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THE ROLE OF SUSPENDED CEILINGS IN FEATURES WELL VERIFICATIONS AND ISO 22955:2021 REQUIREMENTS

Master Thesis in Acustica del Veicolo M

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Table of contents

Abstract

The acoustics comfort in workplaces, like offices, guarantee the wellness of the workers providing concentration and productivity. There are recent standards like *ISO 22955:2021, Acoustics – Acoustic quality of open office spaces* and voluntary point protocols like *WELL certification* (WELL V2 – Sound) wrote in the USA, that give some guidelines to reach the acoustic comfort through a right design of the environments. The main motivation of this study is grown from the fact that sometimes the big companies of designer find themselves working, at the request of the client, with WELL, just because it is a voluntary point protocol, and this is the reason why it may be favoured with respect to the ISO 22955:2021 and its limits. Not always, the criteria they define are applicable, especially where there is a high presence of architectural constraints and the last majority of interventions are rehabilitation works. In this thesis, the preliminar analysis is carried out through different environment configurations defined according to standards and protocols requirements (state of art) and literature (systematic review). A deeper analysis is performed through *in situ* case studies in order to have a global overwiev of the existing Open Plan offices. The environments taken into account do not have furniture and the acoustic treatment applied only to ceiling, in order to consider the ISO 22955:2021 precondition. These requirements can be mutually independent, but they were linked together to develop a comparison and verify their applicability. The analized parameters look at the *Lombard effect* - the involuntary tendency of the speaker to increase the vocal effort, while speaking in loud noise – with the aim of ensuring the acoustic comfort in Open Plan offices.

1 Introduction

The acoustics comfort in workplaces, like offices, guarantee the wellness of the workers providing concentration and productivity. Note that the acoustic of offices is a complex topic, with several critical aspects to keep in mind:

1. A strong acoustic treatment in offices is required, due to the fact that the acoustic discomfort has a negative influence on the productivity;
2. The anthropogenic noise is the main trouble, because it is the noise generated by workers theirself, that then are disturbed, creating a loop cicle;
3. The noise depends also on people behavior, strictly related to the country to which they belong. There are two different kind of countries: countries in which people speak a lot, and countries in which people do not speak so much. For this reason it is hard find some common guidelines from an international point of view.

Each country has its own standards, protocols and voluntary certifications based on the common geometries and characteristics of the environments in which people live and work. These documents define parameters and thresholds that must be respected to reach the comfort. The main idea on which is based the following study born from the fact that sometimes in Italy the major design companies find themselves working, at the request of the client, with American voluntary point protocols instead of standards. The main problem is the fact that in USA the boundary conditions in which the environment are inscribed are different with respect to the Italian BCs. Indeed, for example, in Italy the last majority of interventions, in which these cerifications are applied, are historic rehabilitation buildings interventions, so full of architrectural restraints. On the contrary, in the United States often this kind of problem is not present, the floor surface is fully carpeted, etc; so the respect of the given thresholds is easier to reach.

In countries like Italy, in which people speak a lot, the topic is complex. The masking sound is not used and there are upper limits in the design with $D_{2,s}$. In addition, in lots of countries the design phase is developed according to voluntary point protocols like WELL. This is the main motivation of this thesis and from this point start to grow the *research questions*. They are:

- Which is the minimum level of A (Equivalent Sound Absorption Area) that, in an Italian context, allow the designer to control the environmental noise and the Lombard effect, but at the same time is compatible with the Italian design criteria?
- The international standard ISO 22955:2021 sets in order, first the A requirement, and then the $D_{2,s}$ requirement. The WELL certification puts them in parallel, because in Austalian and New Zeland they work in parallel. In Italy in which way must be treated these two requirements?

The perfomed analysis wants to investigate how standards like *ISO 22955:2021, Acoustics – Acoustic quality of open office spaces* and protocols like *WELL Certification* (WELL V2 – Sound) interact between eachother in design phase, to satisfy the thresholds and reach the comfort through a right acoustic design of the environments. On one hand ISO 22955:2021 is a recent international standard that defines the state of art for the Open Plan offices, strongly based on the French standard NF S 31-199, AFNOR. On the other hand WELL is a voluntary point protocol, wrote in the USA. The WELL V2 Sound defines six features, among *feature S04 – Reverberation Time* and *feature S05 – Sound Reducing Surfaces*. Each feature take inspiration from other local technical standards [5]. The requirements for *feature S04 – Reverberation Time* defined according to three different range of volumes (small, medium, large), to which correspond three different range of Reverberation Time values allowed for each category, in furnished environment condition. The ISO 22955:2021 requirement corresponds to the *feature S05 – Sound Reducing Surfaces* 2 points ($A/S_{floor}>0.9$), while the 1 point S05 has a less stringent requirement ($A/S_{floor}>0.6$) with respect to the other one. In this thesis the analysis is carried out through a comparison between several configurations of environments defined according to standards (state of art), literature (systematic review) and *in situ* measurements. The environments have small, medium and large sizes, length and width defined according to 1:4 propotion. Note that this proportion is interesting from an acoustic point of view because we fall in a situation in which the hypothesis of the Sabine predictive formula for the Reverberation Time could be still valid, but this formula loose its meaning when the environment is furnished and Sabine is no more valid.

From standards, the analysis of parameters was performed following the state of art, with the precise division in range volumes, the sound absorption treatment applied only to ceiling surface and the environments are in not furnished conditions [3, 4].

From literature, the offices defined with the data find out in the systematic rewiev in terms of offices parameters (number of workstations, workstation density, ceiling height and surface); and in terms of categories (absorbent/hard ceiling, yes/no carpet and yes/no partitions and screens) [7, 16, 19, 25, 31, 39].

The very same offices parameters and categories were find out from *in situ* measurements and used for the third part of the analysis.

After properly characterizing the environments, are verified the different scenarios carried out from standards, literature and case studies, in which are analysed ISO 22955:2021 requirements and features S04, S05 thresholds. Remember that the requirements can be independent, but this comparison is developed in order to verify their mutual applicability. The parameters (T, A, $\bar{\alpha}$) used in the analysis are defined according to the two different requirements of S05. Then, was performed a comparison in terms of T and A/S_{floor} in all the defined configurations, for both WELL feture S05 (1 point, $A/S_{floor}>0.6$) and ISO 22955:2021 and WELL feature S05 (2 points, $A/S_{floor}>0.9$) requirements. The Equivalent Sound Absorption Area of the suspended ceiling, precondition for the calculation of T in empty environment, used to take into account the *Lombard effect*, the involuntary tendency of the speaker to increase the vocal effort, while speaking in loud noise [42].

In conclusion, the aim of this thesis is to verify if the ratio $A/S_{floor}>0.9$ defined by ISO 22955:2021, *Acoustics – Acoustic quality of open office spaces* and *WELL certification* (feature S05) could present an incompatibility with the RT requirement (feature S04), especially in Italy where these standard and protocols are applied in renovations of historic buildings [3, 4].

2 Sound in enclosed environments

Acoustics studies the generation, propagation, and reception of sound waves in elastic media (solid, liquid, and gaseous); in addition, ultrasound and infrasound, which are not perceived by the human ear but have the same behavior as audible ones, must also be considered. Making an analogy between waves on the surface of water and sound waves, it is possible to define one of the fundamental properties, in which the wave essentially constitutes a perturbation of the local conditions at rest of the medium, and is perturbation that moves and propagates, not the medium itself. In addition it should be noted that the different particles one after the other all perform the same motion, but with a certain time delay, determined by the speed of propagation of the wave. The sound wave is thus the propagation of an oscillatory motion of particles that communicate each other sequentially, so that they move only around their equilibrium position. The medium must have two characteristics, elasticity and inertia. The former involves a generation of an internal force to the medium. When a particle is moved from its rest position, and this force tends to bring it back to equilibrium; the inetria coincides with having mass, and thus all concepts of classical mechanics, such as momentum and energy transfer, remain valid. Despite this, however, the substantial difference lies in distinguishing the behavior in a fluid medium and in a solid medium, while speaking in terms of auditory sensation what is perceived is a perturbation propagating in the medium, air, altering its equilibrium conditions.

Air particles oscillate in the direction of wave propagation with a given local velocity, called "particle velocity", which is different from the velocity with which the sound wave propagates, the "speed of sound". Oscillation induces changes in density and therefore pressure, that is the most relevant difference from static pressure, in air at atmospheric pressure level, takes the name of "sound pressure". It is what our ear perceives and it is possible to measure it directly with measuring instruments. Wave propagation in fluids is described by the sound wave equation, obtained by the appropriate combination of Euler's equation, the continuity equation and the equation of state, it holds:

$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$$

Formula 2.1 – Sound wave equation.

Where c is the speed of sound propagation in fluids, a characteristic property intrinsic to each fluid and uniquely determined by the thermodynamic properties, pressure, density and temperature. Sound in air propagates as a longitudinal elastic wave, in a direction perpendicular to the vibratory motion of the particles in the medium. Usually, for the determination of the sound field in closed rooms, reference is made to a geometric approximation known as geometric acoustics, for which are valid the following relationships:

$$f = \frac{1}{T}, \quad T = \frac{2\pi}{\omega}, \quad \lambda = cT$$

Formula 2.2 – Definitions of frequency, period and wavelength.

Geometric acoustics is based on the principle that schematizes waves emitted by the source with rays. The sufficient, not necessary, conditions for the principle of geometric acoustics to be valid are:

1. The amplitude (A) of the wave does not change significantly over comparable distances the wavelength λ;

2. The phase velocity of the wave c does not change significantly over comparable distances the wavelength λ.

Thus, in order to approximate sound waves with rays, it is necessary that the amplitude of the wave in the central zone be almost constant and not decay abruptly, and that the path of the elementary beams of sound energy be almost straight; thus, that there not be too strong an effect of refraction. In general, these two conditions are well approximated in the limit of small wavelengths [1].

2.1 Reflection, transmission, diffraction and absorption of the sound waves

A sound wave propagates as it passes from one medium to another, and can be partly reflected, partly transmitted and partly absorbed by the area it passes through. This depends on the characteristics of the separating surface, the interface, and the physical properties of the two media. The transition between fluid-fluid and fluid-solid is different. In fluid-solid the change in properties of the propagating medium occurs abruptly and discontinuously. The behavior of sound within enclosed spaces is determined by the properties of the solid surfaces bordering them. The contributions of absorbed (p_a), reflected (p_r) and transmetted (p_t), sound energy can be sum up together in order to obtain the total sound power indicated by p_i described by the equation:

$$p_i = p_a + p_r + p_t$$

Formula 2.3 – Total sound power.

A further step is performed, dividing both members of the above equation by p_i and obtaining:

$$1 = a + r + t$$

Formula 2.4 – Total sound power as a function of the coefficients.

Where a, r, t, are the absorption, reflection and transmission coefficients, derived from the ratio of the sound energy object of study with the total one. These parameters are useful when we want to define the quantities that influence the acoustic performance of a structure [1].

The istantaneous sound pressure at a point is the incremental change from the static pressure at a given instant caused by the sound wave p (r, t). The effective sound pressure at a point is the root-mean-square (RMS) value of the instantaneous sound pressure at that point. It is described by the following formula

$$p_{rms}(r) = \lim_{T\to\infty} \sqrt{\frac{1}{T} \int_{-T/2}^{T/2} p^2(r,t)dt}$$

Formula 2.5 – Root-mean-square (RMS) value of the instantaneous sound pressure.

A plane wave or harmonic wave is

$$p(r,t) = P_0 \cos(\omega t + \varphi) = Re\left[P_0 e^{i(\omega t+\varphi)}\right]$$

Formula 2.6 – Harmonic wave equation.

The specific acoustic impedance is the complex ratio of the sound pressure at a point to the modulus of the sound particle velocity at that point

$$Z_s = \frac{p(r,t)}{u(r,t)} = R_S + iX_S = |Z_S|e^{i\theta_S}$$

Formula 2.7 – Specific acoustic impedance.

The real part is the specific acoustic resistance; the imaginary part is the specific acoustic reactance.

The characteristic impedance of a medium is the specific acoustic impedance in that medium for a progressive plane wave; it can be shown that it is

$$Z_C = \rho_0 c_0$$

Formula 2.8 – Characteristic acoustic impedance.

Where

- ρ_0: air density;
- c_0: sound speed in air.

REFLECTION AND TRANSMISSION OF THE SOUND WAVES

The reflection and transmission of sound waves are evaluated both by parameters, formulas, and physical quantities that describe their behavior, but also through the analysis and study of surfaces that the sound wave encounters. Indeed if the wavelength (λ) smaller than the size of the obstacle, which has very small irregularities, on which it breaks, the surface is flat. In contrast, sound waves will have different behavior in terms of concentration or dispersion depending on whether the surface is concave or convex. (figure 2.1)

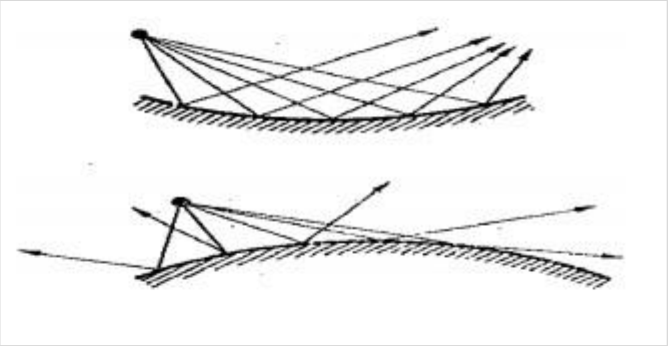


Figure 2.1 Reflections on concave and convex surfaces.

Bearing in mind what was discussed in the previous section, it is possible to reason in terms of reflection and transmission of sound pressure and the respective coefficients obtained through the ratio of reflected or transmitted sound pressure, to total sound pressure. These coefficients can be expressed in terms of the characteristic acoustic impedance of the two media the wave passes through, in fact:

- $r = \frac{Z_2 - Z_1}{Z_2 + Z_1}$, positive or negative according to the values of Z_1 and Z_2
- $t = \frac{2Z_2}{Z_2 + Z_1}$, always positive

Where Z_1 and Z_2 are values of *characteristic acoustic impedance* of the two mediums that sound goes through [1].

The expression of the *reflection factor r* is obtained through the matching of sound impedances at a change of medium. Indeed by removing the rigid wall condition, if some sound power enter into a wall surface (at x=0), there exists a sound field 2 behind the boundary plane. The demostraion of the the reflection factor formula is developed here below.

Two boundary conditions must be fulfilled:

1. The equality of force and counterforce requires equality of the sound pressure

$$p_1(0) = p_2(0)$$

2. The continuity of mass flow requires equality of velocities

$$v_1(0) = v_2(0)$$

On the primary side of tne boundary plane:

$$p_1(0) = p_+ + p_-$$

$$v_1(0) = v_+ + v_- = \frac{1}{Z_1}[p_+ + p_-]$$

On the secondary side of the boundary plane:

$$\frac{p_2(0)}{v_2(0)} = Z_2$$

It follows that:

$$Z_1 \frac{p_+ + p_-}{p_+ - p_-} = Z_2$$

Or

$$r \coloneqq \frac{p_+}{p_-} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

This ratio r is called the *reflection factor* and is, ingeneral, a complex number:

$$r = |r|e^{i\gamma}$$

Formula 2.9 – Final result of reflection factor demonstration.

From t equation, always positive, it can be seen that the sound pressure of the transmitted wave is always in phase with that of the incident wave. To visualize this, a geometric simplification needs to be performed, whereby the wave obliquely impinging on the interface surfaces between the two fluids generates an angle θ, called angle of incidence, reflection, or transmission depending on the phenomenon involved, and according to the *law of mirror reflection,* the reflection angle is equal to the incidence one.

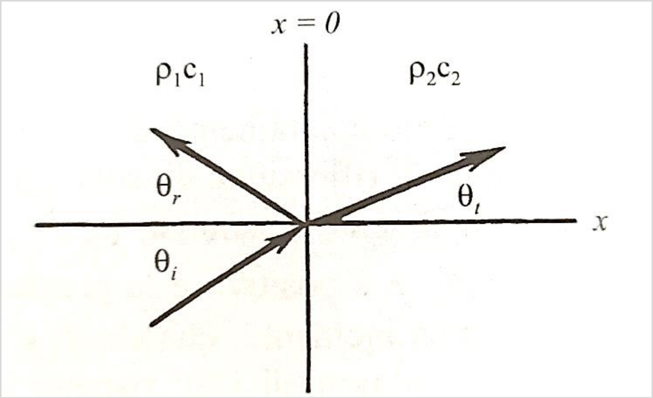


Figure 2.2 – Oblique incidence on separation surface between two fluid media of different acoustic impedance.

In the transition from liquid to solid, the aspects considered so far become complicated, and for this reason it is necessary to perform a simplification, whereby a plane wave is considered to incise orthogonally to the surface of the solid; this allows us to think that only longitudinal waves are excited. Conversely, if the plane wave incises obliquely on the surface of the solid, it becomes impossible to establish the simple relationships between the sound pressures associated with the same incident, reflected and transmitted wave. The physical properties of different solids (porosity and internal elastic structure), condition the nature of the transmitted waves and thus also of the reflected waves. The law for which the angle of reflection is equal to the angle of incidence remains valid [1].

DIFFRACTION OF THE SOUND WAVES

In acoustics, it is common to deal with sounds whose wavelength is the same order of magnitude or larger than the size of the surfaces, objects, and structures in the environment in which the sounds propagate. This phoenomenon is called *diffraction,* is a complex problem to deal with and geometric methods are not sufficient to do so, so an exemplification can be used. Consider a plane wave passing through an aperture of width *d* drilled into a partition element of infinite acoustic impedance, perfectly reflective. If this is greater than the wavelength of the sound breaking the condition is verified $d>\lambda$, the transmission of the portion of the wavefront corresponding to the aperture will occur, and beyond the partition, the wave will be partially confined. (figure 2.3)

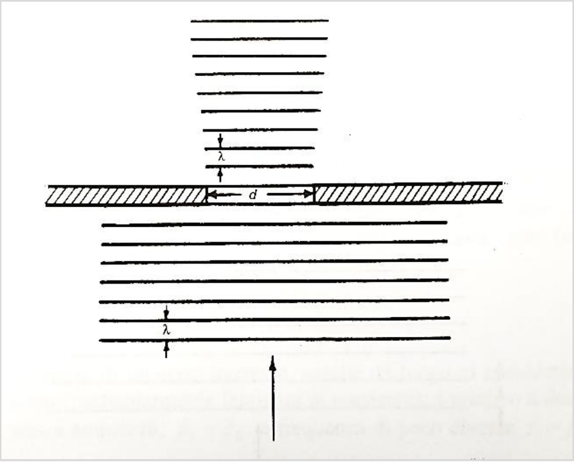


Figure 2.3 – Sound wave diffraction around aperture | λ < d.

However, if, on the contrary, occurs that $d \leq \lambda$, that is, if the resulting wavelength is of the same order of magnitude or larger than the size of the opening made in the partition, the wave will also propagate around the opening itself, in an area called the "acoustic shadow zone". The edges of the opening, interacting with the incident wave, themselves become elemental sources of sound waves that will radiate in all directions (figure 2.4).

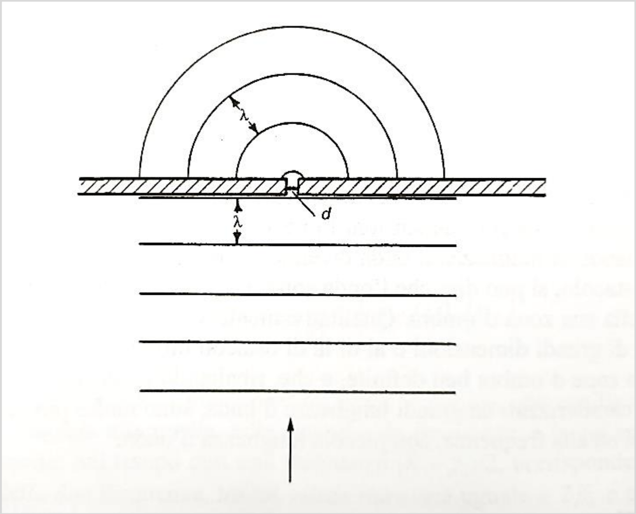


Figure 2.4 – Sound wave diffraction around aperture | λ ≥ d.

A similar process occurs when the sound wave encounters physical obstacles of finite size during propagation. When the wavelength has size larger or comparable to the obstacle, the sound wave "bypass" the obstacle and propagates even in its shadow zone (figure 2.5).

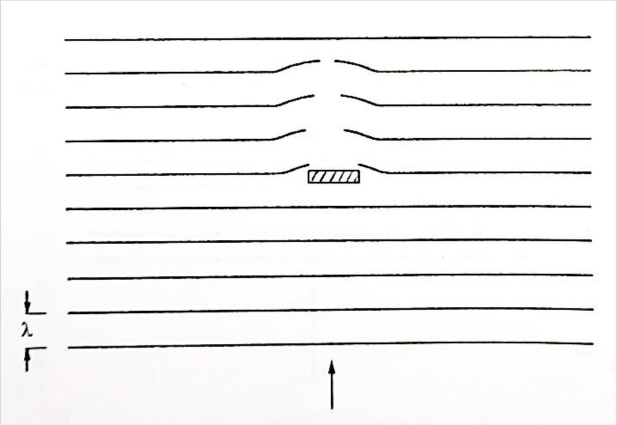


Figure 2.5 – Sound wave diffraction around finite size obstacle | λ ≥ obstacle dimensions.

In contrast, for considerably large obstacles, well-defined shadow areas will form (figure 2.6).

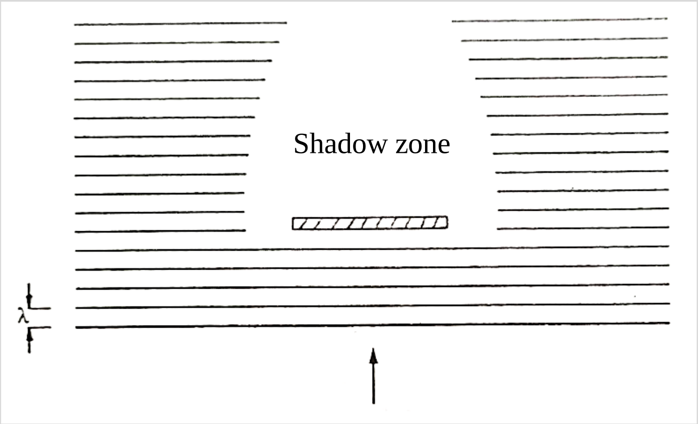


Figure 2.6 – Sound wave diffraction around finite size obstacle | λ < obstacle dimensions.

Qualitatively, it is possible to say that through large openings or over very large obstacles, it is possible to create well-defined shadow zones; in contrast, sounds with low frequency and high wavelength easier diffracted than sounds with high frequency and short wavelength [1].

ABSORPTION OF THE SOUND WAVES

Absorption of emitted sound energy is one of the most effective methods of noise reduction when sound propagation occurs within enclosed spaces. If the medium is confined, bounded by more or less reflective surfaces, it is on these that the most important energy losses occur. Sources of dissipation intrinsic to the medium can be divided into three categories:

- Losses due to viscous effects;
- Losses due to thermal effects;
- Losses associated with molecular relaxation phenomena.

Viscous losses occur between contiguous portions of the medium affected by the compressions and rarefactions, respectively that accompany the propagation of the acoustic wave.

The compression associated with the acoustic wave causes a local increase in temperature, and possible subsequent heat conduction to contiguous regions of lower temperature. This is thus an irreversible process involving dissipation of acoustic energy into heat.

The passage of the acoustic wave through a region of medium causes an increase in the translational kinetic energy of the molecules. The *relaxation time* τ is the time required for the transfer process compared with the period of the acoustic wave, and determines how much acoustic energy is dissipated into heat.

The first two dissipative sources depend on the square of the frequency, referred to as "classical absorption," and are irrelevant in the range of audible frequencies; their effect is only significantly manifested in the high-frequency ultrasonic regime. In contrast, dissipation by molecular relaxation, known as "access absorption," is relevant even at frequencies of a few hundred hertz, particularly in the case of wave propagation over long acoustic paths, even in enclosed spaces [1].

2.2 Acoustic properties of materials

Absorbing materials and elements are used in the acoustic treatment of rooms, particularly in the ceiling, when there is a desire to reduce reverberated sound energy. These are used to control reverberation time and total sound pressure level. Absorption of emitted sound energy is one of the best methods of noise reduction in the case where sound propagation takes place inside enclosed spaces; in addition, absorbing materials can be applied on sound barriers to decrease sound reflection from their surface. The absorbing properties of materials are quantified through the *sound absorption coefficient (α)* and is described by the ratio of the sum of absorbed and transmitted energy divided by the incident energy. It is (formula 2.10) [1]

$$\alpha = \frac{(absorbed\ energy + transmitted\ energy)}{incident\ energy} = 1 - r$$

Formula 2.10 – Sound absorption coefficient.

The sound absorption coefficient α, is a real number and it can be expressed also in terms of acoustic impedances as follow

$$\alpha = 1 - \ |r^2| = 1 - (\frac{Z_2 - Z_1}{Z_2 + Z_1})^2$$

Formula 2.11 – Sound absorption coefficient expression with the acoustics impedances.

So α, describes the fraction of sound energy absorbed by a given material, and has values between 0 and 1, where in the two limiting cases we have:

- α =0: all the incident energy is reflected;
- α =1: all the incident energy is absorbed.

Consequently if α is equal to 0,7 it means that 70% of the incident energy on the material's surface is absorbed. It should be noted that for the same material the value of this coefficient is different depending on the frequencies and angle of incidence of the wave. The sound absorption coefficients are expressed as a function of octave band frequency. This coefficient varies according to the variation of the frequencies and the angle of incidence of the sound wave. In laboratory are measured:

- Sound absorption coefficient at normal incidence;

- Sound absorption coefficient at random incidence.

The first one is quantified by the standing wave method in a tube on small samples, while the second one is measured in a reverberation chamber on large samples, and can also be applied to structures and/or absorbing elements. Given the behavior of sound waves in reality the latter is the one that best describes and represents it [1]. Both behaviours can be seen in the following picture. (figure 2.7)

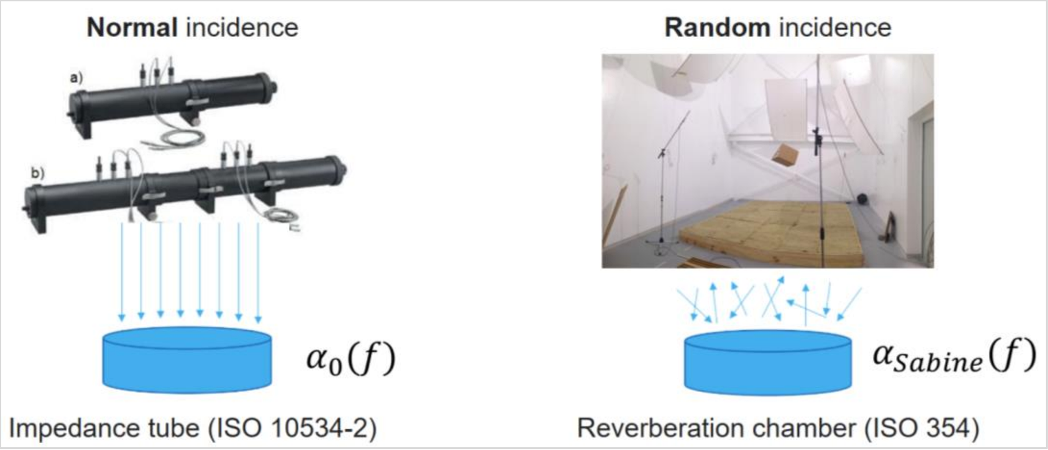


Figure 2.7 – Sound absorption coefficient at normal and random incidence.

