Evaluation of acoustic measurements methods and design of meeting rooms: solutions for an optimal speech perception

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1. ABSTRACT

There are several different ways of measuring the acoustic quality of an existing room, in order to evaluate and understand in which cases and how to intervene with a special acoustic treatment. A quite large variety of software appears useful to calculate some interesting parameters, after previous receiving of input data.
In this preliminary phase of measurements, it appears particularly important to set correctly the whole equipment and remind each time the used settings, in order to guarantee both the repeatability and the reproducibility of the measures, even using a different software. All the measurements and the simulations were made in a frequency range of 125-8000 Hz, in unoccupied rooms conditions.
Among all, ODEON is a specific software generally used world-wide for prediction of room acoustics: given a 3D-model, an appropriate sound absorption coefficient for each material in the room (called surface properties), the acoustics can be predicted, illustrated through graphs and listened to. The first part of this research aims to test the validity of ODEON software not only as a simulation tool, but also as a useful measurement tool. The first operation was then the verification of the acoustic characteristics of the rooms in the current conditions.
A first sample of study cases was analyzed in Turku (Finland), using the Turku University of Applied Sciences' equipment and ODEON 14. This sample includes two categories of rooms, also mentioned in the ISO 3382 standards classification: open plan offices and auditoria, the latter meant as a presentation space used for speaking in public. In Turku, the measurements were taken using both ODOEN and SoundBook, a compact pc, definable as a universal portable measuring system for acoustic. The comparison between the two methods leads to achieve a more specific range of data for the investigated parameters.
A second sample of rooms was then measured and analyzed in Turin (Italy), using the Politecnico di Torino's equipment and ODEON 14. In this case the comparison is both with Aurora (a different software for room acoustics measurements), and with ODEON 15's simulations system.
The purpose was to understand in which measure the ODEON measurements system is

reliable: the aim's satisfying was desired, because the investigated software's methodology appears a very good tool in terms of practicality, learning process, economics and transport. The further comparison of cases measured through a variety of software gives ODEON even more reliability: it can be used in a wider way, also counting on the easy process of output data for analysis. Indeed, it works giving good results only if a previous calibration is correctly made, before measurements: otherwise, some parameters (such as the intelligibility parameter of Speech Transmission Index, or the Sound Pressure Level) appear not trustable at all.
All the measurements were taken in spaces used for speech, not for music, and always in empty rooms conditions. The reference for target values can be found in the ISO 3382 standard, part 1, Annex A: since it's specific for performance spaces, though, some range needs to be adapted for presentations rooms or open plan offices, where people talk and discuss with others.

The second part of this thesis' research is focused on the acoustic design of two cases study, both used as interaction and presentation rooms:

1. The Cafaro meeting room, Energy Department (DENERG), in Politecnico di Torino's headquarters;
2. The Galfer meeting room, in the "Galileo Ferraris" Politecnico's branch.

In this kind of rooms, the understanding and perception of speech represents the main requirement to satisfy. Speech quality "can be further improved by introducing diffusers or acoustic absorbers, with absorbers improving the subjectively perceived speech quality slightly more than the diffuser panels" (Sanavi et al, 2017). The Cafaro meeting room presents a low-quality acoustics because of the understanding of speech, appearing very bad, due to reflections on its singularly shaped ceilings; the Galfer meeting room presents a very noisy projector used during conferences and a coupled room effect, which compromise the audience's listening.

The first step for the indoor spaces treatment was measuring them in unoccupied and untreated conditions: for this purpose, two methods were used and later compared (ODEON's measurements system and Adobe Audition's Aurora). In this way a more accurate

evaluation of the starting conditions was defined, by comparison of the achieved results.
The data were analyzed, as a second step, in order to decide their reliability and truthfulness. This phase was carried out in a more complete way by comparing results to those achieved through the ODEON's simulation system: by doing this, it's extremely important to control and manage the absorption (and eventually *scattering*) coefficients of all the surfaces' materials found in the room.
After calculating the required chosen absorbers and diffusers surface, necessary for the useful acoustics correction, a meaningful number of panels is found as output. These panels were positioned in the rooms following rules pointed out in the DIN 18041 standard and in technical literature.
The above-mentioned research outlined a design workflow, useful for architects and engineers to design better sounding meeting rooms, understanding the sounds reflections.

2.

INTRODUCTION

2. INTRODUCTION

The first phase of the research aims to investigate the acoustic satisfaction in open-plan offices.

Generally categorized by the absence of walls and partitions, the open-plan office concept was first conceived by two West German furniture manufacturers, Eberhard and Wolfgang Schnelle, and was promoted in the United States around the 1960’s (Hundert & Greenfield, 1969). These innovators believed that the open office offered several managerial, economic and working condition advantages, such as better communication between departments, space saving due to the elimination of corridors and better overall environmental conditions (Boyce, 1974; Hundert & Greenfield, 1969; Zalesny & Farace, 1987). By the mid-1970’s, open offices became common in North America, and remain as the primary type of office design. Today, the open-plan office can be defined as “a workspace whose perimeter boundaries do not go to the ceiling. Most often constructed of relocatable panels and panel-hung work surfaces and storage, or of relocatable panels with free-standing furniture or of non-relocatable, drywall boundaries (not to the ceiling) and free-standing furniture” (Brill, Weidemann, & BOSTI Associates, 2001, p. 17).

Common problems associated with the open-plan office include frequent complaints of loss of privacy, aural distractions and frequent interruptions by other employees (Hedge, 1982). Studies have found that intelligible speech is attended to and is more distracting than unintelligible speech or sounds with no information content (Navai and Veitch, 2003).

In open-plan environment the main acoustic problems are due to the nature of the layout itself. The key purpose of this part of the research is indeed to answer to the main question: what acoustic conditions would be satisfactory to occupants of open-plan offices?

The second phase is focused on the acoustic needs of auditoria, defined as “a large public buildings where meetings are held” (dictionary.cambridge.org) e. g. spaces used for

speech. In this kind of indoor spaces, the understanding and perception of speech represents the main requirement to satisfy. Speech quality “can be further improved by introducing diffusers or acoustic absorbers, with absorbers improving the subjectively perceived speech quality slightly more than the diffuser panels” (Sanavi et al, 2017).
In this research, measurements of auditoria are preliminary for studying presentation spaces’ requirements, in order to understand the sound perception’s priorities and carry on a good acoustic treatment in the meeting rooms analyzed in the design part of the thesis.

2.1 Finnish cases study

In Turku (FI) a specimen of 6 cases study was measured and analyzed:

- Data City Meeting room (almost anechoic), used by the Turku
- University of Applied Sciences (TUAS) team of researchers;
- Data City Reverberant room (totally reflective for sound),
- employed for researchers’ tests and experiments;
- Multipurpose auditorium at the ground floor, in the ICT building;
- Truku Concert Hall, mostly used for music;
- Kaarina Talo, multipurpose auditorium;
- Open plan office in Educarium, a building included in the TUAS Campus.

These rooms have different purposes and, for this reason, also various acoustic needs. The measurements were taken referring to the ISO 3382 standard, in its different parts: 1, 2, and 3. The part 1 is specific for performance spaces, while the part 2 gives directions for the reverberation time values in ordinary rooms and the part 3 focuses on open plan offices.
The main goal of this first research was to understand both how the values of the measured parameters change in function of the geometry and the destination of use of the room, and how to intervene with acoustic treatments in case of mismatch between the parameters measured in the rooms and those pointed out by the ISO 3382.

2.2 Politecnico of Turin cases study

In Turin (IT) a specimen of 3 more cases study was measured and analyzed:

- Galfer meeting room, in the "Galileo Ferraris" building, where the Department of Energy of the Politecnico of Turin takes place;
- Cafaro meeting room, in the central venue of the Politecnico, used by physics department researchers and PhD students;
- Aula Magna of the Politecnico, multipurpose auditorium.

As in the Turku cases study, also in this Turin specimen the measurements refer to the ISO 3382 standard in its 3 parts.

In this case the main goals of the research are both to compare the results achieved by measurements with the standard's values, and to learn how to apply an optimal acoustic treatment in disturbing environments, which present in some cases acoustic problems.

2.3 Investigated parameters for rooms acoustic quality and typical values

The whole research investigates two main topics:

1. Acoustic satisfaction in open-plan offices;
2. Acoustic needs of auditoria, defined as "a large public buildings where meetings are held" (https://dictionary.cambridge.org/dictionary/english/auditorium), e.g. spaces used for speech.

The acoustic satisfaction was defined as "a state of contentment with acoustic conditions; it is inclusive of annoyance, loudness, and distraction. Acoustic comfort, defined as the psychophysical condition of satisfying acoustic needs expressed by a person who's carrying out a given activity, is essential reference for understanding the good acoustics of an environment. The open plan offices lack walls and doors. Although one common assumption has been that such a design would encourage communication between co-workers, it has become apparent that the primary source of discomfort for occupants of the open-plan office environment is unwanted sound" (Navai and Veitch, 2003).

The auditoria, meant as indoor environments used for comprehension of speech, require noise, reverberation and speech intelligibility control. A good acoustics in these spaces, indeed, increases the amount of words, phrases and in general concepts understood, giving a rise in auditory processing of presented topics.

Indexes have been introduced, representing the relationship between energy, related to the direct sound and It's necessary to identify the time point for the classification between useful reflections and annoying reflections: depending on its value, indices were proposed, many valid for speech (Thiele and Shultz proposed, in 1953, an interval between 0 and 50ms for speech), others for music.

Some parameters interesting for the two different kind of spaces are investigated considering the acoustic reverberation, the clarity and definition of speech, and the background noise level.

EDT, Early Decay Time [s]

This parameter is definible as the "rate of decay of the sound is often different in the beginning and further down the decay curve" (Springer Handbook of Acoustics, Thomas D. Rossing, 2007): the early decay time parameter measures, as a function of time expressed in seconds, the decay of the sound pressure level in a room, after the sound source has stopped.

It is identifiable with the reverberation time decay curve, between 0 dB and 10 dB below the initial level. According to ISO 3382-1: 2009 standard, a typical range is found between 1,0s and 3,0s. This parameter normally decreases moving away from the sound source and it's useful for a comparison between different measured points in the room. Above all, it is this time of first decay that accounts for the sense of reverberation.

A "short EDT is a good indicator of speech clarity, as early reflections that reach the listener within 50 milliseconds integrate with the direct sound and can improve speech clarity".

T_{20}, Reverberation Time [s]

The reverberation time (T) which is the traditional objective measure of this quality, was invented 100 years ago by W.C. Sabine (Springer Handbook of Acoustics, Thomas D. Rossing, 2007). When the emission of a sound by a sound source in a closed environment is abruptly interrupted, it is noticed that the sound level does not immediately go down to null values: it decreases, more slowly or less.

This phenomenon is due to the presence of reflected waves that keep on bouncing from one surface to another, determining the persistence of a gradually decreasing sound level. The Reverberation Time T, expressed in seconds, is one of the most important parameters considered in the evaluation of a room's acoustics characteristics: this is the measure of time elapsing between the disarming of a sound source and the moment when the sound level is decreased by one millionth of its initial value, or 60dB respectively, and represents the value of resonance of a room. The extent of the reverberation time depends on the environmental absorption.

The indicative values for the reverberation times are indicated as optimal: they depend on the frequencies. Thanks to these values it is possible to evaluate the acoustic quality of a room. In the best case, the reverberation times of a room are within the optimal zone and only small tolerances (about 0,1-0,2s) are admitted.

In architectural acoustics, especially in the case of performance and presentations spaces, rooms are often characterized by high noise levels bottom.

Such noises could be due to the proximity of busy roads, to the expected presence of people, to the noises caused by the systems, or the appliances always in operation, etc.

They can even reach the level of 40, 45dB and above. In similar cases, to perceive an effective decay of 60dB, these premises should be in an absurd acoustic situation, like in presence of sounds from 100 to 120dB, only bearable by robots and not by humans. The ISO 3382 standard intervened, establishing different values of reverberation times, based on various musical needs and extrapolated from the T_{60} to the T_{20}: these are realistic and measurable reverberation times in concrete situations.

To understand this mechanism, two different ideas must be considered:

- the duration of the sound queue;
- the sound level in dB.

The time corresponds to the same time measured by Sabine.

The above-mentioned standard foresees to determine T_{20} as three times the time passing between the point at -5dB and the point at -25dB, comparing to the stationary level (www.angelofarina.it, 21/05/14).

The DIN 18041:2004-05 standard defines optimal values according to volume of the rooms, frequency in octave bands and activity taking place within the measured environments, used for speech. This standard always refers to occupied rooms.

$$T_{20,0,25-2\ kHz,occupied} = 0{,}37\ lg\left(\frac{V}{m3}\right) - 0{,}14\ [s].$$

The UNI 11367:2010 standard, instead, gives indications for optimal Reverberation Time values in empty classroom for environments used for speech:

$$T_{20,0,50-1\ kHz,unoccupied} = 0{,}32\ lg\ (V)\ +\ 0{,}03\ [s].$$

For the determination of T_{20}, "the evaluated range of the decay curves is from 5dB to 25dB below the steady-state level" (EN ISO 3382-2:2008).

The problem of the uniformity of reverberation times in both conditions of public's affluence can be solved using chairs with an absorption coefficient which, in case of unoccupied seats, equals or at least appears similar to the employment condition.

Some requirements become necessary when performing a Reverberation Time measurement (Horvat & Domitrović, 2008).

They can be summarized as:

- the source is supposed to have an omni-directional radiation pattern (or as close to it as possible);
- the sound pressure level needs to be high enough to provide a minimum dynamic range required to perform a reverberation time measurement, to be more specific, at least 45 dB for methods that do not apply synchronous averaging (EN ISO 3382:2000).

C_{50}, Clarity [dB]

The characteristics of an indoor environment, especially when it appears essential to ensure good speech intelligibility, can be well described through parameter C50 (Clarity): it describes the feeling of clearly perceiving speech, depending on distance of the sound receiving point from the source and it's really sensitive to the spatial variation.

The subscript 50 means the time, expressed in milliseconds (ms), of the maximum delay of the useful sound: this early energy fraction is considered a good measure for speech intelligibility, while, for musical clarity, usually an 80ms early-to-late index (also expressed in dB) is used (Barron, 2015).

$$C_{50} = 10lg \frac{\int_0^{50ms} p^2(t)dt}{\int_{50ms}^{\infty} p^2(t)dt}.$$

The logarithm is used, because this parameter is measured or calculated in dB. Energy is expressed as the square of the pressure.

Optimal values of the Clarity index vary between -1 and 1dB (Farina, 2001):

- Higher values than 1dB indicate a too dry sound, similar to the free field sound;
- Values below -1dB indicate excessive sound reverberation.

This parameter was measured according to UNI EN ISO 3382-1:2008; values obtained were then compared with the recommended values expressed by UNI 11367:201015, which indicates as optimal a value higher than or equal to 0dB.

D_{50}, Definition [-], [%]

According to DIN 18041:2004-05, the "Deutlichkeit" (Definition) parameter, is an equivalent criterion to C50: it defines the ratio of sound energy in the first 50ms after the arrival of the direct sound at listener's position to the total sound energy. It is expressed in percentage, or a-dimensional index (AICMA, 2005). Its main use is to evaluate quality of speech perception in rooms. It is strongly connected to the sound reflections and to the receiver's positions (Bradley, ISRA 2010), and characterizes the speech perceived sound.

According to ISO 3382-1: 2009 standard, the single number frequency averaging is obtained between 500 and 1000 Hz of frequency octave bands. A typical range is found between 0,3 and 0,7.

$$D_{50} = \frac{\int_0^{50ms} p^2(t)dt}{\int_0^{\infty} p^2(t)dt}.$$

$L_{A,eq}$, Background Noise Level [dB]

The background noise is usually a complicate issue in open plan offices or speech used rooms. It can be "defined as *all the other signals (noise) different from the one of interest*. It is definible as one of the most important factors affecting speech intelligibility "(Astolfi et al., 2019).

The Background Noise Level is determined, in accordance with DIN 45641, as the A-weighted equivalent continuous sound pressure level over the time that is representative for the disturbance.

In this research it's always measured directly on field experiments, in each sources and receivers position chosen, through a sound level meter.

Acoustic requirements for room based on use	Noise pressure level of the building-generated noise $L_{NA,Bau}$ dB	Suitability for a speaker/listener distance that is	
		Average	Large
I (minimum)	≤ 40	Suitable	Not suitable
II (average)	≤ 35	Suitable	Suitable under certain conditions
III (maximum)	≤ 30	Suitable	Suitable

$L_{A,eq}$ suggestions pointed by the DIN 18041: 2004-2005 standard.

For an average distance between speaker and listener, a separation of 5m to 8m can normally be assumed; for larger distances >8 m.

Subjective listener aspect	Acoustic quantity	Single number frequency averaging [Hz]	Just noticeable difference (JND)
Perceived reverberance	Early Decay Time (EDT), in seconds	500 to 1000	Rel. 5%
Perceived clarity of sound	Clarity, C50, in decibels	500 to 1000	1 dB
Perceived clarity of sound	Definition, D50, a-dimensional	500 to 1000	0,05

Table reporting the typical values suggested by the UNI EN ISO 3382 standard, for the measured and evaluated parameters.

In other columns, also the single number frequency averaging between the two central octave bands is showed (500-1000Hz), each defined parameter with its appropriate JND. This latter is also called subjective limen, meaning the measure of minimum noticed variation of the analyzed value.

