-1 [7].
Measurements should be performed in the empty room and in the room containing the test specimen under conditions of temperature and relative humidity that are almost the same so that the adjustments due to air absorption do not differ significantly. In any case, the relative humidity in the room shall be at least 30% and max. 90% and the temperature shall be at least 15 °C during the whole test. For all measurements, the corrections for the change in air absorption as described in equations (4.1) and (4.3) shall be applied. It is necessary to allow the test specimen to reach equilibrium with respect to temperature and relative humidity in the room before tests are carried out. Also the air in the room shall be sufficiently mixed with fans if necessary.
For this purpose the reverberation room is equipped with an environmental monitoring gear wich give temperature, relative humidity and atmospheric pressure for the room.

3.1.3 Microphones and loudspeakers

Michrophones used shall be omnidirectional, positioned at least 1.5 m apart, 2 m from any source and 1 m from any room surface and the test specimen. Sound sources shall generate an omnidirectional radiation pattern, positioned at least 3 m apart.
The number of spatially independent measured decay curves shall be at least 12. Therefore the number of microphone positions times the number of sound source positions shall be at least 12. The minimum number of

microphone positions shall be three; the minimum number of sound source positions shall be two. This amount of sorce-receiver couples in required especially because of the statistical nature of the interrupted noise method. Like said before the DIN reverberation room set up covers aboundantly the numbers required with 8 different sound sources and 6 microphone positions.

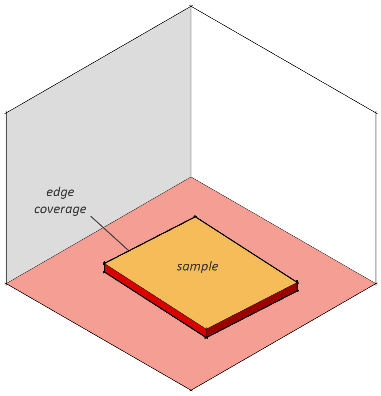
3.1.4 Diffusors

The diffuse sound field hypothesis has to be achieved, as already said. Standards and papers try to suggest the correct placement of diffusing surfaces to grant a sufficently diffuse decaying.
This aspect is still under debate by research laboratories and cannot be addressed here due to its complexity which would deserve a study in its own right. The argument falls within the question of the reproducibility of interlaboratory acoustic measures. For the purposes of the present work, general indications on the actual behavior of the proposed design interventions are sufficient, so it is possible to go beyond specific issues such as this, provided that the field of uncertainty in which we move is known.
It is here enough to say that the measurements developed in the reverberation room were carried out in absence of diffusing devices.

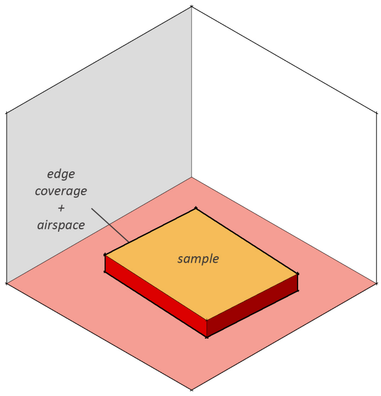
3.1.5 Test specimen

For a plane absorber the test specimen shall have an area between 10 m^2 and 12 m^2; if the volume of the room is greater then 200 the upper limit shall be increased by the factor $(V/200\ m^2)^{2/3}$ (for Department of Indutrial Engineering chamber is 15 m^2). The area to be chosen depends on the room volume and on the absorption capability of the test specimen. The larger the room, the larger the test area should be. For specimens with small absorption coefficient, the upper limit area should be chosen.
The test specimen shall be of rectangular shape with a ratio of width to length of between 0.7 and 1. It should be placed so that no part of it is closer than 1 m to any edge of the boundary of the room; the distance shall be at least 0.75 m. The edges of the specimen shall preferably not be parallel to the nearest edge of the room. If necessary, heavy test specimens may be mounted vertically along the walls of the room, and directly resting on the floor. In this case of course the requirement of at least 0.75 m distance need not to be respected.
Discrete objects (e.g. chairs, free-standing screens or persons) shall be installed for the test in the same manner as they are typically installed in practice. For example, chairs or free-standing screens shall rest on the floor, but they shall not be closer than 1 m to any other boundary. Space absorbers shall be mounted at least 1 m from any boundary or room diffusers and at least 1 m from any microphone. Office screens shall be mounted as

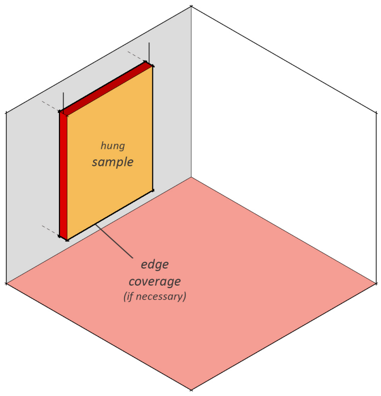
individual objects.
A test specimen shall comprise a sufficient number of individual objects (in general, at least three) to provide a measurable change in the equivalent sound absorption area of the room greater than 1 m^2, but not more than 12 m^2. If the volume V of the room is greater than 200 m^3, these values shall be increased by the factor $(V/200\ m^3)^{2/3}$ (like already said). Objects normally treated as individual objects shall be arranged randomly, spaced at least 2 m apart. If the test specimen comprises only one object, it shall be tested in at least three locations, at least 2 m apart, and the results shall be averaged.
The sound-absorption properties of a material depend on how that material is mounted during a test. The standard ISO 354 [2] gives different mounting types for test materials: A, B, E, G, I and J. Normally a test specimen is tested using only one of the specified mountings. Here it will be enough to explain briefly only type A, E and G.
Type A mounting is used when the sample is placed directly against a room surface (Fig.3.4.a). Adhesive or mechanical fasteners that do not leave a thin air space may be used to hold the test specimen in place during the test. If the sample is made by two or more pieces of material using joints, these have to be covered with non absorbent materials. The perimeter edge of the sample shall also be covered to prevent the edges from absorbing sound. If the edges of the test specimen are exposed when the material is normally installed in an actual application, then the edges of the test specimen shall not be sealed, but the area of the edges shall be included in calculating the test specimen area. The coverage shall be done using a reflective frame. The exposed face of the frame shall be flush with the surface of the specimen.
Type E mounting is used when the test specimen is mounted with an airspace behind it (Fig.3.4.b). The distance of the specimen exposed surface from the room surface behind the sample is expressed in the suffix of the mounting designation (e.g. Type E-X00, where X00 stays for the distance in mmm). The standard suggest 400, 300 and 200 mm distances, but others can be used in addition). The mounting fixture shall be constructed of metal, wood or other non-porous material with a surface density of at least 20 kg m^2, and shall enclose an air space behind the sample that does not have any interior partitions unless provided as part of the sample. Air leakage shall be prevented with all the necessary sealing provisions.
Type G mounting is used when the test specimen is hung parallel to the room surface (Fig.3.4.c). The distance from the face of the sample and the parallel room surface is expressed in the suffix of the mounting designation (e.g. Type G-X00, where X00 stays for the distance in mmm). The standard states at least a 100 mm distance has to be performed; other distances can be used in addition, but they shall be an integer multiple of 50 mm. The sample can be test with or without a perimeter frame depending on how it is used in practise.



(a) Type A mounting

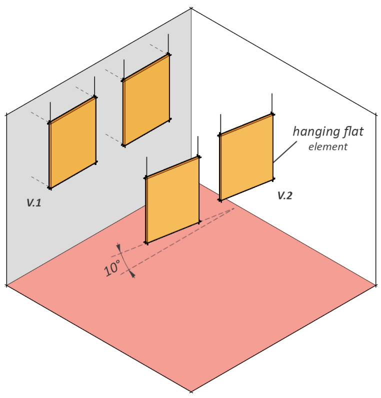


(b) Type E mounting

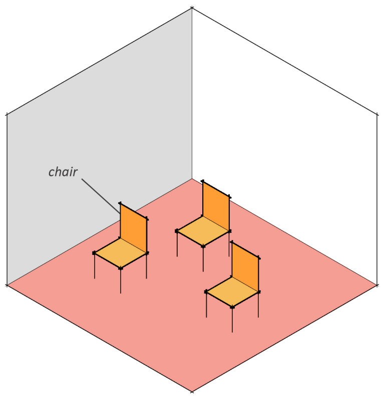


(c) Type G mounting

Figure 3.4: Standard ISO 354:2003 [2] A, E and G mounting type examples.



(a) Type V mounting



(b) Type VIII mounting

Figure 3.5: Standard ISO 20189:2018 [11] reccomendations V.1, V.2 and VIII mounting type examples.

For measurements on objects the standard ISO 20189:2018 gives further mounting specifications. Only those for hanging flat elements and seats are listed here, but arrangenments for sofas or office furnitures are also provided. Hanging flat elements (type V mounting) are arranged according to their intended use, tested hanging according to their actual mounting system. Two submounting types are possible (Fig.3.5.a):

- **Type V.1** - Mounting conditions at a certain specified short distance from a wall (resembling a type G100 mounting) but not closer than 1 m to any other boundary. This mounting is not used as a basis to calculate A_{obj};
- **Type V.2** - Mounting conditions in the middle of a room where the specimen should be mounted freely hanging in the reverberation room, with an angle of at least 10° to any wall and not closer than 1 m to any boundary. This mounting can be used as a basis to calculate A_{obj}, noticing that both side of the samples are exposed.

Chairs, containers, stools or similar (type VIII mounting) are mounted directly standing on the floor in the reverberation room in random positions (Fig.3.5.b).

3.2 Test procedure and results

The insertion of hanging baffle involves diffraction and diffusion phenomena which imply a higher absorption than the area of absorbent material provided. The actual increase can be estimated with measurements carried out on a known sample in a controlled environment.
Starting from the several specimen mountings proposed in the standard ISO 354 [2], many arrangements are attemped to see the different behaviors using the same polyester fiber specimen area of 10.8 m^2.
A sample of nine (1x1.2)m panels are disposed in three different ways (Fig.3.6):

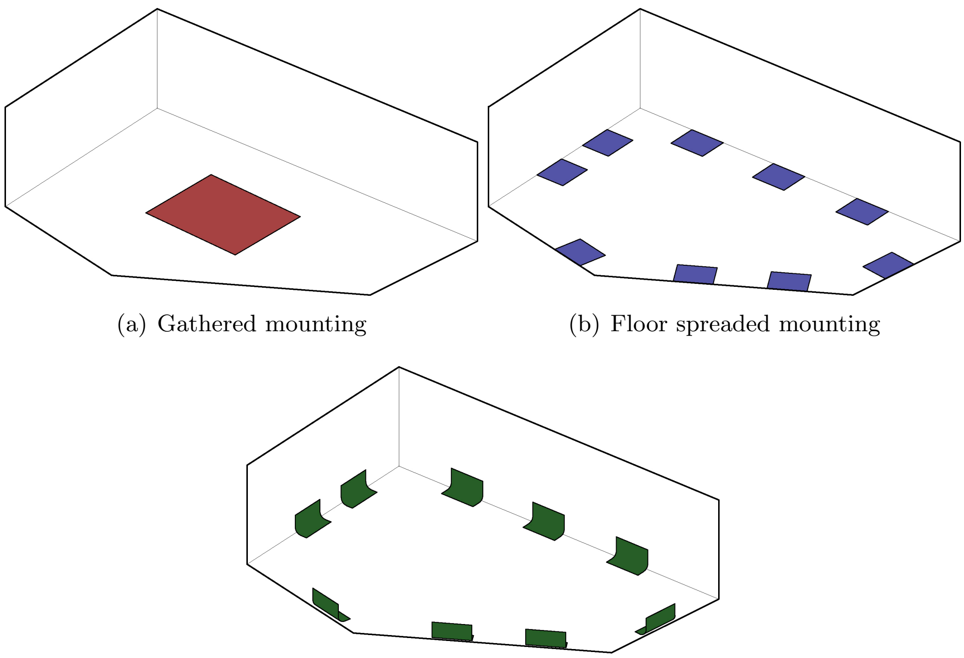
a) panels are gathered in the middle of the floor surface (in compliance of the A mounting type from the standard). This is the default mounting used for sound absorption measurements developed by the laboratory;

b) panels are spreaded all around the boundary of the room. The minumum distance between the room walls and the sample given by the standard is not respected, so the effect of this negligence can be evaluated;

c) from the previous mounting the panels are raised until the material can keep its position, so the sample is curved and half leaning on the wall.

The standard ISO 354 [2] is the reference for this measurement test. All eight sources and six microphones are used. The first measurement session

is conducted on the empty room and the three test mounting session follow. Impulse responses are obtained to evaluate the sound absorption for the different configuration. Also the link between the specimen mounting and the diffuse sound field is investigated. For each session environmental parameters like temperature, relative humidity and atmospheric pressure are recorded.
From measured impulse responses, reverberation times for all the sessions are obtained (Fig.3.7.a). Applying environmental corrections from equation (4.1) and given equation (1.14) it is possible to obtain sound absorption coefficient values for the three sample dispositions (Fig.3.7.b). Results show that the two spreaded configuration are substantially more absorbant then the gathered one which compliances the standard. This outcome can be explained with the edge effect: the spreaded configuration leaves many more edges exposed than the gathered one. From the spatial relative standard deviation it is possible to notice an improvement in the diffusion of the sound field (Fig.3.7.c): the high absorbent specimen produces a detriment in the sound field as already mentioned, but this is less affective when the absorbent area is spreaded instead of gathered.

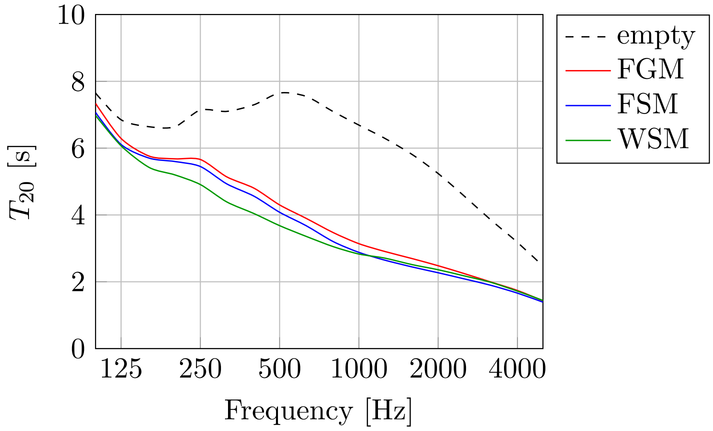


(a) Gathered mounting

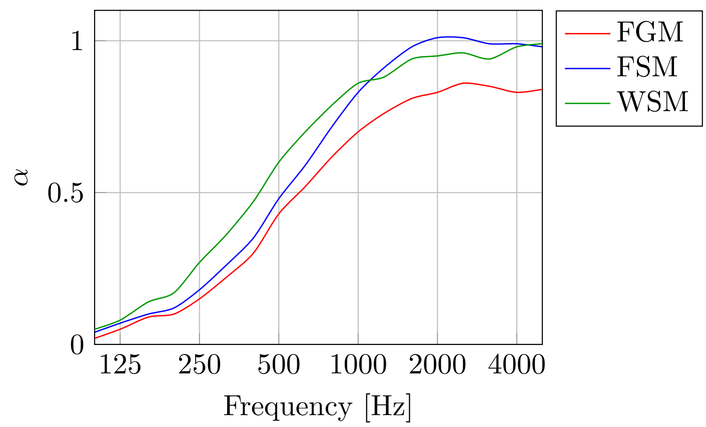
(b) Floor spreaded mounting

(c) Wall spreaded mounting

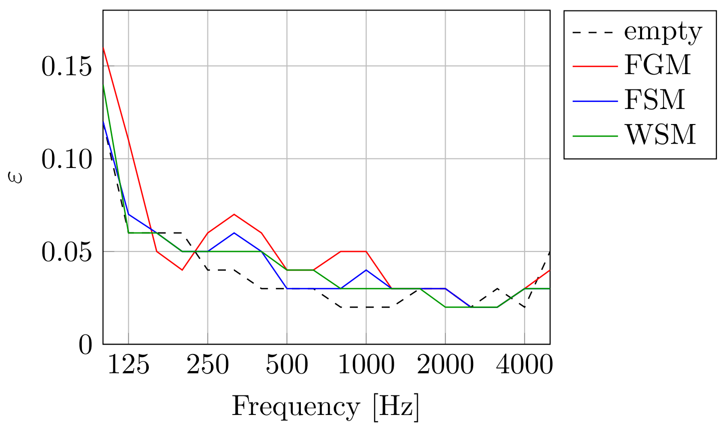
Figure 3.6: Three different test mountings of the same specimen area (10.8 m^2).