The physical principle on which sound absorption is based is the conversion of part of the incident energy into heat, and it occurs in different ways depending on the type and structure of the absorbing element. The following three basic mechanisms of absorption are identified:

1. Absorption by porosity;
2. Absorption by cavity resonance;
3. Absorption by membrane resonance.

They have these three different trends [1]. (figure 2.8)

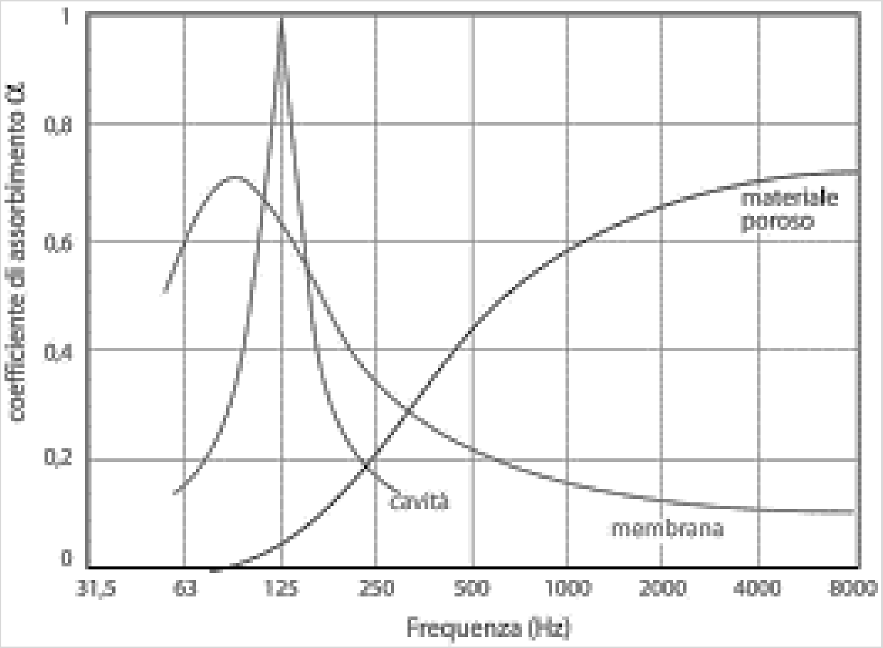


Figure 2.8 – Sound absorption trends of existing materials.

The choice of absorbent material is also affected by other characteristics, such as mechanical strength, appearance, ability to be coated or painted, cost, monitoring method, and fire resistance [1].

ABSORPTION BY POROSITY

Acoustically absorbing porous materials have a pore structure that is also open on the outer surface and communicating with each other, with typical pore sizes less than 1mm, much smaller than the wavelengths of interest. When a wave enters in porous material air molecules, that are forced to vibrate inside pores and connecting channels, lose energy due to friction against the outer surfaces of the fibers or particles that form the structure of the material. Given the size of the pores, it is possible to consider the behavior of the material as that of a homogeneous medium in which viscous losses occur. It is possible to reason in terms of the physical parameters of porous acoustic materials, since they have complex geometric shapes that are difficult to describe with deterministic models; therefore, it is preferable to consider them as a continuous medium to which average properties are known and uniformly distributed in space. The most relevant parameters are flow resistivity, fiber diameter, porosity, and structure factor. Note that absorption increases by increasing porosity, while the structure factor χ defines the influence of geometric shape on wave propagation. The fluid inside the pores increases in density and decreases in vibration velocity in relation to positive or negative accelerations due to their shape. The χ value decreases as the frequency increases. A further aspect to consider is that of the effect of the thickness of the absorbing material. If one imagines inserting a thin layer of absorbing material along the path of any standing wave, it is easy to see that the absorption effect is greatest at the points where the particle velocity is greatest, thus where the absorbing layer subtracts the most energy from the incident wave. In essence, porous materials are effective at high frequencies, but they lose their properties as the frequency decreases and, consequently, as the wavelength increases. The frequency in which α assumes relevant values, depends on the thickness of the material and the gap, if any [1].

ABSORPTION BY CAVITY RESONANCE

In the common practice of building acoustics, the most used absorbers are the Helmholtz one. Such devices consist of a volume of air contained in a cavity with rigid walls, connected to the external environment with a small opening called the "neck" of the resonator. The air inside the resonator is made to vibrate, and as a result, the volume in the cavity is subject to periodic compressions and rarefactions. The air in the neck behaves as a "vibrating mass," while the air in the cavity as an "acoustic spring." Furthermore, if inside the resonator is lined with porous absorbing material, by means of dissipative effects, the value of the absorption coefficient at the resonance frequency decreases, but the frequency range in which absorption is effective increases. (figure 2.9)

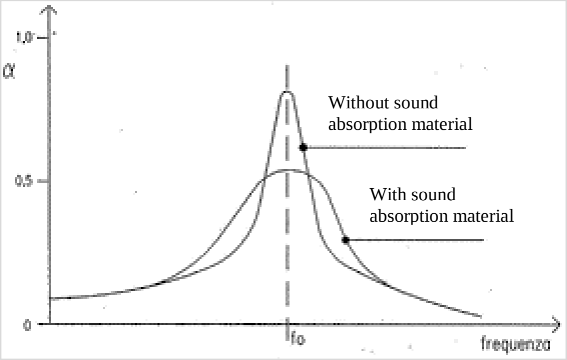


Figure 2.9 – α in a Helmholtz resonator with or without absorbing material.

The principle of the Helmholtz resonator in practice is found in perforated (slots or holes) acoustic panels placed at a certain distance from the wall, and a layer of porous material is inserted into the cavity. The behavior of the single hole can be associated with that of the resonator neck, and the part of air coinciding with the hole is the resonator cavity. The resonant frequency is described by the following relationship (formula 2.12):

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{P}{d\,t}}$$

Formula 2.12 – Resonance frequency of perforated panels.

Where:

- *P*: drilling percentage (ratio of hole area to total panel surface area)
- *d*: Distance from the wall (total thickness of porous material and cavity)
- *t*: panel thickness

The absorption properties of perforated panels could be very high, especially if there is a porous material in the gap [1].

ABSORPTION BY MEMBRANE RESONANCE

The system under consideration here consists of a thin panel placed in front of a rigid wall at not too great a distance, and can be analyzed using the Helmholtz resonator principle. In fact, the panel behaves as a vibrating mass and the air contained in the cavity as an acoustic spring with its own rigidity. The frequency in this case is (formula 2.13):

$$f_0 = \frac{60}{\sqrt{md}}$$

Formula 2.13 – Resonance frequency of thin panels.

Where:

- *m:* areic mass (mass per unit area of the panel)
- *d:* distance from the wall

The absorption of resonant panels is very selective around the resonant frequency, and it is possible to extend its effectiveness by inserting porous material into the gap [1].

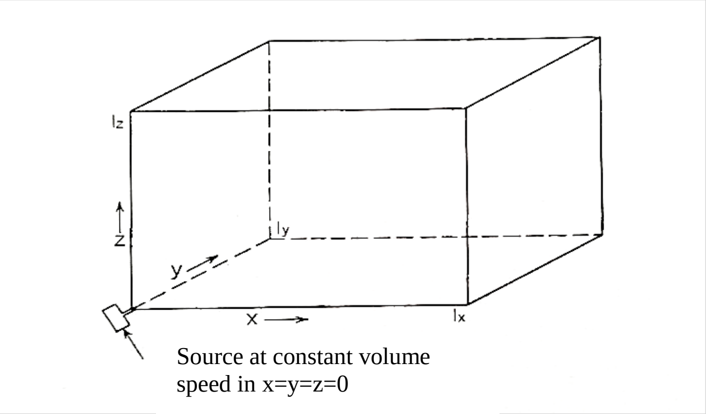
ABSORBENT BODIES AND STRUCTURES

Many times can happen that the sound reducing surfaces are placed only in some regions of the whole surface. An example of these sound reducing surfaces can be high performance panels (with a high value of the sound absorption coefficient). They can be placed on ceiling or wall and their contribution is computed in terms of equivalent sound absorption area A in sqm. This area is defined by the product alpha times surface (both referred to the panel). The performance of these elements is characterized by their configuration, geometry and installation. In the design phase, for the calculation of the reverberation time, must be used the values of the sound absorption coefficient measured in reverberation chamber. Inside a room, for the T calculation must be considered the A of furniture and in occupied conditions people contribution, too [1].

2.3 Workplaces acoustics

For much of his life, humans live and communicate in closed environments, where auditory sensation in each situation is related to the nature of the surroundings. Even today, it is still not possible to describe the actual acoustic behavior of an enclosed environment at an analytical mathematical level, but computational models, based on simplifying assumptions, are used that allow quantitative and reliable predictions in technical acoustics. In addition, an enclosed environment can be small or large depending on the frequency of interest. The "meter" is the wavelength of sound, or more accurately, it is the ratio between the linear dimensions of the room and the wavelength.

Modal theory is the most effective model for describing sound in enclosed spaces, as it allows aspects of wave phenomenology to be represented more precisely. The description is based on solutions of the wave equation, with one term representing the distribution of sound sources in the environment; of this, closed-form analytical solutions are possible for a few simple geometries and a few boundary conditions. In a permanent sinusoidal regime, consider the environment in the shape of a parallelepiped, with the axes oriented as in the following illustration: (figure 2.10)



Source at constant volume
speed in x=y=z=0

Figure 2.10 - RS for an environment with regular geometry.

The solution of that equation, takes the name of the *inhomogeneous Helmholtz equation* and gives the sound pressure *p(x,y,z)* as the sum of complex functions $p_n(x,y,z)$, where they are a natural or normal mode of the environment: (formula 2.14)

$$p(x,y,z) = \sum_{n} p_n(x,y,z) = \sum_{n} |p_n(x,y,z)| e^{i\theta_n}$$

Formula 2.14 – Sound pressure.

The spatial dependence of each mode corresponds to a three-dimensional stationary field due to pairs of plane waves, with the same frequency and amplitude, but moving in equal direction and opposite direction along straight trajectories. There are three types of modes:

1. Axial modes (1D);
2. Tangential modes (2D);
3. Oblique modes (3D).

The reciprocity principle applies to the system considered, so if the point source is placed at a point where a mode is zero, it does not contribute to the sound pressure throughout the room. Then we make the low dissipation assumption whereby it is possible to confuse the resonant frequency with the natural frequency and consider the modal pressure plot around the natural frequency as a resonance curve equal to that of a simple inductance-capacitance system in parallel with low dissipation. The width of the resonance curve is governed by the *damping constant*. An enclosed environment can be considered a multiresonant system, for which reservoirs of kinetic energy cyclically exchange energy with reservoirs of strain potential energy. Modal density represents the number of resonant frequencies within a unit band around the frequency *f*. Given an environment of volume *V*, the modal density increases with the square of the frequency. At low frequencies, few ways contribute whereby the sound pressure level detected in the permanent sinusoidal regime fluctuates widely, moving from point to point in the environment. By recording the sound pressure level at a certain point as the source frequency changes, there will be large fluctuations in the plot in the low frequency region, at high frequencies, on the other hand, there will be a high density of modes exciting the environment with a noise band. When the source frequency is low in the considered environment, the sound pressure is dominated by the sum in amplitude and phase of a few modes. As frequency increases, modal density increases, and with it the degree of superposition of modes. The sound pressure at a point in the environment is the result of the combination of numerous resonantly excited modes, for which the values of amplitude and phase can be considered random. The resulting sound pressure amplitude thus takes on the characteristics of a random variable whose probability density is independent of room type, volume, shape, and nature of acoustic properties. In terms of decay of modes and reverberation, if the source operation is stopped at instant t_i equal to zero each motion decays independently from the others, following the temporal law and the assumption of low dissipation. Sound pressure in the permanent sinusoidal regime consists of a sum of sinusoids at the source frequency, each with a phase relative to that of the source and with an amplitude the greater the closer; the natural frequency of the mode is to that of the forcing source. In acoustics, one of the key interests is the measurement of how quickly, when the source is turned off, the sound dies out in the environment, this is called *Reverberation time* T and it is expressed in seconds. The reverberation time, for a couple source-receiver, is defined as time required for the sound pressure level at the observation point to fall by 60 decibel, starting from the time step in which the source that supported the previous permanent regime is deactivated. It is measured by stressing environment with broadband random noise so that the majority of modules are excited and resonant. Sound pressure level decay is recorded by filtering the sound pressure signal into frequency bands to obtain information on the conventional average decay duration. The sound pressure level of the isolated mode decreases linearly over time with a slope proportional to the damping constant. The reverberation time is derived from the average decay slope. If the modes in a certain frequency band have different damping constants, it is difficult to recognize the decay of the sound pressure level with a single average slope; this depends on the arrangement and nature of the sound-absorbing systems placed in the parallelepiped-shaped room in question.

In conclusion, the modal theory just discussed, refers only to the case of a parallelepiped-shaped room, and cannot be applied for the quantitative determination of the acoustic behavior of any closed environment. Every closed environment, regardless of shape and size, has its own modes with associated resonance frequencies and damping constants. In any case, the nonhomogeneous wave equation can be solved for a nonparallelepiped-closed environment under arbitrary impedance and source conditions. For this purpose, modern, highly computational and equally complex numerical techniques based on finite difference, finite element, and boundary element methods are used. In the daily practice of technical acoustics in enclosed spaces, it is important to detect impulse response as it allows the evaluation of significant descriptors for sound quality and reverberation time [1].

STEADY-STATE, TRANSIENT AND REVERBERATION SOUND PRESSURE

The model that is used to estimate sound pressure is based on the idea that the sound field is caused by a source at an observation point in the environment, and is the combination of a direct field portion and a reverberant field portion. The direct field is if the source-receiver pair is located in the unrestricted free space, while the complex of interactions that the energy emitted by the source has with its surroundings gives the reverberant field.

For the direct field, it is possible to identify the sound energy density D_0 at a certain distance and along a certain direction; on the other hand, for the reverberant field this density is obtained by equaling the incoming power and the outgoing power of the field, and is denoted byD_R. In the total field, it is possible to calculate the sum of the sound energy density of the reverberant field and the direct field in order to obtain the root mean square value of the sound pressure in the room, thus the following relationship applies (formula 2.15)

$$p^2 = D_0 + D_R$$

Formula 2.15 – Sound pressure in the environment.

Near the source, the sound field is dominated by the direct field and remains so for a greater distance the more sound absorbent the environment. In addition, it is also possible to define the "critical distance," denoted by $r_{crit,}$ in terms of the distance from the source, along a specific direction, at which the energy density of the direct field is equal to the energy density of the reverberant field. Critical distance assessment is useful to check, at a given point, which contribution is predominant (direct field or reverberant field). The R, “*constant of the environment*”, is a parameter expressed in square meters and calculated as a function of surface and sound absorption coefficient. When there is the transition from steady state to transient, the equivalent sound absorption area is replaced by $\alpha_{Sab,m}\, S$, where $\alpha_{Sab,m}$ is the Sabine equivalent sound absorption coefficient (in average wrt the environment), and S is the surface of the environment.

Sounds affecting enclosed environments do not have characteristics such as to determine a stationary regime; in fact, speech can be considered a sequence of more or less short sounds with itervals of silence. This acoustic stress has a response of the environment that is rarely maintained in steady state. The environment modifies the sequence of pulses emitted from a source, and such modifications are likely to deteriorate the quality of sound perceived by the listener and thus degrade audio-verbal communication. The problem of speech intelligibility in the late 1800s prompted physicist Sabine, of Harvard University, to study and quantify the time it takes for sound to disappear to perception, starting from the moment the sound source is turned off, thus estimating the duration of the "sound tail". He, after a series of in situ experiments, found that the product of the duration of the sound tail by the absorption of the environment is equal to constant, this discovery is the foundation of Sabine's reverberation time formula, and is written as follows: (formula 2.16)

$$T = 0{,}161 \frac{V}{A}$$

Formula 2.16 – Sabine Reverberation time.

Where:

- *T*: reverberation time (s)
- *V*: volume of the environment (m^3)
- *A*: equivalent sound absorption area (m^2)

Over the years, many other physicists and scholars have applied themselves in the study of reverberation time, producing different formulations, but the fundamental one remains the one written by Sabine in 1898 [1].

DESCRIPTOR PARAMETERS OF OPEN PLAN OFFICES

The Open Plan offices, for reasons of geometry, amount of absorbent material, screens and furniture, the acoustics hypothesis on which the ISO 3382 is based are not verified. Inside this kind of offices the “free paths” distribution is not uniform, the measured reverbaration time are not affected by the boundary conditions and cannot be expected according to EN 12354-6. To sum up, the reverberation time is a low meaning descriptor inside Open Plan environments.

In order to describe the environment inside an Open Plan office the sound field devays in a more or less relevant way moving away from the source. One of the hypothesis is that the energy of the acoustic field decays linearly in space, indeed the ISO 3382-3 [10] wants to measure the spatial decay along a line of recievers set in a region between 2 and 16 meters from the source. In ISO 3382-3 [10], in which the relevant source is the anthropogenic noise, it is proposed the weigthed parameter *Spatial decay rate of speech* $D_{2,S}$, rate of spatial decay of A-weighted sound pressure level (SPL) of speech per distance doubling in decibels. Higer the slope of $D_{2,S}$, higher the environment attenuation of the contribution given by each active speaker to the environmental noise [41].

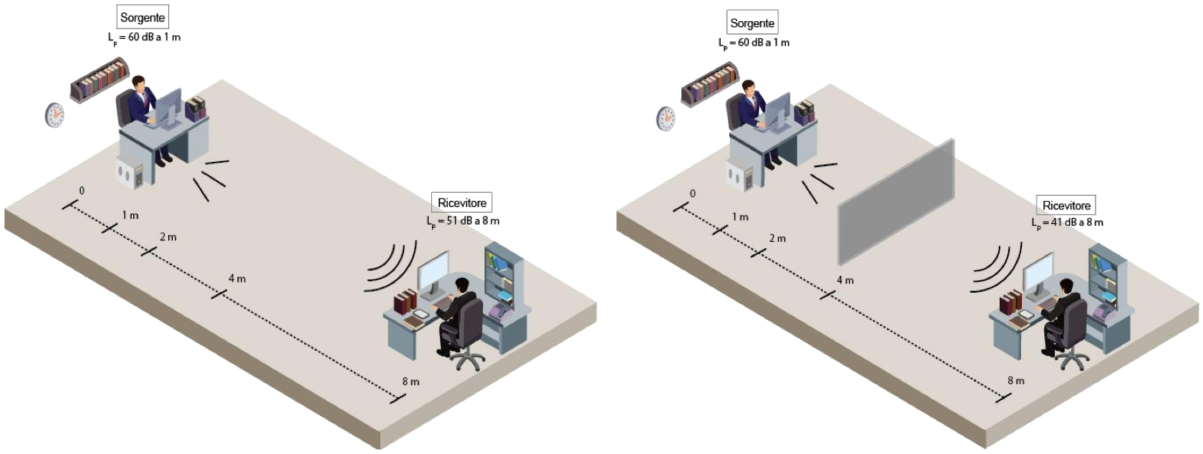


Figure 2.11 – Example of SPL of a speaker at 8m from the source, without screen (left) $D_{2,S}$*=3dB, with screen (right)* $D_{2,S}$*=6dB.*

From the same line decay of the SPL in environment, it could be find out the descriptor $L_{p,A,S,4m}$ - *Speech level at 4 m distance* - A-weighted SPL of speech in decibels at the distance of 4,0 m from the middle point of the OSS (Omnidirectional Sound Source). The source has a vocal effort “normal” and 4m is the fixed distance between two adjacent workstations. Lower the $L_{p,A,S,4m}$, lower will be the worker exposure to the sum of humen noise contributions coming from the closer workstations.

Recently, in 2022, in the revised version of ISO 3382-3, the *comfort distance* r_c, this is the distance in which the sound energy decay crosses the 45 dB level. At this distance it is supposed that the SPL related to an active speaker source it is equal to the background noise inside the office. Strictly related with privacy and productivity it is the decay of the signal correlation matrix, that weighted gives the STI - *Speech Transmission Index* - decay with respect to the source-receiver distance, where STI is quantity describing the transmission quality of speech from speaker to listener. The *distraction distance* r_d is not included in ISO 22955:2021. In current standards does not exists previsional models of STI spatial decay, because the IEC 60268-16:2020 takes into account a Sabine environment.

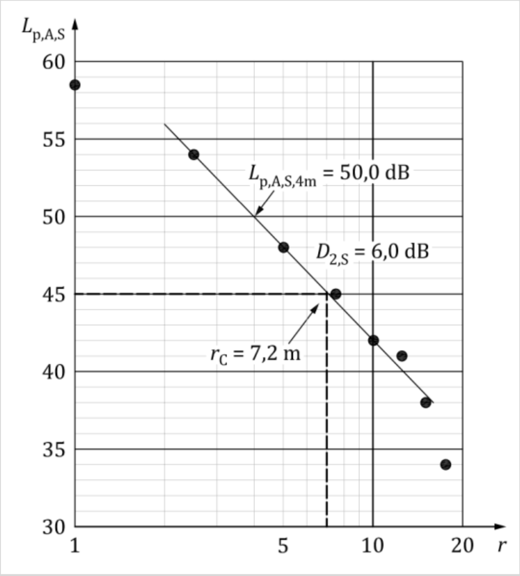


Figure 2.12 – Method used to find out $D_{2,S}$, $L_{p,A,S,4m}$, r_c, starting from spatial decay measures in environment.

Current literature provides the following forecasting formulas to find out in a strong way the parameters $D_{2,S}$, $L_{p,A,S,4m}$. Those formulas are (formula 2.17, 2.18):

$$D_{2,s} = 8\frac{h}{H} + 0.168\frac{L}{H} - 4\alpha_c$$

Formula 2.17 - Spatial decay rate of speech $D_{2,S}$.

$$L_{A,S,4m} = L_{A,S,1m} - 3h - 0.1W - 4.6\alpha_c - 0.8\alpha_f$$

Formula 2.18 - Speech level at 4 m distance $L_{p,A,S,4m}$.

Those two equations were proposed on experimental base and partially verified thourgh numerical simulation [41].

SUPPORT CONCENTRATION IN WORKPLACES

In order to increase the acoustic comfort of open plan offices and support concentration in workplaces can be consedered the influences of absorption, screens and the background noise. These concepts are foundamental to reduce the reverberation time (formula 2.10) and increase the STI inside a room. The contribution of the absorption is considered through the Equivalent Sound Absorption Area, in the reverberation time. This area si computed as it is shown in the following formula [1] (formula 2.19)

$$A = \sum_i S_i * \alpha_i + \sum_j A_{obj,j}$$

Formula 2.19 - Equivalent Sound Absorption Area.

Where:

- S: surface of each considered element
- α_i: sound absorption coefficient, known w.r.t. frequencies
- $A_{obj,j}$: equivalent sound absorption area of the furnishings

All these considereations are developed in unoccupied conditions. In situations in which the requirements of T, given by the standards, are not satified it is possible to increase this area by adding some sound reducing surfaces, to ceiling or walls, like baffles. The influence of the screens can be considered with the spatial decay rate of A-weighted SPL of speech, $D_{2,S}$. This parameter shows that distraction and privacy distances decrease with increased screen height. The influence of background noise affects only the STI parameter, and increasing the backroung noise there is a positive influence on distraction distance and privacy distance. This last one may be a useful parameter when the background noise from human activities is applied.

In conclusion, in order to reach an appropriate noise control in open-plan offices, independently by user's furniture and behaviour, the building owner shall considers the following room acoustic measures:

- Sound masking systems;
- Maximization of ceiling absorption;
- Maximization of wall absorption;
- The use of textile floor coverings.

Always the building owner could considers the soundproofing below:

- Proper isolation of open-plan offices from aisles, corridors, coffee areas, and fronts of meeting rooms;
- Provision of anonymous rooms for silent work by an amount of 1 room per 5 employees, to imporove speech privacy and environmental satisfaction.

Finally, the user could consider these room acoustic and behavioural means:

- High screens, preferably 170 cm or more, when the work requires high speech privacy. The screens should be sound absorbing up to 130 cm height and sound isolating. Transparent screens can be used above 130 cm;
- Provision of mobile soundproof booths for phone conversations, virtual meetings, and small group working pods in the vicinity of workstations;
- The use of the space and behavior in the space (the silent zones, conversational zones, policy of using silent workrooms, and other means to reduce noise) must be respected by all the employees;
- High-quality headsets during phone calls and internet meetings in order to reduce the noise level in the office and improves the communication.

All these parameters and expedients could be used to evaluate the proper room acoustic, in order to reduce the noise and increase the speech privacy in open-plan offices [7].

3 Current standards and guidelines for workplace acoustics

Every country has its standards and voluntary protocols or certifications to guarantee the acoustic compfort in workplaces through the right design of the open plan offices, taking care the geometric characteristics of the environments. In Italy, the big studies of designers sometimes want to work with American protocols, but this could be critical especially because in Italy, the last majority of interventions are of rehabilitation and the buildings are often full of architectural restraints. On the contrary, in the USA for example, there could be the opposite situation and the offices have completely different geometric characteristics with respect to the Italian one. Therefore the aim of this section is to find out as much as possible of the available standards and voluntary certifications (based on local standards), to find out the configurations, the parameters and their thresholds, in order to trying to understand if they are applicable or not in an Italian context [2].

3.1 ISO 22955:2021, Acoustic quality of open office spaces

The open-plan offices are increasingly common. They can cause apprehension from users due to noise and the difficulty of performing two theoretically contradictory activities in terms of acoustics: oral communication and focused individual work. In this type of space, disturbance caused by speech can result in tension between people who want to concentrate and people who are required to talk to perform their activity. ISO 22955:2021 wants to offer principles, descriptors and measurement methods to characterise acoustics, easy ro use and correspond to the perception of the acoustical environment by the occupants of the spaces. This standard establishes a link between acoustic quality and the acoustic performance to be achieved in an open office.

SCOPE

This standard wants to provide a technical guidance to achieve acoustic quality of open office spaces to support dialogue and formal commitment between the various stakeholders involved in the planning, design, construction or layout of open-plan workspaces. Inside the standard, each open-plan office can be indentified in a specific space type according to the activity that is perfomed inside. This ISO is valid for both, new and existing (rehabilitation) buildings.

NORMATIVE REFERENCE

This standard took its references for its requirements and contents from:

- ISO 354, Acoustics – Measurement of sound absorption in a reverberation room
- ISO 11654, Acoustics – Sound absorbers for use in buildings – Rating of sound absorption

TERMS AND DEFINITIONS

In this section of the standard are defined the general terms, the terns related to the workspace layout, the terms related to acoustics, the acoustic descriptors and related terms. The key definitions to keep in mind are:

- *Open-plan space/office, open or shared space*: workspace designed to accommodate multiple persons working without full separation between workstations;
- *Worksation*: position occupied to perform a task;
- *Workspace*: open-plan space, in which the workstations required to perform the activity are sitributed;
- *Open-plan space area*: total floor area, in square meters, of the open plan office;
- *Intelligibility*: percentage of speech understood;
- *Lombard effect*: phenomenon of a person unconsciously altering his/her way of speaking (adaptation of fundamental frequency, sound level and articulation) to make up for the presence of surrounding noise and to be better understood by his/her conversation partners;
- *Signal-to-noise ratio* [dB]: arithmetical difference between the signal level and the disturbing noise level.

While the most important acoustic descriptors and related terms are:

- *Workstation noise level* $L_{Aeq,T}$: L_{Aeq} is the A-weighted, equivalent continuous sound level in dB measured over a stated period of time T

$$L_{Aeq,T} = 10lg\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}\left(\frac{p_A^2(t)}{p_0^2}\right)dt\right]$$

Formula 3.1 – Workstation noise level.

Where:

T: time interval starting at t_1 and ending at t_2 (s)

p_0: rerference acoustic pressure value ($p_0 = 2 \cdot 10^{-5}$ Pa)

$p_A(t)$: istantaneous A-weighted sound pressure at the workstation (Pa)

- *Spatial decay rate of speech* $D_{2,S}$: rate of spatial decay of A-weighted sound pressure level of speech per distance doubling;
- *Reverberation time* T_r: time, in seconds, required for the existing noise level inside a room to decrease by 60 dB, when the noise source is instantly interrupted;
- *In situ acoustic attenuation of speech* $D_{A,S}$: difference, in decibels, between an A-weighted speech source spectrum at 1 m from an omni-directional source in the free field and the A-weighted sound pressure level at a reception point;
- A/S_{floor}: equivalent absorption area divided by the floor surface area.

GENERAL APPROACH

An open-plan space could be defined as a flexible space, used for communications, discussions, free flow of informations and activities associated with a job. However, not all the speech generated in an open-plan office is always helpful for people’s work in every area of this space. The acoustic of this space type must take care of these different activities often performed at the same time. To find an optimum solution in an open-plan space and fully understand the complexity of its acoustics, employee activity, interactions and relative distances between workstations, work teams and departments should be taken into account for a given open-plan space. Site environment and the technical and architectural constraints should also be considered. This standard can be seen as a guideline in design and construction phases of open-plan workspaces. This document considers people (no restrictions in terms of behaviour) as a key element of the acoustic environment.