2.4 Virtuous design requirements

The acoustic design of a room, especially if it's expected to respond to specific requirements, as in the case of auditoria, halls or rooms used for speech comprehension, should be correctly set up since from the geometric shape design.

The main conditions necessary to obtain a good acoustic response in a room are:

1. Geometric shape, the appropriate dimensions and characteristics of the materials;
2. Sufficient sound level in all the listening points;
3. Absence of disturbing noises, or high signal-to-noise ratio;
4. The above investigated Reverberation Time.

A good acoustic rooms quality also requires an optimal transmission of sound messages in an indoor environment, for both speech and music.

The main acoustic conditions have been condensed by Sabine in these simple rules:

1. The sound must reach, in a necessary intense way, all the listening points of the room;
2. The sounds coming in sequence with rapid emissions shall arrive clear and defined to the listener's ears, maintaining their individuality;
3. The spectral components of a complex sound shall maintain unchanged their related intensity.

The presence of the walls increases the sound power perceived by the listeners, if compared to the sound in free field case; indeed, in addition to the direct sound, in each point of the room arrives, even if with some delay, also the sound reflected by the walls.

This phenomenon is known as *reverberation*. An efficient way to keep it controlled is to ensure a heterogenous spatial distribution of sound in the room; the reverberation time shall be as close as possible, or lower, than the optimal value reported for the specific use of the local.

According to Moretti (2009), essential requirements for good comprehension of speech in a room are:

- A minimum level of 65dB, optimal to ensure good speech intelligibility and to avoid an excessive attention effort by listeners;
- Limited background noise, to avoid disturbs in the acoustic intelligibility;
- Absence of acoustic defects (echo, flutter, etc.);
- Absence of distortion or tonal unbalance (caused by different entity absorption in each band of the sound spectrum);
- Homogeneous spatial arrangement of the sound in the room.

3.

ROOMS' DESCRIPTION

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TURKU

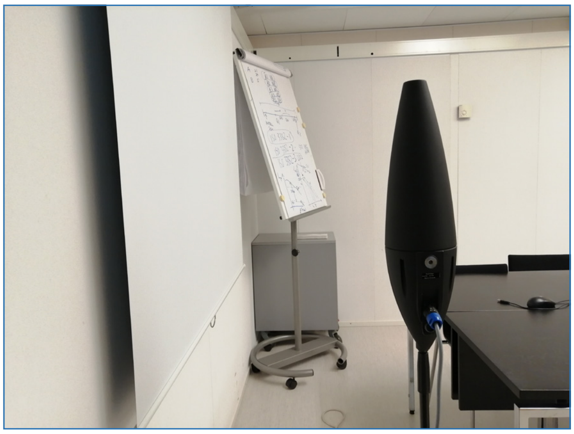
1. Meeting room

Years of construction: 2016
Location in the urban context: A building included in the Science Park, business district near the city center; 5th floor
Destination of use: Meeting room
Workstations: Flexible
Dimensions [m]: 6,74 x 4,63 x 2,71 m
Volume [m^3]: 84,57 m3
Type of ceiling: Drywall
Other notes: Acoustic treatment with absorbent panels, the room appears almost anechoic; not sound reflective
Referred to ISO 3382 standard part: 3.

The meeting room of the Turku University of Applied Sciences campus is located at the 5th floor of the Data City building, part of the Science Park built in Kupittaa district in 2016. This room is used for meetings and presentations, very often performed in the TUAS Indoor Acoustics team of researchers.

The floor is covered in linoleum; the walls and ceilings are plasterboard, acoustically treated with absorbent panels in order to increase the speech understanding inside the room, while isolating the latter from external noises.

There are several desks in the center of the room, about 10 foreseen seats (with woody office chairs), and a big screen illuminated by the projector; an upholstered cot occupies a corner of the room.

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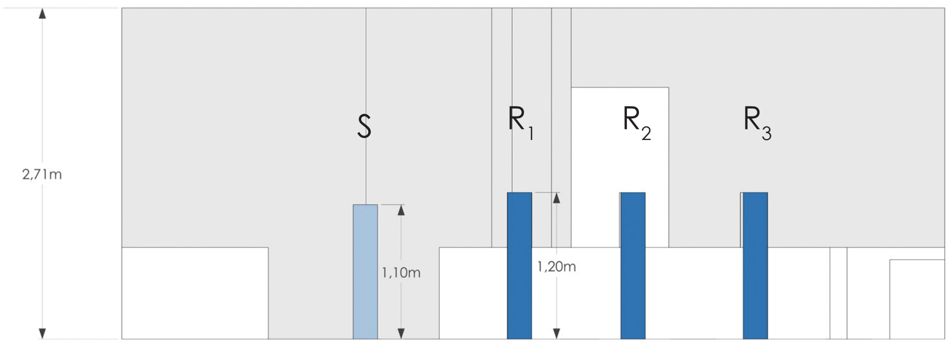

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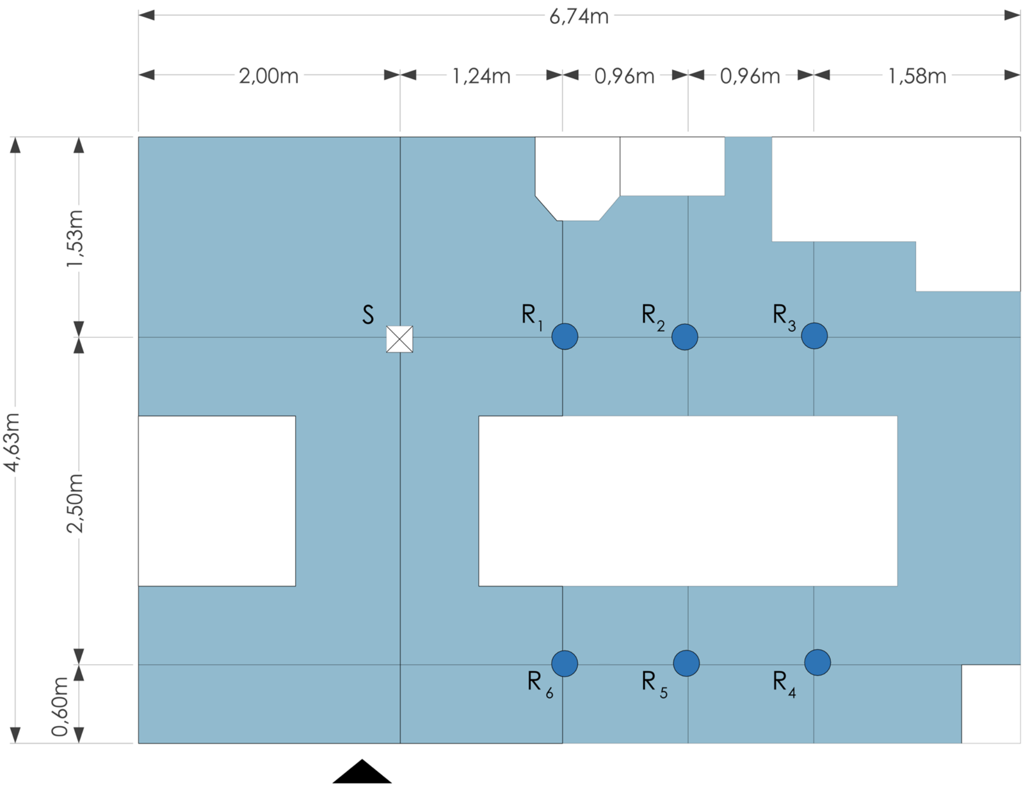

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1,58m
4,63m
1,53m
2,50m
0,60m
S
R1
R2
R3
R6
R5
R4

2. Reverberant room

Years of construction: 2016

Location in the urban context: A building included in the Science Park, business district near the city center; 5th floor

Destination of use: Reverberant room, used for experiments and measurements

Workstations: Flexible

Dimensions [m]: 7,60 x 5,08 x 4,04 m

Volume [m^3]: 155,98 m3

Type of ceiling: Plastered

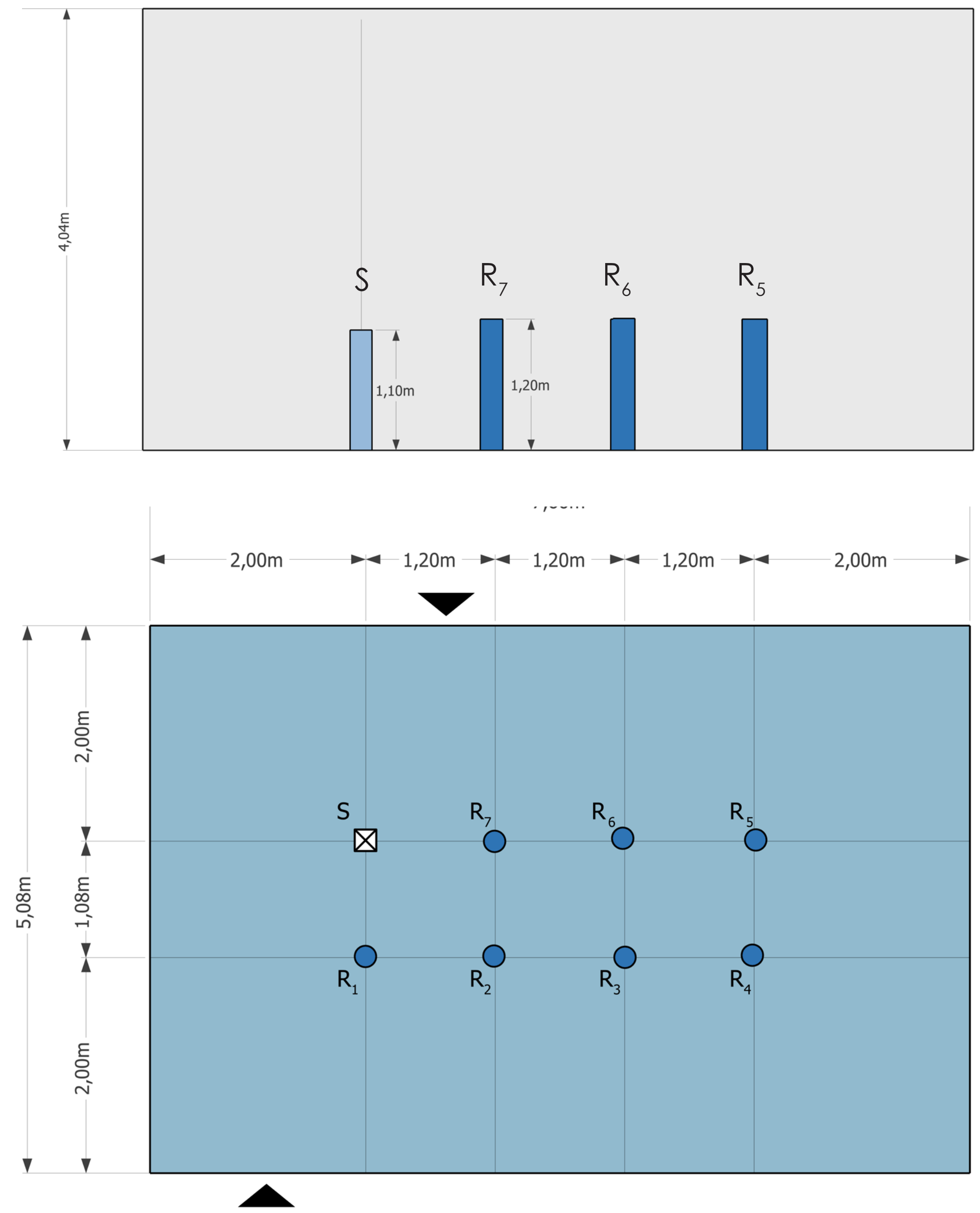
Other notes: Acoustic treatment with reflective panels, the room appears unfurnished and not sound absorbent

Referred to ISO 3382 standard part: 3.

The Reverberant room of the Turku University of Applied Sciences campus is also located at the 5th floor of the Data City building, part of the Science Park built in Kupittaa district in 2016. This kind of room was specially designed for sound experiments that the TUAS team practices everyday for work: it appears empty and unfurnished, with many acoustic panels in polymeric materials, put in a specific orientation and position in order to make the whole room as reflective as possible. In this space is also suggestable to calibrate the acoustic measurements equipment, referring to the Diffuse field specified in the ODEON user manual, as will be discussed further below.

The floor is covered in linoleum and both the walls and ceilings are plastered.

Reverberant room (Turku) settings. Used sources and microphones; general disposition of the diffusive panels in the room.


4,04m
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R_5
R_1
R_2
R_3
R_4

3. ICT Auditorium

Years of construction: 2016

Location in the urban context: A building included in the Science Park, business district near the city center; ground floor

Destination of use: Auditorium, used for presentations and speech in public

Seats: Fixed

Dimensions [m]: 22,95 x 18,12 x 6,79 m

Volume [m^3]: 2'823,65 m3

Type of ceiling: Covered in panels

Other notes: Acoustic treatment in ceilings and back wall with reflective panels; slightly upholstered chairs

Referred to ISO 3382 standard parts: 1; 3.

This case study auditorium is one of the many performance spaces that take place in the ICT building, also included in the Science Park built in Kupittaa district in 2016. It's employed for presentations and conferences, mainly for a single speaker (sound source) talking to a public (receivers). There are two corridors of steps running along the side walls; the audience is organized in 282 fixed total seats, realized in slightly upholstered chairs with small tables; at the lowest part of the room there is the stage, with big desks, 3 heavy upholstered office chairs and one standing station for speakers. On the front wall there is a big screen for presentations.

The room is acoustically treated with resonator panels both on ceilings and the backwall, while absorbent panels are placed along the side walls. This treatment ensures a good intelligibility of the speech to the audience.

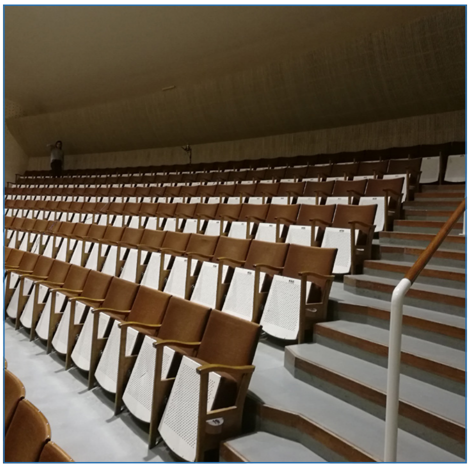
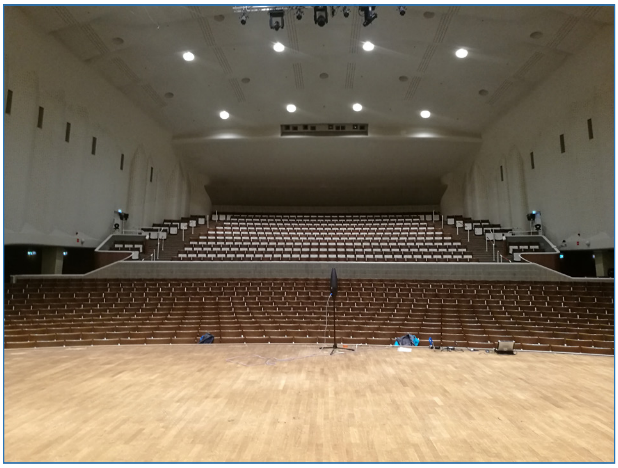
Photos of the ICT Auditorium (Turku) showing different source and microphones positions. They were placed following an ideal grid in plan. This presentation space has a symmetric plan, so it was sufficient to measure just one longitudinal half of the room, including each row of chairs in the audience.

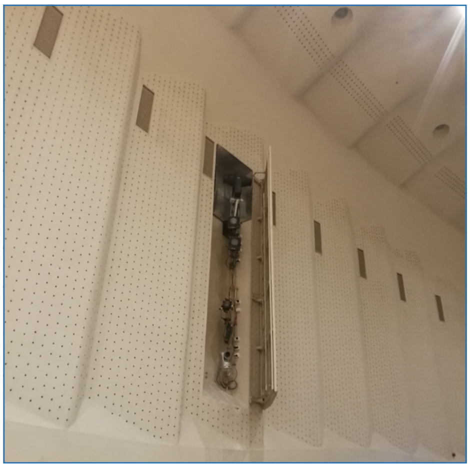
4. Turku Concert Hall

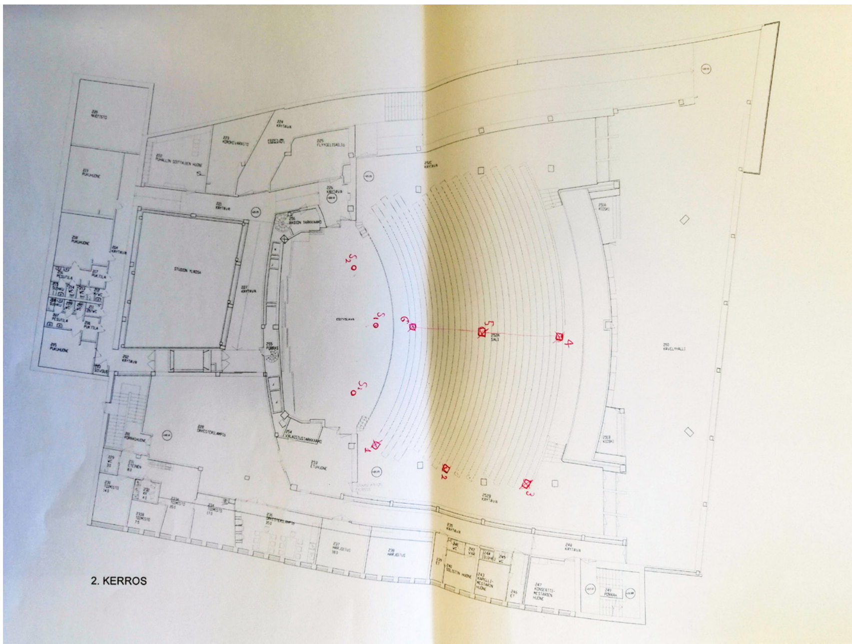
Years of construction: 1952
Location in the urban context: Near the city center and the bus station
Destination of use: Concert and symphonic music hall, performance space
Workstations: Fixed
Dimensions [m]: 37,62 x 28,15 x 11,39 m
Volume [m^3]: 12'062, 04 m3
Type of ceiling: Plastered and wavy
Other notes: Acoustic treatment with reflective panels above the stage, in the side and back walls; the lower part of the chairs is perforated to increase the acoustic quality of the hall
Referred to ISO 3382 standard part: 1.