(a) Reverberation Time - T_{20}.



(b) Sound Absorption Coefficient - α.



(c) Spatial Relative Standard Deviation - ε.

Figure 3.7: Mounting test on a polyester fiber specimen: reverberation time, in seconds, sound absorption coefficient and spatial relative standard deviation, determined in one-third octave bands for empty room (dashed), and with 10.8 m^2 panels gathered (red) and spreaded on the floor (blue) or leaning on the wall (green).

Chapter 4

Method

The present work inquires the acoustical behavior of a selected group of lecture rooms under renovation.
The acoustic measurement procedures as portrayed in the standards are here explained. The measurement campaigns are illustrated describing the equipment and the technique used.
The study samples are presented in all that is necessary for the development of the interventions, like their geometrical features and their ante-operam conditions, compared to the standards limits.
The simulation process is explained in all its aspects as the modeling technique, the calibration method and the simulation algorithms. After that, the settings to reach the simulation parameters are described.
Design proposals to achieve a better acoustic comfort are discussed and illustrated, distinguishing between active and passive intevention.

4.1 Case studies

In June 2019 a three days measurements campaign has been conducted in the lecture rooms of Palazzo Malvezzi-Campeggi taking advantage of the closure for renovation of the property. The audience absence maked possible to work in a large sample of room with different sizes, applications, ceiling types and historical values. The wide records variance opens reflections on the specific needs of the single case and the performances required. It follows that the interventions will also be significantly differentiated.
The purpose of the assignment is the design of acoustic correction interventions in nine classrooms of the university complex located in Bologna Via Zamboni 22 (Fig.4.1), in order to improve their intelligibility and acoustic comfort to promote concentration by students and reduce the vocal effort by teachers. Pertinent characteristics for the acoustic analysis of the classrooms, like geometric, architectural and occupancy feautures, are here listed in two tables, one for the standard lecture rooms and another for the special

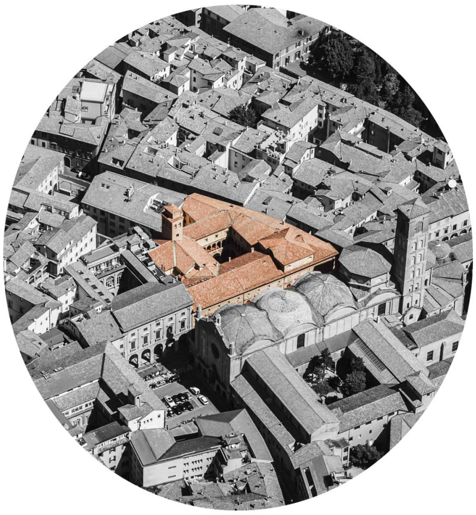
halls which can be used in formal occasion for their prestige and occupancy capabilities.

Table 4.1: Standard lecture rooms feautures: L, W, H, in meters, and V, in cubic meters, are the length, width, height and volume respectively; N is the nominal maximum audience; S_A, in square meters, is the area occupied by the audience; spatial ratio between the volume and the audience size/area are explicited; ceiling and seats type are specified. Notes: * impost/keystone avg; ** short/long side.

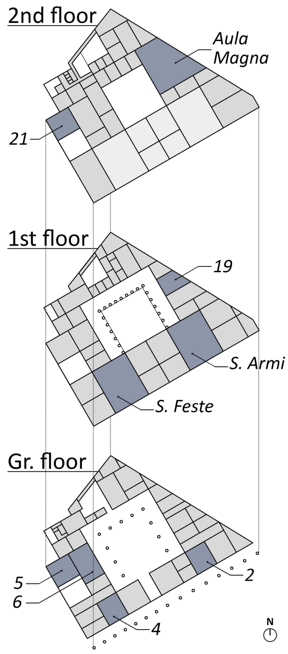
Data	Aula 2	Aula 4	Aula 5	Aula 19	Aula 21
L	9.8	9	6.6	7	6.7
W	7.2	7	6.1	5.2/8.6**	6.2
H	5.3*	5.3*	4.7*	3.8	4.6
V	350	320	200	180	190
N	20	30	15	10	10
S_A	20	27	18	15	11
V/S_A	18	12	13	18	17
V/N	18	11	11	12	19
ceiling	vault	vault	vault	planar	planar
seats	wood	wood	wood	wood	fabric

Table 4.2: Peculiar lecture halls feautures: L, W, H, in meters, and V, in cubic meters, are the length, width, height and volume respectively; N is the nominal maximum audience; S_A, in square meters, is the area occupied by the audience; spatial ratio between the volume and the audience size/area are explicited; ceiling and seats type are specified. Notes: * impost/keystone avg; ** short/long side; *** main/extra volume

Data	Aula 6	Aula Magna	Sala Armi	Sala Feste
L	10.4	15	14	13.5
W	6.9	6.7/14**	12	11.4
H	5*	4/2***	9.3/3.3***	8
V	370	740	2100	1250
N	35	120	50	50
S_A	20	50	35	55
V/S_A	19	15	60	23
V/N	11	6	42	25
ceiling	vault	planar/slope	dome	coffers
seats	tbd	wood	stuffed	wood



(a) Palazzo Malvezzi-Campeggi location.



(b) Plan distribution.

Figure 4.1: Palazzo Malvezzi-Campeggi is located at the intersection of Via Zamboni with Via Marsala, in Bologna (a). Lecture halls studied are are located on three floors of the building (b).

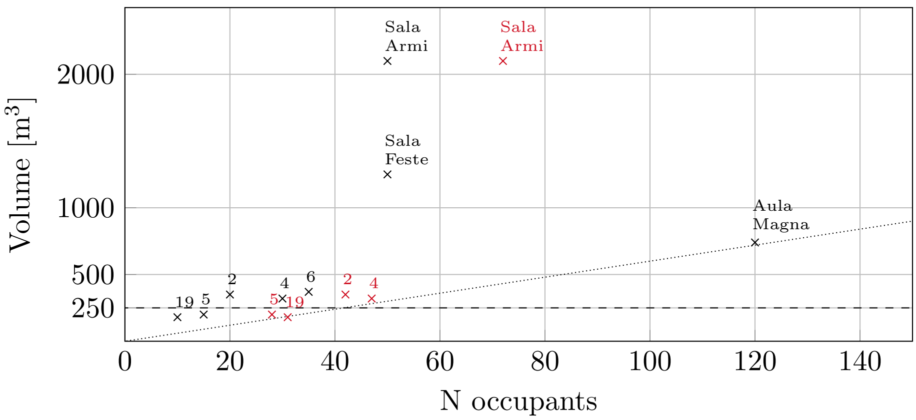


Figure 4.2: Classification scheme for classrooms according to volume. The abscissa indicates the maximum capacities of each classroom. In black the point obtained by the nominal audience occupancy, in red the observed number, when it has been recorded. Aula 21 is implied in Aula 19 due to the same state. The dashed line divides the classrooms with a volume less than or greater than 250 m^3. The dotted line indicates the optimal ratio of a space used for speech (6 m^3/person).

4.1.1 Small rooms

Aula 5, Aula 19 and Aula 21 (Fig.4.3) are considered small classrooms because they have a volume V<250 m^3, a defining parameter for the purposes of regulatory requirements. They are almost square in shape, consisting of rigid and plastered walls. They have similar volumes (190 m^3 ca.) and almost the same geometric and material feautures. Instead the ceiling changes in the three spaces: Aula 5 is vaulted, Aula 19 has a flat ceiling and Aula 21 has a flat ceiling with the presence of small beams. The seats are in wood in Aula 5 and 19, while in Aula 21 there are various slightly padded movable seats in plastic or wood.

(a) Aula 5

(b) Aula 19

(c) Aula 21

Figure 4.3: Small rooms: (a) Aula 5; (b) Aula 19; (c) Aula 21.

4.1.2 Medium-large rooms

Aula 2, Aula 4, Aula 6 and the Aula Magna are considered medium-large classrooms as they have a volume V>250 m^3. Aula 2, Aula 4 and Aula 6 (Fig.4.4.a,b,c) have almost the same geometric and material characteristics, similar volumes (about 350 m^3), rectangular plants and rigid and plastered walls. In Aula 6 the ceiling does not have nails on the sides but consists

of a continuos vaulted surface. The seats are in wood in Aula 2 and Aula 4, while in Aula 6 they will be the subject of design considerations: this room has been measured in a work-in-progress condition with provvisory furnitures, but a renewal project has been drafted to convert the classroom into a court.
The Aula Magna (Fig.4.4.d) has a complex geometry, formed by a trapezoidal plan, a mezzanine at the bottom of the hall which houses further seats to increase its capacity and a ceiling that develops in steps to accommodate the air conditioning and lighting systems. It is considered a large classroom (750 m^3), actually closer in size to the large halls. All surfaces are smooth, rigid and plastered. The seats are made of wood on the main floor and plastic on the mezzanine.

(a) Aula 2

(b) Aula 4

(c) Aula 6

(d) Aula Magna

Figure 4.4: Medium-large rooms: (a) Aula 2; (b) Aula 4; (c) Aula 6; (d) Aula Magna.

4.1.3 Extra large rooms

Sala delle Armi and Sala delle Feste, given their size, cannot be considered properly classrooms but they are more accurately classified as environments, or at least extra large rooms. Sala delle Armi (Fig.4.5.a) is

a large room (2100 m^3), has an almost square plan and a complex height development, consisting of a main volume with a domical ceiling and a second volume with a smaller oval dome. The walls are plastered, rigid and strongly decorated with stuccos and sculptures. The seats consist of slightly upholstered chairs covered in leather. Also the doors are padded with fabric. The speaker takes place on a carpeted stage with a long table and a pulpit, both with a microphone stations.
The Salone delle Feste (Fig.4.5.b), has an almost square plan and a large volume (1250 m^3). The ceiling is coffered in wood while the walls are rigid and plastered. The seats are in wood. The entrance to the classroom has a light iron and plexiglas structure that has the function of conveying the people flows.

(a) Sala delle Armi (b) Sala delle Feste

Figure 4.5: Extra large rooms: (a) Sala delle Armi; (b) Sala delle Feste.

4.2 Acoustic measurements

In order to qualify the lecture halls according to ISO 3382-2 [5], IEC 60268-16 [17] and UNI 11532 [15] standards, measurements was conducted to obtain the room criteria and the intelligibility criteria for speech. The measurements were performed in unoccupied states with furnitures. For some classrooms it has been possible to do it with and without the seats in order to gain a better knowledge of how they influence the acoustics and to obtain the sound absorption of the seats. This infos give some advise for possible designs and improve the accuracy of the numerical models.
Monoaural technique and ESS (Exponential Sine Sweep) signal were used to obtain impulse responses [32]. The equipment was made up of:

- a laptop that launched the ESS signal with length of 512k and sampled at 48 kHz;
- a signal converter (Motu UltraLite AVB);

- an amplifier to increase the signal power (Crown XLS2500);
- a dodecahedron with custom loudspeakers used as an omnidirectional source;
- one monoaural half inch free-field microphones (NTI audio MA220) as receiver.

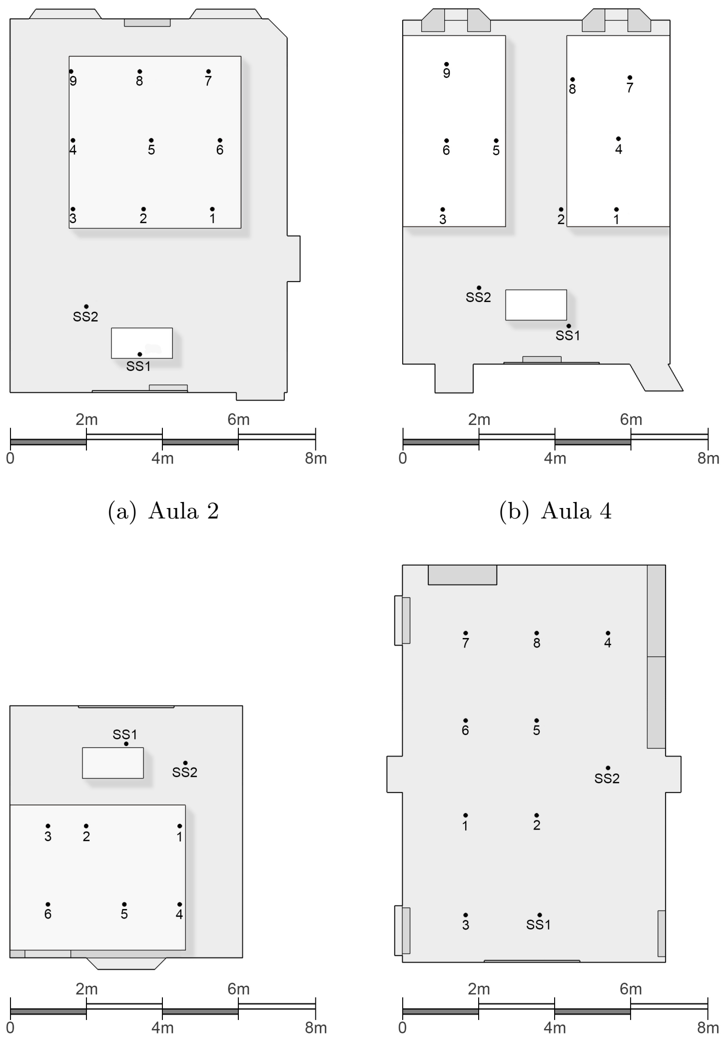
The source was calibrated in reverberation room according to ISO 3741 specifications [6].

4.2.1 Source and receivers positioning

The measurement precision method has been performed: two different source positions and more than three microphone positions are required, for a total of source-receiver combination higher than twelve. Starting from this minumum, the microphone position considered are remarkably higher according to the room size. This condition shall make possible to achieve an appropriate coverage of the entire room. The measurements shall be carried out using source and microphone positions in the position of the person's who talks and who listens, so the sound source is placed near the blackboard and in another not aligned position in front of the audience where the teacher/speaker could walk into. Receiver positions are placed in a regular grid which cover the total seats area at least about 2 m apart. Loudspeaker are placed 1.5 m above the floor while microphones 1.2 m; both shall be at least 0.5 m from tables and at least 1 m from walls and other reflecting surfaces [4]. The placement is shown for each room.

(a) Aula 19 (b) Aula 21

Figure 4.6: Loudspeakers and microphone positioning: (a) Aula 19; (b) Aula 21.



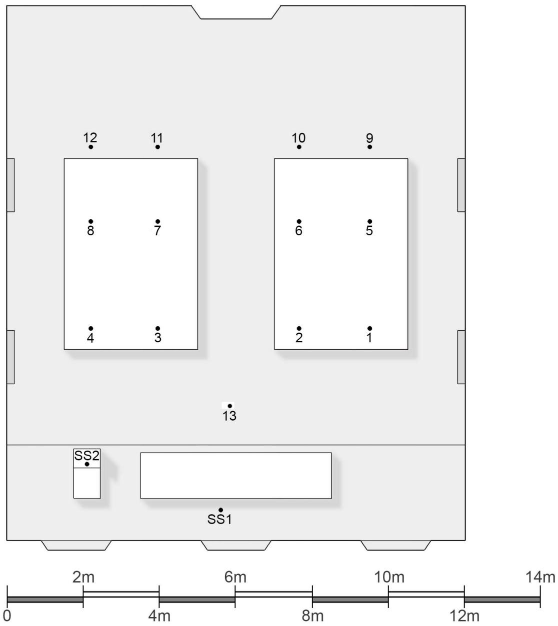
(a) Aula 2

(b) Aula 4

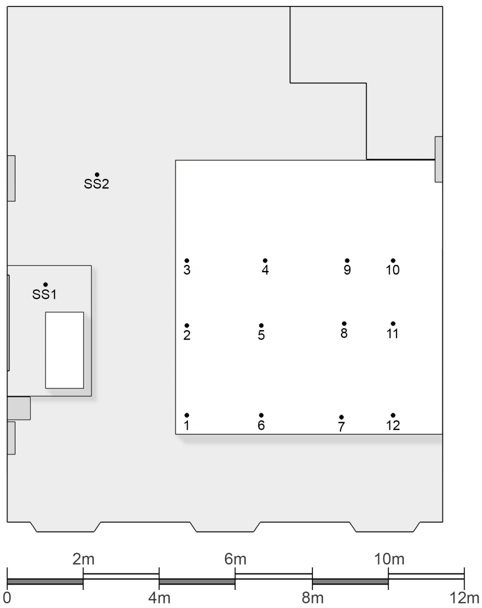
(c) Aula 5

(d) Aula 6

Figure 4.7: Loudspeakers and microphone positioning: (a) Aula 2; (b) Aula 4;(c) Aula 5; (d) Aula 6.