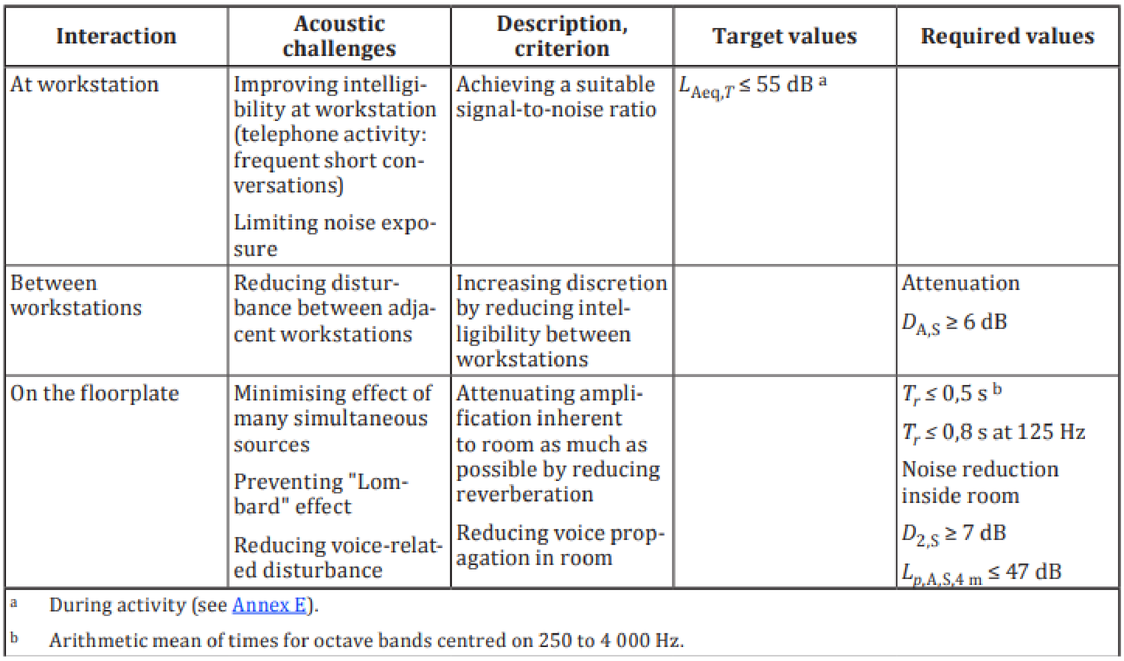
TYPOLOGY, ACOUSTIC CHALLENGES AND REQUIREMENTS

The open workspaces shall be adapted to support all the activities that take place inside. The noise environment can be very different depending on the type of activities. Note that this type of offices are not suitable for activities, which require confidential communication. The ISO defines six types of open-plan space covering all the existing activities and the designer shall refers to them in order to apply the right acoustic criteria. They are:

1. Space type 1: activity not known yet – vacant floor plate;
2. Space type 2: activity mainly focusing on outside of the room communication (by telephone/audio/video);
3. Space type 3: activity mainly based on collaboration between people at nearest workstation;
4. Space type 4: activity based on a small amount of collaborative work;
5. Space type 5: activity that can involve receiving public;
6. Space type 6: combining activities within the same space.

For each space type interaction the standard defines the interaction, the acoustic challenges, the description/criterion, target values and the required values. For each space type here below are reported the tables with the acoustic indicators and values activity based.

- Space type 2: activity mainly focusing on outside of the room communication



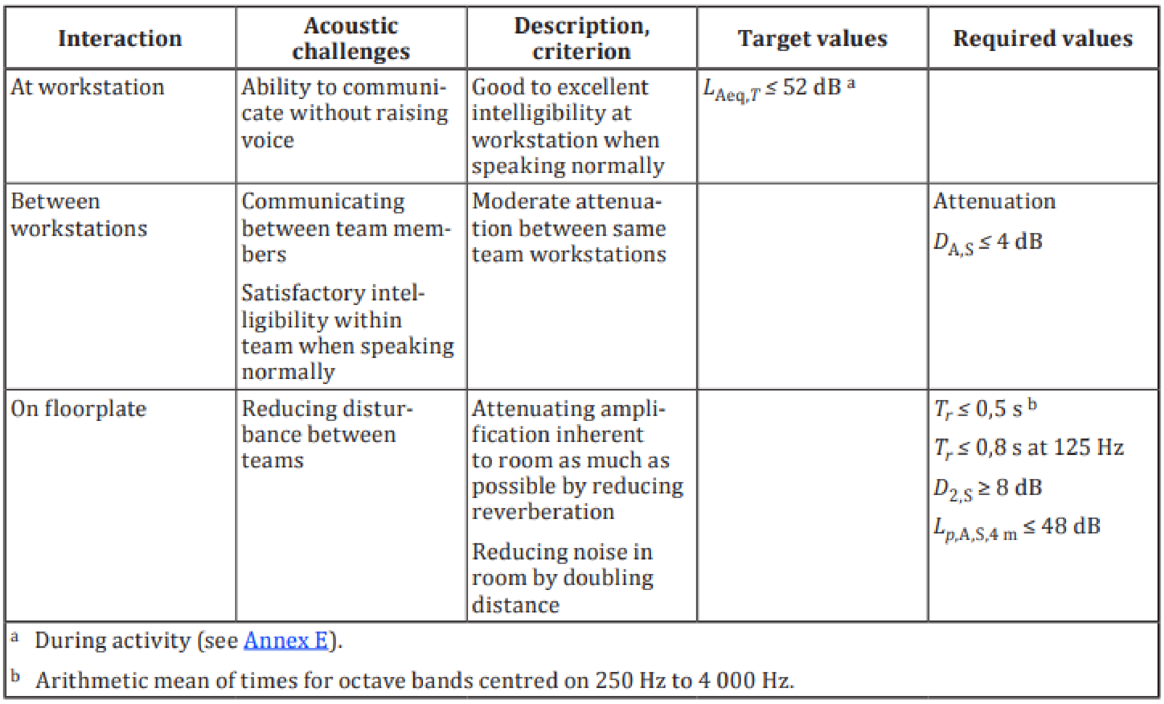
Interaction	**Acoustic challenges**	**Description, criterion**	**Target values**	**Required values**
At workstation	Improving intelligibility at workstation (telephone activity: frequent short conversations) Limiting noise exposure	Achieving a suitable signal-to-noise ratio	$L_{\mathrm{Aeq},T} \le 55$ dB [a]	
Between workstations	Reducing disturbance between adjacent workstations	Increasing discretion by reducing intelligibility between workstations		Attenuation $D_{\mathrm{A,S}} \ge 6$ dB
On the floorplate	Minimising effect of many simultaneous sources Preventing "Lombard" effect Reducing voice-related disturbance	Attenuating amplification inherent to room as much as possible by reducing reverberation Reducing voice propagation in room		$T_r \le 0,5$ s [b] $T_r \le 0,8$ s at 125 Hz Noise reduction inside room $D_{2,\mathrm{S}} \ge 7$ dB $L_{p,\mathrm{A,S},4\,\mathrm{m}} \le 47$ dB

[a] During activity (see Annex E).

[b] Arithmetic mean of times for octave bands centred on 250 to 4 000 Hz.

Table 3.5 – Acoustic indicators and values | Space type 2.

- Space type 3: activity mainly based on collaboration between people at nearest workstation



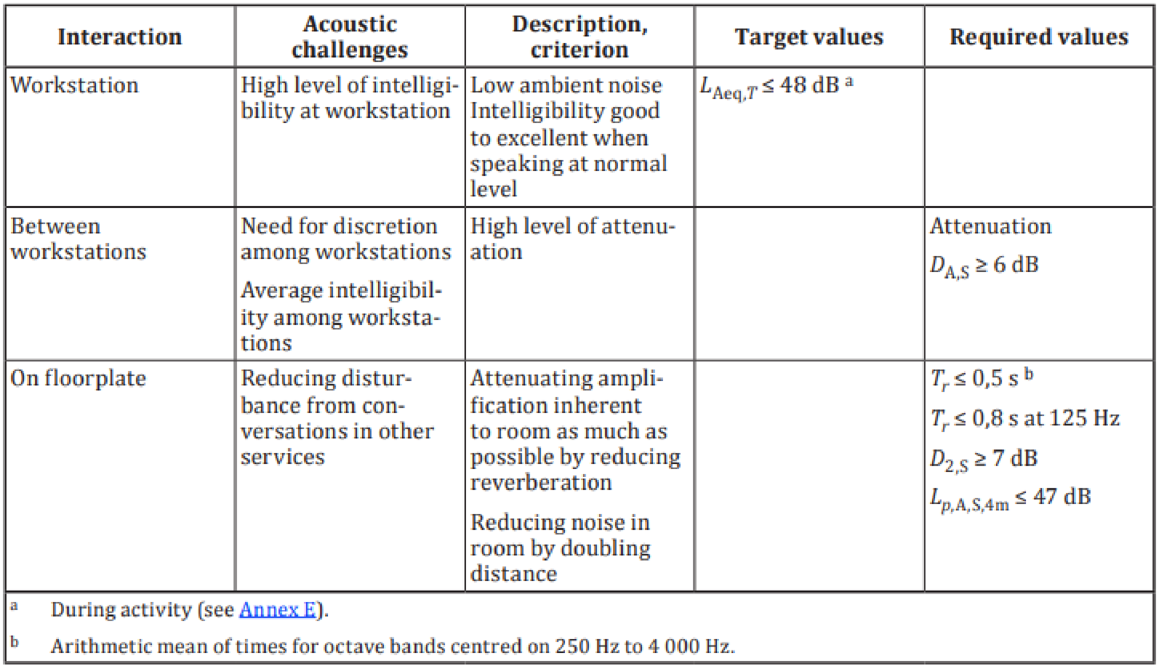
Interaction	Acoustic challenges	Description, criterion	Target values	Required values
At workstation	Ability to communicate without raising voice	Good to excellent intelligibility at workstation when speaking normally	$L_{\mathrm{Aeq},T} \leq 52$ dB [a]	
Between workstations	Communicating between team members Satisfactory intelligibility within team when speaking normally	Moderate attenuation between same team workstations		Attenuation $D_{\mathrm{A,S}} \leq 4$ dB
On floorplate	Reducing disturbance between teams	Attenuating amplification inherent to room as much as possible by reducing reverberation Reducing noise in room by doubling distance		$T_r \leq 0,5$ s [b] $T_r \leq 0,8$ s at 125 Hz $D_{2,\mathrm{S}} \geq 8$ dB $L_{p,\mathrm{A,S,4\,m}} \leq 48$ dB

[a] During activity (see Annex E).

[b] Arithmetic mean of times for octave bands centred on 250 Hz to 4 000 Hz.

Table 3.6 – Acoustic indicators and values | Space type 3.

- Space type 4: Activity mainly based on a small amount of collaborative work



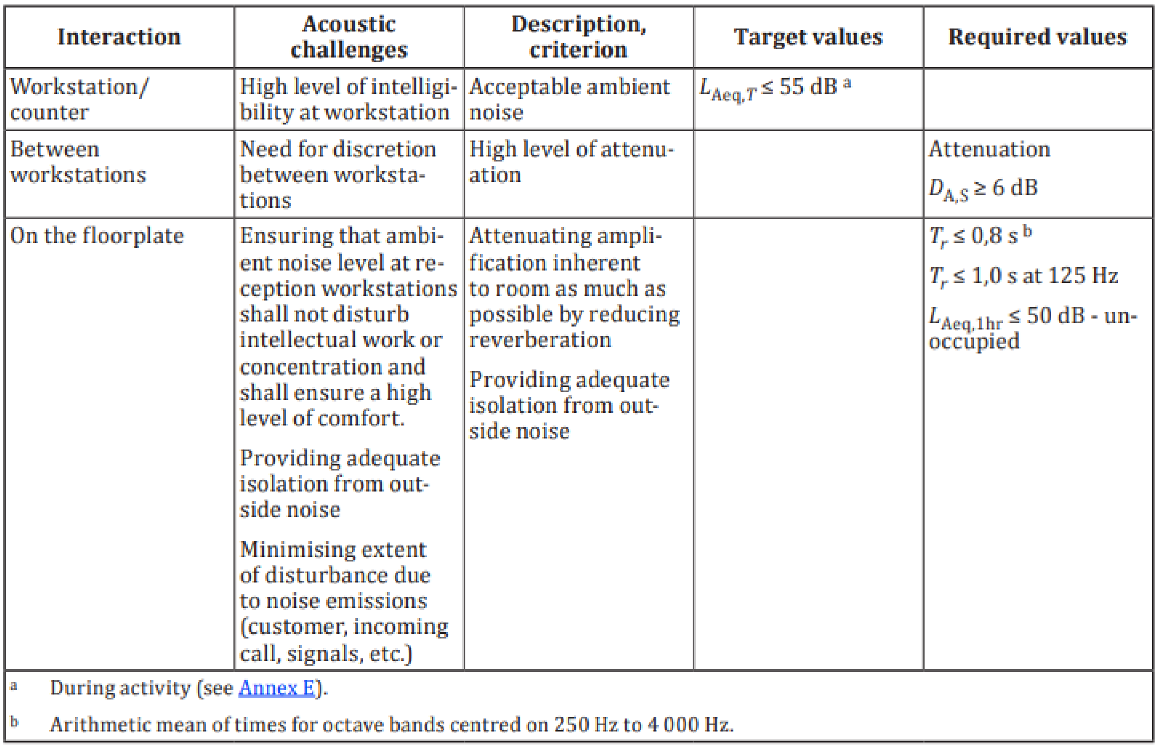
Interaction	Acoustic challenges	Description, criterion	Target values	Required values
Workstation	High level of intelligibility at workstation	Low ambient noise Intelligibility good to excellent when speaking at normal level	$L_{\mathrm{Aeq},T} \leq 48$ dB [a]	
Between workstations	Need for discretion among workstations Average intelligibility among workstations	High level of attenuation		Attenuation $D_{\mathrm{A,S}} \geq 6$ dB
On floorplate	Reducing disturbance from conversations in other services	Attenuating amplification inherent to room as much as possible by reducing reverberation Reducing noise in room by doubling distance		$T_r \leq 0,5$ s [b] $T_r \leq 0,8$ s at 125 Hz $D_{2,\mathrm{S}} \geq 7$ dB $L_{p,\mathrm{A,S,4m}} \leq 47$ dB

[a] During activity (see Annex E).

[b] Arithmetic mean of times for octave bands centred on 250 Hz to 4 000 Hz.

Table 3.7 - Acoustic indicators and values | Space type 4

- Space type 5: activity that can involve receiving public



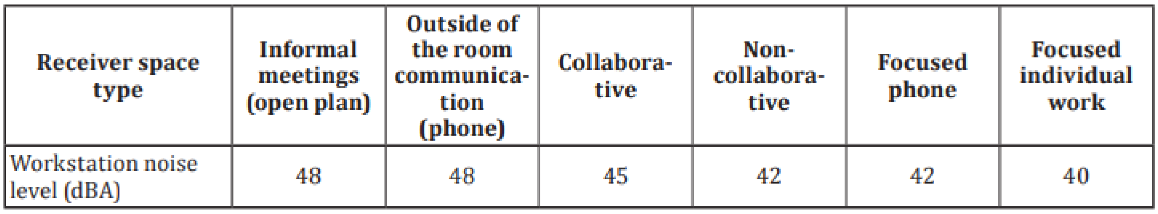
Interaction	Acoustic challenges	Description, criterion	Target values	Required values
Workstation/ counter	High level of intelligibility at workstation	Acceptable ambient noise	$L_{\mathrm{Aeq},T} \leq 55$ dB [a]	
Between workstations	Need for discretion between workstations	High level of attenuation		Attenuation $D_{\mathrm{A,S}} \geq 6$ dB
On the floorplate	Ensuring that ambient noise level at reception workstations shall not disturb intellectual work or concentration and shall ensure a high level of comfort. Providing adequate isolation from outside noise Minimising extent of disturbance due to noise emissions (customer, incoming call, signals, etc.)	Attenuating amplification inherent to room as much as possible by reducing reverberation Providing adequate isolation from outside noise		$T_r \leq 0{,}8$ s [b] $T_r \leq 1{,}0$ s at 125 Hz $L_{\mathrm{Aeq,1hr}} \leq 50$ dB - unoccupied

[a] During activity (see Annex E).

[b] Arithmetic mean of times for octave bands centred on 250 Hz to 4 000 Hz.

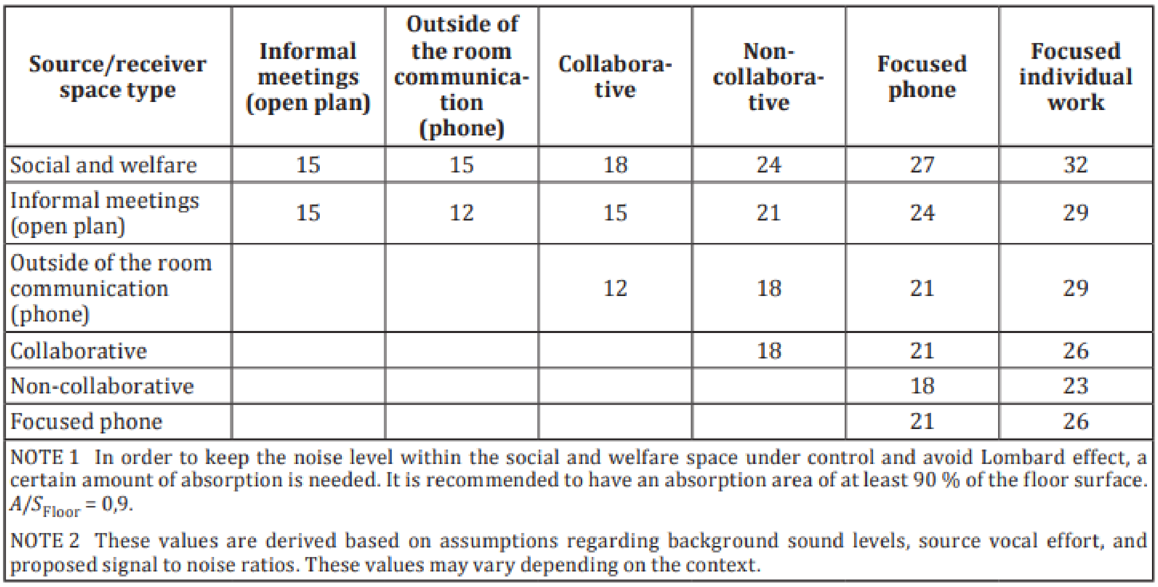
Table 3.8 - Acoustic indicators and values | Space type 5.

- Space type 6: combining activities within the same space



Receiver space type	Informal meetings (open plan)	Outside of the room communication (phone)	Collaborative	Non-collaborative	Focused phone	Focused individual work
Workstation noise level (dBA)	48	48	45	42	42	40

Table 3.9 - Workstation noise levels assumed for different types of activity | Space type 6.



Source/receiver space type	Informal meetings (open plan)	Outside of the room communica-tion (phone)	Collabora-tive	Non-collabora-tive	Focused phone	Focused individual work
Social and welfare	15	15	18	24	27	32
Informal meetings (open plan)	15	12	15	21	24	29
Outside of the room communication (phone)			12	18	21	29
Collaborative				18	21	26
Non-collaborative					18	23
Focused phone					21	26

NOTE 1 In order to keep the noise level within the social and welfare space under control and avoid Lombard effect, a certain amount of absorption is needed. It is recommended to have an absorption area of at least 90 % of the floor surface. $A/S_{\text{Floor}} = 0{,}9$.

NOTE 2 These values are derived based on assumptions regarding background sound levels, source vocal effort, and proposed signal to noise ratios. These values may vary depending on the context.

Table 3.10 - Potential $D_{A,S}$ ratings between different types of spaces | Space type 6.

WORKSPACE LAYOUT AND ROOM ACOUSTICS

Workspace layout and work organisation shall be strictly connected. An open-plan space can be considered succesful if there is coordination between all the features, activities and situations described before. Workstations are based on a team-by-team organization, obtained aftern an analysis on flows and interactions between activity-related teams and production or department objectives. There are some general recommendations and measures to be considered with respect to regulations governing workspace design, especially in relation to personal safety and accessibility. Inside the document, for each type of open-plan space, are defined some indications for:

- Dimensions and geometry;
- Position of support spaces;
- Distance between workstations;
- Principles of room acoustics treatment (appied to ceiling, wall, floor);
- Effect of type of furniture (screen fixed to worktop, free-standing screens and suspended screens);
- Accessibilty and special needs.

[4]

3.2 ISO 3382-3:2022, Measurement of room acoustic parameters – Open plan offices

Open-plan office is a large and open office space where large number of occupants can simultaneously work in well-defined workstations. Both flexible offices and activity-based offices often involve spaces that resemble open-plan offices. Open working areas, which can be considered as open-plan offices, can also be found in many libraries, hospital wards, industrial workplaces, and schools. The method defined in this standard describes the acoustic performance of the open-plan office in a standardized condition where a single occupant is speaking with normal speech effort. It uses omnidirectional sound source to provide reproducible results between measurement operators. Room acoustic quality can be affected by the amount and positioning of wall and ceiling sound absorption materials, room geometry, workstations, screens, other furniture, floor coverings, and background sound level.

SCOPE

The aim of this standard is to identify a method for the measurement of room acoustic parameters in unoccupied open-plan offices. It specifies measurement procedures, the apparatus needed, the coverage required, the method for evaluating the data, and the presentation of the test report.

NORMATIVE REFERENCES

This standard took some contents and requirements from:

- ISO 3382-1, *Acoustics – Measurement of room acoustic parameters – Part 1: Performance spaces*
- IEC 60268-16, *Sound system equipment — Part 16: Objective rating of speech intelligibility by speech transmission index*
- IEC 60942, *Electroacoustics — Sound calibrators*
- IEC 61260*, Electroacoustics — Octave-band and fractional-octave-band filters*
- IEC 61672-1, *Electroacoustics — Sound level meters — Part 1: Specifications*

TERMS AND DEFINITIONS

Some the key parameters, for the evaluation of the acoustic comfort in open plan offices, are:

- *Spatial decay rate of speech* $D_{2,S}$: rate of spatial decay of A-weighted sound pressure level (SPL) of speech per distance doubling in decibels;
- *Speech level at 4 m distance* $L_{p,A,S,4m}$: A-weighted SPL of speech in decibels at the distance of 4,0 m from the middle point of the OSS (Omnidirectional Sound Source);
- *Speech Transmission Index* STI: quantity describing the transmission quality of speech from speaker to listener;
- *Distraction distance* r_d: shortest distance from the middle point of the OSS where the STI is lower than 0,50;
- *Workstation*: furniture ensemble containing at least one chair and one table having a minimum size of 70 cm x 70 cm;
- *Sound masking system*: centralized or networked electronic system used to produce spatially constant background sound in the workstation area.

MEASUREMENT CONDITIONS

In this section of the standard are defined the equipment and the measurement procedure. The first one should be composed of sound source, microphone, analyser and calibrator. While the second one provide guidelines for measurement conditions, acoustic zones and measurements paths, source and microphone positions, measured quantities.

DETERMINATION OF SINGLE-NUMBER VALUES

The parameters used to find out single-number values are:

- Spectrum of normal speech;
- Spatial decay rate of speech (computed with conventional or impulse response method);
- Speech level at 4 meters distance;
- Background noise level;
- Speech transmission index;
- Comfort and distraction distances.

Each of these single-number values have their own precision.

Finally, a full information test report should be provided.

[9]

3.3 AS/NZS 2107:2016, Design sound levels and reverberation times for building interiors

This is the Australian and New Zeland standard with the aim of providing methods for the measurement of compliance in terms of background noise and reverberation times. It recommends design criteria for conditions affecting the acoustic environment within occupied spaces.

SCOPE

The standard recommend some design criteria to be followed in order to reach acoustic comfort of the users inside buildings. The background sound levels recommended take into account the function of the area and apply the sound level measured within the space unoccupied but ready for occupancy. The reverberation times recommended are for the occupied state of the space.

APPLICATIONS AND LIMITATIONS

This standard defines applications and limitations that could be met during the design phase. Indeed this documenti is intended for the use by designers of environments within occupied spaces in new and existing buildings, as for example the selection and assessment of building materials and services used in these spaces. While for limitations, for example, this standard is not intended for application to sounds that are not categorized as steady-state or quasi-steady-state.

REFERENCED DOCUMENTS

This document is referred to standards like AS, AS IEC, AS ISO, AS/NZS, ISO, IEC, NZS, ANSI/ASA and DIN.

DEFINITIONS

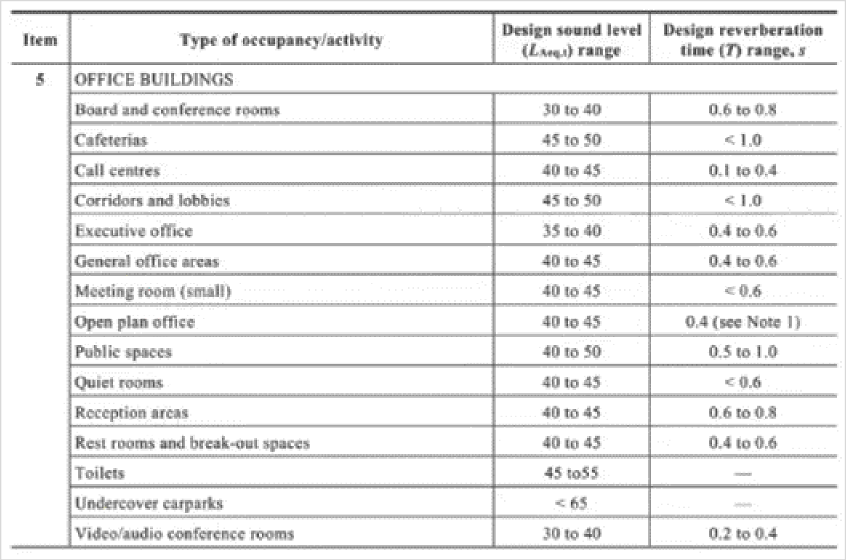
The definitions of the two key parameters for the office buildings used in the standard are those listed below:

- *Design sound level* $L_{Aeq,t}$ *range*: The sound level given in this standard are for the design of spaces in buildings. Sound levels within the given ranges have been found to be acceptable by most people of the space under consideration. When $L_{Aeq,t}$ is grater than the upper level, most of people cuold be dissatisfied, while when $L_{Aeq,t}$ is lower than the lower level, the inadequacy of background sound to provide masking sound can beome problematic (lack of privacy);

- *Reverberation time* T: The reverberation time of an enclosure, for a sound of a given frequency band, is the time that would be requires for the reverberantly decaying sound pressure level in the enclosure to decrease by 60 dB.

RECOMMENDED DESIGN SOUND LEVELS AND REVERBERATION TIMES

In this standard are collected in tables the design sound levels and reverberation times for different areas of occupancy in buildings. The building offices are the item 5 and the ranges are those reported in the table below (table 3.10)



Item	Type of occupancy/activity	Design sound level ($L_{Aeq,t}$) range	Design reverberation time (T) range, s
5	OFFICE BUILDINGS		
	Board and conference rooms	30 to 40	0.6 to 0.8
	Cafeterias	45 to 50	< 1.0
	Call centres	40 to 45	0.1 to 0.4
	Corridors and lobbies	45 to 50	< 1.0
	Executive office	35 to 40	0.4 to 0.6
	General office areas	40 to 45	0.4 to 0.6
	Meeting room (small)	40 to 45	< 0.6
	Open plan office	40 to 45	0.4 (see Note 1)
	Public spaces	40 to 50	0.5 to 1.0
	Quiet rooms	40 to 45	< 0.6
	Reception areas	40 to 45	0.6 to 0.8
	Rest rooms and break-out spaces	40 to 45	0.4 to 0.6
	Toilets	45 to55	—
	Undercover carparks	< 65	—
	Video/audio conference rooms	30 to 40	0.2 to 0.4

Table 3.10 – $L_{Aeq,t}$ and T ranges for office buildings.

Where “Note 1” states that reverberation time should be minimized for noise control.