The Turku Concert Hall is located on the north side of the Puutori market square. The hall was designed by architect Risto-Veikko Luukkonen and constructed in 1952. It was the first concert hall in Finland. The Turku Philharmonic Orchestra primarily performs at the concert hall but there are many top international venues that perform there as well; in addition to concerts, conferences, plays, fairs and other events take place in the hall.

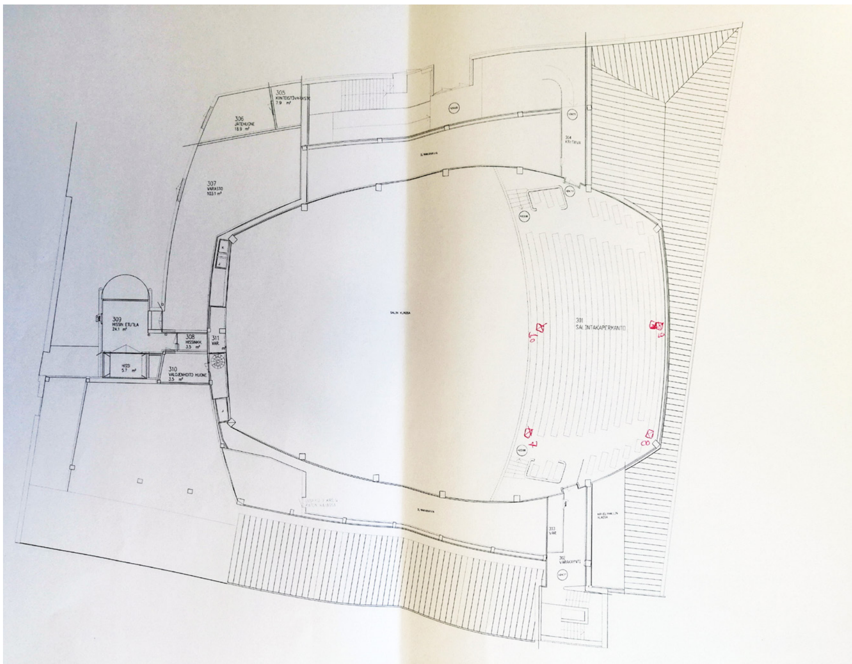
The audience presents 1'002 seats, with the lower part of the woody chairs perforated, in order to increase the acoustic quality of the hall. The floor of the stage is covered in wooden and the acoustical renovation project, carried out during the years 1998 – 2003 (Ruusuvuori, 2003), added some reflective panels in this area's walls for satisfying acoustic needs.
The plastered concrete side walls and ceilings are waved and perforated; the backwall is covered in woody vertical strips, generating a disturbing echo.



Turku Concert Hall, 1st floor



Turku Concert Hall, 2nd floor

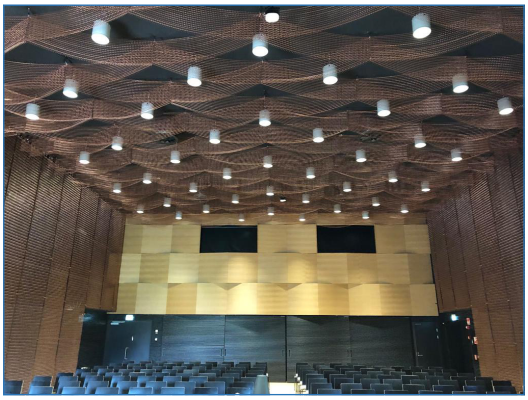
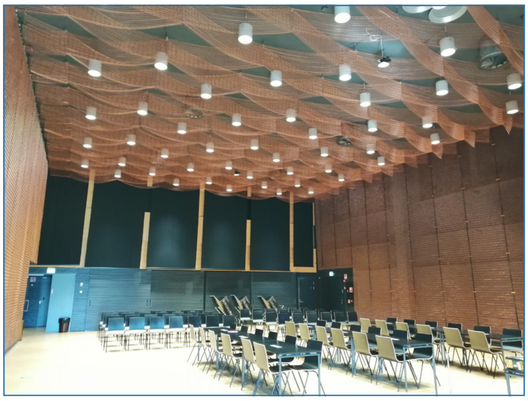
5. Kaarina Talo

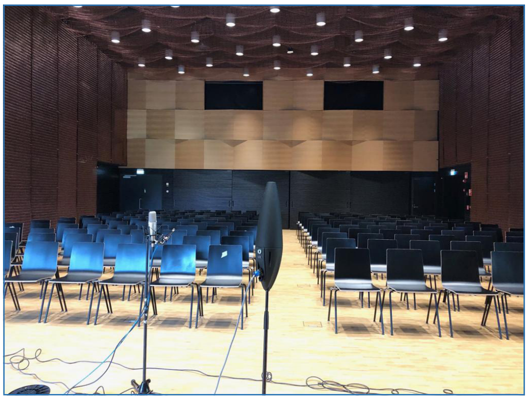
Years of construction: 2018
Location in the urban context: Near the city center and the bus station
Destination of use: Presentations and business meeting space
Workstations: Flexible
Dimensions [m]: 12,56 x 8,76 x 5,70 m
Volume [m^3]: 627,15 m3
Type of ceiling: Woody parallel panels
Other notes: Acoustic treatment with reflective panels; woody reflective chairs; chains on the side walls; copper reflective chains on the ceilings
Referred to ISO 3382 standard part: 1.

Kaarina House is a public building completed in the beginning of 2018 in the center of the city of Kaarina. The House Council Hall, Kaarina Talo, can be converted into a concert hall with approximately 220 flexible seats.
This is often used for conferences, business meetings and presentations in public.
There are different situations available for this hall's use:

- Backwall curtains up
- Backwall curtains down
- All the chairs set
- Unfurnished open plan.

All our measurements were made in heavy curtains up conditions, with all the chairs placed in 2 main blocks (an empty central corridor) and 11 rows for each one.
The floor is covered in wooden, while both the ceilings and the side walls present copper chains: on the latter they cover a tissue surface. The back wall is treated with woody panels having an angled orientation; the opposite wall presents a glass door and woody panels; all the chairs are in ebony.




6. Educarium office

Years of construction: 2017
Location in the urban context: Turku University Campus, near the business district
Destination of use: Open plan office
Workstations: Fixed
Dimensions [m]: 10,84 x 8,86 x 2,84 m
Volume [m^3]: 272, 76 m3
Type of ceiling: Drywall
Other notes: Acoustic treatment with absorbent panels on the walls; desks of adjustable height; screens of adjustable height between the workstations
Referred to ISO 3382 standard part: 3.

The acoustically measured open plan office in Educarium Campus (TUAS) is located at the ground floor of the building. It presents 12 workstations, having big desks and each station is separated from the others through screens made in absorbent tissue. Both desks and screens are characterized by adjustable height and the taken measurements were made in two conditions of tables' height from the floor:

- h1=0,63 m
- h2=0,93 m.

Employers can work both seated and standing, each one in his/her own divided station. In the office is also present a phone box to avoid the disturbing speech.

The floor is covered in absorbent material; the plastered walls are treated with sound absorbing squared panels and a side wall presents 4 big windows with light and movable curtains.

The measurements in this room were all taken using just the SoundBook system.

TURIN

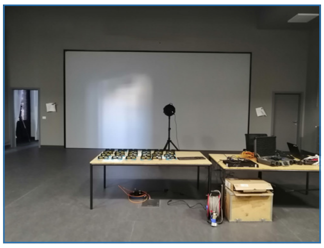
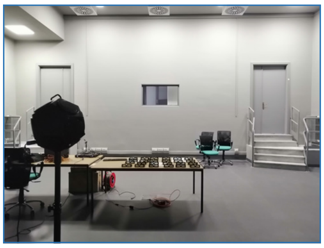
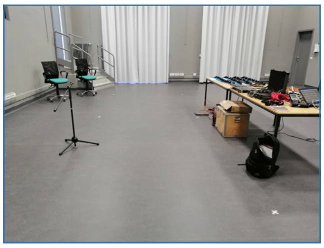
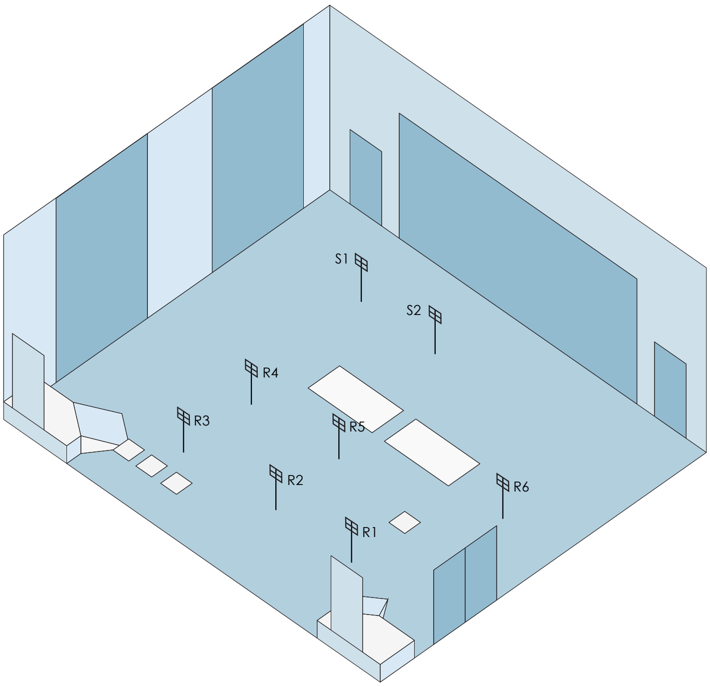
1. Galileo Ferraris meeting room

Years of construction: Historic building
Location in the urban context: Galileo Ferraris building, in front of the Valentino park in the city center
Destination of use: Presentations and meeting space
Workstations: Flexible
Dimensions [m]: 10,71 x 9,32 x 5,21 m
Volume [m^3]: 520,05 m3
Type of ceiling: Plastered drywall
Other notes: A plasterboard wall produces a coupled-room space; big screen on the backwall; large tubes of the HVAC system
Referred to ISO 3382 standard parts: 2; 3.

Located at the 2nd floor of the Department of Energy "Galileo Ferraris" building, in via Morgari, this first case study measured in Turin is a meeting room mostly used for presentations in public, small congresses and conferences. About 20 seats are expected for these kinds of events.

The floor is covered in linoleum; there is a plasterboard wall presenting a big screen where the presentations are projected and this light surface let the noises pass through, creating in this way a coupled-room effect. One of the side walls presents two big windows covered with long curtains of the same height of the room; two big tubes of the HVAC system occupy the plastered ceilings. In the middle of the room there are two big desks and a few office slightly upholstered chairs; two small ramps connect with a higher level second meeting room.



Axonometric view from the tridimensional exploded model of the Galfer meeting room:
R numbered positions represent the microphones, set at 1.20m height from the floor;
S numbered positions represent the sources, set at 1.50m height from the floor.

2. Cafaro meeting room

Years of construction: 1859

Location in the urban context: Politecnico di Torino, small town in the Crocetta residential district

Destination of use: Presentations and meeting space

Workstations: Flexible

Dimensions [m]: 9,11 x 7,62 x 4,29 m

Volume [m^3]: 297,80 m3

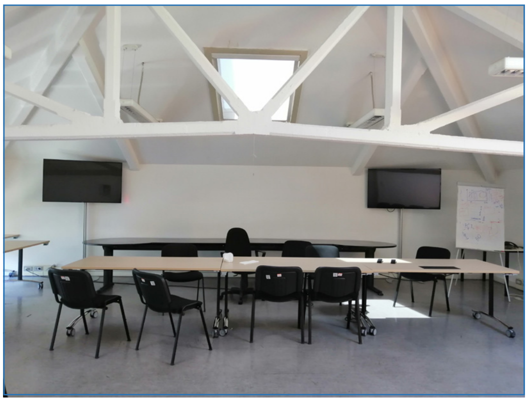
Type of ceiling: Plastered

Other notes: Vaulted ceilings with truss beams; slightly upholstered chairs; a couple of huge desks

Referred to ISO 3382 standard parts: 2; 3.

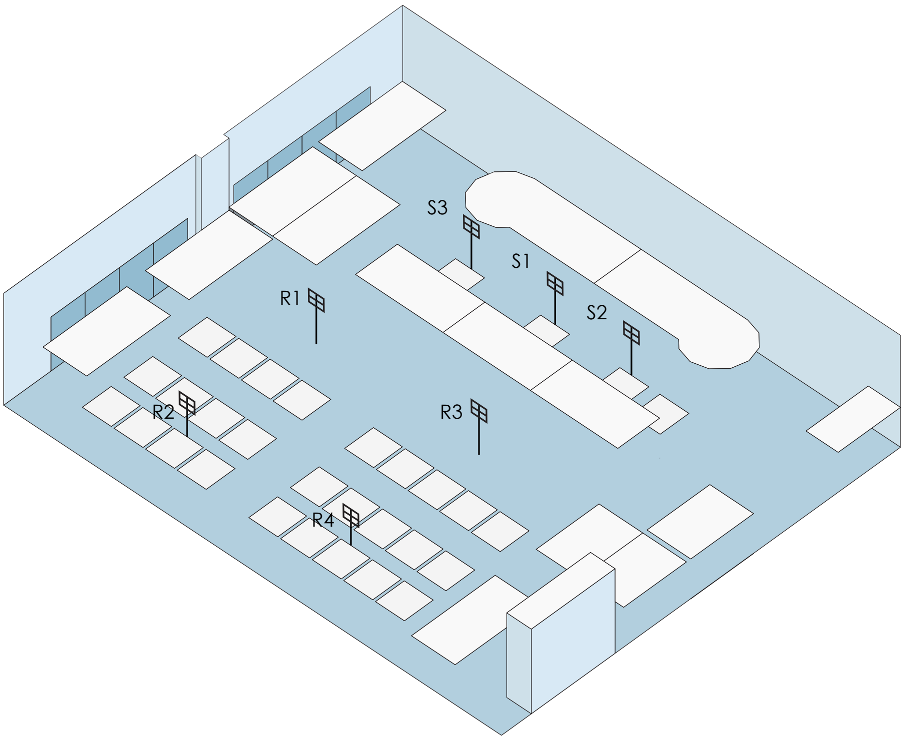
The Cafaro room is mostly used as meeting room by Acoustics researchers, professors and PhD students in Politecnico di Torino: it's located at the 2nd floor in the DENERG Department and it includes about 31 in tissue seats, both for the speakers and for the audience.

The floor is covered in linoleum, the walls are all plastered and, in one of them, 8 small windows (divided in 2 blocks) are placed very low, near the floor; the vaulted ceilings is characterized by truss beams that gives to the room a specific shape. Many big tables and two TV screens on the wall are used for conferences and PhD declarations.



View of the Cafaro meeting room from the entrance, showing the area where the sound sources were set.

View of the Cafaro meeting room showing the audience (receivers) area, with light upholstered chairs.



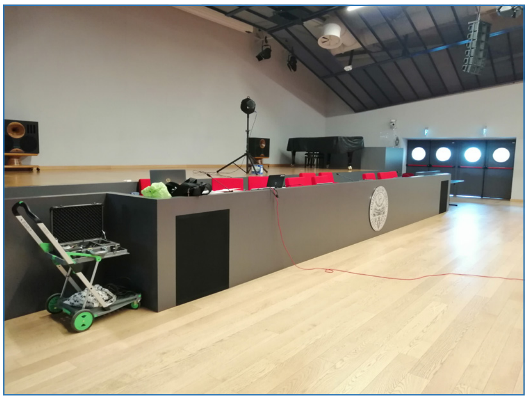
Axonometric view from the tridimensional exploded model of the Cafaro meeting room:
R numbered positions represent the microphones, set at 1.20m height from the floor;
S numbered positions represent the sources, set at 1.50m height from the floor.

3. Aula Magna

Years of construction: 1859
Location in the urban context: Politecnico di Torino, small town in the Crocetta residential district
Destination of use: Presentations, conferences, performances space and degree announcements hall
Workstations: Fixed
Dimensions [m]: 34,55 x 21,50 x 6,55 m
Volume [m^3]: 4'865,50 m3
Type of ceiling: Acoustic panels
Other notes: Ceilings with panels and HVAC system; acoustic treatment on the back wall, on ceilings and side walls; corridor steps; slightly upholstered chairs
Referred to ISO 3382 standard parts: 1-3.