(a) Sala delle Armi



(b) Sala delle Armi

Figure 4.8: Loudspeakers and microphone positioning: (a) Sala delle Armi; (b) Sala delle Feste.

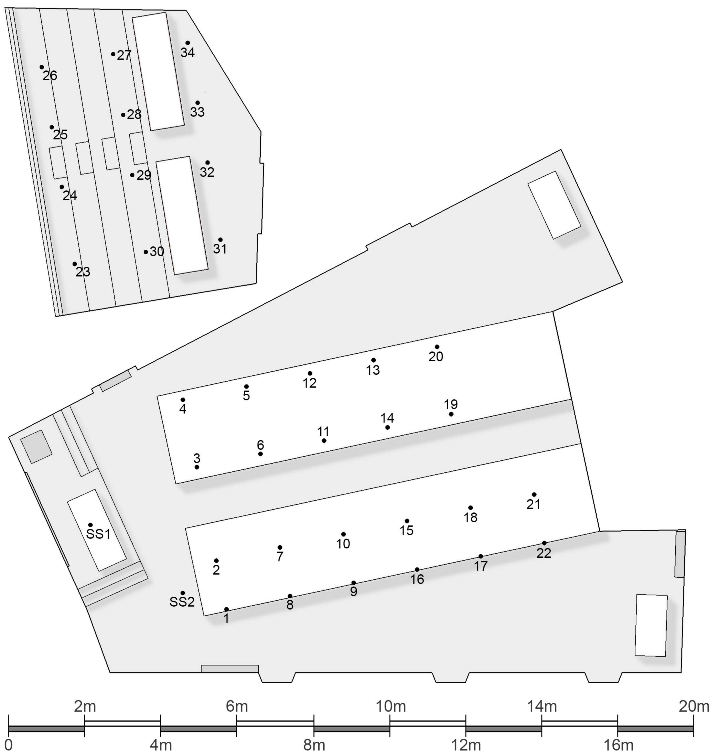


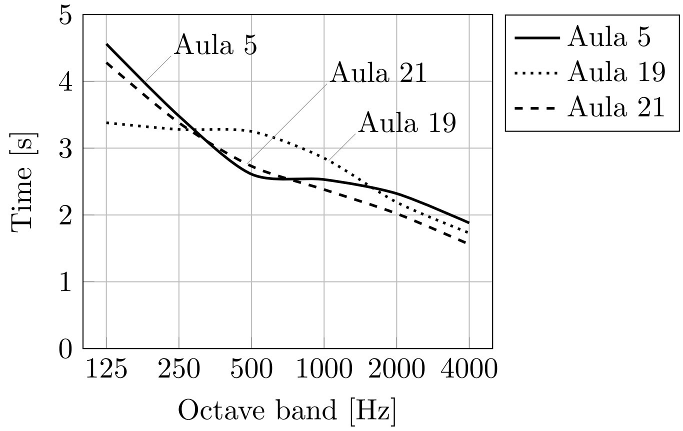
Figure 4.9: Loudspeakers and microphone positioning: Aula Magna.

4.2.2 Measurements results

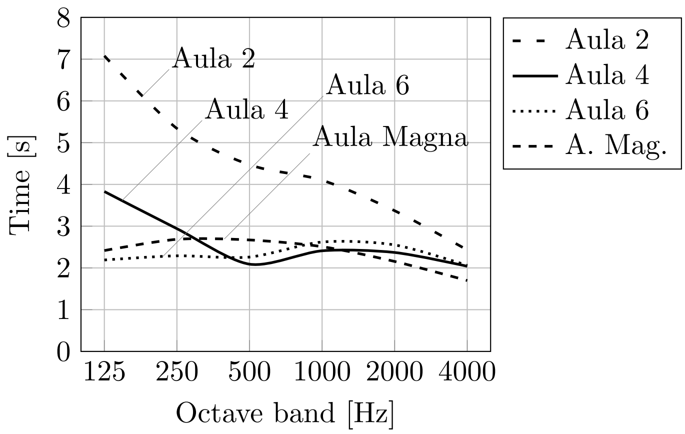
Measured values are reported in Table 4.3 averaged over all source-receiver positions. These values confirm the inadequate acoustic condition of the rooms. Graphs describing the tendency of the acoustic parameters in function of the frequency and source-receiver distance are shown in the following pages (Figg.4.10-4.15).
Results highlight the bad perfomance of the small rooms, wich have a behavior similar to larger one but with half the volume. This could be explained by their near 1:1:1 dimension ratios combined with rigid plastered unfurnished walls which may enanche modal behavior and specular reflections. Also the better results at low frequencies of Aula 19 over Aula 5 and 21 can support this argument, given its non parallel longitudinal walls.
Acoustic parameters are quite uniform in all the measured rooms, except for Sala Armi, Sala Feste and Aula Magna, where the distance from the receiver makes a big difference in the speech intellegibility. This could be given by the size of these lecture halls. The measurements confirm this rooms can benefit from a PA system.

Table 4.3: Ante-operam measurement results: comparison between the average measured values of the room parameters for speech intelligibility and the standard requirements of the classrooms (UNI 11532-2 [15]). The requirements depend on whether the volume of the classrooms is greater or less than 250 m^3. Reverberation time required range is for A2 class from UNI 11532 [15] in unoccupied state (Tab.2.1). The subscripts "3" and "M" respectively indicate the octave bands on which the value was averaged (500÷1000÷2000 Hz and 500÷1000 Hz).

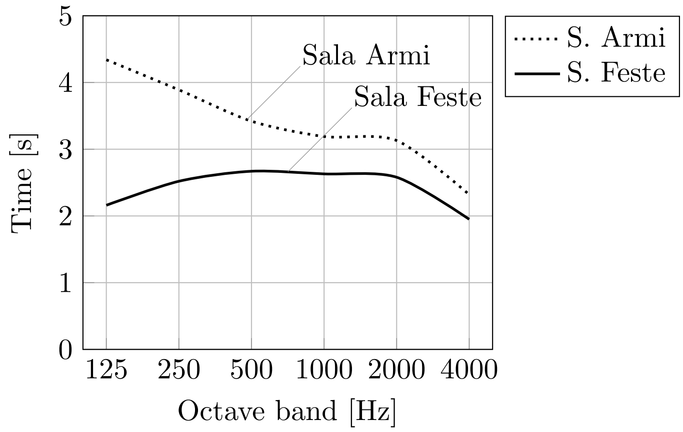
Room	Measured parameters			Standard requirements		
	$T_{20,M}$	$C_{50,3}$	STI	$T_{20,M}$	$C_{50,3}$	STI
Aula 5	2.57	-4.4	0.43	0.63-0.99		
Aula 19	3.05	-5.1	0.42	0.59-0.92	$\geq +2$	≥ 0.55
Aula 21	2.56	-4.3	0.45	0.60-0.93		
Aula 2	4.28	-6.6	0.37	0.70-1.09		
Aula 4	2.25	-4.2	0.44	0.72-1.16	-	≥ 0.50
Aula 6	2.44	-4.2	0.44	0.75-1.21		
Aula Magna	2.59	-4.3	0.45	0.99-1.79		
Sala Armi	3.30	-5.8	0.39	0.89-1.35	-	≥ 0.50
Sala Feste	2.65	-5.1	0.42	0.86-1.35		



(a) Small rooms: ante-operam measured T_{20} values.

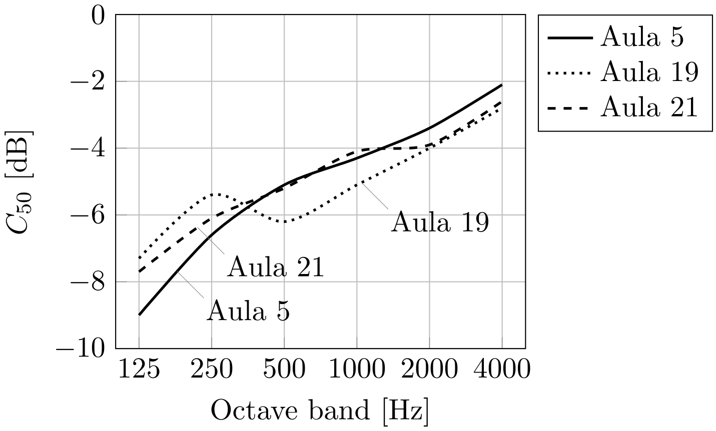


(b) Medium-large rooms: ante-operam measured T_{20} values.

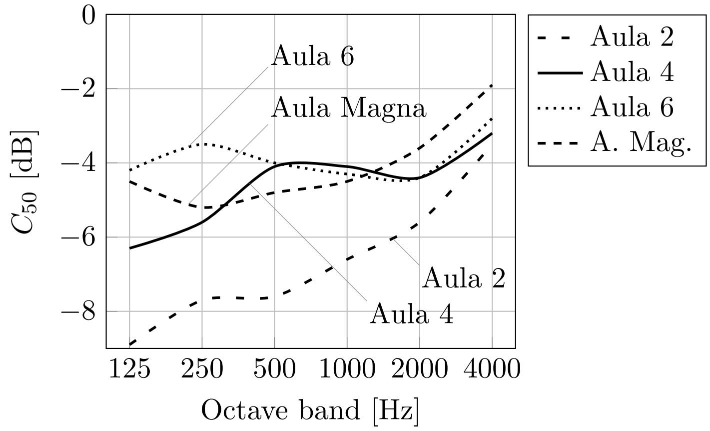


(c) Extra large rooms: ante-operam measured T_{20} values.

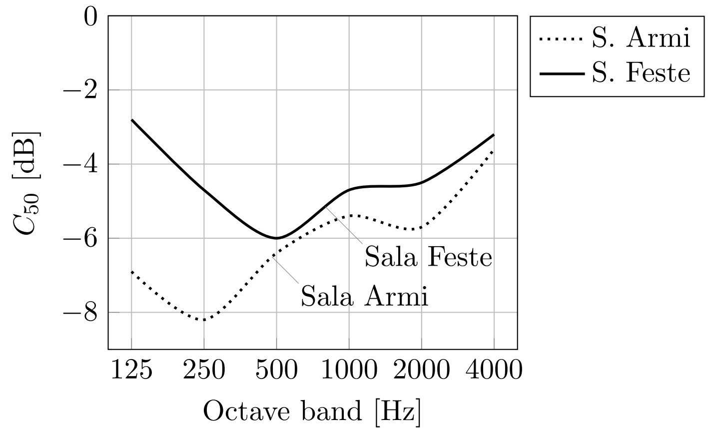
Figure 4.10: Ante-operam measured T_{20} values in function of the octave bands for each room, subdividing the plot by room size type. Values were measured in unoccupied state with an omnidirectional source and are provided averaged over all source-receiver positions.



(a) Small rooms: ante-operam measured C_{50} values.

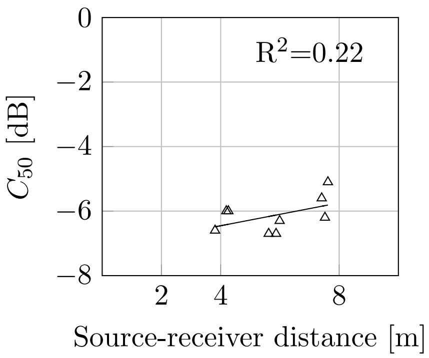


(b) Medium-large rooms: ante-operam measured C_{50} values.

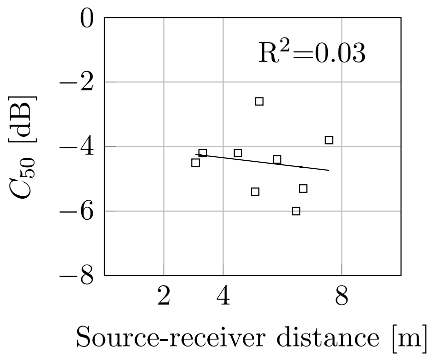


(c) Extra large rooms: ante-operam measured C_{50} values.

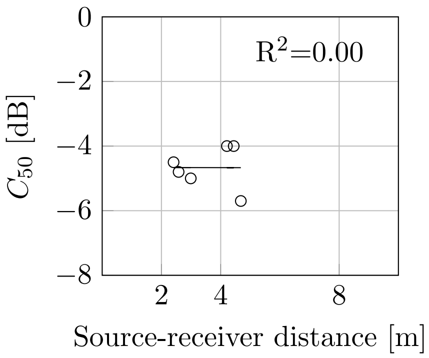
Figure 4.11: Ante-operam measured C_{50} values in function of the octave bands for each room, subdividing the plots by room size type. Values were measured in unoccupied state with an omnidirectional source and are provided averaged over all source-receiver positions.



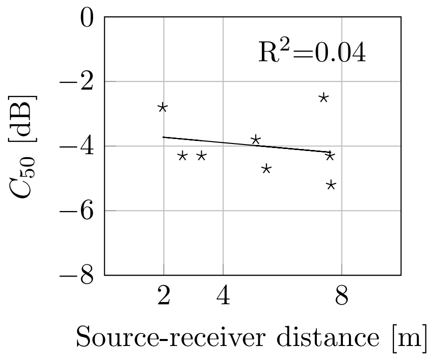
(a) Aula 2: C_{50} - distance.



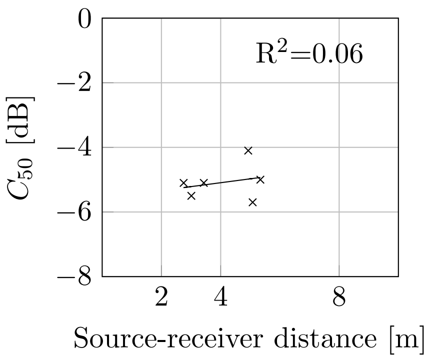
(b) Aula 4: C_{50} - distance.



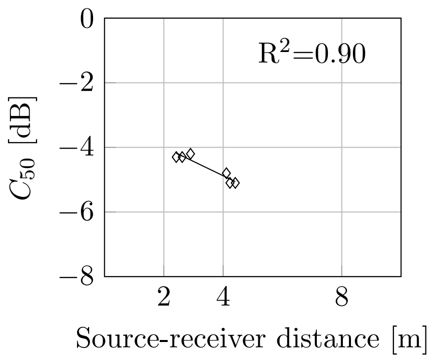
(c) Aula 5: C_{50} - distance.



(d) Aula 6: C_{50} - distance.

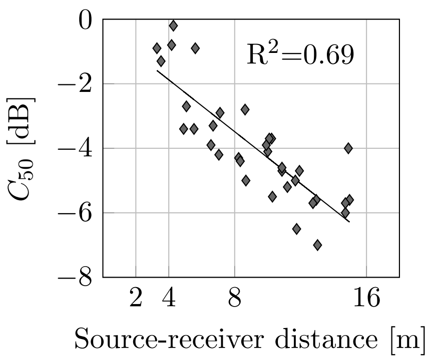


(e) Aula 19: C_{50} - distance.

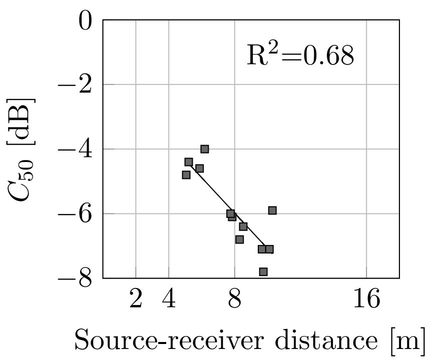


(f) Aula 21: C_{50} - distance.

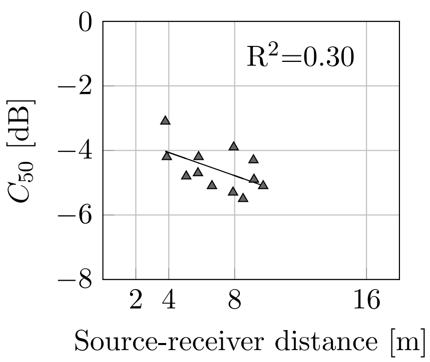
Figure 4.12: Ante-operam measured C_{50} values in function of the source-receiver distance for each small-medium room. Values were measured in unoccupied state with the omnidirectional source SS1, placed in the speaker position. Values are quite uniform all over the audience area. Black continuos line is the linear regression for measured values; the coefficient of determination to evaluate the goodness of the fit is indicated.



(a) Aula Magna: C_{50} - distance.