METHOD OF MEASUREMENT

The standard defines for both parameters the methods to be applied in measurement phase. For the $L_{Aeq,t}$ defines the operating conditions of the building, the measurement locations, the time at which the measurement is taken, the calibration, the field checks, the spectral imbalance and the narrow band signals. While the measurement of T shall comply with the relevant part of ISO 3382.

[5]

3.4 Standard Guide for Open Office Acoustics and Applicable ASTM Standards

There are no full height partitions in an open-plan office to block sound transmission between adjacent workstations. Instead, partial height barriers, a sound absorbing ceiling and absorption on vertical surfaces are used to provide sound attenuation between individuals. These, in combination with workstation layout and appropriate levels of broadband masking sound are used to obtain acceptable degrees of acoustical privacy.

SCOPE

This document discusses the acoustical principles and interactions that affect the acoustical environment and the acoustical privacy in the open offices.

REFERENCED DOCUMENTS

A series of ASTM Standards were used to define the acoustical principles and interactions with the environment applied to open-plan offices. These referenced documents define different test methods accordind to the type of measurement that should be performed.

SUMMARY OF GUIDE

In terms of acoustical privacy, the attenuation of sound between workstations in an open-plan office is less than the one in a closed-office. In any case, a certain degree of acoustical privacy can be reach through a good interaction between all the elements deal all together in the right way. Indeed a succesful open-plan office is the result of careful coordination of several components (ceiling, wall treatments, furniture and furnishings, heating, ventilating and air-conditioning system, and masking sound system). This guide delineates the role and interaction of the several components and the application of the relevant ASTM Standards.

SIGNIFICANCE AND USE

This guide is useful for all the designers involved in the project of an open-plan office, but it is not valid for open-plan schools. This guide wants to clarify the variables that influence the office privacy. In order to develope a successful project the knowledge of the expert should be taken into account and should be done a comparison of test results carried out according to ASTM standards.

GENERAL OPEN OFFICE ACOUSTICAL CONSIDERATIONS

The first important aspect is the attenuation with distance. Indeed, in almost any enclosed space there is some reduction of sound with distance. In typical spaces generally the sound level decreases with distance and reflections from the surfaces (ceiling, wall, floor). In open-plan offices the goal is to maximize this loss with distance in order to improve acoustical privacy. This requires an absorbent ceiling, some absorption on the floor, and careful treatment of nearby vertical surfaces. The ideal is to approach the conditions of the outdoors, where there are no reflecting surfaces. Attaining acoustical privacy between workstations is determined by the degree to which the intruding sounds from adjacent workstations exceed the ambient sound levels at the listener’s ear. The sound pressure levels arriving at listener’s ear from sources in adjacent workstations depend on different aspects like the sound source amplitude, directivity and orientation. Office layout should be designed to avoid noise intrusion possibilities. The loud noises like the raised voices or loud office equipment could cause distraction, so some closed spaces for conferencing should be provided. Devices like computers, copiers, typewriters are noise sources, and this problem could be solved minimizing as much as possible providing special work areas with an adequate noise isolation from the surrounding open plan spaces. In undivided workspaces, the acoustical comfort may be improved by adding horizontal and vertical sound absorption surfaces. ASTM test methods exist for testing components and systems for open plan offices. These include measuring the attenuation between workstations by the ceiling path, the effect of barriers such as furniture panels. The objective determination of speech privacy should be done following specific test methods measuring speech privacy in open-plan offices, it is based on a determination of the articulation index and the speech privacy may be described as *confidential* and *normal* or *non-intrusive*, according to the vocal effort.

COMPONENTS OF THE OPEN PLAN ACOUSTICAL ENVIRONMENT

The components of the open-plan acoustical environment are:

- Ceilings;
- Sound barriers and vertical surfaces (sound reflectors, sound barriers, flanking transmission, barrier height, electrical raceways, hang-on components);
- Special considerations for windows and the application of the absorption to circular columns;
- Sound masking.

EVALUATION OF MOCK-UP OR COMPLETED SPACE

Since the performance of an open office is dependent on the interaction of several components, it is important that the influence of the various elements and components be investigated early in the planning phase. A mock-up of several typical office modules can be evaluated using the techniques in Test Method E1130. If convenient, a field evaluation can be made at or near job completion, to determine if program or specification requirements have been met.

[10]

3.5 WELL Certification

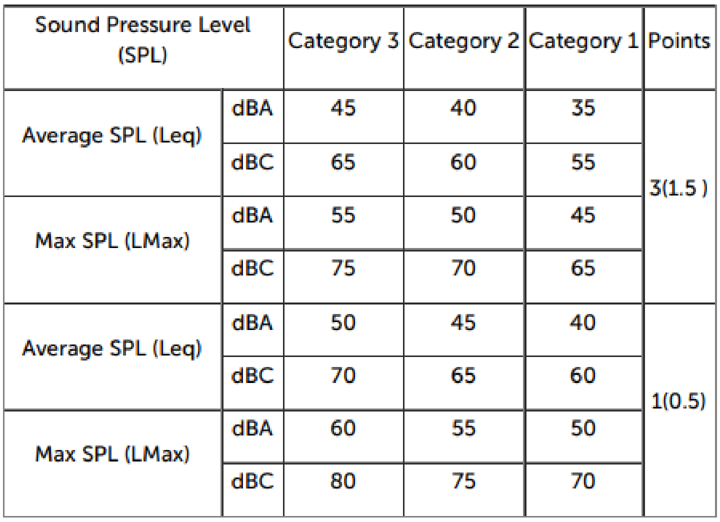
The WELL Building Standard is a standard born in the United States of America in the last few years. This standard is built up on ten concepts and each concept consisits of features with distinct health intents. Features are either preconditions or optimizations. Projects must achieve all the preconditions, as well as a certain number of points towards different levels of WELL Certification (bronze, silver, gold, platinum). WELL V2 operates on a points-based system, with 110 points available in each project scorecard. Projects may pursue no more than 12 points per concept and no more than 100 points total across the ten concepts. In particular, the *WELL V2 – Sound*, the acoustics' section, is made of one precondition and five optimizations. The aim of this concept is to increse acoustical comfort inside the environments and it defines different thresholds according to the geometry, the dimensions, the space type and others factors that chages according to the analyzed feature. Let's analyze in detail all these features.

FEATURE S01 – SOUND MAPPING | PRECONDITION

This WELL feature requires projects to strategize an acoustical plan that identifies sources of noise that can negatively affect interior spaces. For all the spaces inside the building must be submitted a document in which are labeled all the zones throughout the project floor plan or similar schematic documents as loud zones, quiet zones, mixed zones and circulation zones.

FEATURE S02 – MAXIMUM NOISE LEVEL | OPTIMIZATION

This WELL feature prescribes maximum thresholds for ambient background noise that correspond to optimal levels of interior and exterior noise exposure. This feature is valid for all the spaces except dwelling units, commercial kitchen spaces and industrial. The background noise levels are measured over a period of five minutes and average sound pressure levels do not exceed the following thresholds, and these requirements are met: (table 3.1)



Sound Pressure Level (SPL)		Category 3	Category 2	Category 1	Points
Average SPL (Leq)	dBA	45	40	35	3(1.5)
	dBC	65	60	55	
Max SPL (LMax)	dBA	55	50	45	
	dBC	75	70	65	
Average SPL (Leq)	dBA	50	45	40	1(0.5)
	dBC	70	65	60	
Max SPL (LMax)	dBA	60	55	50	
	dBC	80	75	70	

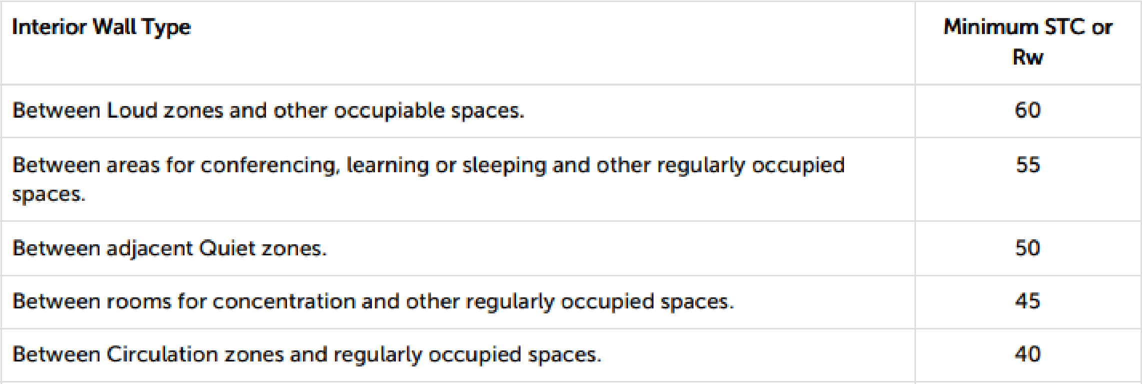
Table 3.1 – Limit background noise level.

Where:

- Category 1: Areas for conferencing, learning or speaking;
- Category 2: Enclosed areas for concentration;
- Category 3: Open areas for concentration, spaces with PA systems and areas for dining.

FEATURE S03 – SOUND BARRIERS | OPTIMIZATION

This WELL feature requires that walls and doors meet a minimum degree of acoustical separation to provide adequate sound isolation and improve speech privacy. In the first part of the design for sound isolation at walls and doors for all the spaces, interior walls meet the following sound transmission class STC or weighted sound reduction (R_W) values. (table 3.2)



Interior Wall Type	**Minimum STC or Rw**
Between Loud zones and other occupiable spaces.	60
Between areas for conferencing, learning or sleeping and other regularly occupied spaces.	55
Between adjacent Quiet zones.	50
Between rooms for concentration and other regularly occupied spaces.	45
Between Circulation zones and regularly occupied spaces.	40

Table 3.2 – Design for Sound Isolation at Walls and Doors.

All the values are expressed in dB and they define a rating of sound isolation of a building wall assembly. Higher is the value, the better is the sound isolation of the wall.

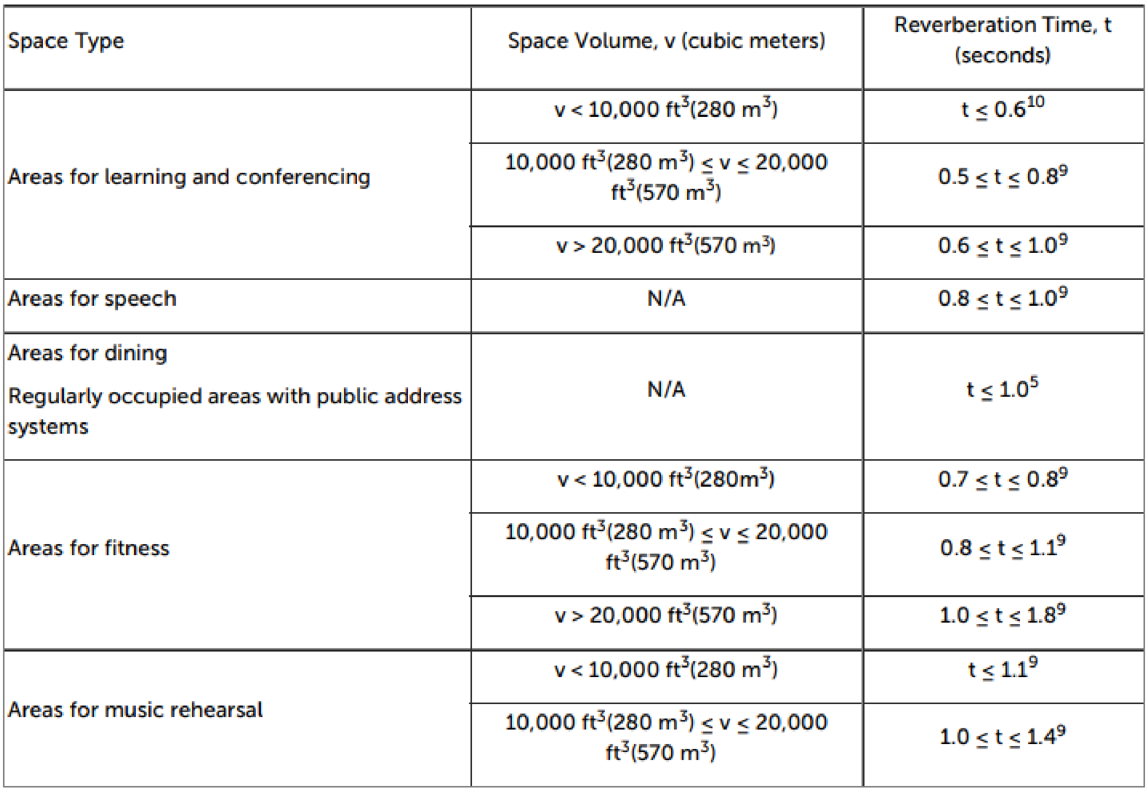
There exisist also a second part with the aim of achieving sound isolation at walls for all the spaces, and to do that it is possible to choose between two different options:

1. Noise isolation class;
2. Speech privacy.

Both have their requirements that must be respected.

FEATURE S04 – REVERBERATION TIME | OPTIMIZATION

This WELL feature requires that steps be taken to address acoustical comfort, by controlling reverberation time based on room functionality. The aim of this feature is to achieve the reverberation time thresholds for all the spaces. Indeed, in design phase, for projects in which the space types listed in the table (table 3.3) cumulatively make up at least 10% of occupable project area, the following requirements should be respected:

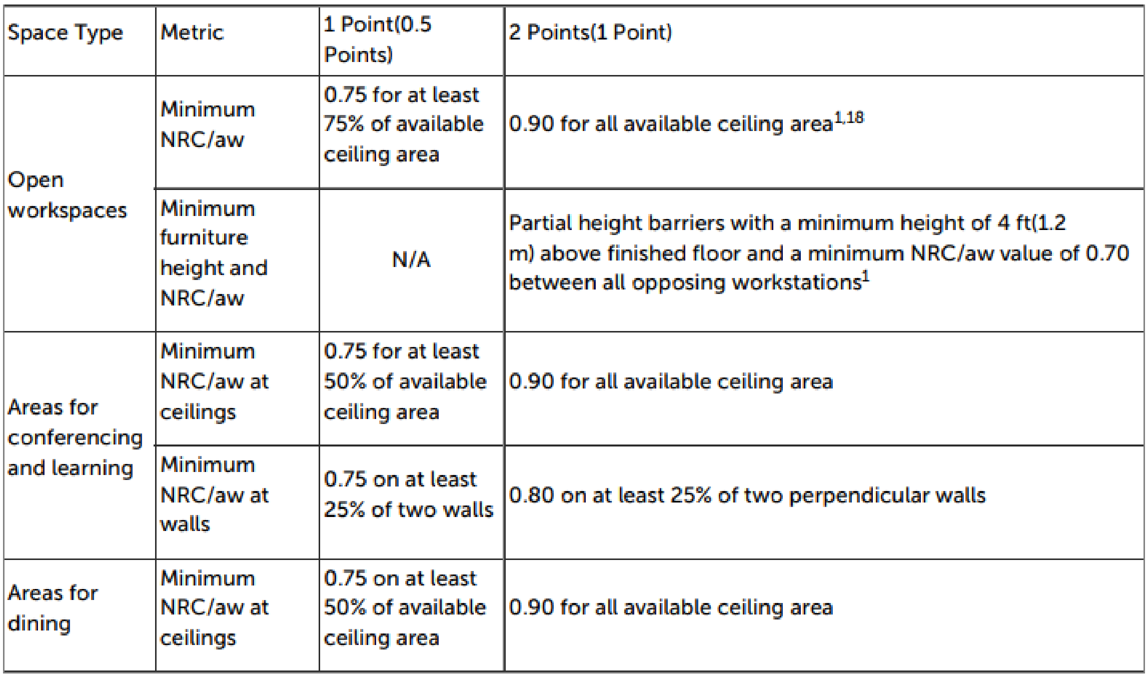


Space Type	Space Volume, v (cubic meters)	Reverberation Time, t (seconds)
Areas for learning and conferencing	$v < 10,000\ ft^3 (280\ m^3)$	$t \leq 0.6$[10]
	$10,000\ ft^3 (280\ m^3) \leq v \leq 20,000\ ft^3 (570\ m^3)$	$0.5 \leq t \leq 0.8$[9]
	$v > 20,000\ ft^3 (570\ m^3)$	$0.6 \leq t \leq 1.0$[9]
Areas for speech	N/A	$0.8 \leq t \leq 1.0$[9]
Areas for dining Regularly occupied areas with public address systems	N/A	$t \leq 1.0$[5]
Areas for fitness	$v < 10,000\ ft^3 (280 m^3)$	$0.7 \leq t \leq 0.8$[9]
	$10,000\ ft^3 (280\ m^3) \leq v \leq 20,000\ ft^3 (570\ m^3)$	$0.8 \leq t \leq 1.1$[9]
	$v > 20,000\ ft^3 (570\ m^3)$	$1.0 \leq t \leq 1.8$[9]
Areas for music rehearsal	$v < 10,000\ ft^3 (280\ m^3)$	$t \leq 1.1$[9]
	$10,000\ ft^3 (280\ m^3) \leq v \leq 20,000\ ft^3 (570\ m^3)$	$1.0 \leq t \leq 1.4$[9]

Table 3.3 – Reverberation time thresholds.

FEATURE S05 – SOUND REDUCING SURFACES | OPTIMIZATION

This WELL feature requires the use of acoustic materials that absorb sound to support concentration and reduce reverberation. The implementation of sound reducing surfaces can be done for all the spaces and for pojects in which the space tyoes listed in the table cumulatively make up at least 10% of occupable project area, the following requirements are met: (table 3.4)



Space Type	Metric	1 Point(0.5 Points)	2 Points(1 Point)
Open workspaces	Minimum NRC/aw	0.75 for at least 75% of available ceiling area	0.90 for all available ceiling area[1,18]
	Minimum furniture height and NRC/aw	N/A	Partial height barriers with a minimum height of 4 ft(1.2 m) above finished floor and a minimum NRC/aw value of 0.70 between all opposing workstations[1]
Areas for conferencing and learning	Minimum NRC/aw at ceilings	0.75 for at least 50% of available ceiling area	0.90 for all available ceiling area
	Minimum NRC/aw at walls	0.75 on at least 25% of two walls	0.80 on at least 25% of two perpendicular walls
Areas for dining	Minimum NRC/aw at ceilings	0.75 on at least 50% of available ceiling area	0.90 for all available ceiling area

Table 3.4 – Implement sound reducing surfaces.

FEATURE S06 – MINIMUM BACKGROUND SOUND | OPTIMIZATION

This WELL feature reqires the use of dedicated artificial sound to uniformly increase speach privacy between occupied spaces. This feature is divided in two parts, the aim of the first one is to provide a minimum background sound and it is only for office spaces, while the second one wants to provide enhanced speech reduction and it is for all the spaces. In particular the requirements for the offices are:

a. A sound masking system is installed in open areas with Quiet zones, Circulation zones and enclosed rooms labeled as Quiet zones and produces a 1/3 octave band adjustable output signal and frequency spectrum of 100 Hz to 5 kHz.
b. The sound masking system is commissioned such that the following sound pressure levels are not exceeded:
    1. Open areas with Quiet zones and/or Circulation zones: 48 dBA;
    2. Enclosed rooms labeled as Quiet zones: 42 dBA.
c. The sound masking system is verified by a professional sound masking system installer in accordance with ASTM 1573-18 or equivalent standard.

BETA FEATURES | OPTIMIZATIONS

In addition to the six features, the International WELL Building Institute (IWBI) develops new interventions for the WELL Building Standard in the form of WELL beta features. These fetaures are developed in collaboration with WELL advisors allover the world according to what was find out during research and applications of the main features listed before. [3]

3.6 LEED Certification

The LEED Certification is a standard that can be applied to all the buildings. The U.S. Green Building Council (USGBC) develops it and the system is based on the awarding of credits for each requirement. The sum of all the credits defines four certification levels (base, gold silver, platinum). Green Building Council Italia (GBC Italia) introduced the LEED Certification in Italy in 2010. Any type of building can be certified with this standard, so the first thing to do is idenìtify the typology and location (new, exisisting, school, hospital, office, etc). In particular, for the *Acoustic Perfomance* the design team can reach between 1 and 2 points. For this credit are defined intent and requirements, let’s focus on them by taking care of *workspaces* requirements.

INTENT

The aim is to guarantee, through an appropriate acoustic design, the acoustic comfort in workspaces for all the occupants.

REQUIREMENTS

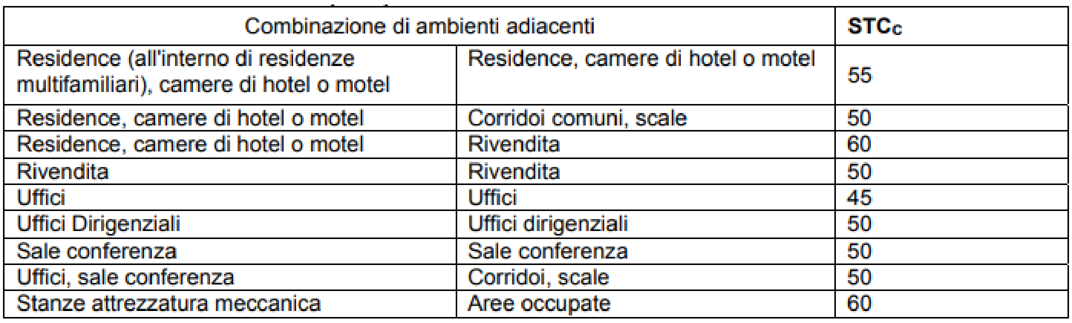
For all the occupants, accordind to the different situations must be satisfied the requirements for background noise, ventilation and air conditioning HVAC, reverberation time, amplification and sound masking.

- Background noise of HVAC systems

  Heating, ventilation, and air conditioning (HVAC) systems shall not exceed the maximum background noise levels indicated in Table 1 of Chapter 48 of the ASHRAE Handbook 2011 or Table 15 of AHRI Standard 885-2008, or in an equivalent local reference. For measurements, use a sound level meter that complies with ANSI Standard S1.4 for Type 1 sound measurement instrumentation (precision) or Type 2 (general purpose), or to an equivalent local reference. Comply with the design criteria for HVAC system noise levels from transmission paths sound as shown in Table 6 of the ASHRAE Application 2011 Handbook guide, or to an equivalent local reference.

- Sound transmission

  In this requirement must be satisfied all the minimun values of STCc defined in the following table (table 3.11), or prescribed in the local building standards if more stringent.

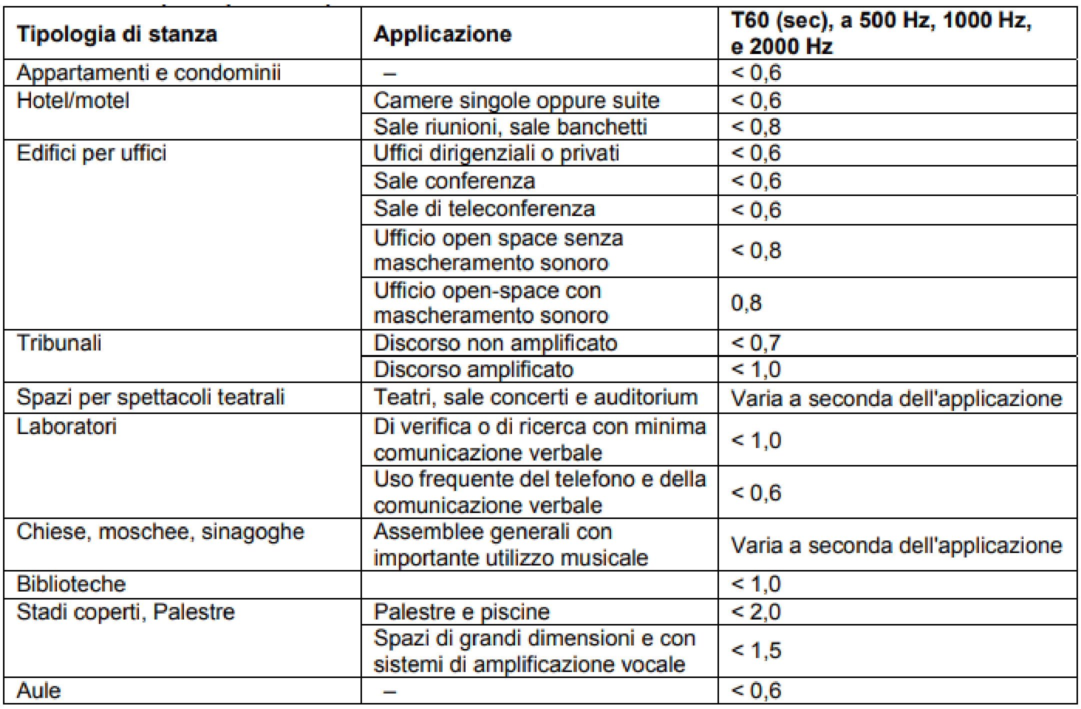


Combinazione di ambienti adiacenti		**STC_C**
Residence (all'interno di residenze multifamiliari), camere di hotel o motel	Residence, camere di hotel o motel	55
Residence, camere di hotel o motel	Corridoi comuni, scale	50
Residence, camere di hotel o motel	Rivendita	60
Rivendita	Rivendita	50
Uffici	Uffici	45
Uffici Dirigenziali	Uffici dirigenziali	50
Sale conferenza	Sale conferenza	50
Uffici, sale conferenza	Corridoi, scale	50
Stanze attrezzatura meccanica	Aree occupate	60

Table 3.11 – Minimum STC index for adjacent spaces.

- Reverberation time

  According to LEED certification must be satified the reverberation time requirements shown in the table below (table 3.12)



Tipologia di stanza	**Applicazione**	**T60 (sec), a 500 Hz, 1000 Hz, e 2000 Hz**
Appartamenti e condominii	–	< 0,6
Hotel/motel	Camere singole oppure suite	< 0,6
	Sale riunioni, sale banchetti	< 0,8
Edifici per uffici	Uffici dirigenziali o privati	< 0,6
	Sale conferenza	< 0,6
	Sale di teleconferenza	< 0,6
	Ufficio open space senza mascheramento sonoro	< 0,8
	Ufficio open-space con mascheramento sonoro	0,8
Tribunali	Discorso non amplificato	< 0,7
	Discorso amplificato	< 1,0
Spazi per spettacoli teatrali	Teatri, sale concerti e auditorium	Varia a seconda dell'applicazione
Laboratori	Di verifica o di ricerca con minima comunicazione verbale	< 1,0
	Uso frequente del telefono e della comunicazione verbale	< 0,6
Chiese, moschee, sinagoghe	Assemblee generali con importante utilizzo musicale	Varia a seconda dell'applicazione
Biblioteche		< 1,0
Stadi coperti, Palestre	Palestre e piscine	< 2,0
	Spazi di grandi dimensioni e con sistemi di amplificazione vocale	< 1,5
Aule	–	< 0,6

Table 3.12 – Reverberation time requirements.

- Amplification and sound masking
  - Sound amplification systems
    In case of big conference rooms and auditorium with occupancy capacity higher than 50 seats, it is necessary to evaluate sound amplification systems and video playing. If necessary these systems must be satisfy the following criteria:

    - STI ≥ 0.6 or CIS = 0.77 in some points on top surface in order to guarantee an appropriate intelligibility;

    - Minimum sound level equal at least to 70 dBA;

    - Keep the sound cover between ±3dB in the octave band of 2000 Hz in all the space.

  - Sound masking
    For the projects that use sound masking systems, the design levels must be less or equal to 48 dBA. The loudspeakers coverage must guarantee a uniformity of ±2dBA and the speech envelope must be properly masked.

[6]

4 A Systematic review for a new data interpretation

A systematic review is a type of research that uses all the existing research on a subject. It is sometimes called ‘secondary research’ or ‘research on research’. Systematic reviews are often required by research funders to establish the state of existing knowledge and are frequently used in guideline development. They involve a comprehensive search to locate all relevant published and unpublished work on a subject; a systematic integration of search results; and a critique of the extent, nature, and quality of the evidence. This kind of analysis if foundamental to collect lots of experimental data coming from different countries in order to find out all the informations necessary to hypothesize an adequate number of Open Plan offices, combining all the recurrent dimensions and characteristics [43].

4.1 Strategy of analysis of existing literature

The main topic of all the analized articles are the open plan offices or open workspaces and all the new standards and certifications related to them. In order to carry out this systematic review were taken into account all the papers published in the last few years. The key words chosen to define this cross-searching are:

- Open-plan offices;
- Open workspaces;
- ISO 3382-3;
- Measurements;
- Standards published after 2012.