The Aula Magna is the main space in the Politecnico di Torino central building: here there are all the Engineering degrees declarations and many conferences, concerts, meetings, workshops and public presentations during the year.
The hall has a fan-shaped plan, with aspect ratios of around 4.5:2.8:1 and typical auditorium features such as stage and raked audience area (Shtrepi et al., 2013). It provides exactly 453 seats, in comfortable slightly upholstered chairs divided in 4 main blocks: 3 corridor steps are used to move the flows of participants and the speakers talk from a main overhead stage.
The whole environment's length is 31m and its width changes from 17m, at the front, to 21,5m at the rear. The hall has been formerly characterized acoustically through in situ measurements.
A recent project, published in 2017 and realized by a team of researchers from the Politecnico of Turin, took into consideration
the acoustic theme, aiming to produce a proposal of an adaptive structure able to increase the efficiency and versatility of close environment, with a specific regard to conference and music halls: music and speech require different reverberation times to provide suitable clarity and definition levels. A static space will always provide the same conditions; the choice of adaptive panels ensures the possibility to modify the space and the acoustic response of the surfaces.

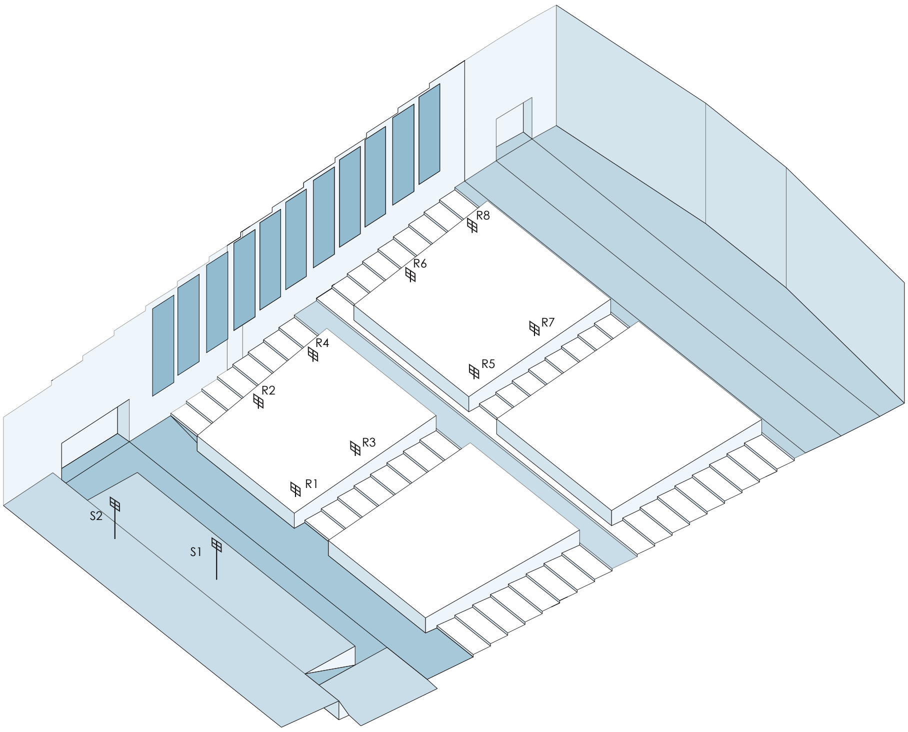
The proposed solution is an adaptive panel, able to modify its spatial configuration by provoking a change in sound reflection, making it rebound on the acoustic of the room (Lo Turco et al., 2017).



Views from the main entrance showing the audience (left picture) and the stage (right picture), where the dodecaedron sound source was positioned.

Views taken during one of the measurements: the sound source was set in central position on the stage, the microphone was almost in one of the furthest rows of chairs from the dodecaedron.

Detail of the rear wall of the Giovanni Agnelli Aula Magna in Politecnico di Torino: it's treated in order to avoid sound reflections, distrubing for the audience.



Axonometric view from the tridimensional exploded model of the Aula Magna, multipurpose auditorium:

R numbered positions represent the microphones, set at 1.20m height from the floor;

S numbered positions represent the sources, set at 1.50m height from the floor.

4. METHODOLOGY

4. METHODOLOGY

All the acoustic measurements were taken using the sweep method: this latter is a signal composed of a pure tone, whose frequency rises over time. The used one is a logarithmic sweep (the frequency rises over time): in this way more energy is given to the low frequencies (critical area) and it's possible to proceed more quickly on the high frequencies, avoiding the burning of the tweeters (Farina, Top Audio 2001).

4.1 Measurements

4.1.1 Turku

In Turku (FI) experiments, a double system of acoustic measurements has been used for the rooms studied: the ODEON acoustic software in his version 14 and SoundBook, a universal portable measuring system. A comparison of the results taken through these different methods was made as a second step, in order to test the reliability of the achieved data. The first experiment involved the testing, according to the parameters defined in the ISO 3382 (parts 1-2-3), of the ODEON integrated Room Acoustic Measurement System in the Turku University of Applied Sciences. This research aims to achieve and compare the acoustic parameters, according to ISO 3382 parts 1-2-3, obtained both through the integrated measurement system of the Room Acoustics Software ODEON 14 (after previous calibration in the Reverberant room) and the alternative software Soundbook.

The methods include measurements taken in Data City TUAS offices, both in the meeting room (similar as Anechoic chamber) and in the Reverberant chamber. These two study cases are acoustically almost opposites and this relevant fact makes the whole experiment even more interesting.

All the acoustic measurements taken in the study cases have been carried out in unoccupied rooms condition.

4.1.1.1 ODEON 14 measurements process

The room impulse response measurements in ODEON can be performed using linear and exponential

bands between 63Hz and 8kHz: sweep signals, which is superior to other methods in suppressing background noise, leading to high Signal-to-Noise ratio and high immunity to distortion. A sweep is simply a pure sinusoidal signal, with frequency increasing monotonically in time. The sweep method for measuring impulse responses is the least sensitive method to time variance and distortion and it is expected to work well on most hardware systems. ODEON uses sweeps to excite a room and record the response to this signal at a microphone (receiver) position in real time.
The energy of low frequency sound usually takes more time to decay than the energy of high frequency sound in a room. Therefore, upward sweeps are preferable over downward ones, in order to ensure that the decay of low frequencies is captured within the recording of the whole sweep response and harmonic distortion is suppressed. An extra decay period of a few seconds is recorded after the end of the sweep, so that the remaining decay for middle and high frequencies is captured.
The sweep method is filtered in octave although the length of the impulse response of the filters is infinite, a finite effective length is used, so 99,9% of the energy of the filtered response is included.
Moreover, reversed filtering is applied for decay analysis: in this way all the transients appear at the tail of the impulse response, instead of the beginning, and the filter phase distortion is suppressed. ODEON automatically excludes the transient tail when processing the impulse response.
For every impulse response the correct onset time is indicated in the display. According to the ISO 3382 standard (ISO 3382-1,2008) the onset of the direct sound and of the whole impulse response should be counted at least -20 dB below the peak level of the direct sound.

4.1.1.1.1 Equipment and settings

An elementary equipment is needed for an initial measurement:

- Two microphones (omnidirectional and figure of 8)
- Sound source

- Sound card
- Amplification
- Computer
- ODEON 14 dongle key
- Ears protection
- Sound level meter
- Cables.

In experiments carried out in TUAS the following equipment has been employed:

- SM 4201, omnidirectional microphone
- Røde Microphones NT2-A, figure 8 microphone
- Bruel & Kjaer 4295 OmniSource, omnidirectional loudspeaker
- Realtek High Definition Audio (Lenovo supported), soundcard
- Roland Rubix 22, amplification
- Lenovo T450 Ultrabook ThinkPad, PC
- Nti Minirator MR-PRO, sound level meter, used for the Background noise level measurements.

A flat frequency response microphone and loudspeaker can help to obtain enough Signal-to-Noise ratio for as many as possible octave bands.

The impulse response can be recorded as a .wav file and be post-processed afterwards in ODEON. According to the specifications in the ISO standard 3382-1 (ISO 3382-1, 2009), the loudspeaker shall be as omni directional as possible. As reported in that part of the standard, the sound source should be able to produce a sound pressure level high enough to provide decay curves with the required minimum dynamic range, without contamination by background noise.

The ISO 3382-3 is a European acoustic standard, specific for the open plan offices: it provides accurate recommendations about the positions and conditions of the measurements, so it covered a main role in this research's experiments.

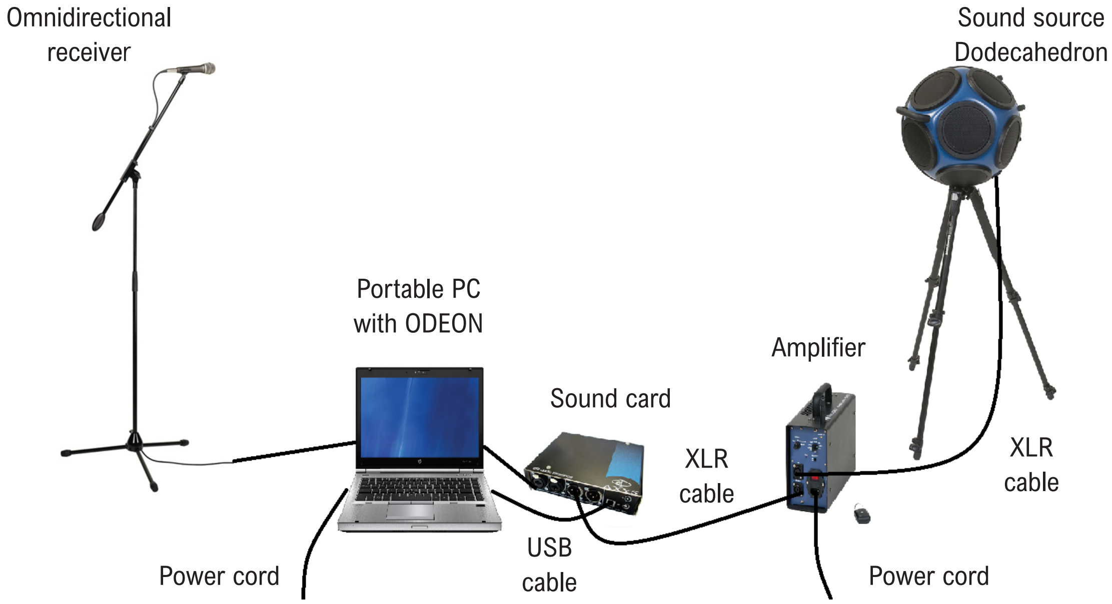
The measurements should be carried out along a line, which crosses over workstations: the preferred number of successive measurement positions in the line is 6 to 10; the minimum number is 4.

The first measurement position shall be located at the nearest workstation on the line and the distance to the most remote measurement position depends on the size of the room.

The measurements shall be taken

using source and microphone positions in workstations in the position of the person’s head.
The positions of loudspeaker and microphone shall be at least 0,5m from tables and at least 2,0m from walls and other reflecting surfaces.
At least two sound source positions shall be used; if only one line of measurement positions is possible, the measurements shall be made with two source positions in opposite directions placed on the same measurement line.
The loudspeaker shall be placed at the height of 1,5 m above the floor.
The microphone shall be placed at 1,2 m above the floor.

The reported scheme at the bottom of this page shows how the whole equipment were connected, in order to be effectively used for measurements in indoor spaces.
The reciver (omnidirectional microphone, on the left) was linked to the pc, to the pc where the used room acoustic software is installed; the pc is also connected to the sound card, where the settings are prepared in accurate way; this latter is linked to the amplifier (also set in appropriate way), which is connected through cable to the dodecahedron (the used sound source). Moreover, both the pc and the amplifier needs further power cables, in order to work correctly.



Some equipment used for measurements

Omnidirectional loudspeaker, Bruel & Kjaer 4295 OmniSource

Dodecahedron loudspeaker, Nor280

Omnidirectional microphone, SM 4201

It is important that the employed sound equipment (sound card, microphone and amplifier) provide a good Signal-to-Noise ratio (SNR): it's defined as the difference between the Signal Level (LS) and the Noise Level (LN), considered as LAeq in the empty measured room. In the opposite case, longer measurement times will be needed, in order to suppress background noise caused by the equipment itself.

The longer is the sweep signal, the higher is the suppression of the background noise. For every doubling of the sweep length a suppression of background noise by 3dB is achieved.

For all the experiments an exponential sweep has been used: it has frequency energy spread equivalent to pink noise and provides longer playback time for low frequencies, thus more energy at this range, differently from the linear sweep, that provides longer playback time at mid and high frequencies.

In most rooms' acoustic measurements, the exponential sweep is preferred against the linear sweep.

In ODEON there are two types of source power spectra that can be used, also in the calibration of the measuring system.

1. A flat frequency spectrum source, called G-ISO 3382-1: it should be chosen for almost all room acoustic cases, covered in the ISO 3382-1 (auditoria, concert halls etc.).
2. A speech spectrum source, called Speech-ISO 3382-3: should be chosen if the measurement is or has been carried out in an open plan office (ISO 3382-3 standard).

In all the studied cases, the speech spectrum source) has been selected: indeed, all the experienced rooms are focused on a speech purpose.

4.1.1.1.2 Calibration process

In order to derive level parameters such as Sound Strength (G) and Speech Transmission Index (STI), the system set-up should be calibrated.

A Diffuse-field calibration in two steps is used.

- 1st phase. Measurements are taken in Reverberant Room, at a pointed distance between Source (S) and Receiver (R) of $d_{S,R} \leq 1{,}00$m in order to encourage the direct sound and avoid the path of first reflections on reflecting surfaces, such as the floor.
- 2nd phase. Measurements are taken in Reverberant Room, but at longer $d_{S,R}$ distances; they produce as output an Intermediate calibration file.
- 3rd phase. An In-situ correction is needed, taking measurements in the study case room at the same distances as the 2nd phase; this produce a final calibration .wav file, followed by the calculation of differences and adjustments between the last couple of phases results.

The placement of the equipment was set referring to the ODEON 14 Application Note. It states suggestions about the Receiver's height hR=1,20m; the Source's height (hS)=1,10m; the Distance of the Receiver from any reflecting surface, pointed ≥2,00m; the Distance of the Source from any reflecting surface, pointed ≥ 2,00m; the Distance of both Receiver and Source from any furnishment, pointed ≥0,50m; the Background noise level $L_{P,A,B}$[dB], always measured through the sound level meter; the Source power spectrum fixed at Speech-ISO 3382-3, the speech spectrum source, for each frequency band; the Exponential sweep (similar to a pink noise) selected.

4.1.1.1.3 Indoor measuring

All the measured positions were chosen following paths that covered as many different points as possible in the room, placing the receivers in the workstations, at the height of an average seated human's ear.

4.1.1.2 SoundBook measurements process

SoundBook MK2 is a universal portable measuring system for acoustic, vibration and generally engineering measurements. It works on SAMURAI™ 2.6 software package that includes a sound level meters (SLM), according to IEC 61672-1.

4.1.1.2.1 Equipment and settings

A similar-to-ODEON elementary equipment is needed also for SoundBook measurements:

- Microphone
- Sound source
- Sound card
- Amplification
- SoundBook portable system
- Ears protection
- Cables.

In experiments carried out in TUAS the following equipment has been employed:

- SM 4201, omnidirectional microphone
- Bruel & Kjaer 4295 OmniSource, omnidirectional loudspeaker
- Realtek High Definition Audio (Lenovo supported), soundcard
- Roland Rubix 22, amplification
- SoundBook, ToughBook Panasonic.

With this latter method of measurement, no figure of 8 microphone has been used, because SoundBook does not support that kind of receiver, in opposite to ODEON. Therefore, no sound level meter is employed, because this method includes such function in its own system.

In the same way as ODEON, the Panasonic device uses a sine sweep to convolve in impulse response afterwards and give, as a feedback, the reverberation time of a room and other subjective acoustic parameters (such as Clarity and Definition).

The Bruel & Kjaer 4295 OmniSource, used as omnidirectional loudspeaker for the experiments, is still capable of emitting a sound power of 105 dB ref. 1 pW (Bruel & Kjaer 4295 OmniSource datasheet, 2018).

Before starting measurements, a setting up of the system is needed: clicking on “Setup Tab” and then on “Signal Generator”, it’ll be possible to edit and enable the channel 1, useful for measuring.

The “Attenuation” value is usually set on 5 or 10 dB, depending on the acoustic kind of the room: if more absorbing, we need a lower value of attenuation, while, if more reflective, a higher value of attenuation is requested. In the studied cases, the value is 25dB: it means that the signal level is decreased (attenuated) of 25dB. It’s very important to always write down the settings of amplifier, in order to repeat the same ones in each measurement.

At this point it’s possible to make measurements and check the signal, looking at the histogram appearing on the SoundBook’s screen. The sine sweep should clearly show the signal: in the histogram, signal is marked in a different color.

In order to obtain the same settings for all the measurements and to successfully compare them in a second time, it’s strongly suggestable to recall the originally set file: in this way it’ll be possible to recall also the proper settings.

After the measuring process, SoundBook offers a possibility to recall the global on-frequency data file, for each measured position: it’ll be sufficient to copy, paste in a text reader and to import them in a more manageable Excel format, useful to analyze and compare the achieved results.

4.1.1.2.2 Indoor measuring

Referring to ISO standards 3382 (parts 2, specific for Ordinary rooms, and 3, specific for Open plan offices, 2009) the distance between two microphones’ positions was set ≥2m; the distance between both the microphone and the source from any reflecting surface (included the floor) was set ≥1m; the symmetric positions were avoided as possible and the duration time of the sweep was set ≥15s.