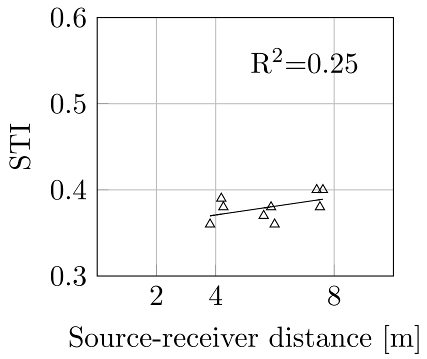


(b) Sala delle Armi: C_{50} - distance.

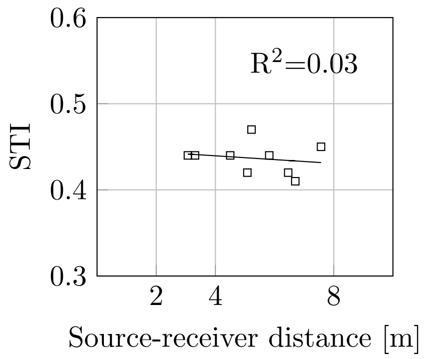


(c) Sala delle Feste: C_{50} - distance.

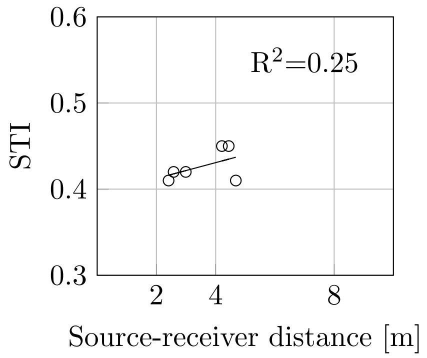
Figure 4.13: Ante-operam measured C_{50} values in function of the source-receiver distance for Aula Magna, Sala delle Armi e Sala delle Feste. Values were measured in unoccupied state with the omnidirectional source SS1, placed in the speaker position. Values decrease with distance. Black continuos line is the linear regression for measured values; the coefficient of determination to evaluate the goodness of the fit is indicated.



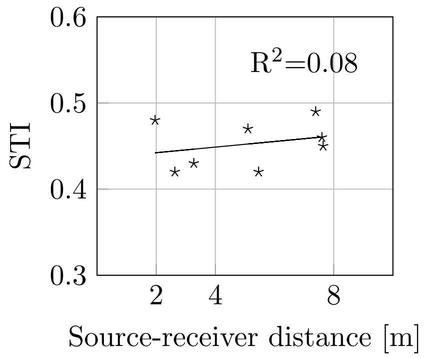
(a) Aula 2: STI - distance.



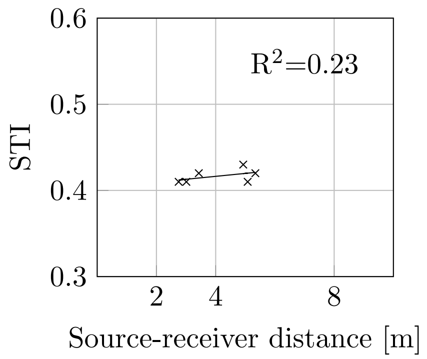
(b) Aula 4: STI - distance.



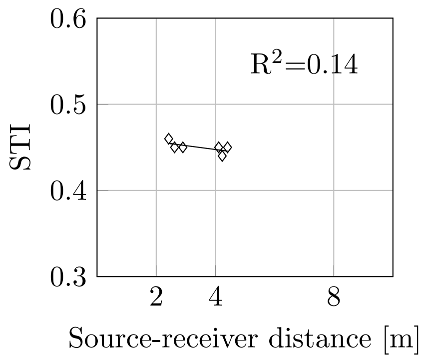
(c) Aula 5: STI - distance.



(d) Aula 6: STI - distance.

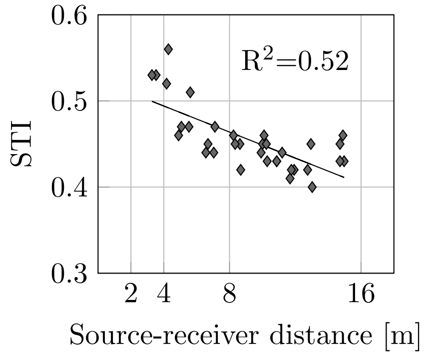


(e) Aula 19: STI - distance.

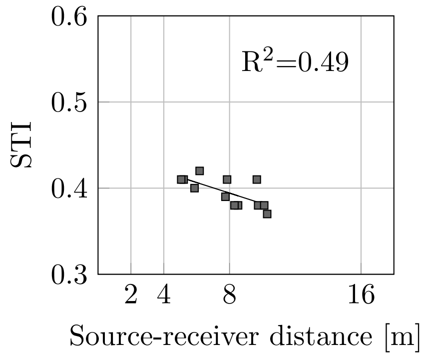


(f) Aula 21: STI - distance.

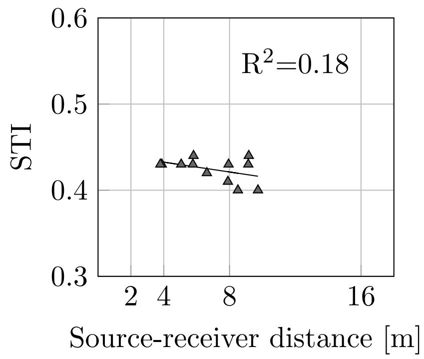
Figure 4.14: Ante-operam measured STI values in function of the source-receiver distance for each room. Values were measured in unoccupied state with the omnidirectional source SS1, placed in the speaker position. Values are quite uniform all over the audience area. Black continuos line is the linear regression for measured values; the coefficient of determination to evaluate the goodness of the fit is indicated.



(a) Aula Magna: STI - distance.



(b) Sala delle Armi: STI - distance.



(c) Sala delle Feste: STI - distance.

Figure 4.15: Ante-operam measured STI values in function of the source-receiver distance for Aula Magna, Sala delle Armi e Sala delle Feste. Values were measured in unoccupied state with the omnidirectional source SS1, placed in the speaker position. Values decrease with distance. Black continuos line is the linear regression for measured values; the coefficient of determination to evaluate the goodness of the fit is indicated.

4.3 Background noise measurements

The background noise was measured using a Class 1 sound meter level NTI Audio XL2 on June 2019 inside classrooms with V>250 m^3, for approximately half an hour of measures each room. The air conditioning systems were off at the time of the measurements therefore the following values are representative of only some components of the background noise.

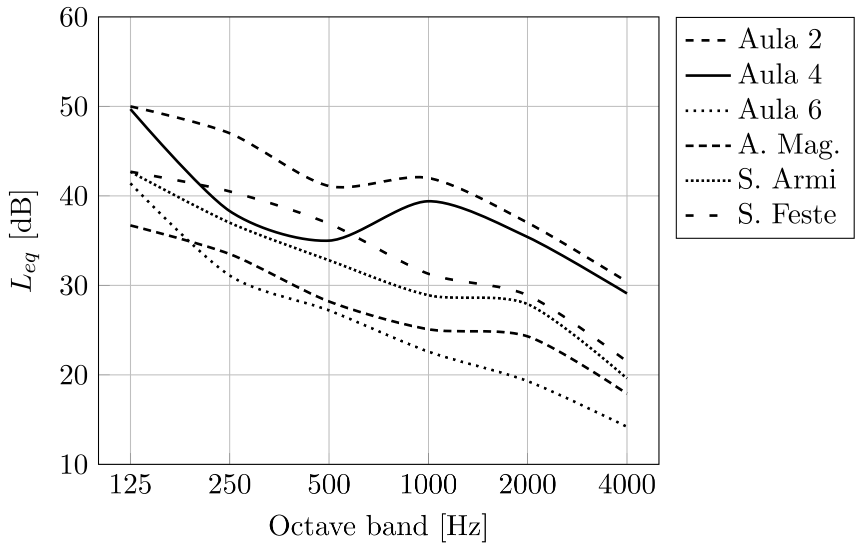


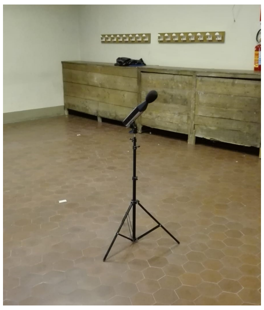
Figure 4.16: Measured background noise values for each octave band. The measurements take place on the 17th of June from 9.30 a.m. to 1 p.m., half an hoiur each room (two position for Aula Magna, on the main floor and on the mezzanine. Placement of the sound meter level are reported (Fig.4.17). Anomaly sound events has been cutted from the measurements.

Table 4.4: Comparison between the values of the A-weighted equivalent levels measured inside the large classrooms (V>250 m^3) and limits of the environmental noise levels foreseen by the technical standard UNI 11532-2 [15].

Room	$L_{Eq,A}$ [dBA]		Noise source
	Measured	Limit	
Aula 2	46	41	traffic
Aula 4	43	41	traffic
Aula 6	31	41	envinron.
A. Magna	36	41	envinron.
Sala Armi	39	41	envinron.
Sala Feste	35	41	envinron.

Equivalent sound pressure levels of background noise are reported for each classroom (Fig.4.16). The sound level meter was placed in a central point of the room facing the speaker, at a height of 1.2 m from the floor (Fig.4.17). The fixtures have previously been closed. The sampling uses Fast time constant (impulsive components are excluded). The building was closed to the public during the measurements. The results show that Aula 2 and Aula 4 are the only ones that have a value of the A-weighted equivalent level greater than the maximum background noise level required by UNI 11532-2 [15]. Also the spectral trend in these two classrooms is different from that of the other spaces. This is due to their position within the building. In fact, they are both located on the ground floor and have openings that face the street making the external background noise component significant. During the design phase particular attention is required for the acoustic insulation performance of the fixtures.

(a) Aula 2



(b) Aula 6

(c) Aula Magna

Figure 4.17: Photos of some background noise measurements placements: Aula 2 on R2 (R=receiver) position (a); Aula 4 in the middle of the seats area; Aula 6 (b); Aula Magna on the mezzanine (c) and on R11 posotion; Salla delle Armi on R13 position; Sala delle Feste on R5 position.

4.4 Previsional models

Previsional models through a calculation paper were made and calibrate with measurements results in order to evaluate the critical issues for every room and identify the appropriate interventions. The aim is to obtain a sizing of the absorbent surfaces. The models used the Sabine's reverberation time (1.15) with Norris-Eyring's sound absorption coefficient correction (1.21).

4.4.1 Modeling criteria

Simple 3D-models were realized with SketchUp software to get an evaluation basis regarding materials and surfaces located in the studied environments.
Modeling for acoustic purposes must necessarily be carried out on a knowledge basis of the physical problem. The detail level of the models must be suitable to the wavelengths considered. Referring to octave bands from 125 Hz ($\lambda \approx 3$ m) to 4000 Hz ($\lambda \approx 10$ cm) it can be said that only objects larger than 10 cm interact with sound waves and are relevant for the acoustic analysis. Useful and practical suggestions are provided by the modeling guides offered by one of the main acoustic simulation software [57], here reported:

- ignore all the irregularity of surfaces smaller than 30 cm, which corresponds to the 1000 Hz wavelength, to obtain a minor computation without losing accuracy of results;

- curved surfaces are approximated into a certain number of planar surfaces;

- the subdivision in layers is based on the function and the material of each object in order to assign the absorbing and scattering coefficients to a defined group;

- avoid to model each step between the audience rows but approximate the auditory area to a box.

From this basis simple models have been defined for each classroom. The layers used distinguish between flooring and walls, but the latter are assimilated to the surfaces of the ceiling when the finish is the same, except in those cases in which it is composed of a different construction system. The objects present in the rooms and shown in the model are limited to those that are more extended and have appreciable acoustic properties: benches, chairs, blackboard, fixtures, platforms and any wardrobes or similar.
This modeling can be reused for further in-depth studies on specific classrooms when a better understanding of how the sound waves/rays propagate and reflect within the environment to reach the audience is required.

4.4.2 Calibration

The models has been calibrated on the measured reverberation time for each octave band. Surfaces for the considered materials are provided by the 3d-modeling of each room. The materials studied were the most relevant ones for the acoustic scope and those with the largest sizes.
For each material or object, the respective sound absorption coefficient or the equivalent sound absorption area has been researched in the literature. Then in order to calibrate the numerical model, the values of walls and ceilings have been increased or decreased with successive steps to reach the measured reverberation time. The operating method concerned these specific surfaces because they are the largest and more likely ones to present characteristics that deviate from those provided, due to the variety of the proposed cases. For example the acoustic behavior of a vault or a stucco is neglected in this simplified modeling if not evaluated through variations of these selected parameters. The absorption coefficients used for recurring materials are here reported (Tab.4.5). The calibration is considered achieved for a deviation of the simulated reverberation time value to the measured one under the %5 (equal to the just noticeable difference for RT), for each octave band. The calibration process, starting from literature values leds to the following sound absorption coefficient values for targeted plastered surfaces (in general walls and ceilings) (Tab.4.6). The values for objects and surfaces not common to all the lecture halls are reported (Tab.4.7). Seats values are also reported (Tab.5.5) and they will be subject to further discussions.

Table 4.5: Recurring materials sound absorption coefficients used for the previsional models, for each octave band, with the literature reference. The coefficients of walls, ceilings and floors have been used as starting values for the calibration.

Material	Reference	α					
		125	250	500	1000	2000	4000
Cotto tiles	UNI 11532 [15]	0.01	0.01	0.02	0.02	0.03	0.03
Parquet	UNI 11532 [15]	0.04	0.04	0.05	0.06	0.06	0.06
Plastered surface	UNI 11532 [15]	0.02	0.02	0.03	0.03	0.04	0.06
Window	UNI 11532 [15]	0.28	0.20	0.11	0.06	0.03	0.02
Wooden door	UNI 11532 [15]	0.10	0.08	0.06	0.05	0.05	0.05
Wooden table	Acoust.Traff.	0.19	0.23	0.25	0.30	0.37	0.42
Blackboard	ASA's Booklet	0.10	0.20	0.10	0.10	0.20	0.20

Table 4.6: Calibrated plastered surfaces sound absportion coefficients, for each octave band. Walls and ceilings are often made of this, except for Sala delle Feste which has a coffered ceiling. The calibrated values differs substantially from the literature ones due to the different scenarios: ceiling shape, stuccos and surface finishes.

Room	$\alpha_{calibrated}$					
	125	250	500	1000	2000	4000
Aula 2	0.016	0.027	0.035	0.040	0.050	0.075
Aula 4	0.035	0.052	0.080	0.060	0.062	0.080
Aula 5	0.020	0.032	0.050	0.050	0.057	0.080
Aula 6	0.080	0.080	0.085	0.075	0.070	0.090
Aula 19	0.030	0.032	0.035	0.045	0.065	0.090
Aula 21	0.023	0.035	0.050	0.055	0.060	0.100
Aula Magna	0.085	0.070	0.070	0.070	0.080	0.090
Sala delle Armi	0.095	0.110	0.130	0.150	0.120	0.140
Sala delle Feste	0.050	0.018	0.010	0.080	0.070	0.090

Table 4.7: Not recurring materials sound absorption coefficients and equivalent sound absorption areas used for the previsional models, for each octave band, with the literature reference. Coffered ceiling values have been modified in the calibration process due to the great uncertainty in determining the properties of this type of architectural element.

Material	Reference	α					
		125	250	500	1000	2000	4000
Raised stage	Cox-D'Antonio [22]	0.40	0.30	0.20	0.17	0.15	0.10
Boiserie	Cox-D'Antonio [22]	0.30	0.25	0.20	0.17	0.15	0.10
Coated door	Cox-D'Antonio [22]	0.14	0.10	0.06	0.08	0.10	0.10
Coffered ceiling	Cox-D'Antonio [22]	0.22	0.19	0.17	0.10	0.10	0.11
Glass banister	Cox-D'Antonio [22]	0.18	0.06	0.04	0.03	0.02	0.02
Glazing box	Cox-D'Antonio [22]	0.35	0.25	0.18	0.12	0.07	0.04
Material	Reference	A_{obj} [m^2 Sabine]					
		125	250	500	1000	2000	4000
Cupboard	UNI 11532 [15]	2.49	2.28	1.56	1.44	1.23	1.35

4.4.3 Air sound absorption

For extra large rooms with a volume of about 1000 m^3 the air sound absorption can be considered to obtain a more refined simulation.
The standard ISO 354:2003 [2] gives the air sound absorption, in Sabine's square meters, through the equivalent sound absorption area of the tested specimen (A_T):

$$A_T = A_2 - A_1 = 55.3V\left(\frac{1}{c_2T_2} - \frac{1}{c_1T_1}\right) - 4V(m_2 - m_1) \quad (m^2) \tag{4.1}$$

$$A_{air} = 4Vm \quad (m^2) \tag{4.2}$$

m is the power attenutation coefficient, in meters to minus one, calculated from the attenuation coefficient, here named β (α in the standards [2], given by ISO 9613-1 [7]):

$$m = \frac{\beta}{10 \cdot \ln e} \tag{4.3}$$

The β values are given in tables or can be calculated with formulas, both given in the standard [7]. It is function of the temperature, the relative humidity and the atmospheric pressure registered in the measured room and it is given for each one-third octave band.
Not having the measurements of these environmental parameters, the result is approximated by using average values: a temperature of 20 °C with 60% relative humidity at 101.325 kPa atmospheric pressure.
The obtained A_{air} values are averaged over the octave bands (Tab.4.8).