From the reading of 84 abstracts of papers published from 2017 to 2023, looking for measures and project datas, 31 articles were selected, for a total amount of 130 case studies of open-plan offices. Analisyng the chosen articles, it comes out that the parameters taken into consideration for several workplase – measurements or laboratory simulation – in these years by different countries all over the world, can be divided in two macro categories:

1. Summary statistics of the offices’ parameters;

2. Summary of categories (total number and percentage).

For each of these two sub categories were defined the parameters to be investigated. Indeed, for the first one – *summary statistics of the offices' parameters* – have been identified:

- Number of workstations (-);
- Workstation density (number/m^2);
- Ceiling height (m);
- Surface area (m^2).

The mean, the standard deviation and the median absolute deviation were computed for each of these parameters and for each analized office.

While for the second one – *summary of categories* - have been identified:

- Ceiling type;
- Carpet;
- Activity-based workplace (ABW);
- Partitions.

For each of these parameters were investigated the type of ceiling, if absorbent or hard; the floor, if there is (or not) the carpet; if is an activity-based workplace and if there are any screen used as partitions.

Note that not all the parameters listed above are exactly defined for each environment. Where the information is not reported in literature, in the data collection is identified as "not defined". In any case, this is a very small percenatage of data with respect to the total amount. [16, 19, 25, 31, 39]

In order to understand clearly the whole followed process, here below is reported a flow chart with all the passages. (figure 4.1)

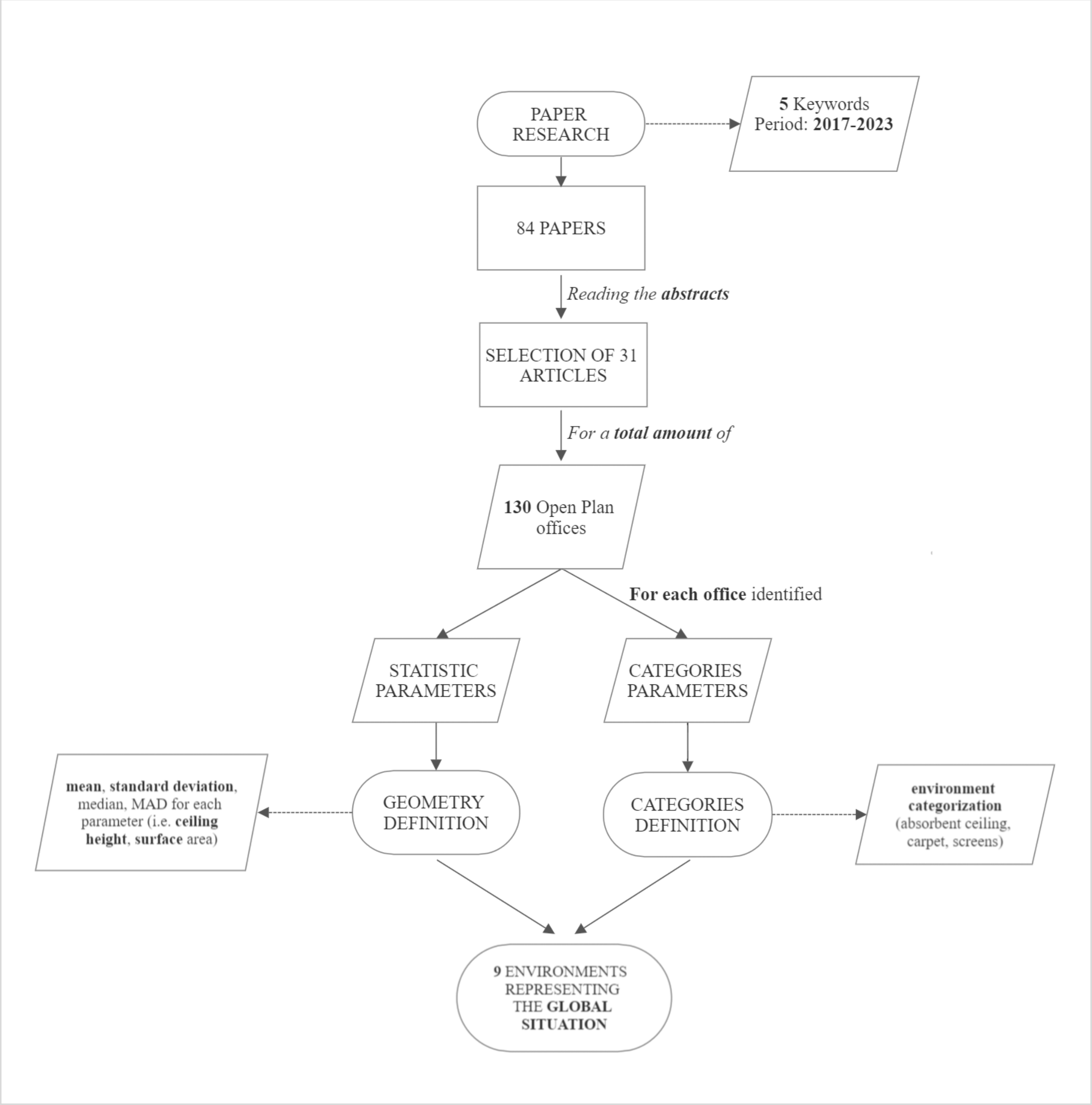
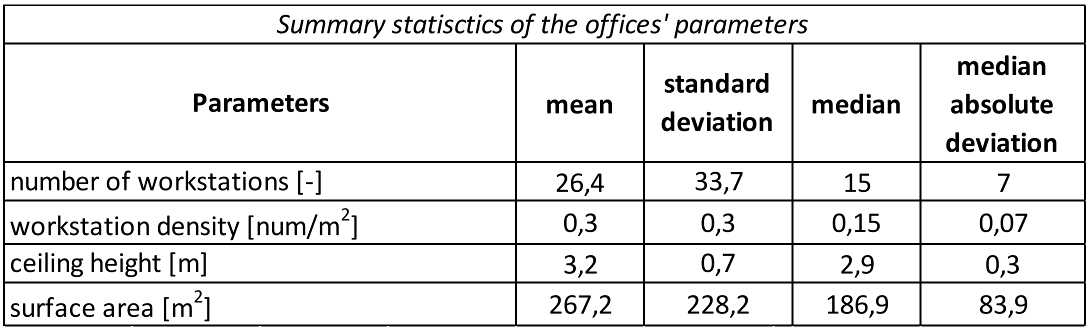


Figure 4.1 - Flow chart of the method followed in the thesis work.

4.2 Results and considerations

All the results obtained, by the analysis of the 130 offices presented in 31 papers, are collected in the following tables, plots and pie plots. The workplace parameters summarized as statistics of the offices' parameters shown in the following table (table 4.1).



Summary statisctics of the offices' parameters

Parameters	**mean**	**standard deviation**	**median**	**median absolute deviation**
number of workstations [-]	26,4	33,7	15	7
workstation density [num/m^2]	0,3	0,3	0,15	0,07
ceiling height [m]	3,2	0,7	2,9	0,3
surface area [m^2]	267,2	228,2	186,9	83,9

Table 4.1 – Workplace parameters | Summary statistics of the offices' parameters.

It is significant to remark that:

- For 5 offices the number of workstations is not defined;
- For 5 offices the number of workstation density is not defined;
- For 27 offices the ceiling height is not defined;
- For 6 offices the surface area is not defined.

The workplace parameters collected in terms of categories with total numbers and percentages, are shown in the table below as follow (table 4.2)

Summary of categories (total number and percentage)			
ceiling type	N° of Open Plan Offices with absorbent ceiling (%)	N° of Open Plan Offices with hard ceiling (%)	N° of Open Plan Offices with not defined ceiling (%)
	70 (56,5%)	35 (28,2%)	19 (15,3%)
carpet	N° of Open Plan Offices with carpet (%)	N° of Open Plan Offices without carpet (%)	N° of Open Plan Offices with not defined carpet (%)
	45 (34,9%)	42 (36,2%)	42 (36,2%)
ABW	N° of Open Plan Offices with ABW (%)	N° of Open Plan Offices without ABW (%)	N° of Open Plan Offices with not defined ABW (%)
	2 (1,6%)	0 (0,0%)	127 (98,4%)
partitions (screens)	N° of Open Plan Offices with partitions (%)	N° of Open Plan Offices without partitions (%)	N° of Open Plan Offices with not defined partitions (%)
	72 (57,6%)	52 (41,6%)	1 (0,8%)

Table 4.2 – Workplace parameters | Summary of categories.

For all the analized open-plan offices, in almost all the papers, is not specified if a workplace is activity-based (ABW) or not. Where an ABW is an organisational strategic framework that recognises that people perform different activities in their day-to-day work, and therefore need a variety of work settings supported by the right technology and culture to carry out these activities effectively.

For each analized parameter, the obtained values are reported and analized in detail in the following plots and pie plots in terms of characteristics and percentages.

Combinig all the results, obtained from the analisys of 130 Open Plan Offices, in terms of *number of workstation* and *floor surface* (S_{floor}), the final plot has the following shape.

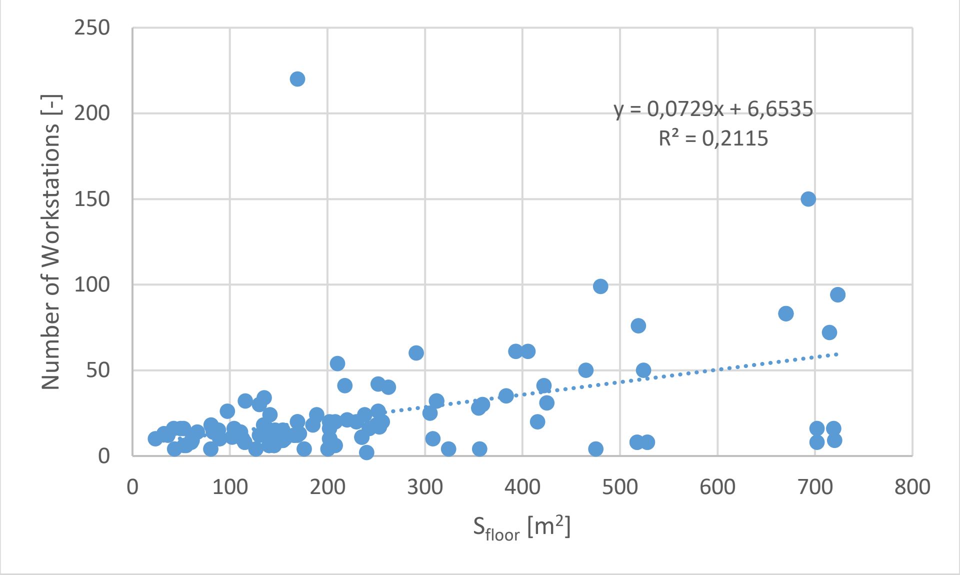


Figure 4.2 – Number of workstations with respect to the available floor surface.

What is turned out is that the majority of the open workspaces have a treated floor surface between 0 m^2 and 300 m^2, with a number of workstation that varies from 0 to 50. Only an open plan office has more than 200 workstations in less than 200 m^2. The remaining offices have a floor surface larger than 300 m^2 and the number of workstations has a wider range, up to 100.

It is relevant to remarck that, among the 130 envinroments considered, only 119 can be taken into account. For the others 11 offices, one or both parameters are not defined.

In the graph is represented a linear regression line has angular coefficient m equal to 0.0729 and the known term q equal to 6.6535.

The coefficient of determination R2, which value is included number between 0 and 1, defines how well a statistical modelcan predict an outcome.

In the obtained results, R2 is equal to 0.2115. It means that the model is far from the perfect prediction of the outcome.

In addition, in the following pages is developed a detailed analysis of all the parameters helpful to define with which categories of elements the other countries, different from Italy, characterize their Open Plan offices. It is important to keep in mind that each country has its own culture, its design modes and criteria, dictated by the boundary conditions related to both architectural and behavioral aspects of the people who inhabit the spaces in question.

Three of the main parameters that define the state of art of the offices acoustic treatment, are strictly based on the *privacy*, the foundamental factor that must be reach. The privacy is related to the intelligibility and it depends on environment reverberation and signal-to-noise ratio (SNR). The aim of the designer is to decrease as much as possible this ratio. To do this, the best way is to decrease the signal contribution through the spatial attenuation, for example with the insertion of partitions (screens) between desks.

On the contrary, the ceiling type (absorbent) and the fully carpeted floor surface contribute to increase the Equivalent Sound Absorption Area (A) of the environment and this means decrease the energy inside it. The A is a property of the environment and it is helpful in the reverberation control. Note that, if on one hand A is an environment property, on the other hand this does not necessarly means that the reverberation time T is an environment property, too. This is valid only for the Sabine's environments.

The environmental noise is the sum of the speech level of each irrelevant talker, and each talker is under the influence of the environmental noise, according to ISO 9921 [46]. Therefore, increasing the A, decrease the environmental noise.

The following graphs represents the outcome of the Systematic review applied to the second sub category which parameters considered are: type of ceiling, the floor, screen used as partitions.

The *ceiling type*'s results are

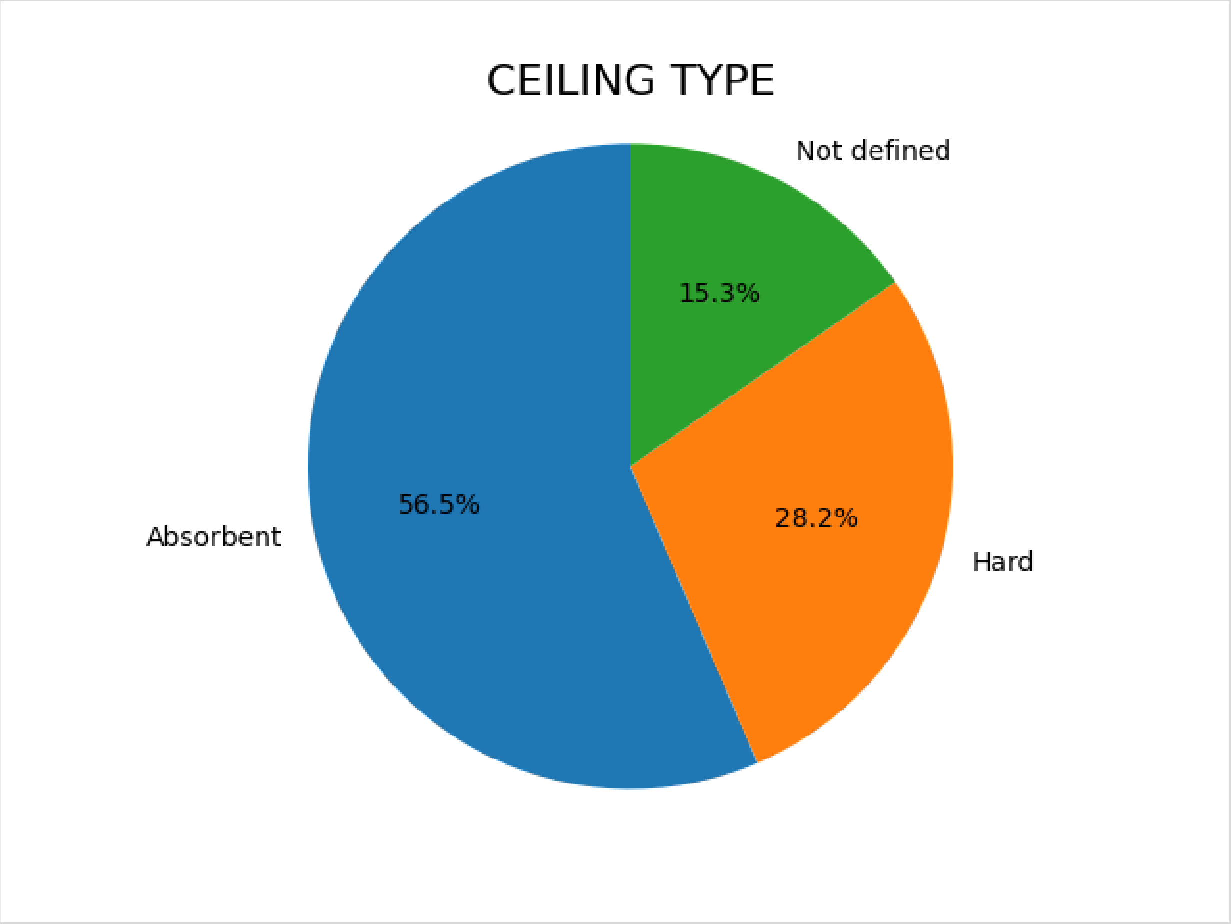


Figure 4.3 – Pie plot | Ceiling type.

In this pie plot, it is possible to see that

- The 56.5% of the offices (70) have the whole ceiling treated with sound absorption materials;
- The 28.2% of the offices (35) have a hard and reflective ceiling area;
- The 15.3% of the offices (19) have a not defined ceiling surface condition.

It is significant to underline that the higher percentage of the offices have the whole ceiling treated with sound reducing surfaces or sound absorption materials, while the remaining slices of the pie plot are defined as totally reflective surfaces or with a "not defined" at all.

The *carpet*'s results are

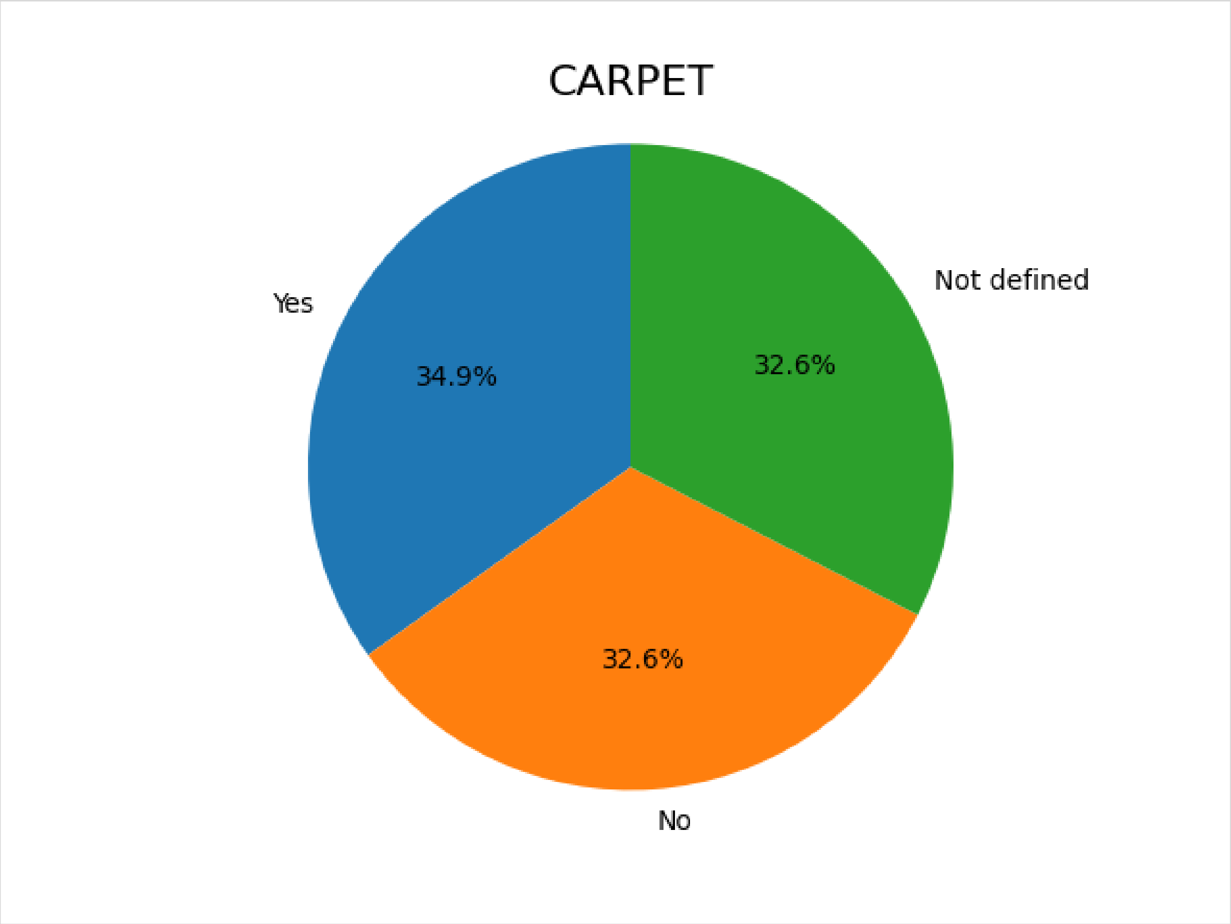


Figure 4.4 – Pie plot | Carpet.

In this pie plot, it is possible to see that

- The 34.9% of the offices (45) have the carpet all over the floor;
- The 32.6% of the offices (42) have a reflective pavement;
- The 32.6% of the offices (42) have a not defined floor surface condition.

It has to be highlight that the higher percentage of the offices have the floor covered with the moquette, while the remaining parts are totally reflective surfaces or with a “not defined” at all.

The *partitions*' results are

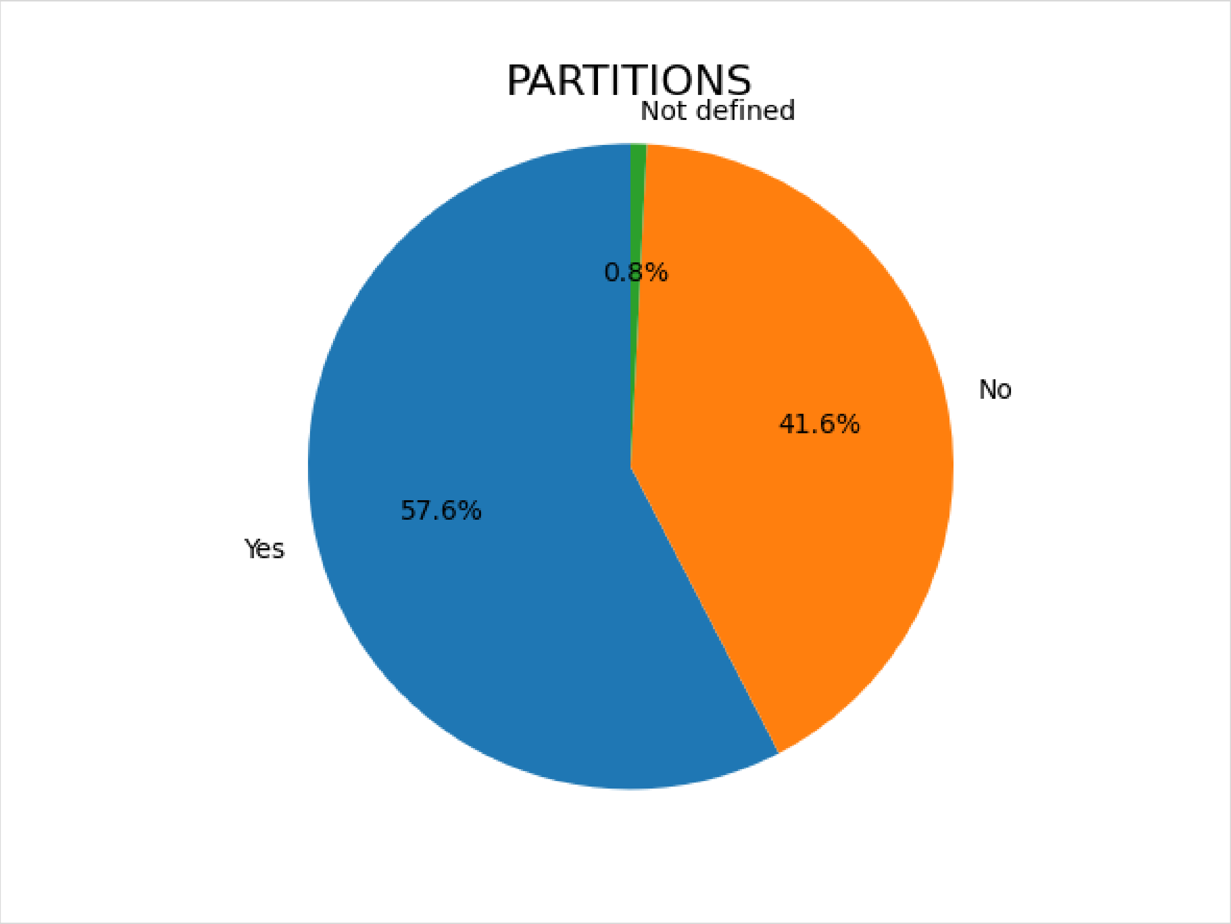


Figure 4.5 - Pie plot | Partitions.

In this pie plot, it is possible to see that

- The 57.6% of the offices (72) have partitions like the screens;
- The 41.6% of the offices (52) don't have partitions at all;
- The 0.8% of the offices (1) it is not specificed the presence of screens or other systems.

It is significant to underline that the higher percentage of the offices have partitions' system done with the screens, while the remaining offices are free from screen or their presence it is "not defined" at all.

[16, 19, 25, 31, 39]

On one hand, the suspended ceiling is the first intervention that is taken into consideration, while floor treatment does not occur as frequently. On the other hand, the use of screens seems to be a common element.

The results obtained from the collection of the experimental data coming from European and non-European countries, like for example Finland, China, South Korea and United States, can be visualized in the following 3D model (figure 4.6). In the picture is reported a typical configuration of an Open Plan office and the percentages of the three key analyzed elements (ceiling type, carpet and partitions).

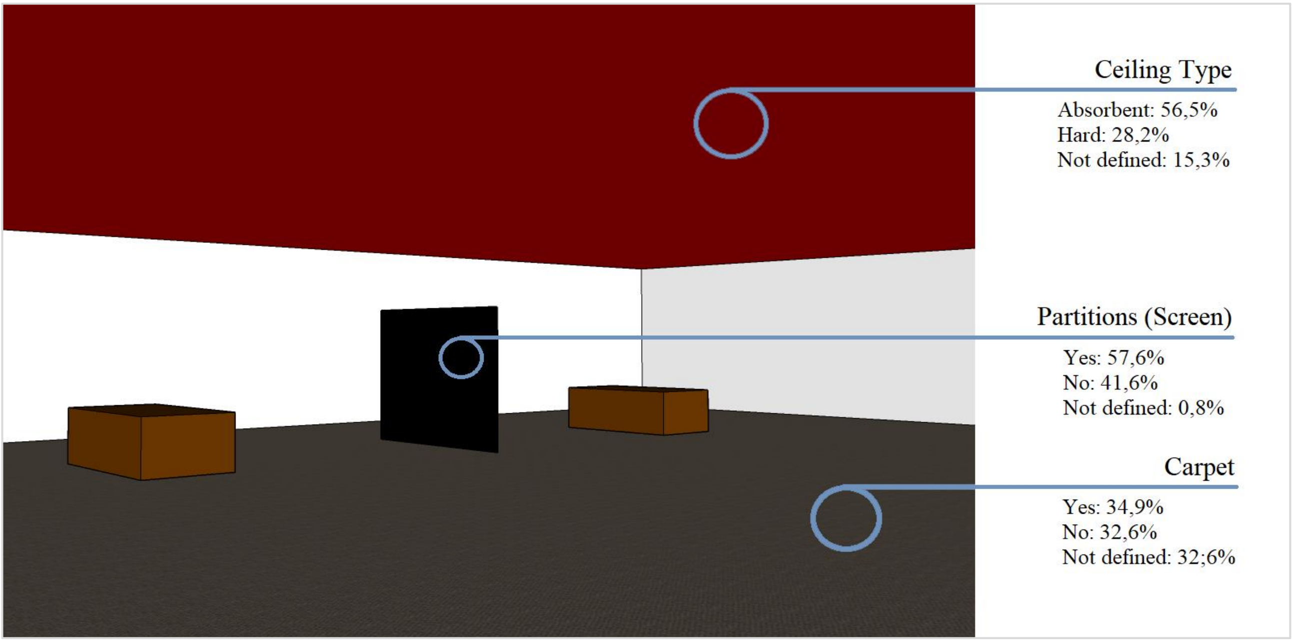


Figure 4.6 – 3D model of an Open Plan office with focus on the analyzed elements.

Figure 4.6 shows immediately the distribution of parameters obtained from the collection of experimental data selected from about one hundred analyzed papers.

In fact, what immediately jumps out is that the majority of open plan offices present in European and non-European countries have high percentages in terms of

- Ceilings properly acoustically treated with sound-absorbing material;
- Screens and/or partitions between workstations.