Therefore, the Precision method pointed out in the ISO 3382-2 was always satisfied, setting in the measured rooms more than 2 source positions and more than 3 microphones (receivers), for a result of about 12 source-microphones combinations.
A higher number of combinations ensure a better evaluation of the room acoustics parameters, inasmuch there's the possibility to understand the sound's behavior in many points of the rooms.
The receivers, where possible, were placed in the workstations, at the height of an average seated human's ear.

4.1.2 Turin

In Turin's specimen, as in the Turku cases study, a double system of acoustic measurements has been used for evaluating the acoustic quality of the environments: the ODEON software in his version 13 and Aurora, a plug-in of the more renowned software Adobe Audition. A comparison of the results taken using this couple of methods was made in a second moment, in order to test the reliability of the achieved measurement results.
The first part of the research involved the testing, according to the parameters defined in the ISO 3382 (parts 1-2-3), of the ODEON integrated Room Acoustic Measurement System in the Politecnico of Turin: the results achieved through this method were then compared to the other data, obtained by Aurora software. In addition, as a further test, all the measured results were compared to the simulated ones: indeed, ODEON includes an acoustic simulating system that produces, as output, interesting data obtained by changing the absorption coefficients of the different materials in the room.
All the acoustic measurements taken in the study cases have been carried out in unoccupied rooms condition.

4.1.2.1 ODEON 13 measurements process

As in the ODEON 14 method of measurements description, explained in 4.1.1, an exponential sweep is used to excite the room and record the response to this signal at a microphone

(employed as a receiver) position in real time. This sweep response is then deconvolved to give the impulse response between the sound source and the microphone: low frequencies decay period of a few seconds is recorded after the end of the sweep (ODEON 13 User's Manual).
Moreover, reversed filtering is applied for decay analysis: in this way all the transients appear at the tail of the impulse response, instead of the beginning, and the filter phase distortion is suppressed. ODEON automatically excludes the transient tail when processing the impulse response.
For every impulse response the correct onset time is indicated in the display. According to the ISO 3382 standard (ISO 3382-1,2008) the onset of the direct sound and of the whole impulse response should be counted at least -20 dB below the peak level of the direct sound.

4.1.2.2 Adobe Audition's Aurora measurements process

In parallel with ODEON 13, a second measurement method has been used to compare the following results: Aurora 3.0.
This is a complete system for measuring electro-acoustical impulse responses and performing auralization through headphones and/ or loudspeakers.
Aurora plugins have many different goals, but they were initially developed or measuring and manipulating room acoustical impulse responses, performing analysis of acoustical parameters and auralization (Aurora User Manual, 2013).
The Aurora package is based on a series of additional modules ("plugins") which are attached to a standard multichannel sound editor, namely Adobe Audition: in this research's case the 3.0 version has been used. The used measurement method is the sine sweep: this signal is graphically represented by a sine function rising from the low frequencies to the highs. As a first step t's time to generate the test signal, just the Sine Sweep, positioned in the track 1 place.
It's suggestable to create a new, empty file in Adobe Audition. The software now asks to choose the sampling rate (48 kHz), the number of channels (mono, as we have just one

loudspeaker) and the resolution; the solo (S) button is held down.

After generating a sine sweep, it's possible to import it in a multitrack view: this kind of visualization is very useful to compare different measured or imported records.

The parameters are left at their default are played first, and an extra values: the start/stop frequencies are 22Hz and 22kHz respectively, the sweep is long 15s, followed by a silence of 10s, and the whole sequence is repeated twice; the record (R) button is held down.

Once achieved the sine sweep wave file, it's advisable to convolve it with clipboard: this module performs linear convolution of the selected waveform with the waveform currently present in the Windows Clipboard. This means that, before using this module, it's required to load in the Windows Clipboard the Impulse Response that is needed to use as a filter.

The impulse response represents the temporal evolution of the sound pressure observed at a point in a room, as a result of the emission of a Dirac impulse at another point in the same room (EN ISO 2282-1:2009).

Opening the obtained impulse response wave file, it's now possible to select it and exporting the acoustical parameters: pushing the button Copy results to clipboard, they are available to be pasted in a text editor software, then analyzed and compared to others in and Excel file.

4.1.2.3 Equipment and settings

Both measurement methods required exactly same equipment and settings, in order to get comparable results.

The basic needed tools are:

- Microphone
- Sound source
- Sound card
- Amplification
- Pc
- Ears protection
- Cables
- Sound level meter.

In experiments carried out in Turin the following equipment has been employed:

- NTi Audio No. 2077, omnidirectional microphone
- Dodecahedron, 12 loudspeakers sound source
- Tascam US-144, sound card

- LAB 300, amplification
- HP, pc
- ODEON 13, dongle key
- Proel, cables
- NTi Audio XL2, sound level meter, used for the Background noise level measurements.

The measurements were taken using in parallel the ODEON and the Aurora methods, running sweeps by both the software before changing the sources and microphones positions in the room: in this way the variables in the data's settings are considerably reduced.

Referring to the ISO 3382 standards, in its three different parts, the positions of loudspeaker and microphone are set at least 0,5m from tables and at least 2,0m from walls and other reflecting surfaces.

Always 2 or 3 sound source positions were used, depending on the room's shape and destination of use. The loudspeaker is placed at the height of 1,5 m above the floor, at the height of an average standing human speaker's mouth; the microphone is placed at 1,2 m above the floor, at the height of an average seated human's ear.

The Tascam sound card was set with the phantom mode on and all the lines at the maximum value; the amplifier has a variable attenuation from -80 to -40dB, depending on two main factors:

geometry and the kind of the measured room: wider and higher indoor environments, e.g. Aula magna, require lower attenuation (-40dB) compared to smaller spaces, e.g. Galfer or Cafaro meeting rooms (about -80dB);

- distance between sound source and receiver: with a longer distance we'll set a lower attenuation, while in a shorter distance case the attenuation will increase.

The goal is to avoid a too saturated sound, because this often causes damages in the measured data, compromising the necessary reliability.

The first thing to provide is the physically setting up of the audio equipment.

The HP portable pc is connected, through USB cable, to a good quality external sound card, like our Tascam. It's necessary being able to keep a controlled input and output gain, so that the whole measurement system can be calibrated.

The soundcard is wired to the omnidirectional microphone, then connected to the amplification system through a double cable, occupying the amplifier's channels A and B; this latter tool is then wired to the dodecahedron loudspeaker. The measurements are performed synchronously, so the same PC will play the test sound and simultaneously record the signal coming from the microphone(s): this process is taken with both ODEON and Aurora plugin methods. This highlights the importance of a completely wired system, with a cable connecting the output of the sound card to the loudspeaker. Another cable will connect the microphone with the input of the sound card, so the whole cables-chain is closed and operational.

4.1.2.4 Indoor measuring

All the measurements were taken referring to the ISO standard 3382, parts 1-2-3.

The distance between two microphones' positions was set ≥2m; the distance between both the microphone and the source from any reflecting surface (included the floor) was set ≥1m; the symmetric positions were avoided as possible and the duration time of the sweep was set ≥15s.

All the loudspeaker's placements were chosen in order to correspond, in the most accurate way as possible, to the effective sound source positions: this include the overhead stage of the Aula Magna and the space close to the screens in the Galileo Ferraris and Cafaro meeting rooms. The receivers were placed at the height of a seated human's ear and in order to cover, in plan, the widest part of the audience surface as possible: in the Aula Magna case, the whole work of measure was carried out in half of the room, because the space has a symmetric geometry.

Evaluation of the "perfect" omnidirectional sound source

According to ISO 3382 standards, an omnidirectional source is understandably attractive from a theoretical point of view, since it should most easily allow different spaces to be compared.

The dodecahedral loudspeaker, or

"dodec," for example, used for some room acoustics measurements in Turku and all the measurements in Turin, is not truly omnidirectional across its usable frequency range. These measurement loudspeakers begin to exhibit pronounced lobing above approximately 1 kHz, and the influence of this directivity on measured room impulse responses and parameters is not well understood. This also calls into question how easily high frequency data taken in different halls can be properly compared, since a slight re-aiming of the loudspeaker might significantly change the results. It is especially interesting to note that the reverberation time is largely independent of source directivity, while other parameters that depend heavily on the direct sound and early reflection sequence (e.g., Early Decay Time) vary strongly with source type (Kirkegaard & Gulsrud, 2011).

Why to sqeeze the frequency range of interest?

An interesting question that could emerge from the above-mentioned description of the data evaluation's settings is: why have we, generally in the room acoustics community, limited our frequency domain to the octave bands between 125 Hz and 8 kHz?

The answer probably lies in the limitations of the equipment historically used for room acoustics measurement. The Typical dodec, probably not coincidentally, has a usable frequency range between about 100 Hz and 5 kHz.

Another major factor is that laboratories

used for sound absorption measurements are not typically qualified at lower and higher frequencies, and so reliable data for building materials outside the standard frequency range are not available. Despite this, loudspeaker technology with significant wider frequency bandwidth is readily available today.

4.1.3 Measured parameters

Although listening is a complex and multidimensional experience, very difficult to describe quantitatively, the acoustics of an environment can be evaluated through different objective parameters.

These ones work relating the physical variations of the sound field of the environment with the variations of a listener's personal judgment positioned inside it; they are based on the impulse response of a room and experimentally measured or simulated by software.

Parameters can be classified in three different categories:

- Referred to the subjective balance between clarity and reverberation;
- Referred to the subjective impression of loudness (meaning the perceived intensity);
- Relating to spatial impression.

In this research, all the investigated parameters were measured in unoccupied rooms conditions: they were then analyzed in order to obtain their values and graphs on frequency.

The background noise level is always measured using a sound level meter, taking values in each source and microphone positions: all the values were then averaged in order to obtain a single number quantity.

This parameter could provide a useful evaluation of the environment's efficiency for rooms requiring not only speech comprehension, but also speech privacy, like the open plan offices investigated in this research.

The graphs below are showing an average trend, calculated between the different positions of the receivers used in each case study. An average value for each sound source was calculated, then these values were averaged too.

The single values were finally obtained by averaging the reverberation times measured between 250 and 2000Hz frequency bands.

The lines represent different measurements methods employed (Odeon 13, Aurora and Dirac 5): they were also compared to the simulated values, achieved from Odeon 15, by modifying the rooms materials' absorption and scattering coefficients.

In these measurements appeared very clearly the importance of this kind of coefficients: the Odeon simulations, indeed, foresee a trial and error approach. This means that many different combinations of materials (given by literature references) must be tried modifying their absorption coefficients, in order to achieve the

interested parameter's values (EDT, T20, C50, D50) as close as possible to the measured ones.
This latter process is usually called the calibration of the 3D model. In similar cases, the final output is a table where all the coefficients used in the model have been classified, always including the reference, as the tables below.

4.1.4 Obtained results and comparison

All the measured values in each case study were put in a spreadsheet, within a table with columns representing rooms and lines indicating the referred acoustic parameters.
In addition to pure values provided by the software (Odeon, SoundBook and Aurora) point by point in each receivers' position, averages including values taken placing the microphone in the other sound sources' positions were calculated. Furthermore, for all parameters an error bar measuring the standard deviation, expressed in percentage, was also calculated. The latter was fundamental to understand the propagation of a parameter in the whole room, as the average value does not express the exact value in each position and, besides, it does not explain the alterations in the environment. The curve instead represents the trend that best approximates all the measured data, between two additional curves: they represent a tolerance of -5% or +5% of the values.
The more the curves deviate from each other, the more differences are present between the methods of measurements and simulations.
In this way, a comparison between the different methods of measurements and simulations was carried out: it's important to evaluate the similarities and differences that the final outputs present, in order to give a stronger reliability to the whole study.
The absorption coefficients given to materials during the simulation in Odeon 15 were listed in tables and then graphically represented, in order to give an idea (considering a 63 to 8000Hz frequency bands interval), of the absorption influence of each material on the average room's acoustic evaluation.

4.2 Simulation in Odeon 15

Beside the two measurement methods employed in this research, a further method is joined, in order to study the achieved data in a deeper and more accurate way: the simulation tool offered by ODEON 15.

This is a room acoustic prediction and measurement program that uses state of the art algorithms from geometrical acoustics. The program is designed to help researchers obtaining accurate predictions and measurements on room acoustics.

In the simulation process the first step was importing a 3D model of the room in question, previously realized in a modelling software.

The current most preferred program for room modelling is *SketchUp* (SU): it's a 3D modelling software which is operated very intuitively and creates geometries directly compatible with ODOEN. Indeed, SketchUp includes an available *SU2Odeon* plug-in that allows users to make direct use of SU models in ODEON.

In the simulations, all the placed receivers (6 in the Galfer meeting room; 4 in the Cafaro meeting room; 8 in the Aula Magna) have been located in the same positions used in the measurement setup and have been arranged in a crossed array configuration that extended to one of the two halves of the audience area at a height of around 1,20 m from the floor level. This chosen height is referred to a typical average height of a sitting listener.

The sound sources were positioned midway between the axis of symmetry of the room and the lateral wall: in general, the ideal positions in plan of the human speakers were considered in the sources placements. In the simulations, directional sources have been used and located in the same position used in measurements for the high-, low- and mid-frequency omnidirectional loudspeaker. This choice was made orienting, in addition, the sources towards the most centered receiver in the room, as an average reference for all the listeners.

According to Shtrepi et al. (2019), the main input settings to perform simulations, that is, the number of rays, the maximum reflection order, and the transition order (TO), have to be decided carefully according to the aim of the simulations. First, a reasonable number of rays could be estimated by considering that an expected error of less than 1 JND is regarded as sufficient when estimating the objective acoustic parameters. In all the 3 simulated cases, the number of rays was fixed at 10'000 rays, in order to lead to more specific results.

In order to achieve realistic auralizations, it is important to have a well-calibrated model. A simulation is well calibrated when the difference between simulation and measurement is less than the JND of each objective acoustical parameter. Based upon this statement, the calibration in this study was made by comparing the simulated objective parameters to the measured ones in real conditions of the hall. Furthermore, some of the indications given in the general procedure described in Postma and Katz (2015) have been used.

Referring to Shtrepi et al. (2017), the ODEON's calibration steps can be summarized as listed below:

- **Assuming diffuse field conditions:** The acoustic conditions used for this study do *not represent* a diffuse sound field. Since this might influence the correct estimation of the material properties, a different configuration of the hall has been used, and the diffuse field is assumed as an approximation to estimate the absorption coefficients. The models used for the material calibration are presented in the following section, *5.Data Analysis*. There model have been chosen since they were considered to have a sufficiently diffuse field based on the achieved spatial uniformity of the reverberation time. The diffusive surfaces have been modeled as B.A.D. hybrid diffuser squared panels.

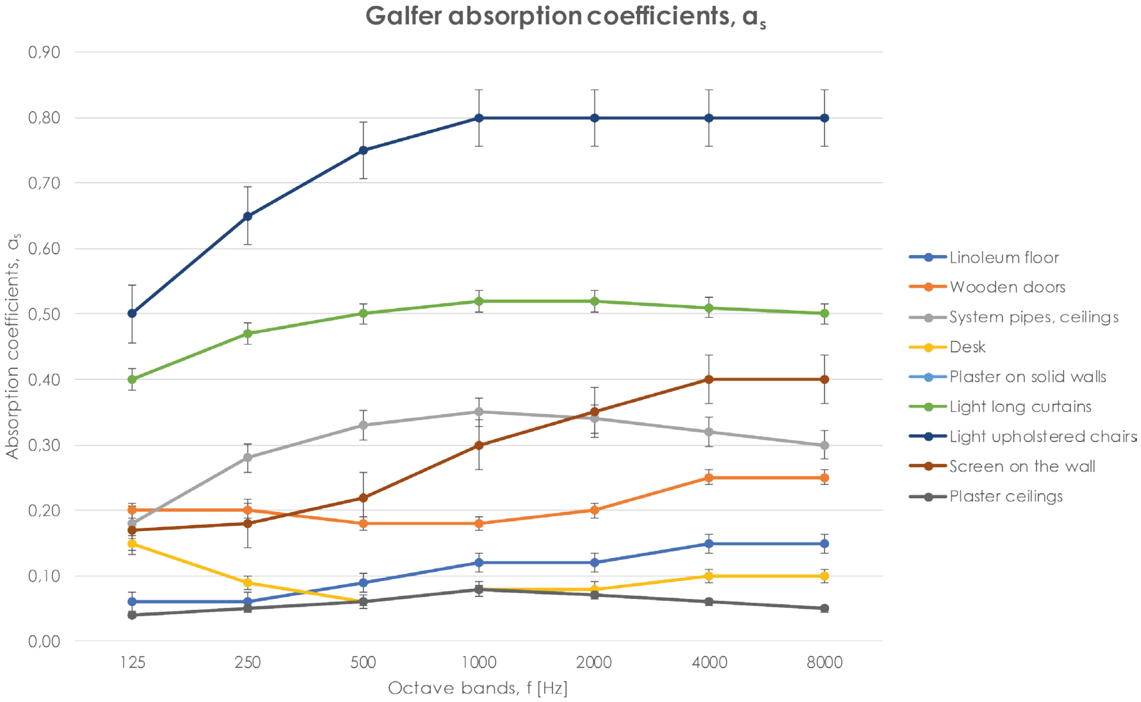
- **Preliminary acoustical properties:** As far as the absorption coefficients are concerned, in order to start the calibration process, preliminary acoustical properties have been assigned to the geometrical model's surfaces based on the data reported in the project reports and standard literature. Based on the standard settings given by

ODEON's room acoustic system, the scattering coefficients were set to 0.10 for all flat surfaces. Since no data could be found for the absorption coefficient of the structure and for the diffusive configuration of the panels, the same absorption coefficients, the B.A.D. hybrid diffuser panels bt RPG's scattering coefficient was fixed at 0,50, referring to the ODEON 15 User's Manual suggestions.