Table 4.8: Air sound absorption: air equivalent sound absorption areas, in Sabine's square meters, for the largest lecture halls (V> 700 m^3), for each octave band. For the smaller classrooms the value are so low they can be ignored.

Room	A_{air} [m^2 Sabine]					
	125	250	500	1000	2000	4000
Aula Magna	0.30	0.85	1.90	3.30	6.60	18.35
Sala delle Armi	0.80	2.40	5.40	3.40	18.60	52.00
Sala delle feste	0.50	1.45	3.20	5.60	11.10	31.00

4.5 Design of acoustic treatments

The surfaces and materials disegned to improve the acoustic comfort of the classrooms are described here. The design purpose is not necessarely to reach values within the regulatory limits. The goal is to obtain improvements of the acoustic comfort with an appropriate interventions acording to the context in compliance with the principles of reversibility and distinctiveness, respecting as far as possible in the budget offered for the completion of the works. The magnitude and type of possible effective interventions is highly variable; the design choices here adopted are not the only ones possible nor those that lead to a complete resolution, but a possible proposal that may combine all the different design needs. Moreover the acoustic design is conceived according to the integration of the lighting design, not covered in this work. The project choices were therefore made by trying to relate these two aspects of environmental comfort. This way it is been possible to avoid the antagonism of acoustic solutions against the lighting ones and vice versa, as can be easily seen when the two comforts are designed on a stand alone basis.

Table 4.9: Minimum equivalent sound absorption area A_{req} required to comply the standard, in Sabine's square meters, in octave bands. The surfaces needed to achieve these values (for $\alpha = 0.5$ is the double of A_{req}) is considerably high and it is difficult to reach that coverages in a historical environment. Notice that when a PA system is installed, A_{req} can be halved.

Room	A_{req} [m^2 Sabine]					
	125	250	500	1000	2000	4000
Aula 2	52	62	60	59	56	50
Aula 4	43	50	43	47	46	43
Aula 5	32	38	35	35	33	30
Aula 6	36	50	50	53	53	47
Aula 19	28	35	35	34	31	27
Aula 21	31	37	34	33	30	26
Aula Magna	61	88	88	85	77	63
Sala delle Armi	183	229	217	209	208	170
Sala delle feste	76	125	129	128	126	101

Improvements were developed considering the different typology, characteristics and specific use of each lecture hall. The intervention proposal consists of two macro-categories, the first one is the passive acoustics treatment and the second one is the introduction of a proper public address (PA) system. Passive acoustic treatments were designed in order to achieve the requirements provided by the national standard UNI 11532 [15], which refers to DIN 18041 [12] method. Therefore, optimal reverberation time was found

with UNI 11532 [15] formulas in occupied state. Revers formula of reverberation time permits to calculate the needed equivalent absorption area A_{req}, in Sabine's square meters, and thus, the quantity and the behavior in frequency of sound absorbing materials to be introduced in each lecture hall to accomplish the standard (Tab.4.9). These required values are too high to be installed in classrooms in a historical building. Nevertheless, adding the adequate sound absorption area is not enough to obtain a good speech intelligibility because the placement of these surfaces play a key role in enhancing the sound clarity and the sound energy distribution throughout the space. Understanding where positioning the sound absorbing panels becomes a fundamental aspect to achieve the goal since it could heavy change C_{50}, with variations until 4 dB, and speech levels received, with variations until 3 dB [48].
As seen, UNI 11532 [15] and scientific literature describe how to obtain a good placement. It is important to leave the ceiling free from absorption because it is helpful to enhance the early reflections. But edges and backparts can be covered with some absorbing material along the perimeter. Some absorption can be introduced also in the center part but it is reccomendable to leave reflective spots. The rear wall represents the ideal zone to cover with passive acoustic treatments because it is the surface where the most of late reflections come from. Morehover it should be treated to prevent echo effects, especially if the distance between the back wall and the speaker is greater than 9 m due to the late arriving time of these reflections.

The design proposals are presented and discussed individually for each classroom given the peculiarities and different needs required, but the used material are here described.
The products used in these proposals are supplied by a dedicated seller. The choice was necessary to have some characteristics on which to support the calculations, but other equivalent products are possible.

Table 4.10: Acoustic absorber feautures, referred to single objects: LxW are lenght and width, in meters; d is the depth of the panel, in millimeters; o.d.s. is the overall depth of system, in millimeters; weight, in kilograms; nearest NCS colour sample.

Product	LxW	d	o.d.s.	Weight	Color
Solo wall abs.	1.2x0.6	40	48	4.5	S 1500-N
Array wall abs.	2.7x1.2	40	50	4.0	S 1500-N
Vertical baffle	1.2x0.6	40	1200	4.5	S 1500-N
Horiz. sqr. baffle	1.2x1.2	40	1000	6.5	S 1500-N
Horiz. rect. baffle	1.8x1.2	40	200	6.5	S 1500-N

The manufacturer provides certifications regarding indoor air quality, recyclability, fire safety (class A2-s1,d0 according to EN 13501-1), humidity resistance, visual appearence, cleanabilty and schemes for installation.

Figure 4.18: Some of the product certifications provided by the manufacturer.

The acoustic performances of the products were used as a sample to simulate the material behavior. The absorption provided by the manufacturer in the form of an equivalent sound absorption area of the single object A_{obj}, in Sabine's square meters, includes the effect of the mounting (for example the distance between the baffles, the air gap from the ceiling, ..) expressed by certified reverberation room measurements. The given A_{obj} has been evaluated converting it into an absorption coefficient, known the area of the object (Fig.4.19). This operation result may be a value greater than the unit. However, the subsequent correction of the α coefficients from equation (1.21) can be applied to obtain a more reliable value.
The logarithmic operation tends to flatten the results which however remain quite different, confirming the variable acoustic properties given by the mounting on the almost same material (Fig.4.20).

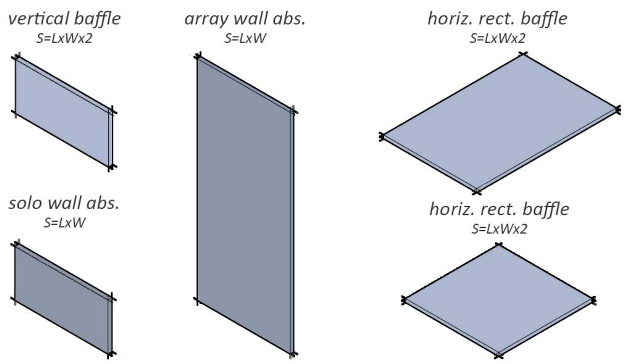


Figure 4.19: Surface used to evaluate the sound absorption coefficient from A_{obj} for each absorber treatment porposed.

Table 4.11: Equivalent sound absorption area A_{obj}, in Sabine's square meters, of the acoustic absorber proposed, for each octave band. The value is intended for the single object and for the mounting as reported in Tab.4.10

Product	A_{obj} [m^2 Sabine]					
	125	250	500	1000	2000	4000
Solo wall abs.	0.2	0.6	1.0	1.1	1.0	0.9
Array wall abs.	0.8	2.5	3.3	3.3	3.3	3.3
Vertical baffle	0.2	0.2	0.5	0.6	0.6	0.6
Horiz. sqr. baffle	0.4	1.1	2.0	2.9	2.9	2.8
Horiz. rect. baffle	0.6	2.0	2.9	3.4	3.3	3.1

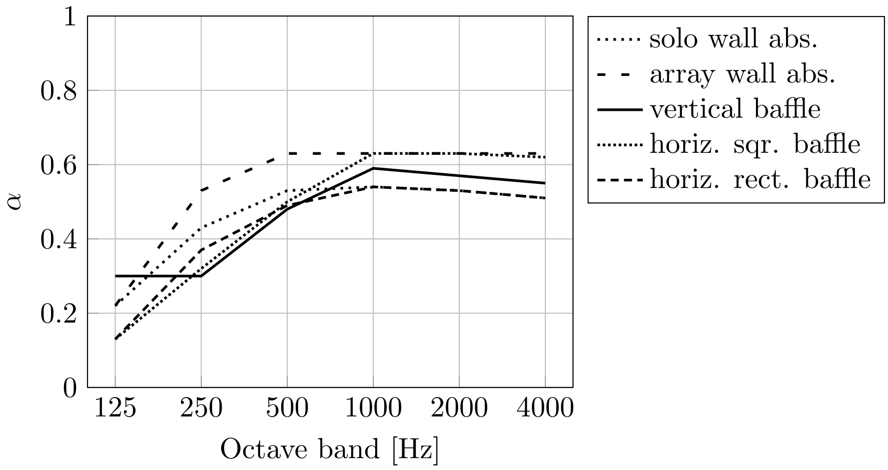


Figure 4.20: Sound absorption coefficients of absorber used, in each octave band. The values are obtained from the absorption areas provided by the manufacturer divided by the surface (Fig.4.19) and corrected according to the (1.21) equation.

Table 4.12: Mean sound absorption coefficient of the acoustic absorber proposed, for each octave band, averaged over all absorber from Fig.4.20.

Octave band [Hz]	125	250	500	1000	2000	4000
$\overline{\alpha}_{abs}$	0.20	0.40	0.55	0.60	0.60	0.60

(a) Solo wall absorber

(b) Array wall absorber

(c) Vertical baffle

(d) Horizontal square baffle

(e) Horizontal rectangular baffle

Figure 4.21: Advertising images of the acoustic products in place.

A possible solution to cover large portions of the wall is the application of sound absorbing planks (Fig.4.22). They are recommended for recently renovated environments, such as the Aula Magna, where there are no particular restrictions, and a more massive intervention is possible. The absorbent planks here considered are made of wood and carved to take advantage of absorbent properties of Helmholtz resonators and vibrant membranes. These panels are made up of more layers, the first is a set of strips spaced by an empty space which permits to brake the wave front. Behind this, a layer made of a succession of holes allows to absorb sound energy based on the principle of Helmholtz resonators. The last layer is spaced from the previous one to create an air cavity and it is made with a porous absorbing material. This kind of panels have an high absorbing power in the middle and high frequencies (Tab.4.13).

Table 4.13: Sound absorption coefficient of sound absorbing planks., for each octave band, as they are given from the supplier and corrected with (1.21) equation.

	α					
	125	250	500	1000	2000	4000
Provided	0.7	0.9	0.9	0.9	0.9	0.8
Corrected	0.5	0.6	0.6	0.6	0.6	0.55

Figure 4.22: Sound absorbing plank appearance and stratigraphy.

Acoustic treatments are summarized in Tab.4.14 and detailed for each classroom in the following pages.

Table 4.14: Acoustic design interventions for each room by type: N is the number of single elements used; S is the surface covered, in square meters; $A_{eq,M}$ is the equivalent sound absorption area mean value over 500÷1000 Hz octave bands introduced, in Sabine's square meters; the last column states if a PA system is requested.

Room	Interv. type	N	S	$A_{eq,M}$	PA sys
Aula 2	vertical baffles	21	30.2	11.5	no
	solo wall abs.	4	2.9	4.2	
	windows fix.	2	6.6	-	
Aula 4	vertical baffles	15	21.6	8.3	no
	solo wall abs.	4	2.9	4.2	
	windows fix.	2	6.6	-	
Aula 5	hor. sqr. baffles	4	11.5	9.8	no
	solo wall abs.	4	3.6	5.3	
Aula 6	diffus. boiserie	-	21	2	yes
	upholst. seat	35	14	8	
Aula 19	array wall abs.	4	13	13	no
Aula 21	hor. rect. baffles	6	13	18.9	no
	solo wall abs.	4	2.9	4.2	
Aula Magna	plank abs.	-	65	40	yes
Sala delle Armi	thick carpet	-	81	52	yes
	upholst. seat	50	35	29	
Sala delle Feste	draped tapestry	-	21	20.8	yes
	upholst. seat	50	56	46	

4.5.1 Aula 2

The proposed intervention concerns the installation of about 30 m^2 of sound-absorbing hanging baffles arranged in rows (twentyone 1200x600 mm panels organized on seven raws; raw spacing is about 1.2 m to 0.6 m). The spacing between the columns of elements is necessary to keep the place for the lighting system. The porous material ensures good performance at medium to high frequencies, while the baffle system induces a partial vibrating panel behavior to obtain benefits at low frequencies. The choice of dimensions and positioning respects the layout of the lighting system, as well as the recommended colors of the surfaces are taken in accordance

with the visual requirements as not to interfere with the illumination of the visual tasks. To avoid disturbing flutter echoes caused by reflections on the back wall, it is advisable to place a sound-absorbing panel between the two windows (2400x1200 mm, about 3 m^2). The chosen color has the purpose of integrating the intervention into the context and avoiding glares.
Background noise must be reduced and brought below the regulatory threshold of 41 dB(A) from 46 dB(A). Since the traffic is the main noise source, the sound insulation can be improved by replacing the windows.

Figure 4.23: Photographic insertion of the acoustic treatments proposed for Aula 2: hanging baffles arranged vertically in several rows and an absorbent surface placed on the back wall.

4.5.2 Aula 4

Aula 4 is very similar in size and acoustics to Aula 2, so the interventions planned are almost the same: about 20 m^2 of sound-absorbing hanging baffles arranged in rows (fifteen 1200x600 mm panels organized on five raws; raw spacing is about 1.2 m) to provide the main sound absoprtion surfaces, absorbent panel on the back wall to avoid flutter echoes and replacement of the fixtures to increase the sound insulation.

4.5.3 Aula 5

The small size and the almost cubic volume of Aula 5 make this room very reverberant even if small. It is necessary to distribute absorbent material or jagged surfaces to break the eigenmodes. Bookcases or shelves are not proposed here to avoid crowding the walls and restricting an already narrow room. The planned intervention includes about 10 m^2 of hanging baffles arranged parallel to the floor (four 1200x1200 mm square panels) leaving about 100 cm air space from the ceiling top. The small length size would make the vertical arrangement less convenient. The placement exploits the small flat portion of the ceiling to hang as many baffles as possible. To avoid flutter echoes due to the back wall placed immediately in front of the teacher's vocal source, about 4 m^2 of absorbent panel are positioned at the sides of the window: a 2400x1200 mm panel on the empty side and a 600x1200 mm one upon the door on the other side.

Figure 4.24: Photographic insertion of the acoustic treatments proposed for Aula 5: horizontal baffles hanging in the central flat part of the vaulted ceiling and absorbent surfaces placed in the free spaces of the back wall.

4.5.4 Aula 6

Acoustic design of Aula 6 needs particular attention because it is expected to be used as court of law simulator. The architectural project for the arrangement of the courtroom was provided and taken into account. It is recommended the use of highly upholstered chairs, in order to insert absorbent material and stabilize the room performance even in conditions of low occupancy. A PA system will be installed with multiple microphones positions. A wide sound-diffusing surface placed on the back wall is necessary due to the PA installed in a room small room. Here a possible proposal is briefly contextualized in according to the operative scenario (Fig.4.25).

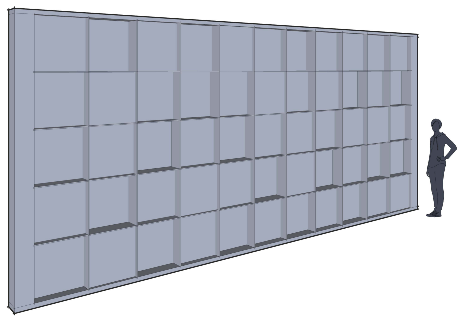


Figure 4.25: Possible design solution for the 7x3 m diffusing surface on the back wall of the courtroom: a surface diffuser composed of a pseudorandom checker distribution. The width of the squares (60 cm) corresponds to about 1/2 of the wavelength at 250 Hz. The different levels create throats whose depth varies from 4 cm to 20 cm, related to 1/4 of the operating wavelengths by design (speech range of 500÷2000 Hz octave bands).