In addition, most offices also seem to have their floors entirely carpeted, but there is also some homogeneity between "nonabsorbent" floors and floors whose conditions are “not defined”.

In the light of all the considerations made so far, it is necessary to fully understand the characteristics of the environments and how these affect their behavior. Therefore, the research of experimental data is fundamental to have the widest possible view of the global landscape of open plan offices.

In conclusion, the collected data will help the research in the right definition of different configurations of offices (9) with proper surfaces, heights and volumes close as much as possible to those that actually exists in other countries, different from Italy. In the next step, this will contribute to have a larger point of view on which could be the behavior of the environments, increasing the reliability of analysis.

5 Acoustic design of Open Plan offices

It has been established that the acoustic comfort in work environmets, like Open Plan Offices, increase the concentration and productivity of the workers.

Starting from the state of art, through standards and protocols were defined nine Open Workspaces configurations. Then, according to the results obtained in chapter four, were defined geometry characteristics of the rooms (length, width, volume, height, floor and ceiling surface). The combination of these parameters gives nine different configurations of Open Plan offices plausible to the European and non-European context. In the end were considered 14 case studies of offices, measured in situ. All the environments considered were divided and classified as small, medium and large environments, according to WELL feature S04 - Reverberation Time thresholds. This big amount of collected data is helpful in order to have a complete overwiev of the existing Open Plan offices coherent with the reality. The aim of this chapter, starting from the base of the results obtained in chapter four, is to analyze the WELL features for the Open Workspaces and compare them with the requirements of the standard ISO 22955:2021, in order to find out applications compatibility and some considerations for a proper design of offices according to different cases. In this design stage, families of environments were used, divided as follows (table 5.).

	Small size ($V<280m^3$)	**Medium** size ($280 \le V \le 570m^3$)	**Large** size ($V>570m^3$)
State of Art	A, B, C	D, E, F	G, H, I
Systematic rewiev	A, B, C	/	D, E, F, G, H, I
Case studies (in situ)	Offices 10, 11, 12, 13, 14	Office 7	Offices 1, 2, 3, 4, 5, 6, 8, 9

Table 5.1 - Abacus of the analyzed environments.

The passeges followed to perform the analysis are graphically shown in the following flow chart (figure 5.1).

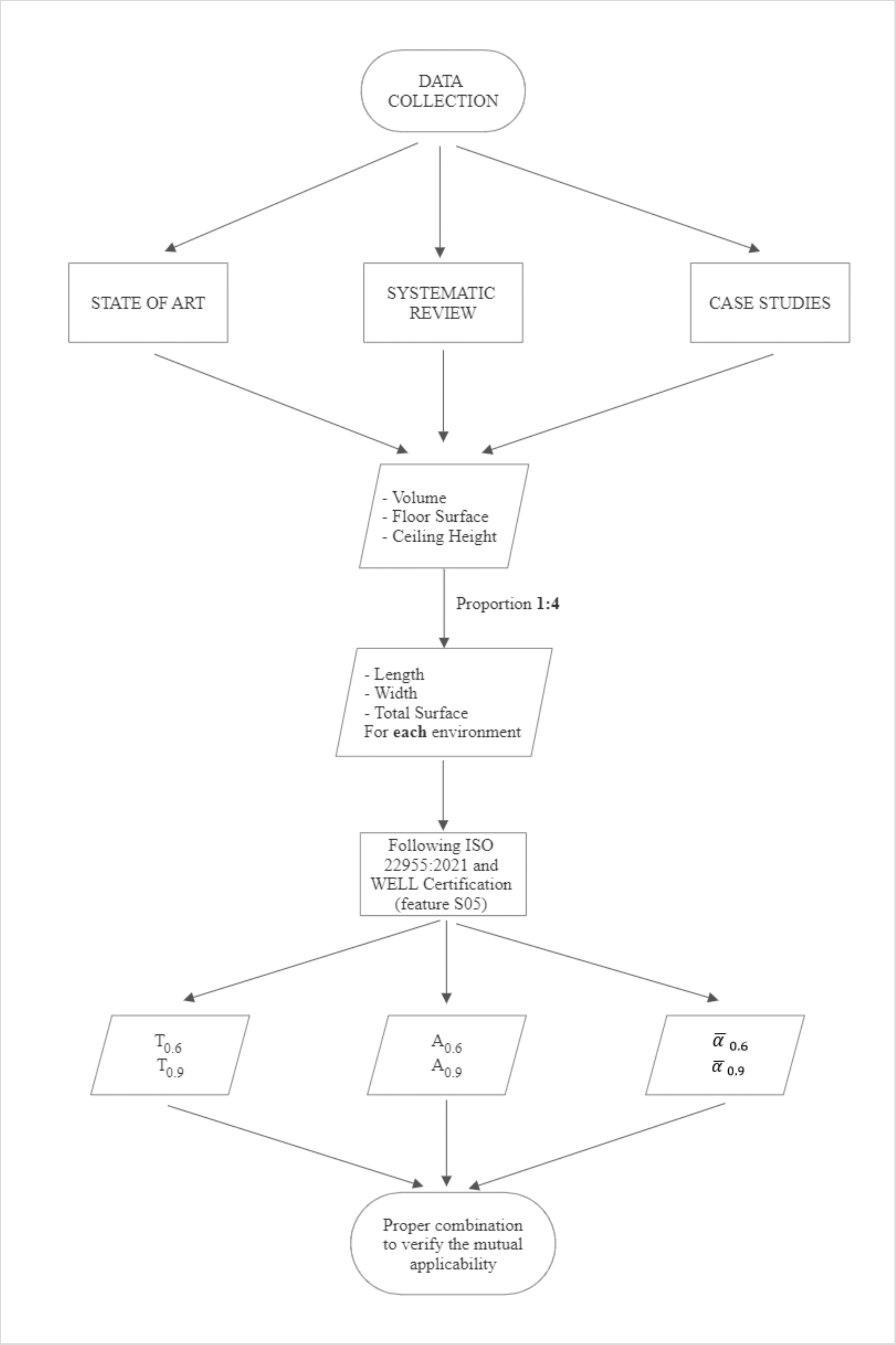


Figure 5.1 – Flow chart of the calculation procedure.

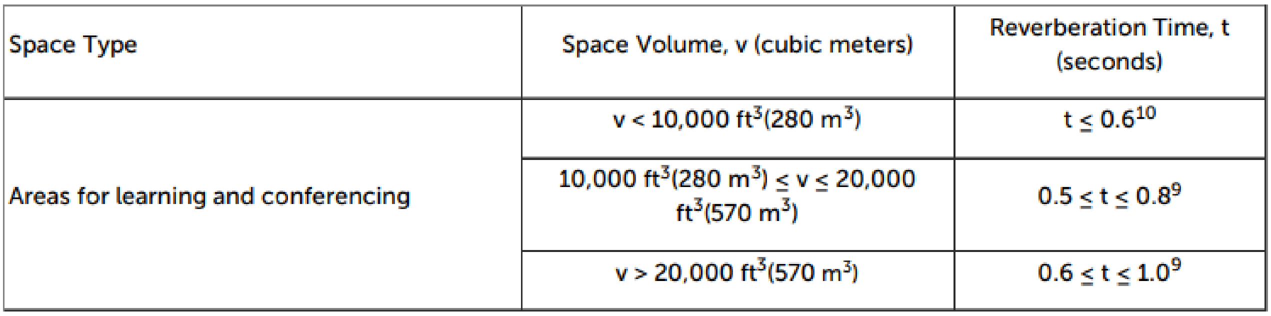
5.1 Design of Open Plan offices through the state of art

The Sound Section of the WELL V2, Q2 2022 provides, in addition to the necessary conditions for the certification, some optimizations like feature S04 – Reverberation Time and S05 – Sound Reducing Surfaces. According to this protocol, in the following paragraphs will be analyzed nine scenarios of Open Space offices, created with defined proportions equal to 1:4 to satisfy the hypothesis of the Sabine predictive formula for the calculation of the reverberation time. The results, obtained from the case studies, will be compared to the requirements of the standard ISO 22955:2021, in order to find out compatibilities in the application of both protocols [3, 4].

WELL AND ISO 22955:2021

In the following sections, the reverberation time and absorption area requirements defined by ISO 22955:2021 and WELL Certification will be analyzed for possible compatibility and mutual application in Mediterranean countries, such as Italy.

Considering the *feature S04 – Reverberation Time* for the Space Type: Areas for learning and conferencing defines the volumes and the reverberation time thresholds as shown in the following table [3]. (table 5.2)



Space Type	Space Volume, v (cubic meters)	Reverberation Time, t (seconds)
Areas for learning and conferencing	$v < 10{,}000\ ft^3 (280\ m^3)$	$t \leq 0.6$[10]
	$10{,}000\ ft^3 (280\ m^3) \leq v \leq 20{,}000\ ft^3 (570\ m^3)$	$0.5 \leq t \leq 0.8$[9]
	$v > 20{,}000\ ft^3 (570\ m^3)$	$0.6 \leq t \leq 1.0$[9]

Table 5.2 – Reverberation Time thresholds | feature S04 [3].

WELL *feature S05 – Sound Reducing Surfaces* identifies two different possibilities according to the score that you want to reach. To achieve 1 point, must be satisfied the equation (formula 5.1) [3]

$$\frac{A}{S_{floor}} > 0.6$$

Formula 5.1 – Ratio to reach 1 point | feature S05 [3].

While to reach 2 points, must be satisfied the equation (formula 5.2) [3]

$$\frac{A}{S_{floor}} > 0.9$$

Formula 5.2 – Ratio to reach 2 points | feature S05 [3].

Where:

- A: equivalent sound absorption area (m^2);
- S_{floor}: floor surface (m^2).

Feature S05 is defined in empty environment conditions in order to omit the positive contribute given by the furniture. For the same work environments, the standard ISO 22955:2021 requires a certain amount of sound absorption area greater or equal to at least the 90% of the floor surface. The aim is to keep the noise level under control ensuring the wellness of workers in these environments and contain the Lombard Effect [42]. The A/S_{floor} requirement defined by ISO 22955:2021 is the same expressed from the equation 5.2 [3, 4].

METHOD APPLIED FOR GEOMETRIES' DEFINITION

Nine configurations of ideal Open Plan Offices were hypothesized, characterized by three specific volumes (250, 450, 650 m^3), based on the categories of volumes defined by WELL, as shown in table 5.2. All the defined geometries have prescribed heights, length, and width calculated with proportion 1:4 to satisfy the hypothesis of the Sabine predictive formula for the calculation of the reverberation time.

	Space type	*Areas for learning, lectures and conferencing*				
	volume [m^3]	**height [m]**	**S_{floor} [m^2]**	**length$^{(1)}$ [m]**	**width$^{(1)}$ [m]**	**S_{tot} [m^2]**
A	250	2,70	92,6	19,2	4,8	315,1
B		3,00	83,3	18,3	4,6	303,6
C		3,30	75,8	17,4	4,4	295,1
D	450	2,70	166,7	25,8	6,5	507,6
E		3,00	150,0	24,5	6,1	483,7
F		3,30	136,4	23,4	5,8	465,4
G	650	2,70	240,7	31,0	7,8	690,9
H		3,00	216,7	29,4	7,4	654,1
I		3,30	197,0	28,1	7,0	625,5
$^{(1)}$ calculated with proportion 1:4						

Table 5.3 – Geometry of the case studies.

RESULTS AND DISCUSSIONS

These calculations want to compare through the nine different configurations, defined in table 5.3, in not furnished conditions, the values of reverberation time and A/S_{floor} according to WELL certification and ISO 22955:2021. The WELL considers $A/S_{floor}>0.6$ and $A/S_{floor}>0.9$, while the ISO 22955:2021 only $A/S_{floor}>0.9$. In both cases, it is considered only the ceiling area, and this ratio can be used as precondition for the reverberation time calculation in empty environment for controlling and decreasing as much as possible the Lombard Effect.

Based on the defined the geometries of the rooms (table 5.3), for each of the 9 spaces it has been evaluated the equivalent sound absorption area, the reverberation time and the average sound absorption coefficient, in two cases:

1. $A_{0.6}$, $T_{0.6,}$ $\bar{\alpha}_{0.6}$ with $A/S_{floor} > 0.6$
2. $A_{0.9}$, $T_{0.9,}$ $\bar{\alpha}_{0.9}$ with $A/S_{floor} > 0.9$

The results are reported in table 5.4.

	$A_{0,6}$ [m^2]	$A_{0,9}$ [m^2]	$T_{0,6}$ [s]	$T_{0,9}$ [s]	$\overline{\alpha_{0,6}}$ [-]	$\overline{\alpha_{0,9}}$ [-]
A	56	83	0,72	0,48	0,18	0,26
B	50	75	0,80	0,53	0,16	0,25
C	45	68	0,88	0,59	0,15	0,23
D	100	150	0,72	0,48	0,20	0,30
E	90	135	0,80	0,53	0,19	0,28
F	82	123	0,88	0,59	0,18	0,26
G	144	217	0,72	0,48	0,21	0,31
H	130	195	0,80	0,53	0,20	0,30
I	118	177	0,88	0,59	0,19	0,28

Table 5.4 – Results for each configurations.

First step was the treatment of the ceiling, using the gypsum board (equivalent sound absorption area), from which the results in cases 1 ($0.6 \cdot S_{floor}$) and 2 ($0.9 \cdot S_{floor}$) are obtained. For each of these situations the RT is calculated and the obtained values can be reduced adding the furniture. The important thing is that the only ceiling gypsum board contribution does not make the reverberation time results too low with respect to the minimum requirement. Comparing $T_{0.6}$ and $T_{0.9,}$ in empty environments with WELL thresholds, it has that in $T_{0.6}$ the rooms A, B, C (volume 250 m^3) have reverberation times higher than the maximum value allowed (0.6 seconds), but adding the furniture this value is going to decrease, likely inside the limit. The same it is valid for the environments E, F (volume 450 m^3). In case of $T_{0.9}$ for the enviroments D (volume 450 m^3) and G, H, I (volume 650 m^3) the reverberation time is lower than the minimum thresholds defined in WELL ($0.5 \leq t \leq 0.8$s in D and $0.6 \leq t \leq 1$s in G, H, I). Therefore adding the furniture $T_{0.9}$ will continue to decrese, going far to low from the minimum limit. The trends of the reverberation times can be seen in figure 5.2 [3].

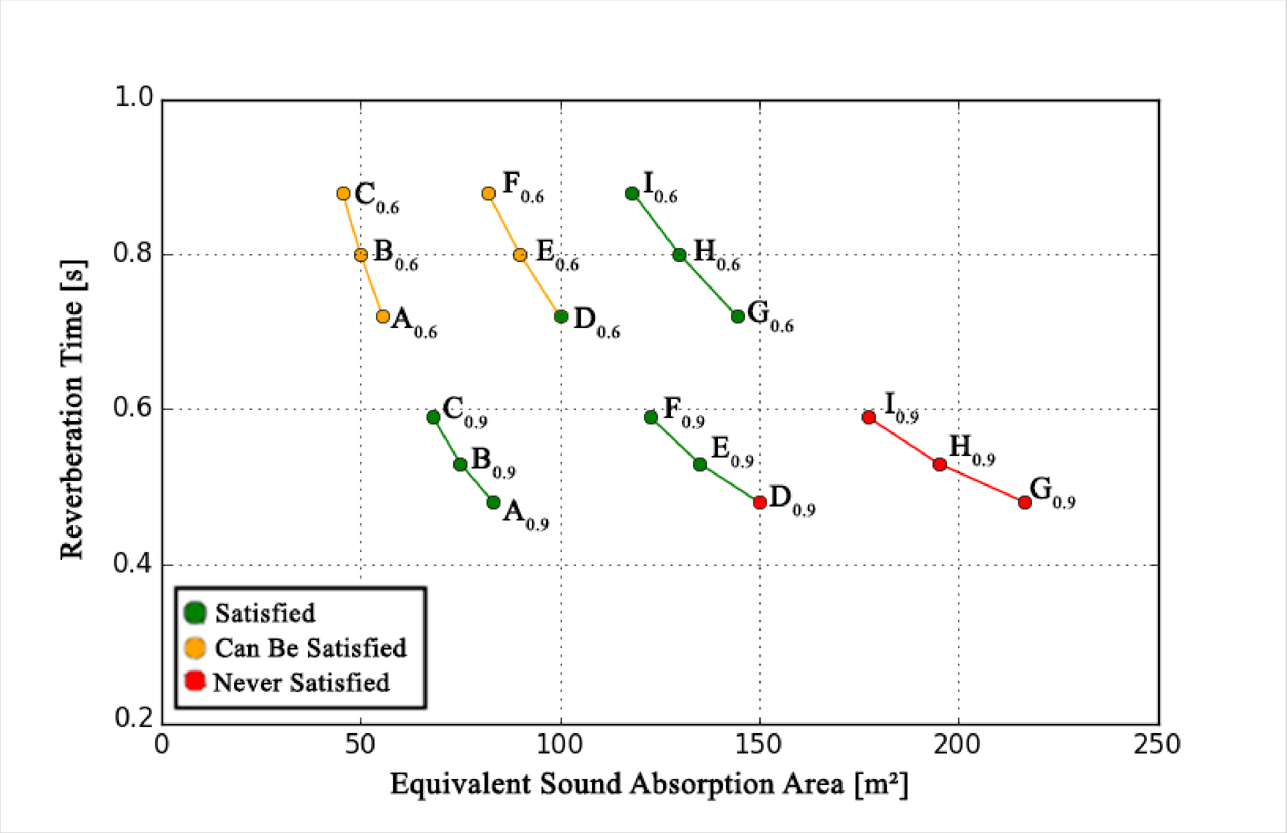


Figure 5.2 – Reverberation times classification according to WELL limits [3].

It is important to note that the Average Sound Absorption Coefficients $\bar{\alpha}_{0.9}$ are indicative of an estrangement from the assumptions on which are based the predictive formulas in ISO 12354-6 [44]. This occurs for two main reasons: the coefficients are higher than the Sabine validity region ($\bar{\alpha}<0.2$); the average α value is distributed in a not homogeneous way in the offices (sound absorption concentrated on ceiling) [3, 4].

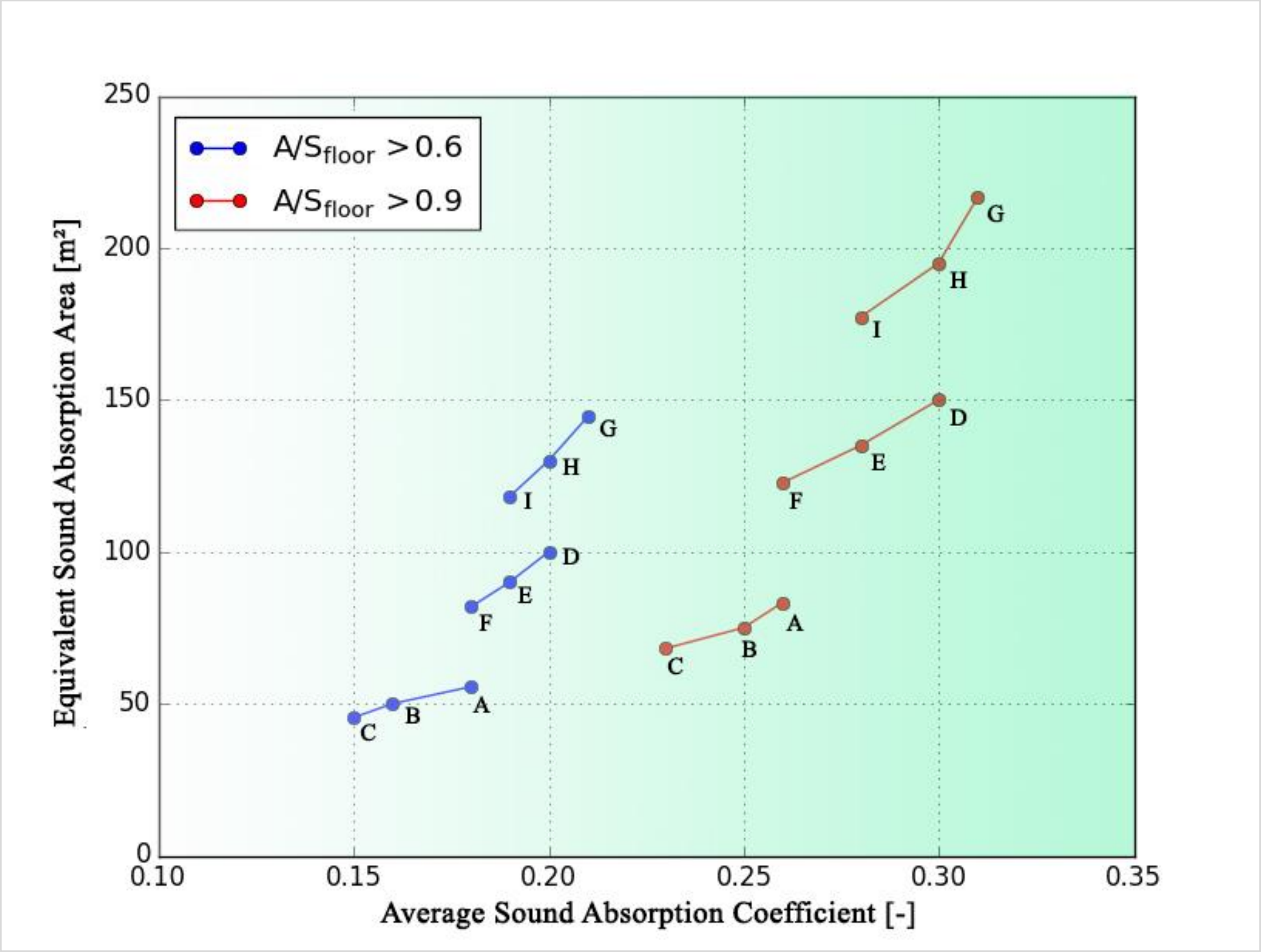


Figure 5.3 – A/S$_{floor}$ for each configuration.

The obtained results from the analisys of the nine configurations are collected in figure 5.3. The curves obtained from the values interpolation of ($\bar{\alpha}_{0.6}$, $A_{0.6}$) and ($\bar{\alpha}_{0.9}$, $A_{0.9}$) decrease with a non-linear trend. For the case A/S$_{floor}$>0.6 the $\bar{\alpha}_{0.6}$ on average is equal to 0.18, while for the case A/S$_{floor}$>0.9 the $\bar{\alpha}_{0.9}$ on average is equal to 0.28. These average values of absorption coefficients were obtained from the average of the values of absorption coefficients obtained for each room in the two cases analyzed. Both situations are in condition of empty enviroments (no furniture and no people inside) and with the only ceiling treatment. Adding the contribution of the furniture, the value of the Equivalent Sound Absorption Area is going to increase and the environment will tend not to be under Sabine condition anymore.

In conclusion, the values of $T_{0.6}$ in some configurations are higher than the limits identified by WELL and they can be reduced, for example, adding the furniture. On the contrary, in some cases $T_{0.9}$ presents lower values than the minimum WELL threshold. The calculation is developed in empty environment conditions, so the addition of furniture will contribute to decrease more and more the $T_{0.9}$ values and increase the estrangement from the minimum limit. To these values of $T_{0.9}$ correspond $\overline{\alpha}_{0.9}$ values grater or equal to 0.3, and as it is possible to notice in figure 5.2, they are the farthest from Sabine's region. The WELL, as the ISO 22955:2021, in feature S05 defines a ratio $A/S_{floor}>0.9$ that, in some cases, may presents an incompatibility with the reverberation time requirement defined by feature S04 for large dimensions environments [3, 4].

The contents reported in section 5.1 have already been presented with an oral presentation to the 49° Convegno Nazionale of Associazione Italiana di Acustica (AIA), 7-9 June 2023, Ferrara. (See the full paper in the "attachments" section of the thesis).

5.2 Design of Open Plan offices through experimental data collection

In chapter four was performed a systematic review, and following what M. Yadav model for data collection, were considered 130 Open Plan Offices and for almost each of them was found out the floor surface and the height, then compute the mean, the standard deviation, the median and the median absolute value. In order to apply a comparison, as in the previous paragraph, the mean value of floor surface and heigth and then sum and subtract them their standard deviation were taken into account, dividing in three groups the different floor surfaces (38.9, 267.2, 495.4 m²), considering for each group three different heigths (2.4, 3.2, 3.9 m). Nine different configurations were obtained with nine different volumes. The geometries analized are reported below (table 5.5) [16, 19, 25, 31, 39].

	Space type	*Areas for learning, lectures and conferencing*				
	S_{floor} [m^2]	**height [m]**	**volume [m^3]**	**length(1) [m]**	**width(1) [m]**	**S_{tot} [m^2]**
A	38,9	2,4	94,5	25,0	6,2	462,9
B		3,2	123,2	25,0	6,2	508,8
C		3,9	151,8	25,0	6,2	554,7
D	267,2	2,4	648,9	65,4	16,3	2534,3
E		3,2	845,6	65,4	16,3	2654,6
F		3,9	1042,3	65,4	16,3	2775,0
G	495,4	2,4	1203,2	89,0	22,3	4503,8
H		3,2	1568,0	89,0	22,3	4667,7
I		3,9	1932,7	89,0	22,3	4831,6
(1) calculated with scale factor 1:4						

Table 5.5 – Geometry of the case studies.

In order to carry out the calculations, the same prescpriptions as before, given by WELL and ISO 22955:2021, were followed with the same thresholds and the same parameters. All the obtained results are collected in the following table. (table 5.6)

	$A_{0,6}$ [m^2]	$A_{0,9}$ [m^2]	$T_{0,6}$ [s]	$T_{0,9}$ [s]	$\overline{\alpha_{0,6}}$ [-]	$\overline{\alpha_{0,9}}$ [-]
A	23,4	35,0	0,65	0,43	0,05	0,08
B	23,4	35,0	0,84	0,56	0,05	0,07
C	23,4	35,0	1,04	0,69	0,04	0,06
D	160,3	240,4	0,65	0,43	0,06	0,09
E	160,3	240,4	0,84	0,56	0,06	0,09
F	160,3	240,4	1,04	0,69	0,06	0,09
G	297,2	445,9	0,65	0,43	0,07	0,10
H	297,2	445,9	0,84	0,56	0,06	0,10
I	297,2	445,9	1,04	0,69	0,06	0,09

Table 5.6 – Results for each configuration.

The first important thing to remark is that the obtained Open Plan Offices can be classified, according to WELL, as:

- A, B, C: small size OP Offices (volume < 280 m^3);
- D, E, F, G, H, I: large size OP Offices (volume > 570 m^3).

It is significant to underline that there is a high prevalence of large Open Workspaces (six out of nine Open Plan offices).

The considered open plan offices taken from literature comes from different countries, like Finland, Germany, Austria, Spain and Great Britain to Austalia, China and Korea, and the majority of them have the floor full carpeted, a fully absorbent ceiling and partitions like screens almost always present.