- **Variation of the acoustical properties:** The acoustical properties of the used absorptive surfaces, structure, and diffusive panels have been modified since they have the most significant impact on the overall value of the equivalent sound absorption area, due to high absorption coefficients and surface extension, respectively. The variation has been performed manually and step by step until the overall mean differences (for the source and receiver configuration) between measurement and simulated results for EDT, T_{20}, C_{50}, and D_{50} resulted in less than one JND. However, the variation of the absorption coefficient of these surfaces has been restricted in order not to lose the typical acoustic properties of the material they represent. Having in mind this constraint, a compromise has been made in order to stop the calibration process when differences between simulated and measured EDT, T30, C80, and D_{50} reached values of about one JND. The results of the material calibration are shown at the end of this section and the results of the objective acoustic parameters after calibration are depicted in the following pages.

Galfer meeting room

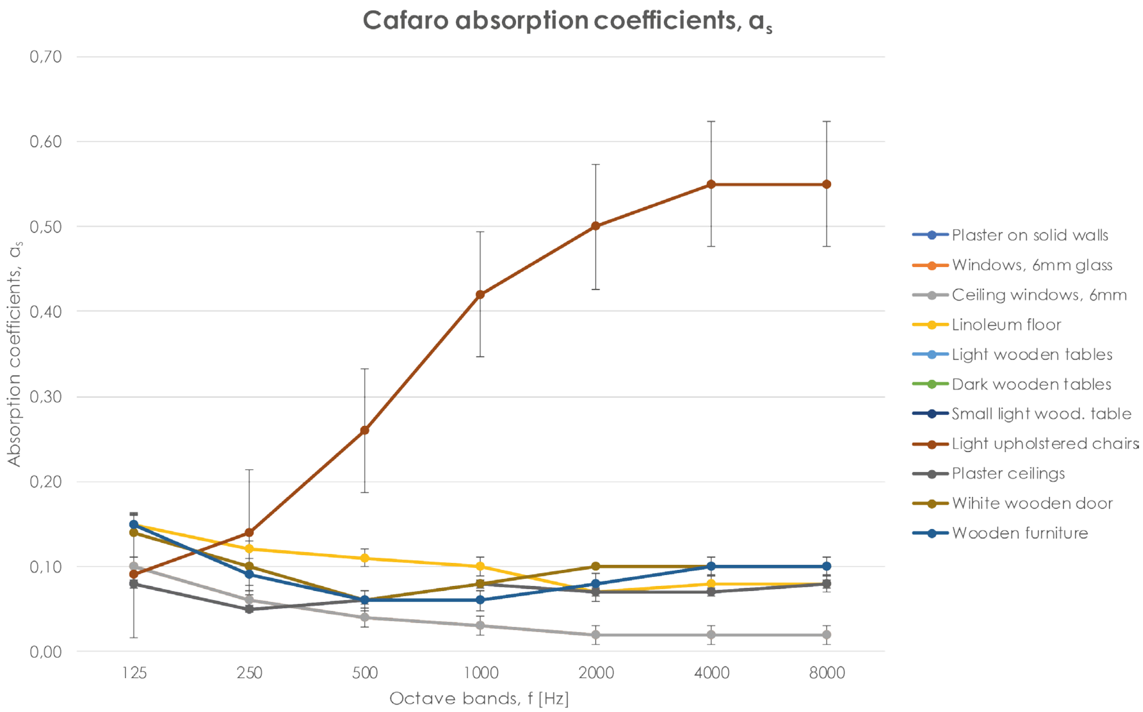
Materials	Sup, m^2	Absorption coefficients (α), adimensional						
		125	250	500	1000	2000	4000	8000
Linoleum floor	102,46	0,06	0,06	0,09	0,12	0,12	0,15	0,15
Wooden doors	11,34	0,20	0,20	0,18	0,18	0,20	0,25	0,25
System pipes, ceilings	3,50	0,18	0,28	0,33	0,35	0,34	0,32	0,30
Desk	3,28	0,15	0,09	0,06	0,08	0,08	0,10	0,10
Plaster on solid walls	143,57	0,04	0,05	0,06	0,08	0,07	0,06	0,05
Light long curtains	27,17	0,40	0,47	0,50	0,52	0,52	0,51	0,50
Light upholstered chairs	0,81	0,50	0,65	0,75	0,80	0,80	0,80	0,80
Screen on the wall	23,86	0,17	0,18	0,22	0,30	0,35	0,40	0,40
Plaster ceilings	99,82	0,04	0,05	0,06	0,08	0,07	0,06	0,05



Absorption coefficients listed in table and represented in graph, showing the values used for the room acoustics simulation in ODEON 15 in Galfer's case.
The graph highlights how some materials, like curtains and chairs affect the whole room absorption, particularly at high frequencies (2000-8000 Hz).

Cafaro meeting room

Materials	Sup, m^2	Absorption coefficients (a), adimensional						
		125	250	500	1000	2000	4000	8000
Plaster on solid walls	63,45	0,08	0,05	0,06	0,08	0,07	0,07	0,08
Windows, 6mm glass	5,15	0,10	0,06	0,04	0,03	0,02	0,02	0,02
Ceiling windows, 6mm	0,98	0,10	0,06	0,04	0,03	0,02	0,02	0,02
Linoleum floor	69,42	0,15	0,12	0,11	0,10	0,07	0,08	0,08
Light wooden tables	13,12	0,15	0,09	0,06	0,06	0,08	0,10	0,10
Dark wooden tables	4,50	0,15	0,09	0,06	0,06	0,08	0,10	0,10
Small light wood. table	0,70	0,15	0,09	0,06	0,06	0,08	0,10	0,10
Light upholstered chairs	9,04	0,09	0,14	0,26	0,42	0,50	0,55	0,55
Plaster ceilings	136,92	0,08	0,05	0,06	0,08	0,07	0,07	0,08
Wihite wooden door	1,52	0,14	0,10	0,06	0,08	0,10	0,10	0,10
Wooden furniture	4,60	0,15	0,09	0,06	0,06	0,08	0,10	0,10



Absorption coefficients listed in table and represented in graph, showing the values used for the room acoustics simulation in ODEON 15 in Cafaro's case.
The graph highlights how the light upholstered chairs affect the whole room absorption, particularly at high frequencies (2000-8000 Hz).

Room acoustic simulation in Odeon 15: process

Once the model is imported, the second step was defining a grid with the appropriate button *Define grid*, in the ODEON toolbar: this way allows an easier following placement of the sound sources and receivers. It's suggestable to create a horizontal grid, covering the floor's surface and positioned at the height of the seated human's ear (h=1,20m); the length (the grid divides the space in squared portions) will be about 0,50m, similar to an average human's shoulders size.
As a third step, for setting-up the model we define the Sources and Receivers positions in the room, in order to calculate a point response: ODEON let the user set the position and orientation of both sources and microphones, giving to all the points a useful name or description. Usually, sources are positioned in the effective place of the speaking people, while microphones (receivers) are set in the most efficient way to cover all the audience surface.
Once defined them, ODEON suggests as a forth step the materials assignment (icon *Assign materials*) to the different surfaces in the room: in order to obtain reverberation results, all the surfaces must have an assigned material. Referring to many sources, the most appropriate material for each part of the room was found and selected. This phase is carried out following a trial and error approach: that means the absorption coefficients given to each material present in the analyzed room are taken from the scientific literature references and, after several materials' combinations, the one closest to the measured results was found.
The scattering coefficients were left like the default values (0,01) that Odeon sets for each material. The only diffusion taken into account was the one due to the seats area, in the empty audience part of the room: the scattering value of the chairs' material was taken to 0,60 (12354/6 standard). Surface scattering has become an important input parameter in the work on geometric models and in the research concerning the enhancement of auralized sound (Shtrepi et al., 2013). The choice of changing just the most influent material was made

because of the armchairs' shape: they are much more scattering and reflective than the other surfaces in the studied rooms, inasmuch they present a rough and upholstered surface.

The *Quick estimate* calculation is then useful to get an idea of the global reverberation time in the room, for each octave band. This calculation is very useful while assigning materials for direct evaluation of different configurations and their impact on the reverberation time: in this phase it may be helpful, for the final outputs, to try different materials and see the change in the reverberation time.

In the *Room setup* phase it's possible to select the impulse response length (it should cover at least 2/3 of the decay curve), in order to calculate T20 of the room: in our case it was always fixed at 1000ms. The number of rays was selected at 10'000, to get accurate info of the measured indoor space: in this phase it's particularly important that the 3D model is well closed, otherwise the rays could come out, nullifying the whole simulation.

The performing of calculations is then made by running the *Job list button*: this is the interface where different ODEON tasks can be defined. Up to 300 jobs (tasks) can be defined for a room, in order to obtain various acoustic results for different combinations of sources and receivers.

Clicking on the *View single point response* button it'll be possible to display different outputs, of which the main interesting for these experiments are:

- Parameters curves;
- Energy parameters;
- Decay curves.

The last step is to copy the results to clipboard and import them in an Excel file, in order to analyze the achieved data in an accurate and readable way. They are compared to the data measured in two different methods (Christensen, Koutsouris, *ODEON Quick Start Guide*, 2016).

5. DATA ANALYSIS

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Physical Phenomenon	Acoustic Quality	Architectural Feature
First lateral reflections	Sound wrapping	Room's width (within 20-25m)
First frontal reflections	Clarity	Reflective ceilings Acoustic chamber on stage
Sound tail	Reverberation	Large volumes Reflective materials
First reflections from ceilings and walls	Sound intensity	Room's dimensions not too large (about 100-1200 seats)
First reflections in a few ms from the direct sound arrival	Intimacy	Sound source and audience in the same architectural volume
Reflections after the first 80ms	Spaciousness	Diffusing structures Large volumes

Relationship between acoustic qualities, architectural features and physical phenomena.

In acoustic design the shape of the environment must be such as to achieve a uniform distribution of reflections, both in time and in space.
The above reported table relates the main architectural features to the acoustic qualities and physical phenomena within an environment.
The listed acoustic qualities are related to a subjective perception of the listener inside the room: the corresponding architectural features are found in aspects of the built environment that most affect the perception of sound.
Such informations are useful for architects and engingeers, in the room's design phase: the acoustic treatment is considered not just an aspect to add after the indoor space's construction, but a problem to solve together with the design process realization.

5.1 Evaluation of the results

Data achieved from the measurements

were listed in a spreadsheet and, in a second moment, classified in tables: keeping the values on frequency, in the octave bands interval from 125 to 8000 Hz, an average between all the microphone positions is calculated. As a third step, an average value between the different source positions is required, in order to obtain as output a single data of the investigated parameter for each octave band frequency.

The final step is to create a graph with the table's results, comparing all the different methods used for measurements and the simulations' results given by Odeon.

Some refence values for the analyzed parameters are pointed out by the ISO 3382 part 1, even though they are referred to rooms used for music, not properly for speech.

5.1.1 Typical values' references

Some investigated parameters are taken into account comparing to these typical values:

- The **Early Decay Time (EDT)** is linked to subjective listener aspect of the perceived reverberance. The typical range is normally about 1,0-3,0 seconds. This parameter has a just noticeable difference (JND) of 5%: it represents the amount of value that must be changed to get a sensible difference, detectable at least half the time (this is called absolute threshold).
- The **Clarity (C_{50})** is related to the subjective listener aspect of the perceived quality of sound: differently from the rooms used for music, where the C_{80} needs to be measured, in indoor environments used for speech an interval of 50ms is enough to ensure a correct evaluation of the perceived speech quality. A typical range is pointed out between -5dB and +5dB: referring to Farina (2001) optimal values of the Clarity index vary between -1 and 1dB. In this paper Farina specifies that:
  - Higher values than 1dB indicate a too dry sound, similar to the free field sound;
  - Values below -1dB indicate excessive sound reverberation.

  The UNI 11367: 2010-15 indicates as optimal a value greater than or equal to 0 dB.
- The **Definition (D50)** parameter is also linked to the

subjective perception of clarity of a sound: the typical range indication is normally between 0,3 and 0,7. This can be expressed both in index form and in percentage. It represents a similar criterion for evaluating the perceived speech quality to the C_{50} and has a very sensitive just noticeable difference of 0,05.

Acoustic quantity	Typical range
Early Decay Time (EDT), in seconds	1,0 s; 3,0 s
Clarity, C50, in decibels	-5 dB; +5 dB
Definition, D50, a-dimensional	0,3; 0,7

Typical values pointed out by the UNI EN ISO 3382-1 standard, referring to performance spaces.

No typical values for reverberation time are mentioned, depending on the rooms' volume and surfaces.

5.1.2 Calculation of the average

All the values presented in the on-frequency tables are the result of an average calculated by steps:

1. The first average is between all the microphone positions, measured or simulated using a sound source placed in a fixed position;
2. A second average is then made between the resulting values of the same octave band, from different loudspeaker's positions;
3. The resulting table after the second step presents values on frequency: all the values were measured and simulated in a considered octave bands range within 125 and 8000 Hz.
4. The final average is calculated between the two central frequency bands: 500 and 1000 Hz, according to ISO 3382-1 standard, Annex A.

The single number frequency averaging denotes the arithmetical average for the octave bands; the results measured for the range of source and microphone positions can be then combined either for separate identified areas or for the room as a whole to give spatial average values. This spatial averaging shall be achieved by arithmetic averaging of the reverberation times; it is given by taking the mean of the individual

reverberation times for all the independent source and microphone positions.
A final single number value is given as output, always considering unoccupied rooms; the standard deviation, then, may be automatically determined using a worksheet for data to provide a measure of accuracy and spatial variance of the reverberation time (ISO 3382-1: 2009) and of the other measured and simulated acoustic parameters.
A specific attention should always be paid in averaging measures taken over space, time and frequency. While making measurements at a limited number of seating positions is a practical reality in the consulting world, it is too easy to assume that the room is "well characterized" even if the number of measurement positions greatly exceeds those outlined in the ISO 3382 standard: understanding the differences among various seating locations may be even more important than their averaged values. Indeed, the most interesting and significant qualities of the parameters are often how they vary within the measured room (Kirkegaard & Gulsrud, 2011).
In this research's cases, all the specimens were accurately chosen in order to have the most heterogeneous geometric shape as possible, in each point of the considered indoor environment.

6.

RESULTS AND COMMENTS

6. RESULTS AND COMMENTS

In this part of the research, achieved results were showed and analyzed, comparing both different study cases to others and data found out from measurements and simulations to the typical range values listed in the ISO 3382-1 standard.

6.1. Interesting parameters measured in different kinds of rooms

Some parameters were chosen as the most suitable to describe an indoor environment used for speech: they were analyzed and graphs comparing different measurements (and simulations) methods were built.

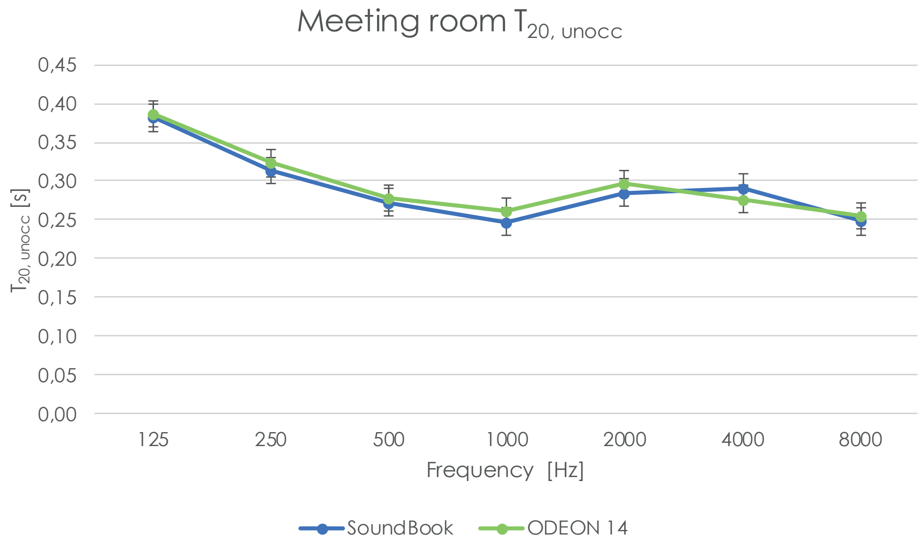
Reverberation Time T_{20}

The Reverberation Time T_{20} is the first reference to evaluate the acoustic quality of a room: an optimized reverberation reinforces early reflected energy of sound, which arrives at a receiver position at times less than 50 ms from that of the direct sound, and increase speech intelligibility. On the other hand, the late energy, which arrives at a receiver position at times later than 50 ms, may mask the direct sound, hence effectively increasing the background noise, and decreasing speech intelligibility (Gramez & Boubenider, 2017).