4.5.5 Aula 19

The layout of Aula 19 is already relatively favorable to the acoustic behavior of the room: the side walls with different inclinations provide a positive contribution to reflections. An absorbent array of panels for a total of about 10 m^2 could be considered enough to avoid harmful reflections on the back wall and lower the reverberation time.

4.5.6 Aula 21

The small size and cubic dimension ratio of Aula 21 give bad starting conditions. The design consists in horizontal baffles positioned at 20 cm from the ceiling in the two spaces included between the beams placed above the students, leaving the central part of the second field empty; this way detrimental late reverberations are prevented while useful reflections on the rest of the ceiling are allowed. A total of six 1800x1200 mm panels are used, leaving about 20 cm air space from the ceiling and covering about 13 m^2. About $3m^2$ of sound absorbing panels on the back wall prevents flutter echoes.

Figure 4.26: Photographic insertion of the acoustic treatments proposed for Aula 19: a high strip of absorbent surface on the back wall.

Figure 4.27: Photographic insertion of the acoustic treatments proposed for Aula 21: horizontal baffles hanging arranged on the edge portions of the ceiling and an absorbent surface on the back wall.

4.5.7 Aula Magna

Acoustic behavior of Aula Magna can be improved with a PA system. This is highly reccomended due to the lenght of the room. Two couples of line array are needed, one placed on the sides of the blackboard and one for the mezzanine. The shapes of the ceiling and the slope of the walls already have a solid contribution to a good acoustics considering the large volume. Sound absorbing panels shall cover the back walls of both main floor and the mezzanine. This way the detrimental reflection are blocked and a large areas of sound absorption material (about 65 m^2) can be mounted to achieve good results for this large volume.

4.5.8 Sala delle Armi

The historical value of this environment significantly limits the operational possibilities. The hall is used as a representative location for ceremonies. In order to enhance acoustic performances, the mounting of an adequate amplification system is suggested to combine active and passive interventions. In addition, a thick carpet can be laid on the floor, introducing absorbent material while organizing the plant. If placed in the seating area the total floor covering can be of about 80 m^2. The insertion of curtains is also a possible improvement.

4.5.9 Sala delle Feste

Sala delle Feste requires a careful and reversible design. Accordingly a PA system is suggested. Passive interventions involve the insertion of sound absorbing material through the furnishings. It is possible to use the large empty portion of the rear wall to hang tapestries in according with the architectural value of the hall. It is advisable to leave a little distance (5-10 cm) between the surface of the fabric and the wall in order to increase the absorption provided. Even more important is the arrangement of these tapestries: taking care to set large drapes and folds it is possible to increase the effectiveness of this solution considerably (Tab.4.15). Upholstered seats can be used to improve the acoustic perfomance and ensure benefits even in low occupancy scenario.

Table 4.15: Curtains sound absorption coefficients from literature [55] show how foldings and drapings improve perfomances.

Curtain arrangement	Octave band [Hz]					
	125	250	500	1000	2000	4000
Not folded	0.10	0.38	0.63	0.52	0.55	0.65
Folded	0.12	0.60	0.98	1.00	1.00	1.00

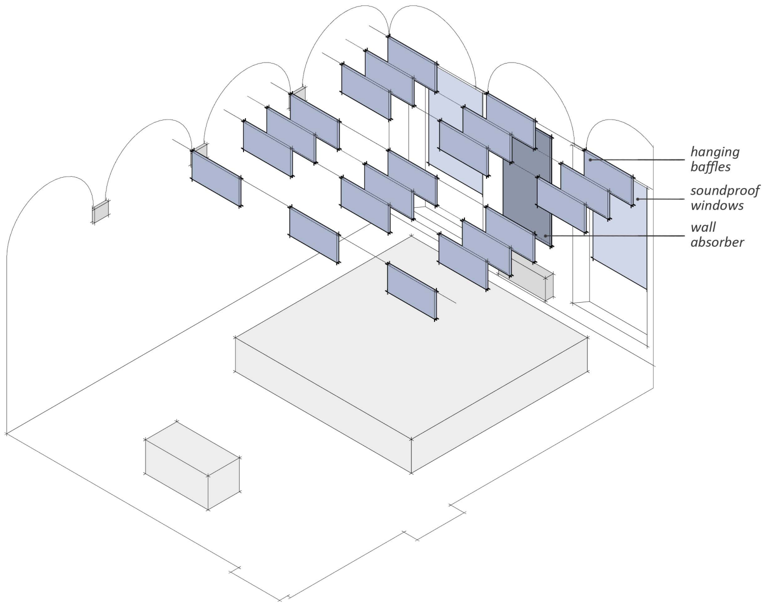


Figure 4.28: Aula 2: acoustic design proposal.

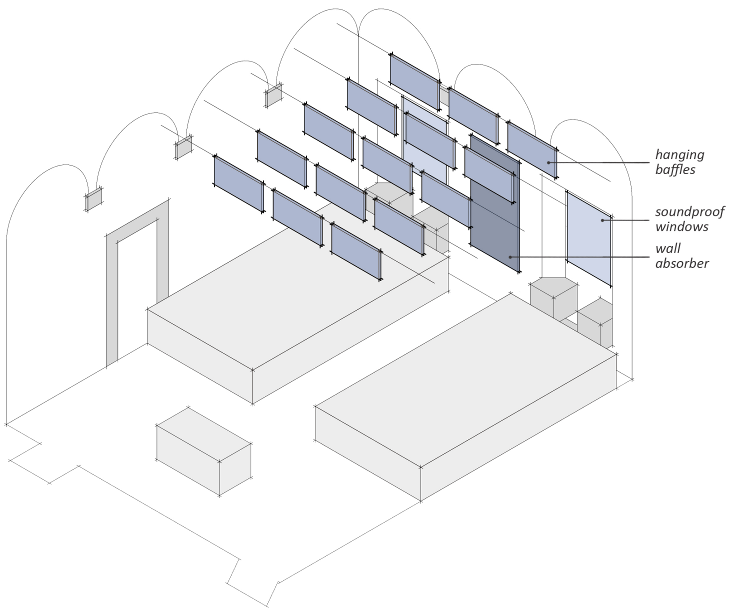


Figure 4.29: Aula 4: acoustic design proposal.

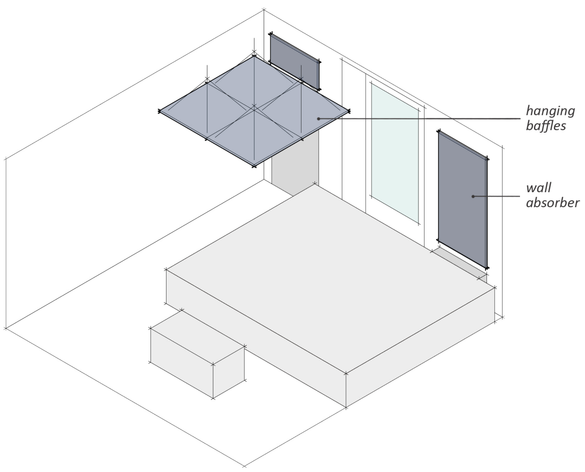


Figure 4.30: Aula 5: acoustic design proposal.

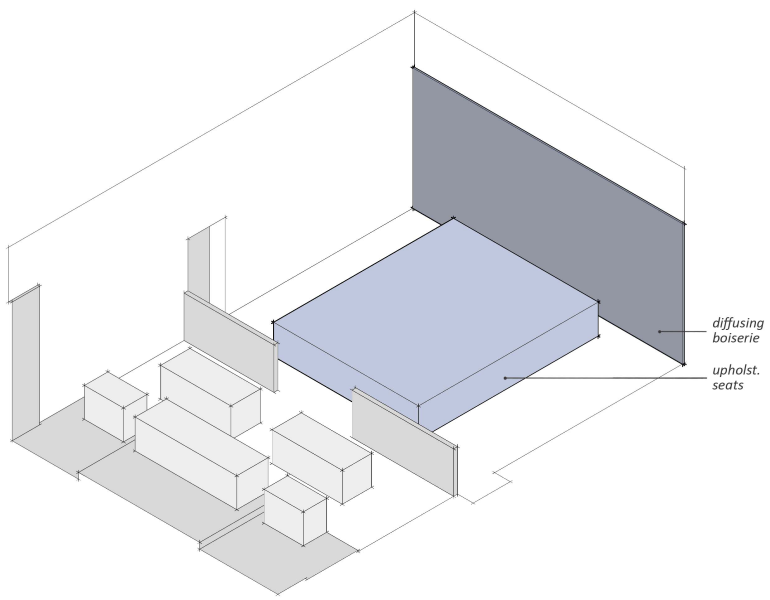


Figure 4.31: Aula 6: acoustic design proposal.

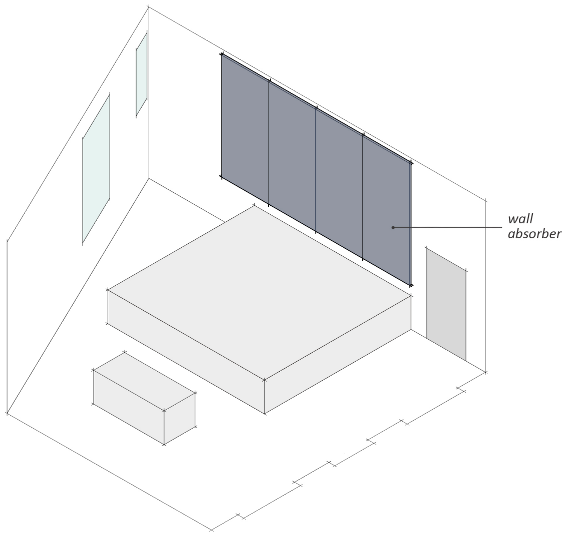


Figure 4.32: Aula 19: acoustic design proposal.

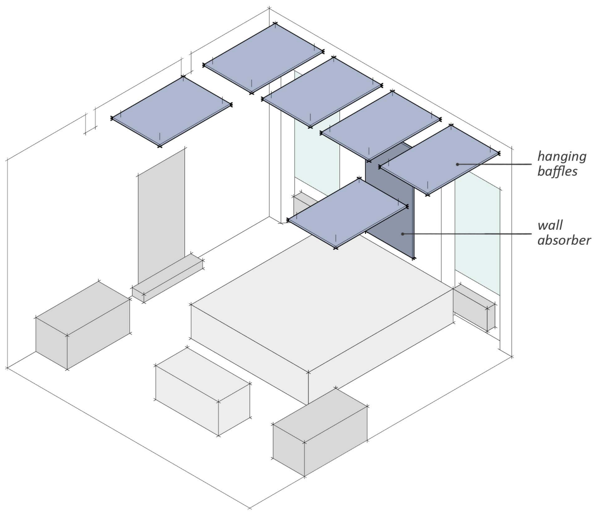


Figure 4.33: Aula 21: acoustic design proposal.

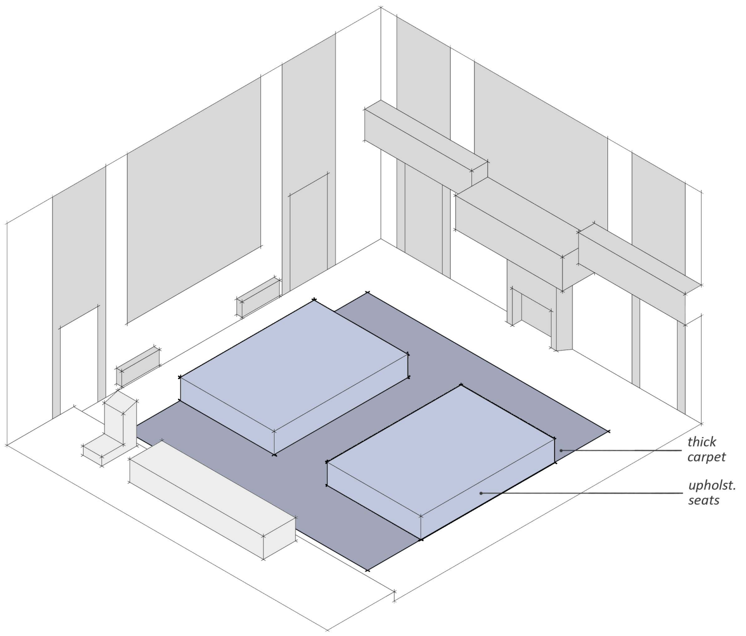


Figure 4.34: Sala Armi: acoustic design proposal.

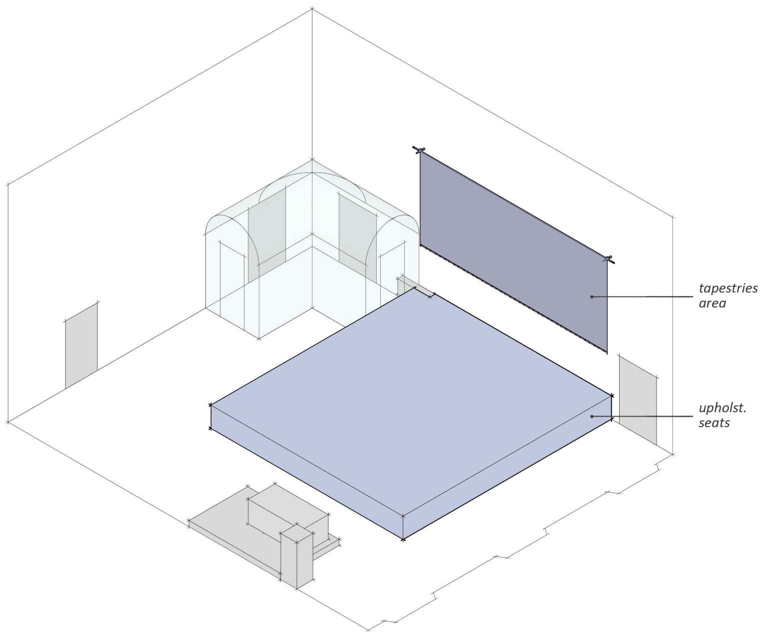


Figure 4.35: Sala Feste: acoustic design proposal.

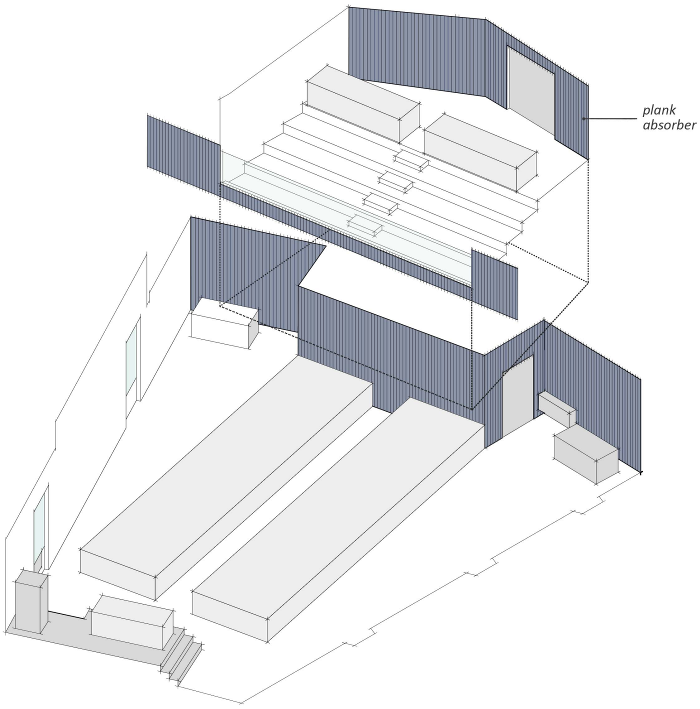


Figure 4.36: Aula Magna: acoustic design proposal.

4.6 Design of PA systems

The use of an incorrect system can often lead to a deterioration in performances if used in an environment that does not have good passive requirements. When properly chosen, the inclusion of a line array amplification system allows the sound energy to be directed precisely to the listeners. This make possible to increase the direct component and overcome reflections that could deteriorate intelligibility. Furthermore, it allows fewer restrictions in the spatial arrangement of passive interventions.
A proper PA systems is required for Aula 6, Aula Magna, Sala delle Armi and Sala delle Feste. While for the extra large lecture halls this is made necessary by the detriment of speech intelligibility due to the distance (Figg.4.13,4.15), in Aula 6 it is planned as a necessary feature for the simulated court. Notice that in Aula Magna two further fillers installed on ceiling are necessary to ensure good listening even for the mezzanine audience.
The choice and design positioning of the PA systems are not discussed here, due to the in-depth electroacoustic studies required for the purpose, which take no part in the goals of this work. However, the installation of them can be considered essential for these rooms.