It turns out that are no results in terms of medium size Open Plan Offices. The attention must be moved on large dimensions offices and their reverberation time range ($0.6 \leq t \leq 1.0$ s). Some configurations present the same problem found out in the previous paragraph for $T_{0.9}$. Indeed:

- D with $T_{0.9} = 0.43$s
- E with $T_{0.9} = 0.56$s
- G with $T_{0.9} = 0.43$s
- H with $T_{0.9} = 0.56$s

All these configurations, in not furnished and unoccupied conditions, with the equivalent sound absorption area defined according to the ratio $A/S_{floor}>0.9$ present in both WELL and ISO 22955:2021, have a reverberation time lower than the minimun defined by the WELL feature S04. Therefore, adding furniture and considering people sound absorption contribution the reverberation time will tends to decrease moving away every time more from the minimum limit defined by the

WELL certification. In case of Sabine's reverberation time calculated with an equivalent sound absorption area obtained from the ratio $A/S_{floor}>0.6$, the $T_{0.6}$ of all configurations fall inside the WELL threshold, or is a little bit larger than the upper limit. In any case, the addition of furniture and people contribution help the reverberation time to fall within the boundaries defined by the certification. All these considerations can be graphically seen in the following plot. (figure 5.4)

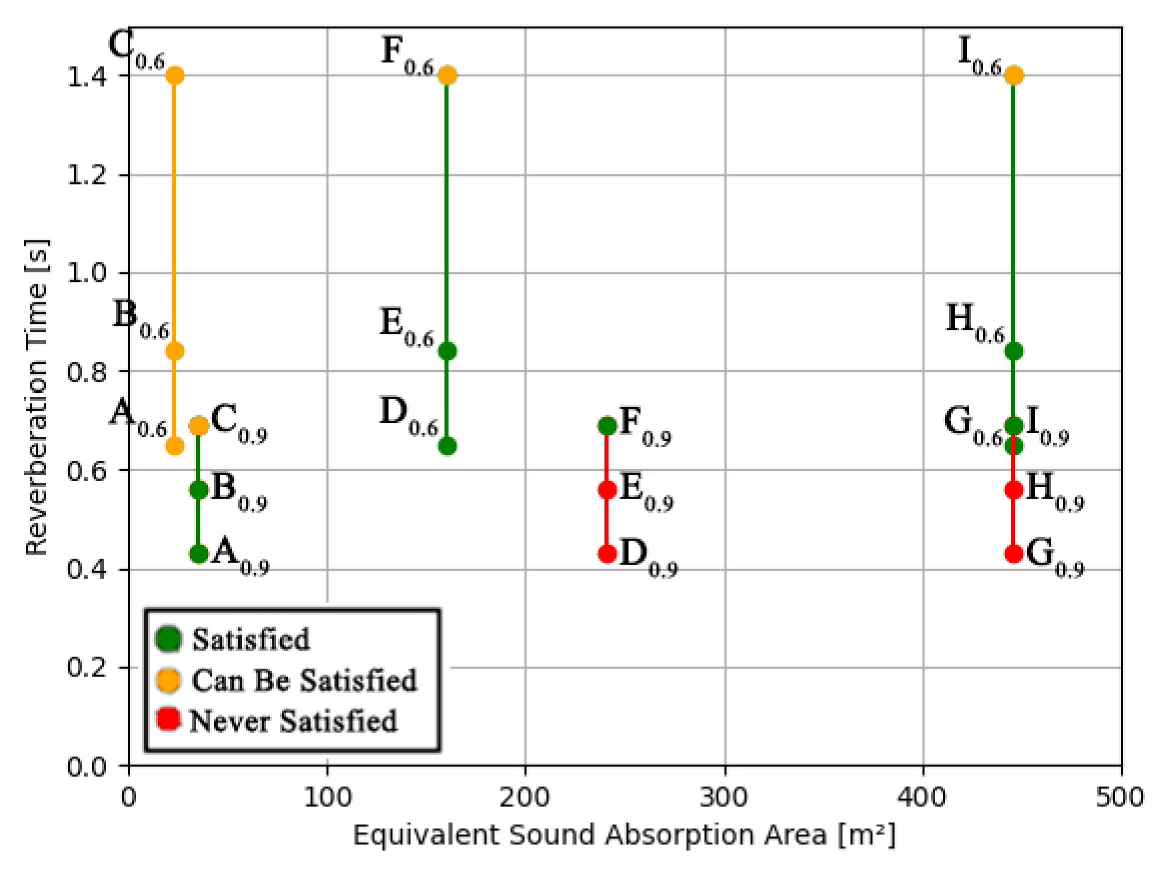


Figure 5.4 – Reverberation times classification according to WELL limits [3].

Evaluating the ratio between the equivalent sound absorption surface and the floor surface, the calculations were carried on starting from ceiling surface values obtained from literature systematic review (38.9, 267.2, 495.4 m²). Then treated with an average sound absorption coefficient equal to 0.6 for 1 WELL point, and equal to 0.9 for 2 WELL points. The two relations are:

1. $A_{0.6} = 0.6 \cdot S_{floor}$ (m²)

2. $A_{0.9} = 0.9 \cdot S_{floor}$ (m²)

By plotting the results, for each configuration, it was obtained the following graph (figure 5.5)

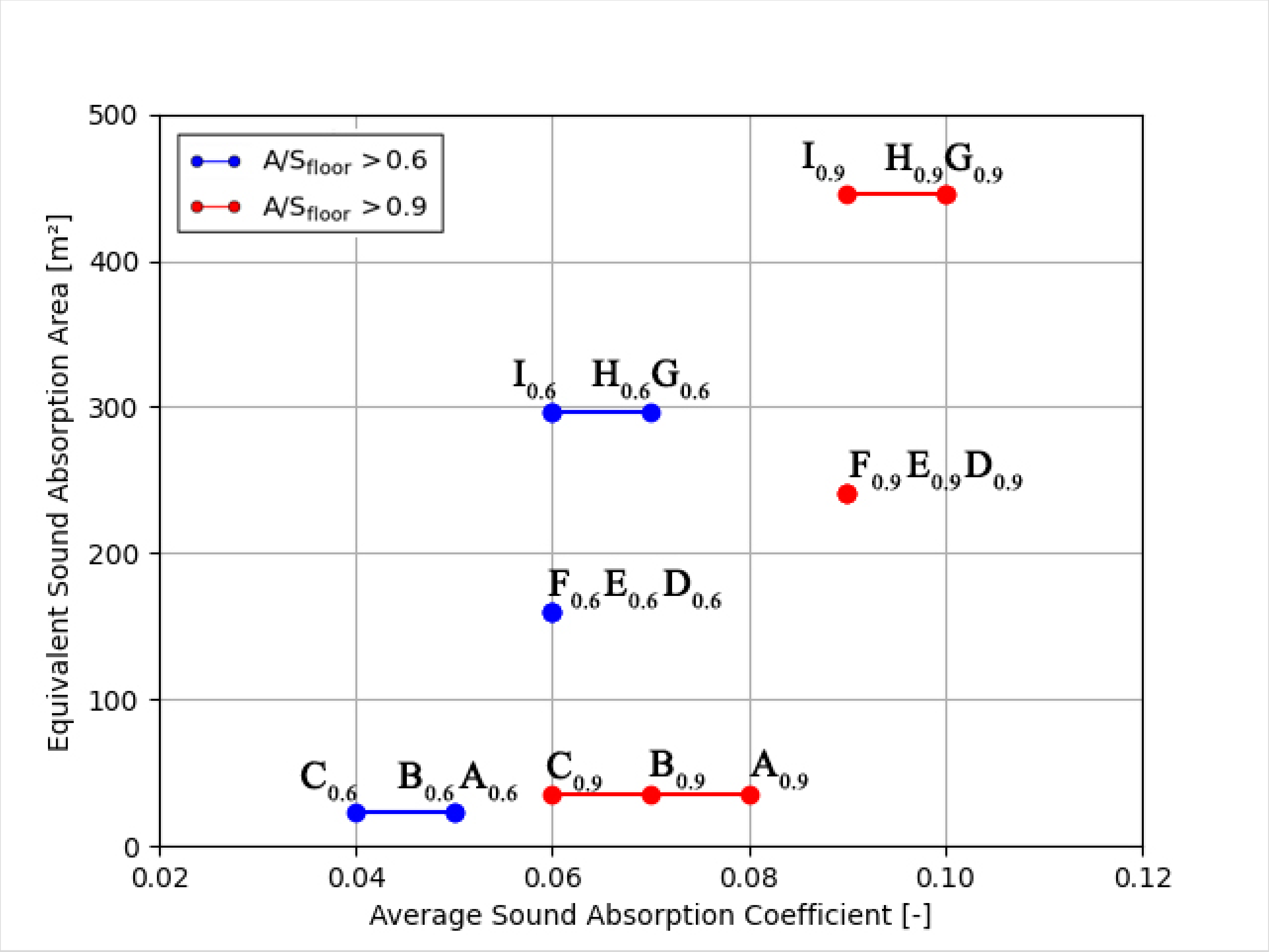


Figure 5.5 – A/S_{floor} for each configuration.

The first most important thing to notice is that in both cases A/S_{floor}>0.6 and A/S_{floor}>0.9, the coefficients $\bar{\alpha}_{0.6}$ and $\bar{\alpha}_{0.9}$ fall inside Sabine validity region ($\bar{\alpha}$<0.2). All the configurations have only the ceiling surface treated with sound absorption materials, and the environments are considered not furnished and unoccupied. Then, adding the furniture contribution and considering people contribution the value of the Equivalent Sound Absorbtion Area is going to increase and the environment will tend not to be under Sabine condition anymore [3, 4, 16, 19, 25, 31, 39].

5.3 Design of Open Plan offices through case studies

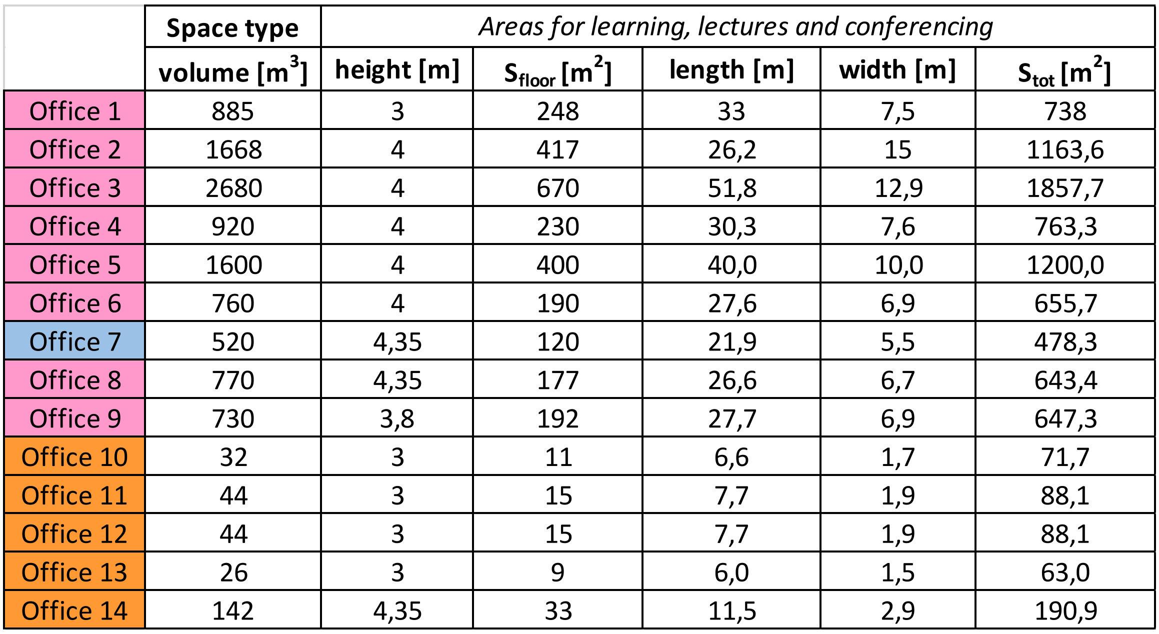
In this paragraph are analized 14 Open Plan offices directly measured through *in situ* surveis and belonging to different companies [42, 43, 44]. The general key informations are:

- From 26 to 61 workstations;
- Floor surface from 192 to 417 m^2;
- Ceiling treated with sound absorption materials;
- Glass walls along the main sides and between some offices;
- Screens of different heights and between desks.

The calculations are developed as in the two previous paragraphs, considering the same parameters, standards and geometric characteristics. The results are presented in different plot configurations. Indeed, due to the variety of results, the values are divided and reported as follow:

1. $A_{0.6}$, $T_{0.6,}$ $\overline{\alpha}_{0.6}$ with $A/S_{floor} > 0.6$
2. $A_{0.9}$, $T_{0.9,}$ $\overline{\alpha}_{0.9}$ with $A/S_{floor} > 0.9$

The geometries of each measured Open Workspace are collected in the following table (table 5.7)



	Space type	*Areas for learning, lectures and conferencing*				
	volume [m^3]	**height [m]**	**S_{floor} [m^2]**	**length [m]**	**width [m]**	**S_{tot} [m^2]**
Office 1	885	3	248	33	7,5	738
Office 2	1668	4	417	26,2	15	1163,6
Office 3	2680	4	670	51,8	12,9	1857,7
Office 4	920	4	230	30,3	7,6	763,3
Office 5	1600	4	400	40,0	10,0	1200,0
Office 6	760	4	190	27,6	6,9	655,7
Office 7	520	4,35	120	21,9	5,5	478,3
Office 8	770	4,35	177	26,6	6,7	643,4
Office 9	730	3,8	192	27,7	6,9	647,3
Office 10	32	3	11	6,6	1,7	71,7
Office 11	44	3	15	7,7	1,9	88,1
Office 12	44	3	15	7,7	1,9	88,1
Office 13	26	3	9	6,0	1,5	63,0
Office 14	142	4,35	33	11,5	2,9	190,9

Table 5.7 – Geometry of the in situ case studies. Colours refer to offices' size (see text for details).

Where:

- Orange: $V < 280\ m^3$ (small size);
- Blue: $280\ m^3 \leq V \leq 570\ m^3$ (medium size);
- Pink: $V > 570\ m^3$ (large size).

Based on the known geometries of the rooms, it has been determined the equivalent sound absorption area, the reverberation time and the average sound absorption coefficient, in two cases:

1. $A_{0.6}$, $T_{0.6}$, $\overline{\alpha}_{0.6}$ with $A/S_{floor} > 0.6$
2. $A_{0.9}$, $T_{0.9}$, $\overline{\alpha}_{0.9}$ with $A/S_{floor} > 0.9$

The results are reported in table 5.8.

	$A_{0,6}$ [m^2]	$A_{0,9}$ [m^2]	$T_{0,6}$ [s]	$T_{0,9}$ [s]	$\overline{\alpha_{0,6}}$ [-]	$\overline{\alpha_{0,9}}$ [-]
Office 1	148,5	222,8	0,95	0,64	0,20	0,30
Office 2	250,2	375,3	1,07	0,71	0,22	0,32
Office 3	402,0	603,0	1,07	0,71	0,22	0,32
Office 4	138,0	207,0	1,07	0,71	0,18	0,27
Office 5	240,0	360,0	1,07	0,71	0,20	0,30
Office 6	114,0	171,0	1,07	0,71	0,17	0,26
Office 7	72,0	108,0	1,16	0,77	0,15	0,23
Office 8	106,2	159,3	1,16	0,77	0,17	0,25
Office 9	115,2	172,8	1,01	0,68	0,18	0,27
Office 10	6,6	9,9	0,78	0,52	0,09	0,14
Office 11	9,0	13,5	0,78	0,52	0,10	0,15
Office 12	9,0	13,5	0,78	0,52	0,10	0,15
Office 13	5,4	8,1	0,77	0,51	0,09	0,13
Office 14	19,8	29,7	1,15	0,76	0,10	0,16

Table 5.8 – Results for each configuration.

Let's note that in this case, on the contrary compare to the other two cases, standards and literatures, the most critical situation could be the one related to the environments with small dimensions ($V<280\ m^3$). In these offices the Reverberation Time $T_{0.9}$ is already lower than the WELL threshold, it means that adding the furniture and considering the occupation, it will tends to decrease and decrease going far away from the minimum defined by the WELL feature S04.

Just to have a clearer vision of the different behaviours of the open workplaces used in calculations, the obtained results for the Reverberation Time are collected in different plots, according to the ratios $A/S_{floor} > 0.6$ and $A/S_{floor} > 0.9$.

Therefore, the results for $T_{0.6}$ and $T_{0.9}$ are reported in the graphs below (figure 5.12, 5.13)

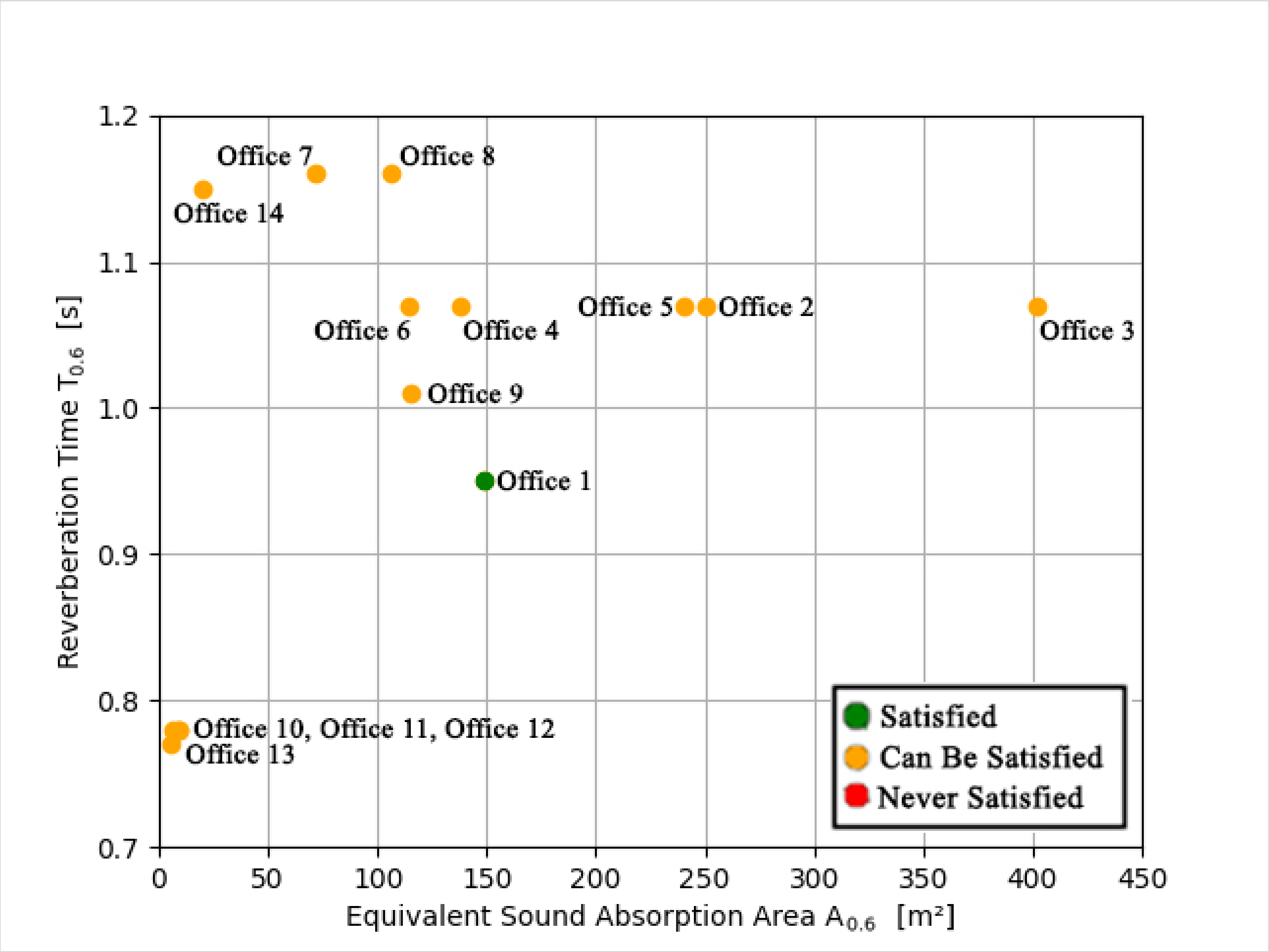


Figure 5.12 – Reverberation times $T_{0.6}$ classification according to WELL limits [3].

All the configurations have a reverberation times $T_{0.6}$ calculated considering only the sound absorption contribution of the ceiling ($A_{0.6}$). As shown in figure 5.11, just the Office 1 is still verified falling in the range identified by WELL ($0.6 \leq t \leq 1$ s). The other offices have a Reverberation Time higher than the WELL threshold, but considering furniture and people, these values will tend to decrease and fall inside the ranges defined by the protocol for each category of volume.

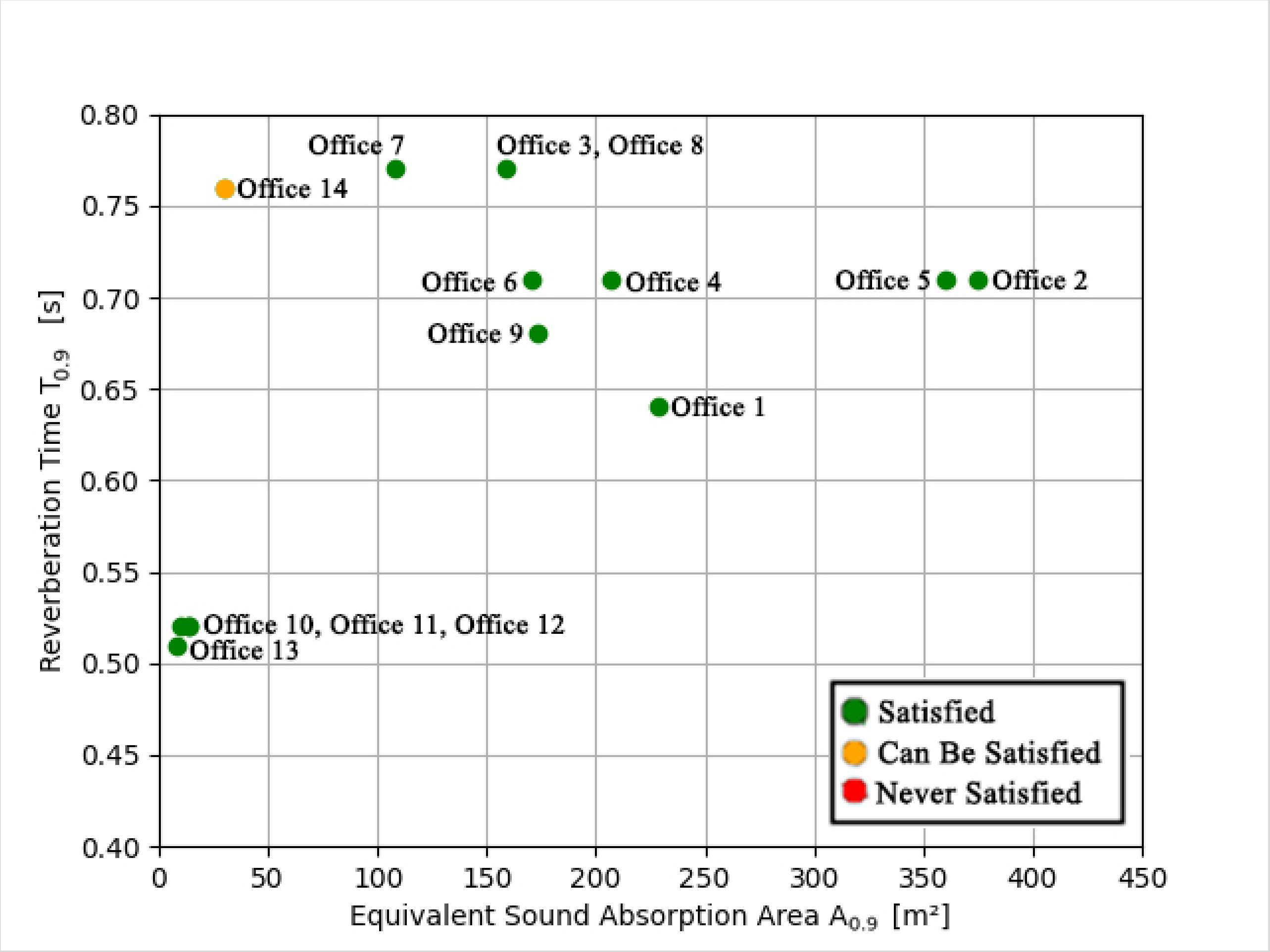


Figure 5.13 – Reverberation times $T_{0.9}$ classification according to WELL limits [3].

In this case all the Reverberation times $T_{0.9}$ are calculated considering only the whole surface of the ceiling teated with an average sound absorption coefficient equal to 0.9. From figure 5.13 it is possible to notice that almost all the $T_{0.9}$ have values that still satisfy the WELL thresholds, except for the Office 14 that presents an higer value with respect to the limits set by the protocol, but considering furniture and people contributions, it will tend to decrease and respect the given limits.

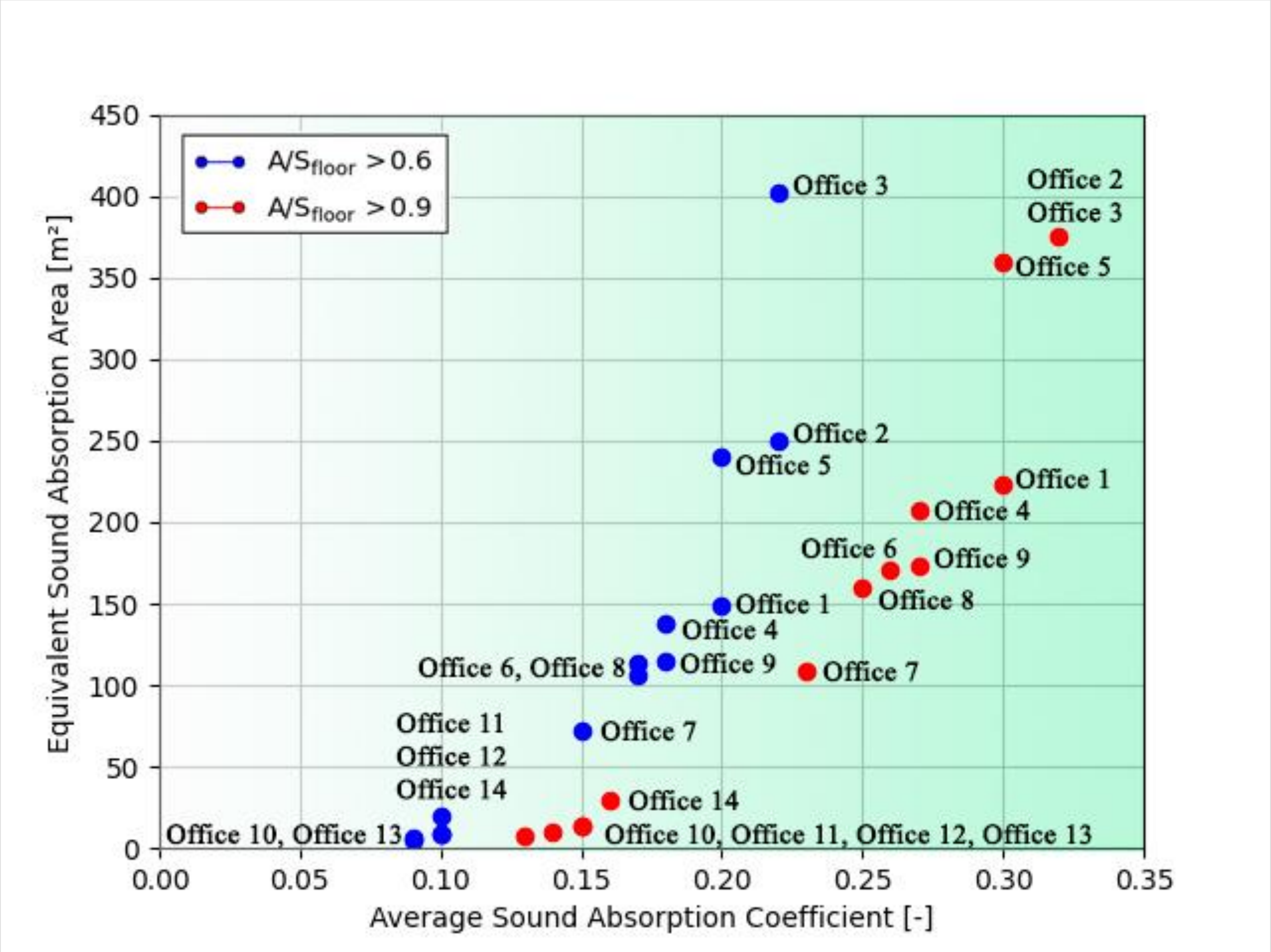


Figure 5.14 – A/S$_{floor}$ for each measured Open Plan office.

In figure 5.14, from a comparison between the two situations it is possible to notice that the first configuration (A/S$_{floor}$>0.6) presents a sound absorption coefficient on average equal to 0.15, so the majority of $\overline{\alpha}_{0.6}$coefficients fall inside Sabine validity region ($\overline{\alpha}$<0.2). There are two exceptions, Office 2 and Office 3, that are a little bit higher. The second configuration (A/S$_{floor}$>0.9) presents a sound absorption coeffecient on average equal to 0.23, and half of the offices, specially those with small sizes have a $\overline{\alpha}_{0.9}$ lower than 0.2 so they fall inside Sabine's validity region, while the other remainig offices have values higher than 0.2 start going far away from Sabine's region. Both situations are in condition of empty environments (no furniture and no people inside) and with the only treated ceiling, thus adding the contribution of the furniture, the value of the Equivalent Sound Absorption Area is going to increase and the environments will tend not to be under Sabine condition anymore [3, 4].