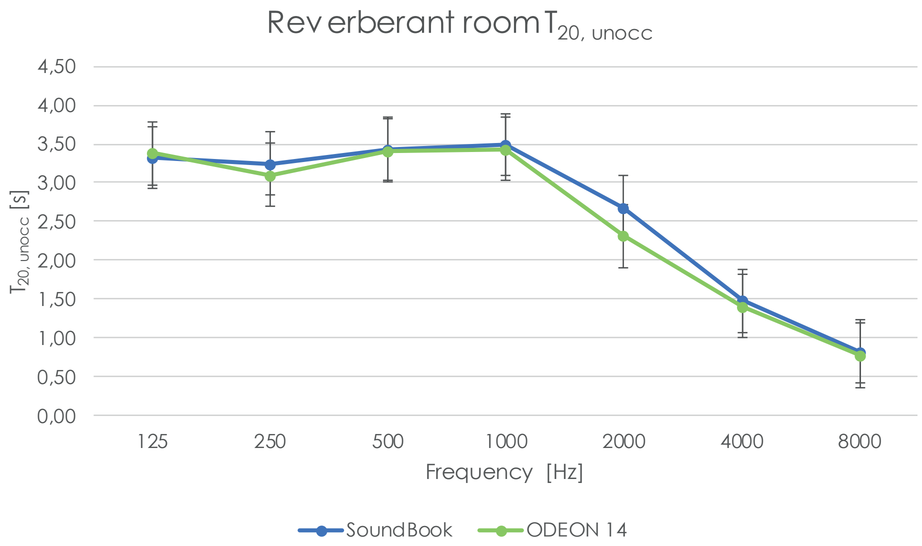
Looking at the graphs reported below, the reverberation time values expressed in seconds appear in the Finnish cases study very close to each other, in both the lines of measurements methods: specially at the low and middle frequencies (within the considered range of 125-8000 Hz), values achieved through ODEON 14 measurements are very similar to the SoundBook results.

On the other hand, focusing on the results obtained from measurements taken in Turin: the values pointed out by ODEON 13 look, in each case study, *lower* than the output values given by Aurora slightly out of the tolerance range. The simulation carried out using the ODEON's room acoustic simulation system gives values placed on average, between the two reference lines of the measurements' results.

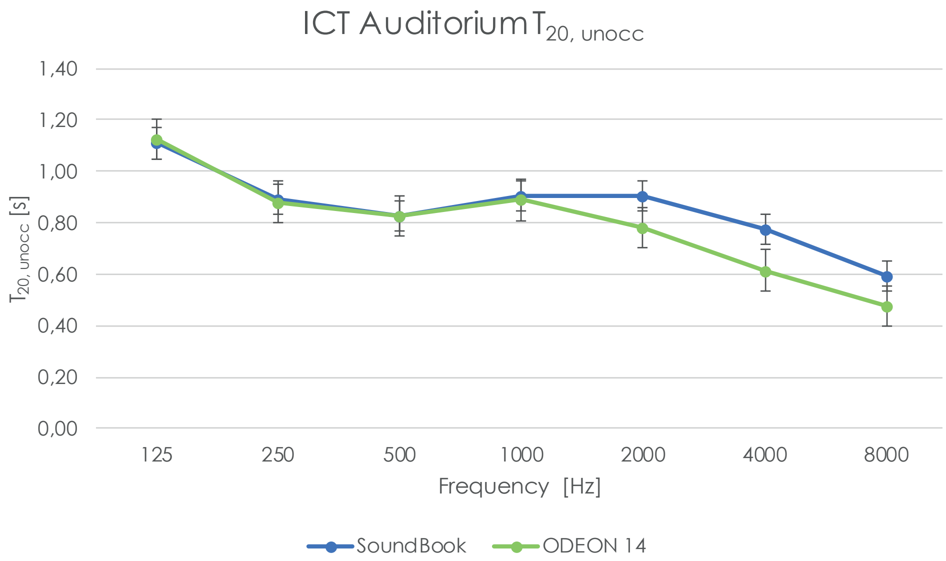
Meeting room	125	250	500	1000	2000	4000	8000
$T_{20,\ SoundBook}$	0,38	0,31	0,27	0,25	0,28	0,29	0,25
$T_{20,\ ODEON14}$	0,39	0,32	0,28	0,26	0,30	0,28	0,26



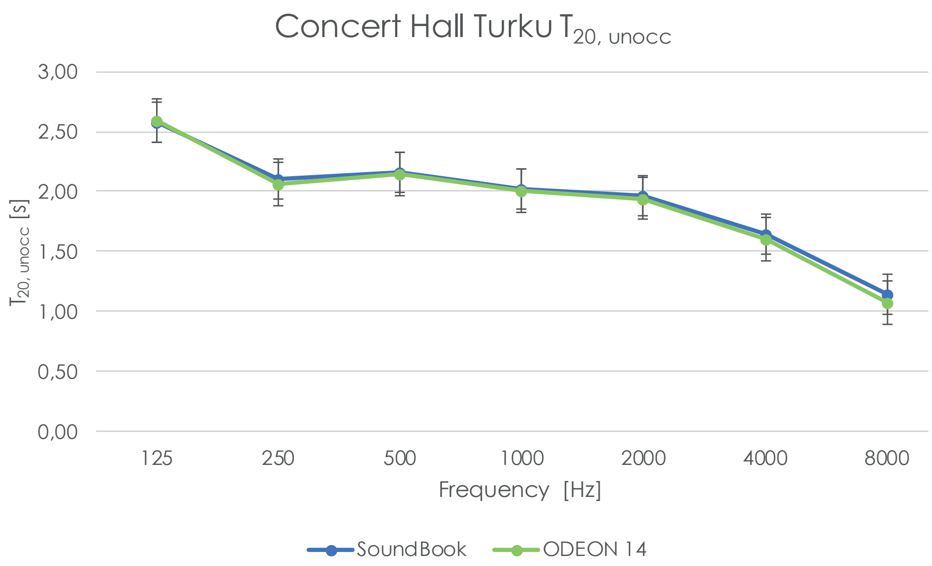
Reverberant room	125	250	500	1000	2000	4000	8000
$T_{20,\ SoundBook}$	3,33	3,25	3,43	3,49	2,68	1,48	0,83
$T_{20,\ ODEON14}$	3,38	3,10	3,41	3,43	2,32	1,41	0,78



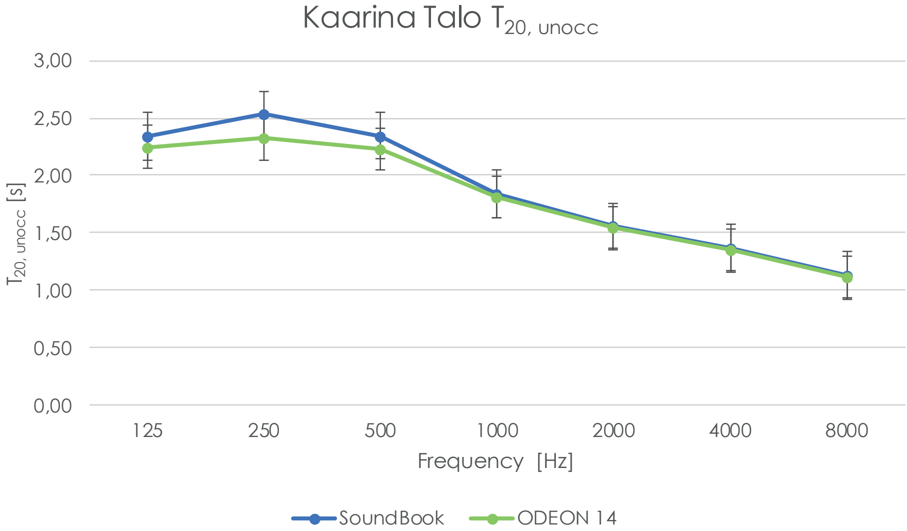
ICT Auditorium	125	250	500	1000	2000	4000	8000
$T_{20,\ SoundBook}$	1,11	0,89	0,83	0,90	0,91	0,77	0,59
$T_{20,\ ODEON14}$	1,12	0,88	0,83	0,89	0,78	0,62	0,48



Concert Hall Turku	125	250	500	1000	2000	4000	8000
$T_{20,\ SoundBook}$	2,58	2,10	2,16	2,02	1,96	1,65	1,15
$T_{20,\ ODEON14}$	2,59	2,07	2,15	2,00	1,94	1,61	1,07

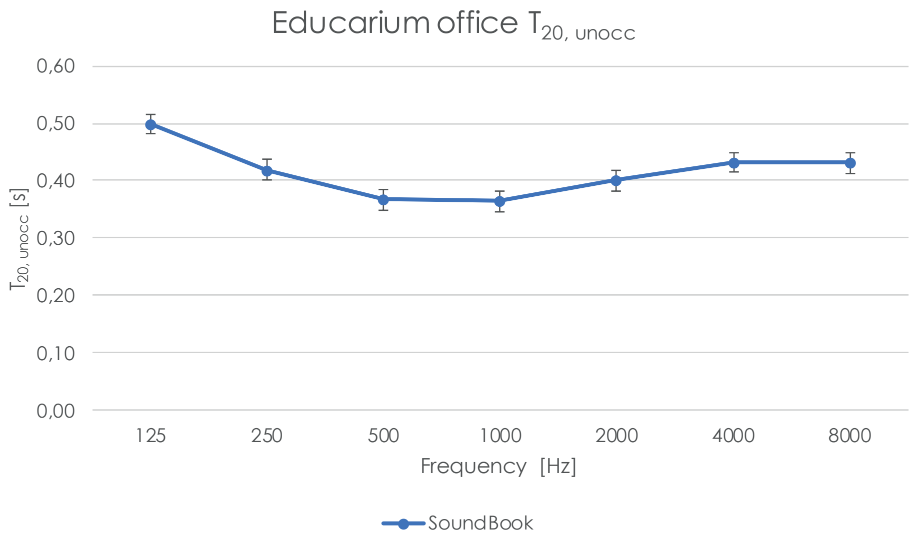


Kaarina Talo Auditorium	125	250	500	1000	2000	4000	8000
$T_{20,\ SoundBook}$	2,34	2,53	2,35	1,84	1,56	1,37	1,13
$T_{20,\ ODEON14}$	2,25	2,32	2,23	1,81	1,55	1,35	1,11



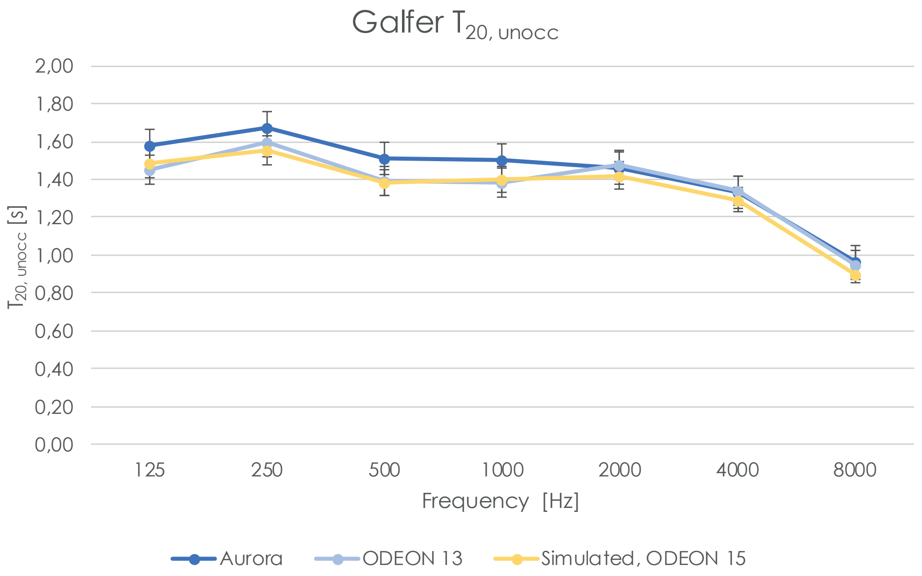
Despite ICT Auditorium and Kaarina Talo show quite the same destination of use, because of their design studied for speech during presentations and interaction between the single speaker (the sound source) and the audience (the receivers), comparing their graphs it is noticeable that the ICT Auditorium shows an on-frequency line closer to the Turku Concert Hall: this is unusual, because the main purpose of the above-mentioned hall is the good optimal perception of *symphonic music*, not speech. This destination of use leads to a different choice of architectural features in shape, materials, audience layout and room's volume: just the volume's difference between the measured auditorium (smaller) and concert hall (huge) represents one of the reasons for the higher T_{20} values in this latter case study.

Educarium office	125	250	500	1000	2000	4000	8000
$T_{20,\ SoundBook}$	0,50	0,42	0,37	0,36	0,40	0,43	0,43

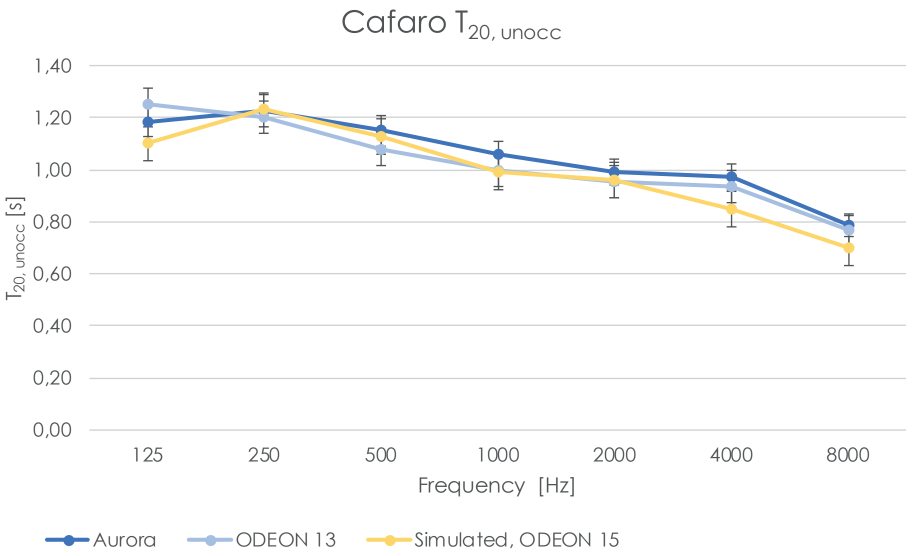


The Educarium open plan office was measured just using SoundBook, not comparing to ODEON's data: this room was a clear example of why the Reverberation Time should not be considered as the only significant parameter in evaluating the acoustic quality in a room. Indeed, even if these measured values are low and perfectly included in the typical range (not so far from the Meeting room, almost anechoic chamber, reverberation data), the perception of speech in that office isn't very qualitative.
When employers speak on the phone, their words are clearly audible by the other colleagues: this represents a real gap in the requirements of an open plan office, where the speech privacy plays a primary role. As a remedy against the distraction matter caused by the phone speeches, Finnish built some little and acoustically isolated single cabins.

Galfer	125	250	500	1000	2000	4000	8000
$T_{20,\ Aurora}$	1,58	1,67	1,51	1,50	1,46	1,33	0,97
$T_{20,\ ODEON13}$	1,45	1,59	1,39	1,38	1,48	1,34	0,95
$T_{20,\ ODEON15}$	1,49	1,55	1,38	1,40	1,42	1,29	0,90



Cafaro	125	250	500	1000	2000	4000	8000
$T_{20,\ Aurora}$	1,19	1,23	1,15	1,06	0,99	0,97	0,78
$T_{20,\ ODEON13}$	1,25	1,20	1,08	1,00	0,95	0,93	0,77
$T_{20,\ ODEON15}$	1,10	1,23	1,13	0,99	0,96	0,85	0,70

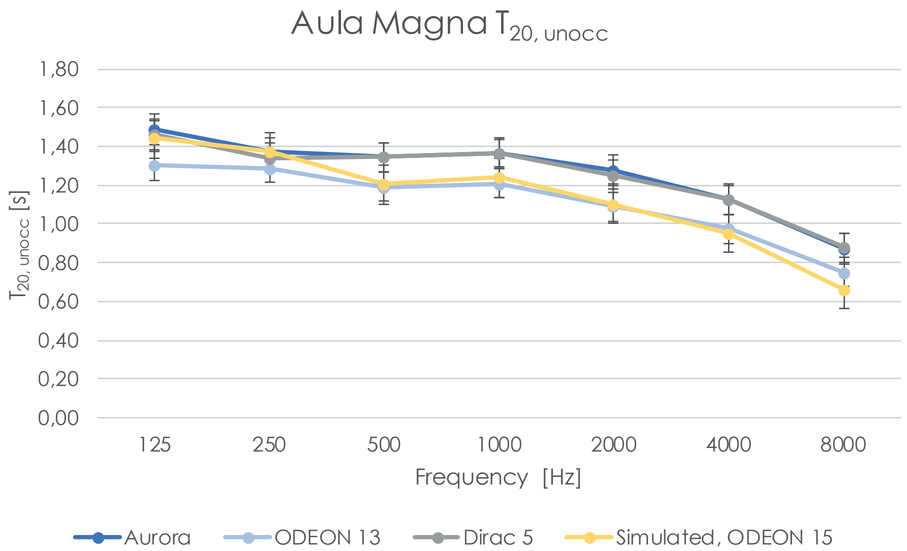


Galfer, located in Lamsa, and Cafaro meeting rooms, both in Politecnico di Torino's energy department, were chosen as cases study for the acoustic treatment carried out in the second part of this research.
The rooms are used for the same purpose: presentations and speech in public.
Galfer meeting room has a bigger volume than the Cafaro interaction room, having also higher ceilings; this leads to greater Reverberation Time values. The two analyzed environments were measured both with ODEON 13 and Aurora: the values achieved by ODEON looks lower than the Aurora's data. In the gap between the two measurements lines, as showed in the graphs, the ODEON 15 simulation's line finds its place.
This room acoustics prediction is quite accurate, that means the absorption coefficients used for indoor objects modeled for the aocustic simulation were particularly close to the real absorption effectiveness of the materials present in the studied room. The reported error bars show the range within the values can vary in each considered frequency.