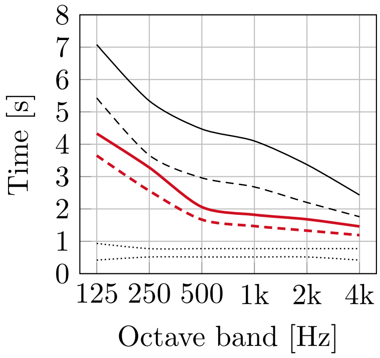
Chapter 5

Results

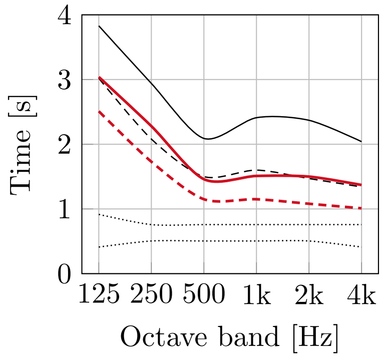
The results of numerical predictive models are here presented. From the obtained design reverberation times, acoustic comfort parameters (sound clarity index and Speech Transmission Index) are evaluated thruough previsional formulations in order to gain a more comprehensive knowledge on the desing effects. Ante-operam and post-operam scenarios are compared.
The measurements to verify the sound absorption of the seats placed in situ are here presented according to the reference standards ISO 354 [2] and ISO 20189 [11], and compared with literature ones.

5.1 Previsonal model outcome

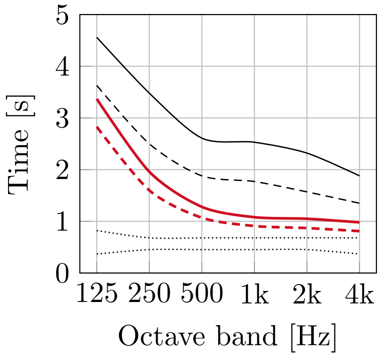
The effects of passive treatments can be verified with the aid of the numerical model. It provides the reverberation time for the design configuration known the absorbent properties of the material introduced in the measured state, thanks to the calibration performed. The logarithmic nature of the problem means that an ever greater increase in the surfaces introduced corresponds to an ever lesser effect on the acoustics. After a certain intervention threshold, the condition settles around final values, which indicate the improvement limit of the environment itself. This limit is higher for historical environments that were not designed for teaching.
This behavior is showed by the predicted reverberation time: the proposed acoustic treatments tries to reach the magnitude at which the effectiveness is balanced by a reasonable and adequate outcome. The design scope was to bring the reverberation time, for the range of 500÷1000 Hz octave bands, below 1.5 s and as close as possible to 1 s. This can be sometimes hardly achieved. The performances for the 125÷250 Hz octave band range, relevant for low-frequency phonemes of speech, could still be problematic for some classrooms. In general, sound absorption at low frequencies is more difficult to achieve; if actual deficiencies are verified in the testing phase, it may be appropriate to provide for ad hoc corrective actions.



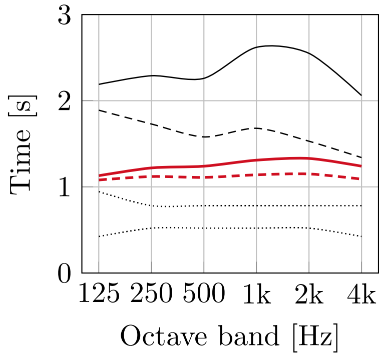
(a) Aula 2: T_{20} ante/post-operam.



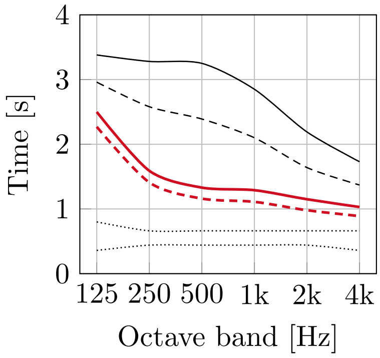
(b) Aula 4: T_{20} ante/post-operam.



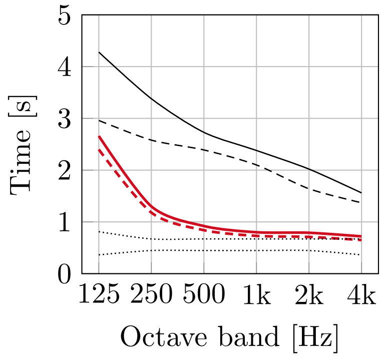
(c) Aula 5: T_{20} ante/post-operam.



(d) Aula 6: T_{20} ante/post-operam.

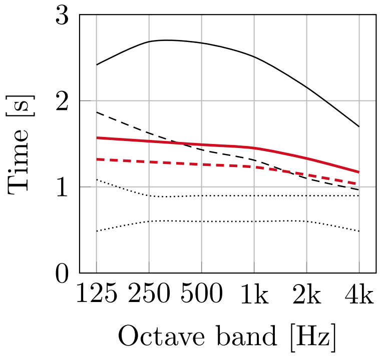


(e) Aula 19: T_{20} ante/post-operam.

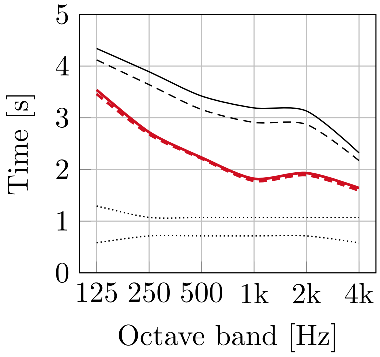


(f) Aula 21: T_{20} ante/post-operam.

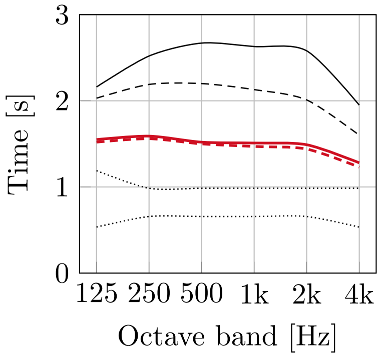
Figure 5.1: Ante-operam and post-operam T_{20} comparison for small-medium rooms, for each octave band. Black lines are ante-operam measured values, red lines are post-operam simulated results from previsional model. Continuos lines state for unoccupied condition, dashed lines state for occupied condition (80% occupancy). Standard requirements are signed with dotted lines.



(a) A. Magna: T_{20} ante/post-operam.

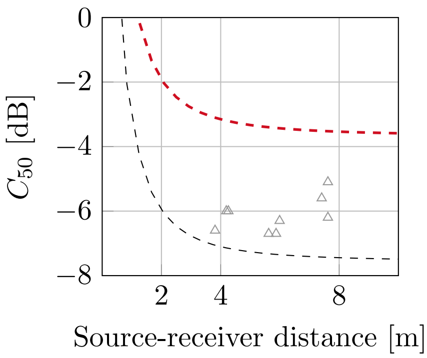


(b) S. Armi: T_{20} ante/post-operam.

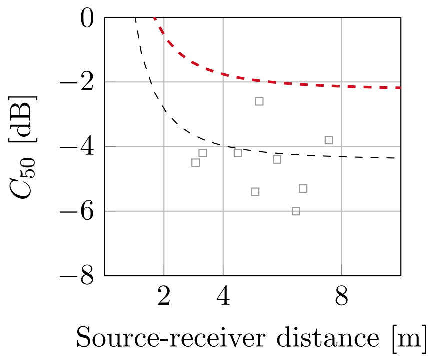


(c) S. Feste: T_{20} ante/post-operam.

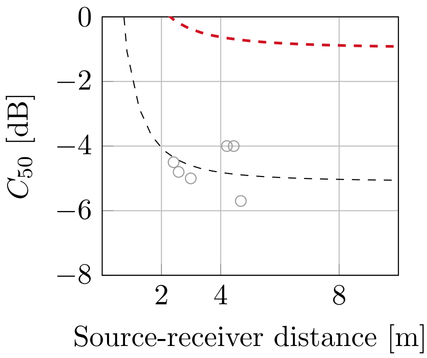
Figure 5.2: Ante-operam and post-operam T_{20} comparison for Aula Magna, Sala delle Armi e Sala delle Feste, in each octave bands. Black lines are ante-operam measured values, red lines are post-operam simulated results from previsional model. Continuos lines state for unoccupied condition, dashed lines state for occupied condition (80% occupancy). Standard requirements are signed with dotted lines.



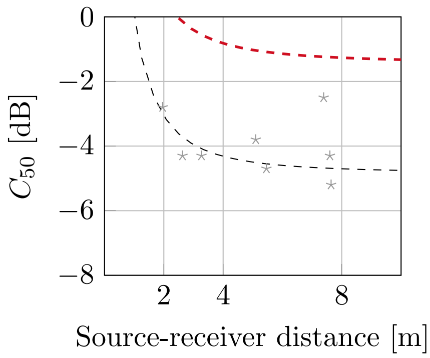
(a) Aula 2: C_{50} - distance.



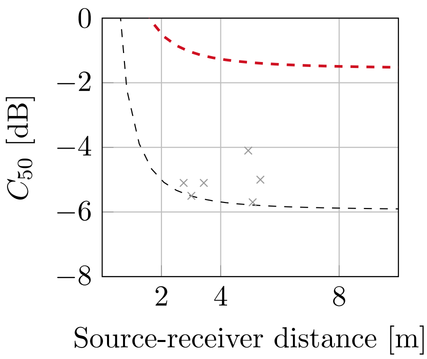
(b) Aula 4: C_{50} - distance.



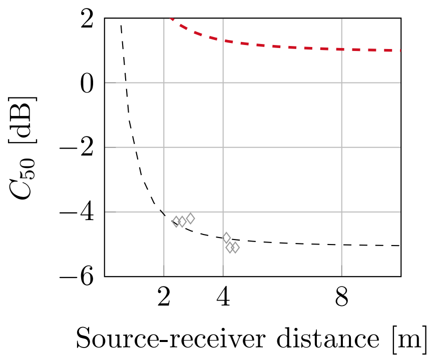
(c) Aula 5: C_{50} - distance.



(d) Aula 6: C_{50} - distance.

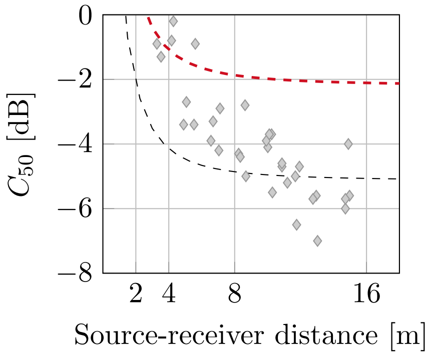


(e) Aula 19: C_{50} - distance.

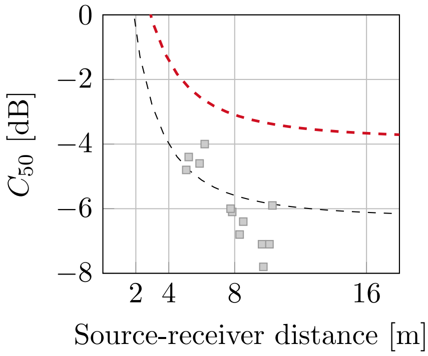


(f) Aula 21: C_{50} - distance.

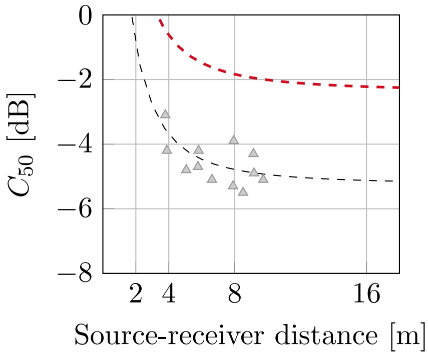
Figure 5.3: Ante-operam and post-operam C_{50} values comparison in function of the source-receiver distance for each small-medium room. Points are measured ante-operam values, dashed black line is Barron&Lee's theory trend in ante-operam condition, dashed red line is Barron&Lee's theory in post-operam condition. Reverberation time used in the equations are the average values over 500÷1000 Hz octave bands. Values are referred to unoccupied state.



(a) Aula Magna: C_{50} - distance.



(b) Sala delle Armi: C_{50} - distance.



(c) Sala delle Feste: C_{50} - distance.

Figure 5.4: Ante-operam and post-operam C_{50} values comparison in function of the source-receiver distance for each large-extra large room. Points are measured ante-operam values, dashed black line is Barron&Lee's theory trend in ante-operam condition, dashed red line is Barron&Lee's theory trend in post-operam condition. Reverberation time used in the equations are the average values over 500÷1000 Hz octave bands. Values are referred to unoccupied state.

Table 5.1: Ante-operam and post-operam STI comparison. The post-operam values can be evaluated for lecture halls where background noise is known. The method B in the Annex A of UNI 11532 [15] has been used. It is effective when the hypothesis of diffuse sound field is verified and direct sound is negligible, which occurs when the source-receiver distance is greater than five times the critical distance. Both distances are reported, in meters. Subscript "3" indicates the value is the average over the 500÷1000÷2000 Hz octave bands. STI values refers to the background noise measure point. STI values in ante-operam state and post-operam states.

Room	Pos.	r	$r_{c,3}$x5	STI$_{meas}$	STI$_{prj}$
Aula 2	R2	3.80	2.70	0.36	0.44
Aula 4	center	5.20	3.35	0.44	0.48
Aula 6	Fig.4.17	3.75	3.45	0.44	0.53
A. Magna	R11	6.55	4.95	0.44	0.51
S. Armi	R13	7.65	7.20	0.41	0.43
S. Feste	R5	5.75	6.15	0.43	0.49

From the obtained reverberation time in design state it is possible to evaluate other acoustic comfort parameters, like C_{50} and STI.
Sound clarity is given by Barron&Lee's predictive equation (2.8): once the reverberation time and the volume of the room are known, the trend in function of the distance is provided. The reverberation time avereged over 500÷1000 Hz octave band is used. Barron&Lee's formula gives a result closer to the measurable trend for classrooms with a volume <250 m^3. The design outcomes for Aula 5 (200 m^3), Aula 19 (180 m^3) and Aula 21 (190 m^3) are substantially good (Fig.4.2).
STI can be evaluated for the positions where background noise has been measured. Annex A of UNI 11532 [15] gives the calculation procedure. The standard gives three different methods, as already seen. B method is used because of the distance between the speaker and the point in the classrooms where the background noise level is known. This is greater than at least five times the critical radius of the room (averaged over 500÷1000÷2000 Hz octave bands), so the effect of direct sound field can be ignored. The check about this requirement and STI ante-operam and post-operam comparison are both reported (Tab.5.1). As UNI 11532-2 [15] suggests, for the determination of the STI descriptor, the values obtained in the 4k Hz octave band can also be extended to the 8k Hz octave band if data are not available. This is the case for post-operam reverberation time.

5.2 Seats sound absorption mesurements

Starting from normative reccomendations [2][11], the acoustic absorption measurements of the seats placed in lecture halls studied are presented. Their acoustic supplying is assessed and contextualized in the design aim.
Measurements with and without seats have been conducted for some rooms in order to observe their acoustic behavior. From these it is possible to estimate the values of equivalent sound absorption object area and to compare them with the ones reported in literature [55]. These measurement cannot be considered as the ones carried out in reverberation room certifications: they have an indicative validity and are a useful evaluation tool for this work. However despite the measurement conditions are not exactly like those of the laboratory, some requirements have been indirectly respected because they are shared in part with the reference standards for measurements for the acoustic characterization of the rooms [5][15]. It is also intresting to compare the equivalent sound absorption area of the lecture halls studied with the maximum value allowed for reverberation rooms.

Table 5.2: Equivalent sound absorption area, in Sabine's square meters, of empty lecture halls compared to the standard requirements for equivalent reverberation rooms with the same volume, in octave bands. The lecture halls shown are those for which measures in absence of seats are available. Values from ISO 354 requirements are avereged over the octave bands.

Room	Octave band [Hz]					
	125	250	500	1000	2000	4000
Aula 2	7.3	9.8	11.7	12.6	14.9	21.0
Req. V=350 m^3	9.4	9.4	9.4	10.2	13.5	18.9
Aula 4	12.7	16.7	23.7	19.9	20.1	25.3
Req. V=320 m^3	8.9	8.9	8.9	9.6	12.7	17.8
Aula 5	6.4	9.3	11.4	12.4	13.7	17.8
Req. V=200 m^3	6.5	6.5	6.5	7.0	9.3	13.0
Sala delle Armi	73.2	74.4	77.4	83.9	95.9	131.4
Req. V=2500 m^3	31.2	31.2	31.2	33.6	44.6	62.3

Tab.5.2 shows how the equivalent area (empty classroom, in the absence of chairs) recorded for the classrooms does not deviate excessively from the maximum values provided for an equivalent reverberant room (with the same volume). This data, in addition to indicating the poor performance of these spaces, gives more credibility to the absorption results measured on the chairs.
The recorded A_{obj} values of the seats for each classroom are reported (Tab.5.3).