5.4 Solutions and comparisons

In this paragraph, it is presented a comparison between all the obtained results in terms of $T_{0.6}$, $T_{0.9}$, $A_{0.6}$, $A_{0.9}$, $\overline{\alpha}_{0.6}$ and $\overline{\alpha}_{0.9}$.

The $T_{0.6}$ values have no criticalities regarding the requirements, because all of them could fall into the WELL thresholds with some specific expedients. Indeed in the last majority of case studies, the results of the Reveberation Times calculated with the Equivalent Sound Absorption Area $A_{0.6}$ are higher than the thresholds given by WELL. In this case, the addition of furniture and people can contribute in the respect of those limits.

While for the Reverberation Time $T_{0.9}$ calculated with an $A_{0.9}$, defined according to WELL feature S05 (2 points) and ISO22955:2021 the obtained values and results are the most critical one. Indeed in the first paragraph (environments defined with respect to standards) and in the second paragraph (enviroments deined from current literature) were find out lots of problems with thresholds especially for large size enviroments (V>570 m^3). Those Open Plan offices have a $T_{0.9}$ lower than the minimum value of the interval (0.6 seconds) imposed by WELL protocol to reach 2 points ($0.6 \leq t \leq 1$s). The addition of furniture and considering the room in “an occupied condition” (with people inside) can only contribute to decrease the reverberation time for those enviroments moving T far away from the threshold interval. Note that this problem is not present in Open Plan offices measured *in situ* where everything seems verified or at least can be verified. It is important to consider the fact that, also in these cases were not considered furniture and people contributions, so adding them in reverberation time calculations these $T_{0.9}$ values could decrease, going out from the feature S04 requirement.

From the analisys carried out for the ratios $A/S_{floor}>0.6$ and $A/S_{floor}>0.9$, the results show that for the environments defined starting from standards the $\overline{\alpha}_{0.6}$ values are almost all inside Sabine’s region, except for the two environments G and H (large size). For $A_{0.9}$ all the offices have an $\overline{\alpha}_{0.9}$ grater than 0.2, so they are far away from the region defined by Sabine. For the Open Plan offices defined with respect to current literature, in both cases all the values of $\overline{\alpha}_{0.6}$ and $\overline{\alpha}_{0.9}$ fall into Sabine’s region and the maximum obtained value of the Average Sound Absorption coefficient is equal to 0.10.

The Open Plan offices measured *in situ*, all the environments, for $A/S_{floor}>0.6$ have a $\overline{\alpha}_{0.6}$ lower than 0.2 except for the large size Open Workspace Office 2 which is higher. Whereas for $A/S_{floor}>0.9$, on one hand the Average Sound Absorption Coefficient for small OP offices is lower than 0.2, on the other hand all the remaining enviroments have a $\overline{\alpha}_{0.9}$ grater than 0.2. Note that, in this case too, all the presented situations are in condition of empty enviroments and with the ceiling treatment only, thus adding the contribution of the furniture, the value of the Equivalent Sound Absorbtion Area is going to increase and the environment will tend not to be under Sabine condition anymore [3, 4].

6 Conclusions

The key concept on which is based the whole analysis is related to the acoustic comfort in workplaces, to guarantee wellness, productivity and increase the concentration of the workers. Each conutry has its own standards and voluntary certifications based on proper geometries, parameters and thresholds that must be respected to reach the comfort. The main idea of this conducted study grown from the fact that sometimes in Italy the big companies of designer find themselves working, at the request of the client, with voluntary point protocols developed in the USA, where the boundary conditions are completely different (for example no architectural restraints, floor fully carpeted, etc). Therefore, problems can occur in design, application, and compliance with limits given by non-Italian protocols.

The perfomed analysis wants to investigate how standards like ISO 22955:2021 and voluntary protocols like WELL Certification, and their requirements interact between eachother. For reaching the aim, a comparison was developed between several configurations carried out from:

- The state of art | Standards;
- Literature | Systematic rewiev;
- In situ measurements;

Applied to small, medium and large size environments. Length and width are defined according to 1:4 proportion, interesting from an acoustic point of view because we fall in a situation in which the hypothesis of the Sabine predictive formula for the Reverberation Time could be still valid, but this formula lose its meaning when the environment is furnished and Sabine is no more valid.

From standards, the analysis of parameters was performed following the state of art, with the precise division in range volumes (250, 450, 650 m^3), the sound absorption treatment applied only to ceiling surface and the environments are not furnished [3, 4].

From literature, the offices defined with the data find out in the systematic rewiev, have shown number of workstations equal to 26.4±33.7, the workstation density is 0.3±0.3 num/m^2, with a ceiling height equal to 3.2±0.7 m and a surface area of 267.2±228.2 m^2. While in terms of categories the 56.5% of the offices have an absorbent ceiling, the 34.9% a floor fully carpeted and the 57.6% of the Open Plan have partitions and screens [16, 19, 25, 31, 39].

From *in situ* measurements, the case studies have a number of workstations that varies from 26 to 61, floor surface from 192 to 417 m², ceiling treated with sound absorption materials, the glass walls along the main sides and between some offices, screens of different heights and between desks.

In this comparison were analized the Reverberation Time T ($T_{0.6}$, $T_{0.9}$) and A/S_{floor} ($A/S_{floor}>0.6$, $A/S_{floor}>0.9$) values obtained from the mutual interaction and combination of the WELL features S04, S05 and ISO 22955:2021 requirements. In A/S_{floor} ratio, it is considered only the suspended ceiling surface (S_{floor}) in terms of sound absorption contribution, and it is used as precondition for the calculation of the reverberation time in empty environment to decrease as much as possible the Lombard effect [42].

On one hand in lots of the analized configurations (large size), coming from the state of art, literature and in situ measurements, the reverberation time $T_{0.6}$ calculated with $A/S_{floor}>0.6$, has values higher than the maximum threshold defined by WELL in *feature S04 – Reverberation Time thresholds*. However, adding the furniture contribution there is a high probability that those values of Reverberation time will tend to decrease and fall inside the given limits.

On the other hand, the reverberation time $T_{0.9}$ calculated with $A/S_{floor}>0.9$, specially for large size environments, taken from state of art, literature, in situ measurements, have values lower than the minimum limit given by WELL feature S04, and the addition of furniture will contribute to decrease and decrease those T values, making the environment drier and drier. Therefore, in this situation there is a high probability to create a situation of “discomfort” for people that work inside those environments.

Indeed, increasing the Equivalent Sound Absorption Area in an office, means increasing the intelligibility of the irrelevant speech. In an Open Plan office an employee hears what others of his colleagues are saying at workstations far from his own, more than 4m distance, losing concentration.

To conclude, WELL Certification, same as ISO 22955:2021, in *feature S05 - Sound Reducing Surfaces* defines an $A/S_{floor}>0.9$ that in some cases could present a possible incompatibility with the reverberation time requirement T defined by *feature S04 – Reverberation Time thresholds* for large size environments [3, 4].

Attachments

Associazione Italiana di Acustica
49° Convegno Nazionale
Ferrara, 7-9 giugno 2023

IL RUOLO DEI CONTROSOFFITTI NELLA VERIFICA DELLE FEATURES WELL E I REQUISITI ISO 22955:2021

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SOMMARIO
La sezione Sound del protocollo WELL V2, Q2 2022 prevede, oltre alle condizioni necessarie per la certificazione, delle ottimizzazioni tra cui le *features S04 – Reverberation time* e *S05 – Sound Reducing Surfaces*. In funzione di tale protocollo, di seguito verranno analizzati nove scenari di uffici *open space* con proporzioni definite. I risultati ottenuti verranno confrontati con i requisiti dello standard ISO 22955:2021, al fine di individuare compatibilità nell'applicazione di entrambi i protocolli.

1. Introduzione

Il comfort acustico negli ambienti di lavoro, quali gli uffici, garantisce una maggiore concentrazione e produttività dei lavoratori. Esistono protocolli, come il WELL, e standard, come la ISO 22955:2021, che si occupano del miglioramento della qualità acustica all'interno di tali ambienti. Il *WELL V2, Q2 2022 – Sound*, definisce sei *features* a ciascuna delle quali, per ogni tipologia di ambiente analizzato, viene assegnato uno specifico punteggio, a seconda del grado di dettaglio e del criterio. La condizione preliminare necessaria per l'applicazione del protocollo WELL è la *feature S01 – Sound Mapping*, per cui è richiesta la mappatura degli ambienti in base al rumore che si può generare al loro interno. Due dei criteri di ottimizzazione applicabili sono la *feature S04 – Reverberation time* e la *feature S05 – Sound Reducing Surfaces*. Queste due *features* prevedono l'impiego di materiale assorbente per supportare la concentrazione dei lavoratori tramite la riduzione della riverberazione all'interno degli uffici [1]. I requisiti delle *features* della certificazione WELL sono tratte dalla norma australiana/neozelandese AS/NZS 2107:2016, *Acoustics - Recommended design sound levels and reverberation times for building interiors* [2]. L'obiettivo del presente articolo è analizzare le *features* del WELL per *Open Workspaces* e confrontarle con i requisiti dello standard ISO 22955:2021, al fine di individuare compatibilità nelle loro applicazioni [3].

2. Protocollo WELL e ISO 22955:2021

La *feature S04 – Reverberation time* per lo *Space Type: Areas for learning and conferencing* definisce volumetrie e limiti del tempo di riverberazione come riportato in tabella 1 [1].

Tabella 1 – Soglie del tempo di riverberazione [1].

Space Type	Space Volume, v (cubic meters)	Reverberation Time, t (seconds)
Areas for learning and conferencing	v < 10,000 ft^3(280 m^3)	$t \le 0.6^{1,2}$
	10,000 ft^3(280 m^3) ≤ v ≤ 20,000 ft^3(570 m^3)	$0.5 \le t \le 0.8^2$
	v > 20,000 ft^3(570 m^3)	$0.6 \le t \le 1.0^2$

La *feature S05 – Sound Reduction Surfaces* del WELL identifica due possibilità diverse a seconda del punteggio che si vuole raggiungere [1]. Per il raggiungimento di 1 punto, si ha (1):

$$\frac{A}{S_{floor}} > 0.6 \quad [-] \tag{1}$$

Per il raggiungimento di 2 punti, si ha (2):

$$\frac{A}{S_{floor}} > 0.9 \quad [-] \tag{2}$$

dove:
A è l'area di assorbimento equivalente [m^2];
S_{floor} è la superficie del pavimento [m^2].

La *feature S05* è definita in condizioni di ambiente vuoto, quindi non prende in considerazione i miglioramenti che si otterrebbero in condizione arredata. Lo standard ISO 22955:2021, per gli stessi ambienti di lavoro, richiede una quantità di area di assorbimento equivalente pari ad almeno il 90% della superficie del pavimento. Si ha così il risultato di mantenere il livello di rumore sotto controllo, garantendo il benessere dei lavoratori all'interno degli spazi, e di contenere l'effetto Lombard [4]. Vale dunque la stessa relazione espressa dall'equazione 2 riferita al protocollo WELL.

3. Metodo

Si sono ipotizzate nove configurazioni di uffici ideali, caratterizzati da tre volumi specifici (250, 450, 650 m^3) e tre altezze (2.70, 3.00, 3.30 m), sulla base delle categorie di volume indicate dal WELL [1], come si vede in tabella 2. Tutte le geometrie studiate hanno le altezze descritte, con proporzione tra lunghezza e profondità di 1:4 [5].

Tabella 2 – Geometrie dei casi studio.

	Space type	*Areas for learning, lectures and conferencing*				
	volume [m^3]	**altezza [m]**	**S_{floor} [m^2]**	**lunghezza$^{(1)}$ [m]**	**profondità$^{(1)}$ [m]**	**S_{tot} [m^2]**
A	250	2,70	92,6	19,2	4,8	315,1
B		3,00	83,3	18,3	4,6	303,6
C		3,30	75,8	17,4	4,4	295,1
D	450	2,70	166,7	25,8	6,5	507,6
E		3,00	150,0	24,5	6,1	483,7
F		3,30	136,4	23,4	5,8	465,4
G	650	2,70	240,7	31,0	7,8	690,9
H		3,00	216,7	29,4	7,4	654,1
I		3,30	197,0	28,1	7,0	625,5

(1) calcolato con proporzione 1:4

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4. Risultati e discussioni

Una volta note le caratteristiche geometriche degli ambienti, si è proceduto a calcolare l'area di assorbimento equivalente, il tempo di riverberazione e il coefficiente di assorbimento medio, nei due casi:

1. $A_{0.6}$, $T_{0.6}$, $\overline{\alpha}_{0.6}$ con $A/S_{floor} > 0.6$
2. $A_{0.9}$, $T_{0.9}$, $\overline{\alpha}_{0.9}$ con $A/S_{floor} > 0.9$

I risultati sono riportati in tabella 3.

Tabella 3 – Risultati per ogni configurazione.

	V [m^3]	$A_{0,6}$ [m^2]	$A_{0,9}$ [m^2]	$T_{0,6}$ [s]	$T_{0,9}$ [s]	$\overline{\alpha_{0.6}}$ [-]	$\overline{\alpha_{0.9}}$ [-]
A	250	56	83	0,72	0,48	0,18	0,26
B		50	75	0,80	0,53	0,16	0,25
C		45	68	0,88	0,59	0,15	0,23
D	450	100	150	0,72	0,48	0,20	0,30
E		90	135	0,80	0,53	0,19	0,28
F		82	123	0,88	0,59	0,18	0,26
G	650	144	217	0,72	0,48	0,21	0,31
H		130	195	0,80	0,53	0,20	0,30
I		118	177	0,88	0,59	0,19	0,28

I tempi di riverberazione sono stati calcolati con un'area di assorbimento equivalente definita dal solo contributo del controsoffitto ($0.6 \cdot S_{floor}$ e $0.9 \cdot S_{floor}$). I T ottenuti si possono abbassare con l'aggiunta degli arredi, ma l'importante è che il solo contributo del controsoffitto non li renda troppo bassi rispetto al requisito minimo. Confrontando $T_{0.6}$ e $T_{0.9}$, in ambiente vuoto con i limiti definiti dal WELL, si ha che nel caso di $T_{0.6}$ gli ambienti A, B, C (volume 250 m^3) hanno tempi di riverberazione più alti del valore massimo consentito (0.6 secondi), ma con l'aggiunta degli arredi questo tenderà a scendere e quindi verosimilmente a rispettare il limite. Lo stesso vale per gli ambienti E, F (volume 450 m^3). Nel caso di $T_{0.9}$ per gli ambienti D (volume 450 m^3) e G, H, I (volume 650 m^3), il tempo di riverberazione è più basso dei valori minimi indicati dal WELL (tra 0.5 e 0.8 secondi nel caso D, e tra 0.6 e 1 secondi nei casi G, H, I), quindi aggiungendo gli arredi $T_{0.9}$ tenderà a scendere, allontanandosi sempre di più dalla soglia minima. Gli andamenti dei tempi di riverberazione sono visibili in figura 1.

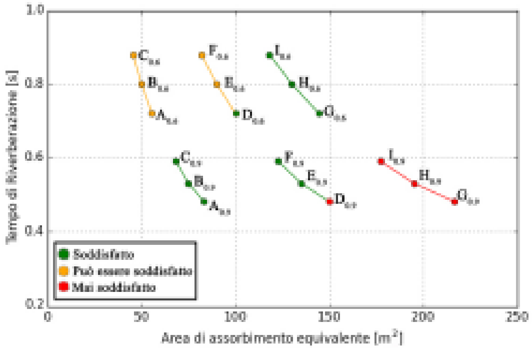

Figura 1 – Classificazione dei tempi di riverberazione secondo i limiti WELL.

È utile notare che i coefficienti di assorbimento medi relativi alla condizione $\overline{\alpha}_{0.9}$ sono indice di un allontanamento dalle assunzioni alla base delle formule previsionali fornite dalla ISO 12354-6 [6]. Questo avviene sia perché sono più elevati rispetto alla regione di validità della formula di Sabine ($\overline{\alpha}$<0.2), sia perché rappresentano un valore medio di α distribuiti non omogeneamente nella stanza (assorbimento concentrato sul controsoffitto).

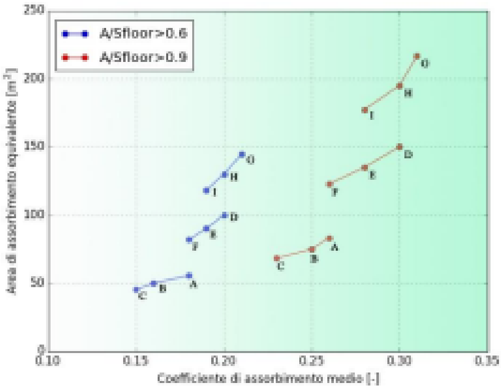

Figura 2 - A/S_{floor} per ogni configurazione.

I risultati ottenuti dall'analisi delle nove configurazioni, sono raccolti in figura 2. Le curve che si ottengono dall'interpolazione dei valori di ($\overline{\alpha}_{0.6}$, $A_{0.6}$) e ($\overline{\alpha}_{0.9}$, $A_{0.9}$) decrescono in modo non lineare. Per il caso A/S_{floor}>0.6 si ha un $\overline{\alpha}_{0.6}$ in media pari a 0.18, mentre per il caso A/S_{floor}>0.9 si ha un $\overline{\alpha}_{0.9}$ in media pari a 0.28. Entrambe le situazioni sono in ambiente vuoto e con il solo trattamento a soffitto, quindi, aggiungendo il contributo degli arredi, aumenterà il valore dell'area di assorbimento equivalente e l'ambiente tenderà a non essere più sabiniano.

5. Conclusioni

Il presente lavoro ha voluto confrontare tramite nove configurazioni diverse in condizioni non arredate, i valori del tempo di riverberazione e di A/S_{floor} secondo certificazione WELL e ISO 22955:2021. Il WELL considera A/S_{floor}>0.6 e A/S_{floor}>0.9, mentre lo standard ISO solo A/S_{floor}>0.9. In entrambi i casi viene considerata solo l'area del controsoffitto, e questo rapporto può essere usato come condizione preliminare al calcolo di T in ambiente vuoto per ridurre al minimo l'effetto Lombard [4]. I valori di $T_{0.6}$ in alcune configurazioni sono più alti dei limiti identificati dal WELL e quindi possono essere ridotti, a esempio, inserendo gli arredi. Al contrario $T_{0.9}$ in alcuni casi presenta valori inferiori rispetto al minimo riconosciuto dal WELL. Il calcolo è in ambiente vuoto, quindi l'aggiunta degli arredi contribuirà a far diminuire ulteriormente i valori di $T_{0.9}$ e ad aumentare l'allontanamento dal limite minimo. A tali valori di $T_{0.9}$, corrispondono valori di $\overline{\alpha}_{0.9}$ pari o superiori a 0.3, e come si nota in figura 2 sono anche i più lontani dalla regione di Sabine. Il WELL, così come la ISO 22955:2021, nella *feature S05* definisce un rapporto A/S_{floor}>0.9 che in alcuni casi può presentare un'incompatibilità con il requisito di T definito dalla *feature S04* per ambienti di grandi dimensioni.

6. Bibliografia

[1] WELL Building Standard V2, Q4 2020, International WELL Building Institute, 2020.
[2] AS/NZS 2107:2016, *Acoustics - Recommended design sound levels and reverberation times for building interiors*
[3] ISO 22955:2021, *Acoustics – Acoustic quality of open office spaces*
[4] Lombard E., *Le signe de l'élévation de la voix*, 1911
[5] Yadav M., *Sound in occupied open-plan offices: Objective metrics with a review of historical perspectives*, Applied Acoustics, 2021
[6] ISO 12354-6:2003, *Building Acoustics – Estimation of acoustic performance of buildings from performance of elements - Sound absorption in enclosed spaces*

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Bibliography

[1] Spagnolo, R. (Ed.). (2001). *Manuale di acustica applicata*. UTET libreria.

[2] Choi, Y. J. (2023). Towards better acoustic conditions in school buildings in Korea-a need for Korean standard for classroom acoustics. *The Journal of the Acoustical Society of Korea*, *42*(2), 113-123.

[3] WELL Building Standard V2, Q4 2020, International WELL Building Institute, 2020

[4] ISO 22955:2021, Acoustics – Acoustic quality of open office spaces

[5] AS/NZS 2107:2016, Acoustics - Recommended design sound levels and reverberation times for building interiors

[6] LEED v4 for Building Design and Construction, 2016

[7] Hongisto, V., & Keränen, J. (2018). Open-plan offices-New Finnish room acoustic regulations. *Proceedings of EuroNoise2018*.

[8] Rindel, J. H., & Christensen, C. L. (2012, May). Acoustical simulation of open-plan offices according to ISO 3382-3. In *Proceedings of the Euronoise* (pp. 10-13).

[9] ISO 3382-3:2022, Acoustics – Measurement of room acoustic parameters – Part 3: Open plan offices

[10] ASTM E1374, Standard Guide for Open Office Acoustics and Applicable ASTM Standards

[11] Yadav, M., Kim, J., Cabrera, D., & De Dear, R. (2017). Auditory distraction in open-plan office environments: The effect of multi-talker acoustics. *Applied Acoustics*, *126*, 68-80.

[12] Zaglauer, M., Drotleff, H., & Liebl, A. (2017). Background babble in open-plan offices: A natural masker of disruptive speech?. *Applied Acoustics*, *118*, 1-7.

[13] Utami, S. S., Arifianto, D., & Nadiroh, A. (2017). Study on the effect of partition heights in open plan office to the privacy and distraction level utilizing computational fluid dynamics. *Procedia engineering*, *170*, 195-201.

[14] Larrieu, F., & Harvie-Clark, J. (2017, July). Contrasting open plan office design implications from emerging French, German and Finnish standards. In *INTERNATIONAL CONGRESS ON SOUND AND VIBRATION* (Vol. 24).

[15] Iannace, G., Ciaburro, G., & Trematerra, A. (2018). Heating, ventilation, and air conditioning (HVAC) noise detection in open-plan offices using recursive partitioning. *Buildings*, *8*(12), 169.

[16] Cabrera, D., Yadav, M., & Protheroe, D. (2018). Critical methodological assessment of the distraction distance used for evaluating room acoustic quality of open-plan offices. *Applied Acoustics*, *140*, 132-142.

[17] Delle Macchie, S., Secchi, S., & Cellai, G. (2018). Acoustic issues in open plan offices: A typological analysis. *Buildings*, *8*(11), 161.

[18] D'Orazio, D., Rossi, E., & Garai, M. (2018). Comparison of different in situ measurements techniques of intelligibility in an open-plan office. *Building Acoustics*, *25*(2), 111-122.

[19] Selzer, J., & Schelle, F. (2018, May). Practical aspects of measuring acoustics in German open plan offices. In *11th European Congress and Exposition on Noise Control Engineering (Euronoise), Crete* (pp. 27-31).

[20] Dickschen, A., Bertazzoni, R., & Liebl, A. (2018, May). Evaluating room acoustic quality in open-plan offices by adding the distribution of possible source and receiver positions to the simulation. In *Proceedings of Euronoise* (pp. 27-31).

[21] Petersen, C. M., & Rasmussen, B. (2018). Acoustic design of open-plan offices and comparison of requirements in the Nordic countries. In *Baltic-Nordic Acoustics Meeting 2018* (pp. 1-8). Nordic Acoustic Association.

[22] Kemppainen, J., Niemi, H., Kylliäinen, M., & Mikkilä, A. The cost effects of acoustics in open-plan office. In *Proceedings of the Joint Baltic-Nordic Acoustics Meeting. Reykjavik* (pp. 15-18).

[23] Barros, M. N., Raeder, A., & Borin, M. (2018). A comparison study between prediction models and in situ measurements of acoustic clouds in open plan offices. Euronoise.

[24] CAMARGO, D. (2018). Development and application of questionnaires to assess acoustic environment in open plan offices. *EURONOISE, Grécia*.

[25] Yadav, M., Cabrera, D., Love, J., Kim, J., Holmes, J., Caldwell, H., & de Dear, R. (2019). Reliability and repeatability of ISO 3382-3 metrics based on repeated acoustic measurements in open-plan offices. *Applied Acoustics*, *150*, 138-146.

[26] Wenmaekers, R., & van Hout, N. (2019). *How ISO 3382-3 acoustic parameter values are affected by furniture, barriers and sound absorption in a typical open plan office*. Universitätsbibliothek der RWTH Aachen.

[27] Harvie-Clark, J., Larrieu, F., & Opsanger, C. (2019). *Iso 3382-3: Necessary but not sufficient. a new approach to acoustic design for activity-based-working offices*. Universitätsbibliothek der RWTH Aachen.

[28] Lee, P. J., Park, S. H., & Lee, B. K. (2019, January). Impact of acoustic enviornment on work in open-plan offices across job characteristics. In *Proceedings of the 26th International Congress on Sound and Vibration, ICSV 2019*.

[29] Braat-Eggen, E., Reinten, J., Hornikx, M., & Kohlrausch, A. (2020). The influence of background speech on a writing task in an open-plan study environment. *Building and Environment, 169*, 106586.

[30] Lou, H., & Ou, D. (2020). The effects of speech intelligibility on English scientific literature reading in Chinese open-plan offices. *The Journal of the Acoustical Society of America*, *147*(1), EL1-EL6.

[31] Lüthi, G., & Desarnaulds, V. (2020). Analysis of open plan acoustic parameters based on Swiss and international databases of in situ measurements. *Proceedings of the ICSV27, Prague, Czech Republik*, 12-16.

[32] Keränen, J., Hakala, J., & Hongisto, V. (2020). Effect of sound absorption and screen height on spatial decay of speech–Experimental study in an open-plan office. *Applied Acoustics*, *166*, 107340.

[33] Hongisto, V., Keränen, J., Labia, L., & Alakoivu, R. (2021). Precision of ISO 3382-2 and ISO 3382-3–A Round-Robin test in an open-plan office. *Applied Acoustics*, *175*, 107846.

[34] Lenne, L., Chevret, P., & Parizet, É. (2021). Measurement uncertainty and unicity of single number quantities describing the spatial decay of speech level in open-plan offices. *Applied Acoustics*, *182*, 108269.

[35] Teixeira, T., Prata, A., Mcdade, A., Martins, F., & Inacio, O. (2020, December). An experimental, numerical and subjective approach for open plan office acoustics. In *Forum Acusticum* (pp. 2721-2725).

[36] Harvie-Clark, J., & Hinton, R. (2021, June). The value of control for acoustic satisfaction in open plan offices: a case study. In *The 13th ICBEN Congress on Noise as a Public Health Problem, Sweden*.

[37] Madzharova, Z., Kirechev, A., & Antovska, M. (2020, December). Influence of acoustic environment upon work performance in open plan offices. In *Forum Acusticum* (pp. 2225-2231).

[38] Kang, S., Mak, C. M., Ou, D., & Zhang, Y. (2022). The effect of room acoustic quality levels on work performance and perceptions in open-plan offices: A laboratory study. *Applied Acoustics*, *201*, 109096.

[39] Kang, S., Mak, C. M., Ou, D., & Zhang, Y. (2022). An investigation of acoustic environments in large and medium-sized open-plan offices in China. *Applied Acoustics, 186*, 108447

[40] Jo, H. I., Santika, B. B., Lee, H., & Jeon, J. Y. (2022). Classification of sound environment based on subjective response with speech privacy in open plan offices. *Applied Acoustics, 189*, 108595.

[41] D. D’Orazio, L. Parati, Lo scenario di sviluppo della UNI 11532-3 (parte 2), Ferrara, AIA 2023.

[42] Lombard, E. (1911). Le signe de l'elevation de la voix, Annales des Maladies de l'Oreille, du Larynx, du Nez et du. *Pharynx, 37*, 101-119.

[43] De Croon, E., Sluiter, J., Kuijer, P. P., & Frings-Dresen, M. (2005). The effect of office concepts on worker health and performance: a systematic review of the literature. *Ergonomics*, *48*(2), 119-134.

[44] ISO 12354-6:2003, Building Acoustics – Estimation of acoustic performance of buildings from performance of elements - Sound absorption in enclosed spaces

[45] UNI 11532-2, *Caratteristiche acustiche interne di ambienti confinati – Metodi di progettazione e tecniche di valutazione – Parte 2: Settore scolastico*

[46] ISO 9921:2003, Ergonomics — Assessment of speech communication