Table 5.3: Measured A_{obj}, in Sabine's square meters, of the seats for each octave band.

Room	Seat type	Octave band [Hz]					
		125	250	500	1000	2000	4000
Aula 2	Wooden seat	0.01	0.02	0.02	0.03	0.04	0.05
Aula 4	Wooden seat	0.01	0.02	0.02	0.03	0.03	0.00
Aula 5	Wooden seat	0.02	0.00	0.03	0.01	0.00	0.00
Sala delle Armi	Lightly up. seat	0.06	0.16	0.28	0.29	0.15	0.18

Table 5.4: A_{obj}, in Sabine's square meters, of the seats, for each octave band, taken from literature.

Seat type	Reference	Octave band [Hz]					
		125	250	500	1000	2000	4000
Wooden seat	Vorlander [55]	0.02	0.02	0.03	0.04	0.04	0.04
Lightly up. seat	Vorlander [55]	0.10	0.20	0.25	0.30	0.35	0.35

The measured values do not differ substantially from those provided in the literature. The deviations can be explained by the simplification in the measurements method respect to the reference standards (ISO 354 [2] and ISO 20189 [11]) and by the influence of the surrounding environment on the absorption of objects. On this basis the sound absorption coefficients from literaure (Tab.5.5) have been used for the previsional model.

Table 5.5: Sound absorption coefficient α of the seats (two seats per square meter), for each octave band, taken from literature.

Seat type	Reference	Octave band [Hz]					
		125	250	500	1000	2000	4000
Wooden seat	Vorlander [55]	0.05	0.08	0.10	0.12	0.12	0.12
Fabric seat	Vorlander [55]	0.06	0.10	0.10	0.20	0.30	0.20
Lightly up. seat	Vorlander [55]	0.40	0.50	0.58	0.61	0.58	0.50

Upholstered seats have been proposed by design for scenarios where it is advisable to obtain a stabilization of the acoustic performances even in conditions of low occupancy. In fact, like the standard shows (Tab.2.2), as the absorption of the seat increases, the differential absorption introduced by the the person decreases, and the unoccupied and occupied condition tend to be equivalent. This is particularly useful for environments for which full occupancy is not normally provided.

Chapter 6

Discussions

An overview of the outcome of the proposed acoustic correction is addressed. The emerging data are analyzed in relation to the users' perception to get knowledge about the improvement of acoustic comfort. The evaluation criterion is provided through the just noticeable difference (JND) of the acoustic parameters considered.
Measurement uncertainty is calculated on a statistical basis as from UNI 11532 [15] to better contextualize the JNDs found.
The diffusion of the sound field under ante-operam conditions is detected for future comparisons.

6.1 Perceived effect of acoustic design

The just noticeable difference (JND) of reverberation time is given by ISO 3382-1 [4] (single number frequency averaging over 500÷1000 octave bands). The value is provided as the ±5 % of the measured time. This assumption is based on Seraphim's work [52]. Further studies [43][28] has found an overall JND of RT of about 24.5%. However, by comparing the JND value related to the reverberation time measured in ante-operam with the decrease due to corrective actions, it is possible to highlight the magnitude of the design outcome. ISO 3382-1 [4] also states the sound clarity index JND equal ±1 dB. But for Bradley [30], to improve the acoustical characteristics of a room for speech it is necessary to increase C_{50} by approximately 3 dB to create a readily detectable enhancement in everyday situations. In the same paper is reported the JND of STI corresponding to a ±1 dB sound clarity difference, equal ±0.03, and to a ±3 dB sound clarity difference, equal ±0.1. Where the improvement produces less than a 3 dB increase in C_{50} (or less than a 0.1 increase in STI), it will probably not lead to an obvious improvement in conditions for speech. If the modifications to the room lead to no more than a 1 dB increase in C_{50} values (or no more than a 0.03 increase in STI) the effect will probably be inaudible.

Table 6.1: Perceived acoustic comfort improvement: reverberation time (T_{20}). For each lecture hall ante-operam reverberation time ($T_{M,meas}$) is compared to post-operam value ($T_{M,prj}$), both in seconds and in not occupied state (subscript "M" indicates the value is the average over the 500÷1000 Hz octave bands). Value for each lecture hall is the average over all source-receiver couples. From ISO 3382-1 [4] JND=5% for measured reverberation time is evaluated. Also the difference between measured and design times is explicited. The delta-to-JND ratio is used as a perception index of acoustic comfort enhancement.

Room	$T_{M,meas}$ [s]	JND [s]	$T_{M,prj}$ [s]	ΔT_M [s]	$\|\Delta\|$/JND
Aula 2	4.28	±0.21	1.94	-2.34	11
Aula 4	2.25	±0.11	1.49	-0.76	7
Aula 5	2.57	±0.13	1.19	-1.38	10.5
Aula 6	2.44	±0.12	1.28	-1.17	10
Aula 19	3.05	±0.15	1.31	-1.74	11.5
Aula 21	2.56	±0.13	0.86	-1.69	13
A. Magna	2.59	±0.13	1.47	-1.12	8.5
S. Armi	3.30	±0.17	2.03	-1.28	7.5
S. Feste	2.65	±0.13	1.52	-1.13	8.5

Table 6.2: Perceived acoustic comfort improvement: sound clarity index (C_{50}). For each lecture hall ante-operam sound clarity index ($C_{50,3,meas}$) is compared to post-operam value ($C_{50,3,prj}$), both in decibels and in not occupied state(subscript "3" indicates the value is the averaged over the 500÷1000÷2000 Hz octave bands). Value for each lecture hall is the average over all source-receiver couples. The difference between measured and design value is explicited. From ISO 3382-1 [4] JND for C_{50} is equal 1 dB. For Bradley [30] it is equal 3 dB. Considering JND=1 dB, the delta-to-JND ratio is used ad a perception index of acoustic comfort enhancement (value defaulted to half unit).

Room	$C_{50,3,meas}$ [dB]	$C_{50,3,prj}$ [dB]	$\Delta C_{50,3}$ [dB]	$\|\Delta\|$/JND
Aula 2	-6.6	-3.0	+3.6	3.5
Aula 4	-4.2	-1.8	+2.4	2
Aula 5	-4.4	-0.2	+4.1	4
Aula 6	-4.2	-2.3	+2.0	2
Aula 19	-5.1	-0.7	+4.4	4
Aula 21	-4.3	+1.9	+6.1	6
A. Magna	-4.3	-1.4	+2.9	2.5
S. Armi	-5.8	-2.8	+3.1	3
S. Feste	-5.1	-1.5	+3.6	3.5

Table 6.3: Perceived acoustic comfort improvement: Speech Transmission Index (STI). For each lecture hall ante-operam speech transmission index (STI_{meas}) is compared to post-operam value (STI_{prj}), both in not occupied state. Value for each lecture hall is the average over all source-receiver couples. The difference between measured and design value is explicited. From ISO 3382-1 [4] JND for STI is equal 0.05. For Bradley, a good JND related to STI it is equal 0.1 [30]. Considering JND=0.05, the delta-to-JND ratio is used ad a perception index of acoustic comfort enhancement.

Room	STI_{meas}	STI_{prj}	Δ STI	$\|\Delta\|$/JND
Aula 2	0.36	0.44	+0.08	1.6
Aula 4	0.44	0.48	+0.04	0.8
Aula 6	0.44	0.53	+0.09	1.8
A. Magna	0.44	0.51	+0.07	1.4
S. Armi	0.41	0.43	+0.02	0.4
S. Feste	0.43	0.49	+0.06	1.2

6.2 Measurement uncertainty

The uncertainty of measurement should preferably be determined in accordance with UNI CEI 70098-3 [16], but, at the current state of knowledge, it seems impossible to formulate an explicit analytical model such as that required for the various sizes in the sector building acoustics. Therefore, the quantitative uncertainty assessments are based on the experimental approach in terms of repeatability and reproducibility (by UNI ISO 5725 series [13]), which leads to an assessment of the uncertainty typical of a given measurement method based on inter-laboratory tests.
Taken as the standard uncertainty of the reproducibility standard deviation σ_m (Tab.6.4), the extended uncertainty U is calculated as:

$$U = K \cdot \sigma_m \tag{6.1}$$

Where K is the coverage factor, linked to the confidence level that you want to assign to the result statement (Tab.6.5). The chosen coverage factor must be specified.
The useful value X, i.e. the value to be taken for comparison with the limit values, is obtained by applying the following equation:

$$X = X_m \pm U \tag{6.2}$$

Where X_m is the average value over the reference octave bands, and $\pm$ indicates how extended uncertainty U should always be detrimental to performance (+ for reverberation time, – for C_{50} and STI).

Table 6.4: Reproducibility standard deviation σ_m for acoustic parameters used, from UNI 11532 [15] and ISO 3382-1 [4].

param.	σ_m %
RT	5%
C_{50}	1 dB
STI	0.05

Table 6.5: Coverage factor K values associated with various confidence levels for a Gaussian probability distribution and a one-sided test, from UNI 11532 [15].

K	conf. lv. %
1.00	84
1.28	90
1.65	95
1.96	97.5
2.58	99.5
3.29	99.95

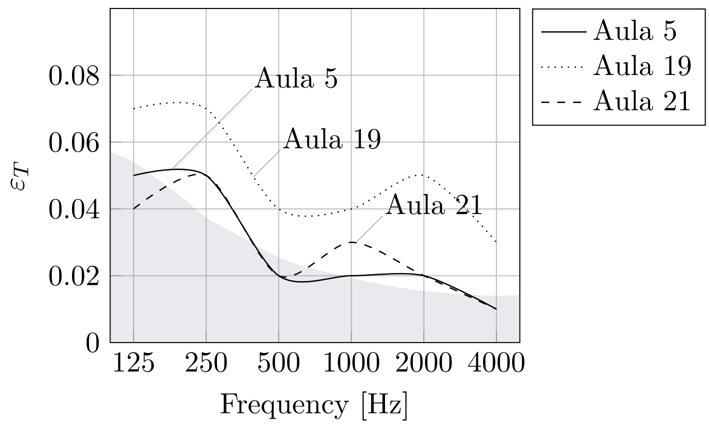
Comparing extended uncertainty U from equation (6.1) with values from Tabs.6.4 and 6.5 with JNDs from literature [28][30] it is possible to state that:

- Reverberation time JND=24.5% is beyond the confidence level of 99.95%;
- C_{50} JND=3 dB is almost at the confidence level of the 99.95%;
- STI JND=0.1 is about at the confidence level of the 97.5%;

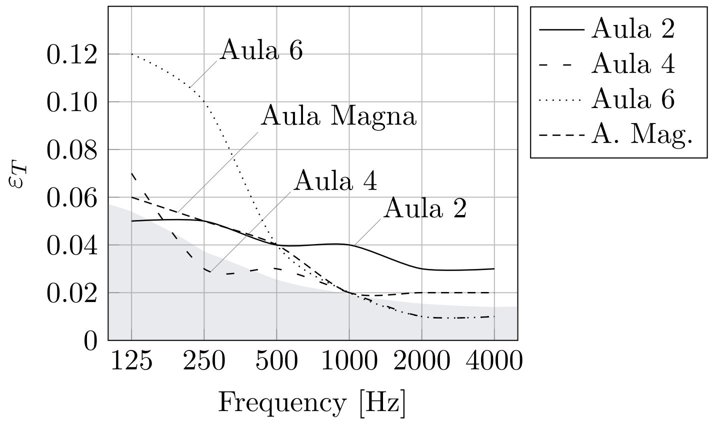
JNDs from the standards UNI 11532 [15] and ISO 3382-1 [4] refers to a coverage factor equal the unit, so they fall into less reliable confidence ranges.

6.3 Evaluation of the sound field diffusion

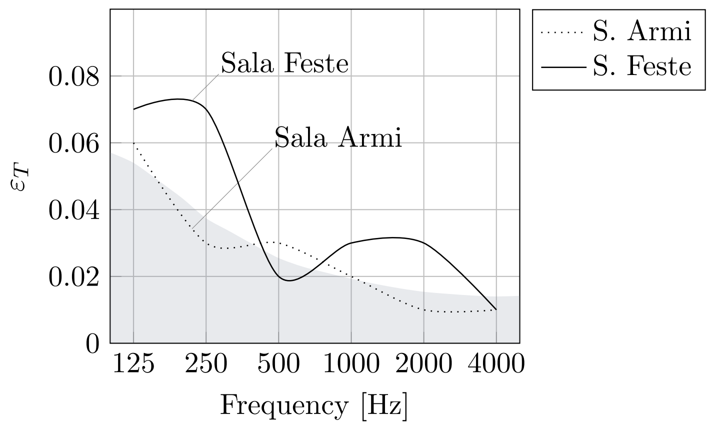
It is possible to investigate the diffusion of the sound field in the ante-operam condition, so that it can be compared with future measurements after interventions. The parameter taken as an indicator of the diffuse field is the spatial relative standard deviation of reverberation time T_{20}, as from equation (1.23). As might have been expected, results indicate that the sound field is most diffuse in more furnished environments (Fig.6.1). In post-operam condition it is expectable that ε_T will drop further due to the introduction of sound-absorbing material and edges.



(a) Small rooms: ante-operam ε_T values.



(b) Medium-large rooms: ante-operam ε_T values.



(c) Extra large rooms: ante-operam ε_T values.

Figure 6.1: Ante-operam sound field diffusion express by spatial relative standard deviation of reverberation time ε_T in function of the octave bands for each room, subdividing the plot by room size type. Values were measured in unoccupied state with an omnidirectional source. The blue area is a reference range for good diffusion [2] as in equation (1.24).

Conclusions

Correct acoustics in school environments are essential in the learning process. Good speech intelligibility allows a good communication flow between teacher and student, with less vocal effort for the speaker and fluent understanding for the listener. Acoustic correction interventions become essential in those contexts in which the basic conditions are not respected, as in the nine case studies classrooms treated here. Correction in cultural heritage is as necessary as it is discreet, so acoustic design, in compliance with other building and comfort aspects, requires differentiated and customized programs on each episode. A measurement campaign carried out in the redevelopment site at Palazzo Malvezzi-Campeggi, according to ISO 3382, showed the acoustics inadequacy of the lecture halls inquired. A simplified but necessary analysis of the physical problem regarding the acoustics of enclosed spaces has been briefly reported in order to supply some tools to contextualize the critical issues of the considered volumes and provide indications and motivations to support the design. The analysis of the present condition has allowed, with the aid of the standard UNI 11532:2020 and experimental laboratory tests, to propose a series of corrective actions aimed at a substantial improvement of the acoustic comfort. Improvement, still not full observation of the regulatory limits, which are designed for new construction environments where acoustics should be a design criterion already from the planning stages. The sufficiency of the project proposals has been verified thanks to a previsonal model, useful for establishing a good balance between the magnitude of intervention and the benefit obtained. A further field of development could include laboratory measurements of the various material configurations, in order to identify the performance increase more precisely and possibly refine the forecast model for future uses. The main intelligibility parameters were assessed through forecasting formulas. The reliability of these results can be verified by in situ measurements, providing a first basis for reflections on the effectiveness of the new regulation. The comparison between the ante-operam and post-operam conditions was then contextualized for performance increase perception, in relation to the measurement uncertainties. The several studies regarding the actual JND of the quantities involved can be developed following statistical surveys on the sample treated here.

This work is positioned in a phase in which the construction site is still in full swing. Proposals and refutations are in progress, with the client and among the technicians. Concerted planning can and must be extended beyond the current integrated lighting and acoustic design of the classrooms, with the inevitable consequent compromise required by all parties involved. This is part of the design changes to satisfy every functional and standard requirement as far as possible. If not well rooted, the acoustic design can easily fall into the background, entailing a detriment of the whole university academic performances.
The purpose of this work is to provide a varied and customized range of construction possibilities to address the problem of the acoustic correction design. The data presented develops a starting point for future improvements. After design implementations, testing measures will be possible to verify the effectiveness of the intervention and adopt additional acoustic correction to remedy any deviation from the previsional model or phenomena that are more easily recognized in reality. This final phase is of crucial importance for achieving a good degree of effective comfort. It could also be implemented through questionnaires addressed to students and professors in order to investigate the perceived comfort of attending the lesson and carrying it out. The outcome evaluation of the acoustic design is relevant for practical but also academic purposes, within a cutting-edge framework in the search field on a national level.

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