The Cafaro meeting room lacks in acoustic insulation and most of the external noises and speeches are clearly audible standing inside the room, causing annoyance and disturbance to listeners: this phenomenon is certainly favored to the characteristic shape of its covering, that reflects sounds returning, as measurements and simulations' output, higher values of reverberation time than normal.

On the other hand, the Galfer meeting room is affected by a *coupled-environment* phenomenon: this is due to the presence of a screen occupying a whole wall of the room, that divides it to the adjacent space, where the projector is placed. This screen is indeed used to project images and videos during presentations and meetings, but it does not insulate the Cafaro interaction room.
Just this coupled environment effect helps to rise the reverberation time values obtained and the number of sound reflections on the space's surfaces.

Aula Magna	125	250	500	1000	2000	4000	8000
$T_{20,\ Aurora}$	1,49	1,37	1,34	1,36	1,27	1,13	0,87
$T_{20,\ ODEON13}$	1,30	1,29	1,19	1,21	1,09	0,98	0,75
$T_{20,\ Dirac5}$	1,46	1,34	1,34	1,37	1,25	1,12	0,88
$T_{20,\ ODEON15}$	1,44	1,37	1,20	1,24	1,10	0,95	0,66



The Politecnico di Torino's Aula Magna (Giovanni Agnelli multipurpose room) was measured comparing different measurements' methods: reading the above-reported results, Aurora and Dirac give back very similar values, while ODEON 13 tends to underestimate the Reverberation Time values. This effect could be due to a possible error in the equipment's calibration phase, or an error made during the Room Acoustic Setup in ODEON, while preparing for the real measurements, or still for a software's bug.

Aula Magna has been acoustically treated: indeed it presents good values for the reverberation time. Absorbent panels were placed both along the two longitudinal walls and on the rear wall: they were also positioned in the multipurpose auditorium's ceilings.

Early Decay Time, EDT (s)

The Early Decay Time parameter, expressed in seconds, represents the first reflections of sounds arriving from the sourcs. This includes all the reflections measured in the first 15 seconds of the sound tail, for this reason the results returned by this parameter of acoustic evaluation appear quite similar to those obtained by evaluating the Reverberation Time (T_{20}) extrapolated in the first 20 seconds after the sound source is stopped (if the measurements are taken using a sine sweep, like in all the study cases carried out in this whole research).

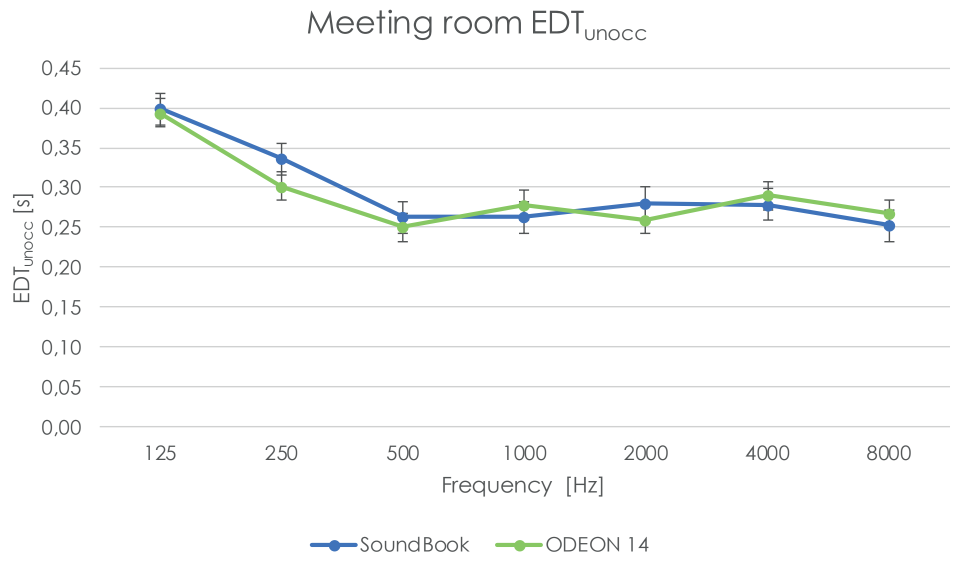
All the measurements were taken in unoccupied and normally furnished rooms, always considering a frequency range between 125 and 8000 Hz: in the graphs returned by the Finnish study cases, both the green line (Soundbook measurements) and the blue line (ODEON 14 measurements) appear close to each other. This means the ODEON's measurement system is reliable and data achieved using SoundBook work, in this phase of the research, as a validity confirmation of the results returned by ODEON.

The ICT Auditorium is the only Finnish case where the SoundBook values of EDT looks lower than the ODEON's results, in each frequency band, specially at middle and low frequencies.

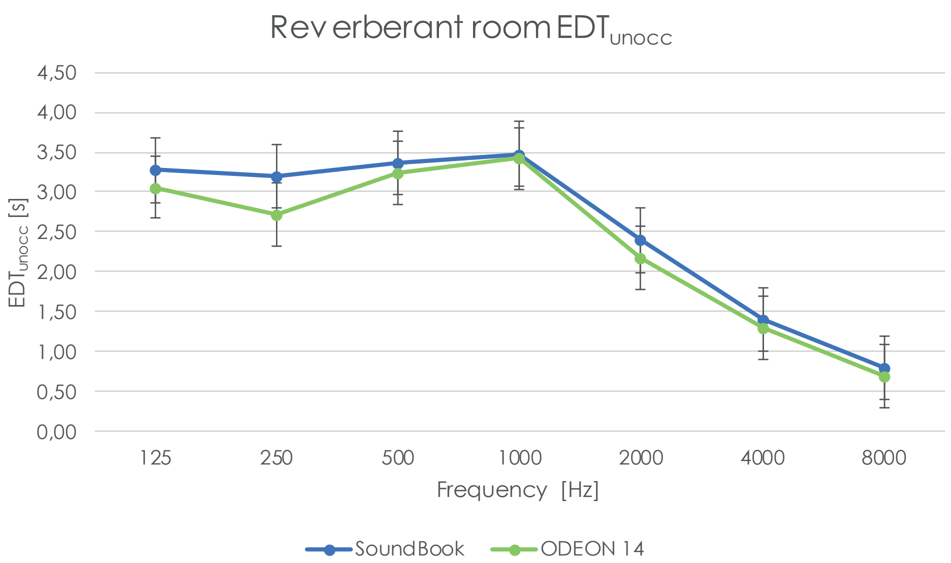
In the Torino's sample, the gap between the two blue lines (representing the Aurora's results, in darker blue, and the ODEON's ones, in lighter blue) is very low, that means the two measurements methods are quite equivalent. This considerations are valid for Galfer and Cafaro meeting rooms, while the Aula Magna's EDT values present a deeper gap between the measurements lines, with a usual underestimation of the first sound reflections by ODEON 13.

The simulated obtained values are placed on average between the two blue lines in the Aula Magna's results, while they deviate more from the average of the measurements lines in the Galfer and Cafaro cases study.

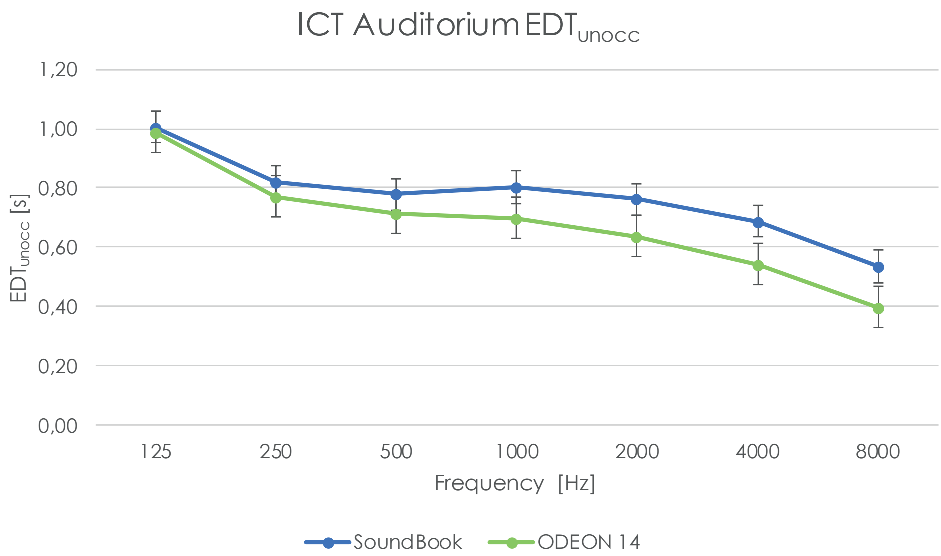
Meeting room	125	250	500	1000	2000	4000	8000
$EDT_{medio,\ SoundBook}$	0,40	0,34	0,26	0,26	0,28	0,28	0,25
$EDT_{medio,\ ODEON14}$	0,39	0,30	0,25	0,28	0,26	0,29	0,27



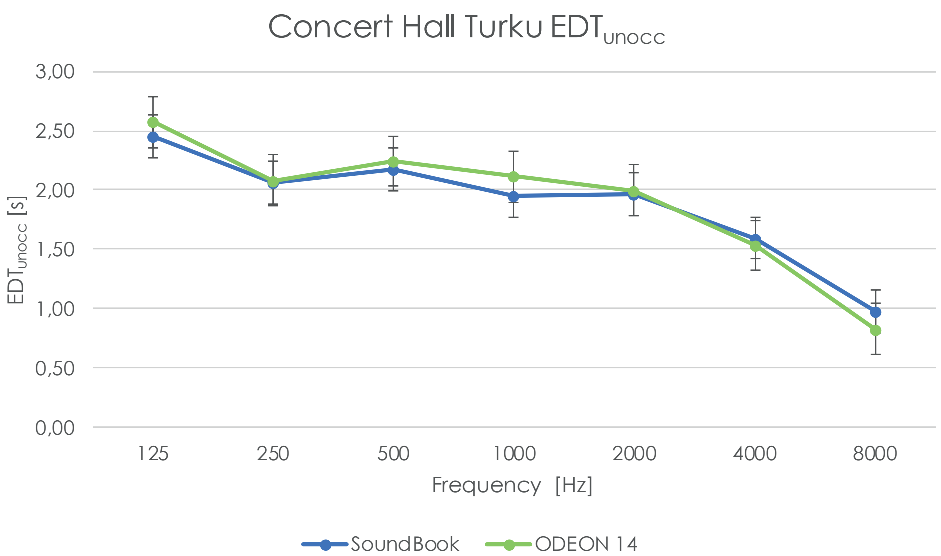
Reverberant room	125	250	500	1000	2000	4000	8000
$EDT_{medio,\ SoundBook}$	3,27	3,20	3,37	3,47	2,40	1,41	0,80
$EDT_{medio,\ ODEON14}$	3,06	2,72	3,24	3,42	2,17	1,30	0,69



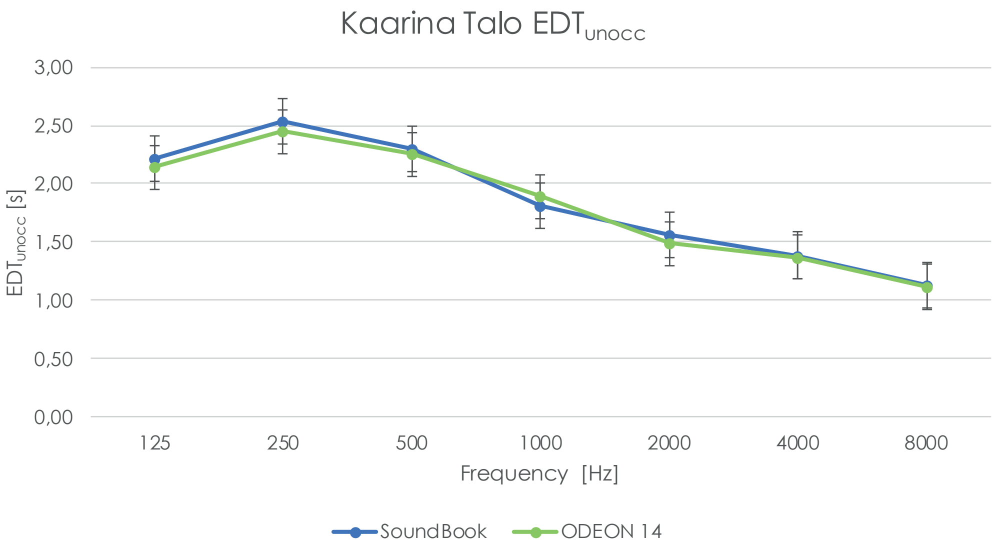
ICT Auditorium	125	250	500	1000	2000	4000	8000
EDT$_{medio, SoundBook}$	1,00	0,82	0,78	0,80	0,76	0,69	0,54
EDT$_{medio, ODEON14}$	0,99	0,77	0,72	0,70	0,64	0,54	0,40



Concert Hall Turku	125	250	500	1000	2000	4000	8000
EDT$_{medio, SoundBook}$	2,45	2,07	2,17	1,96	1,96	1,60	0,97
EDT$_{medio, ODEON14}$	2,57	2,08	2,24	2,11	1,99	1,53	0,83



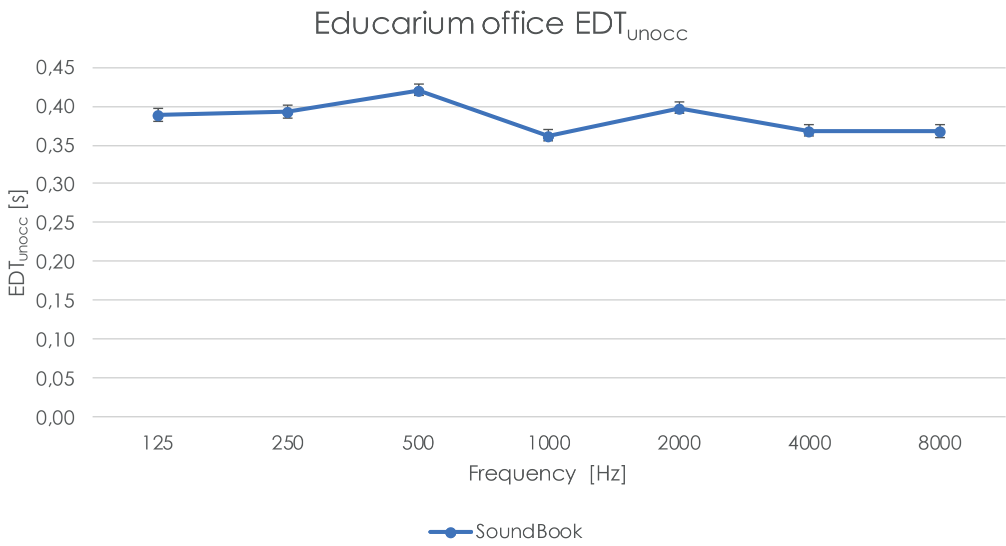
Kaarina Talo Auditorium	125	250	500	1000	2000	4000	8000
$EDT_{medio,\ SoundBook}$	2,22	2,53	2,30	1,81	1,56	1,39	1,13
$EDT_{medio,\ ODEON14}$	2,14	2,45	2,26	1,89	1,49	1,37	1,12



In the environments measured in Finland, outcame data from the experiments and showed in the above-reported graphs are very similar in the two different lines: there is no substantial difference or underestimation of the values neither using the SoundBook's measurement system, nor in the ODEON one.

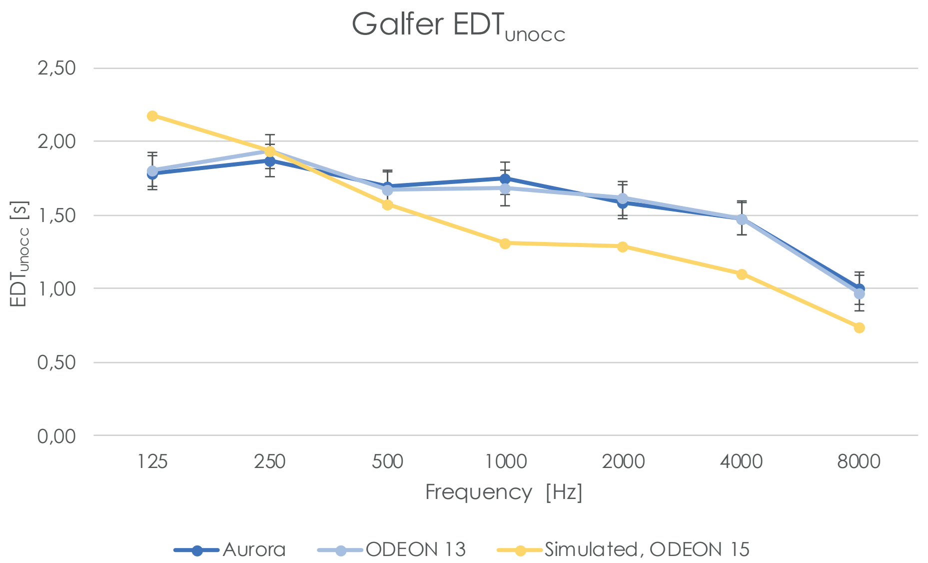
This is a good results for the methods' evaluation, because confirms the reliability of the measurements taken in ODEON comparing to those carried out using the compact portable pc.

Educarium office	125	250	500	1000	2000	4000	8000
$EDT_{medio, SoundBook}$	0,39	0,39	0,42	0,36	0,40	0,37	0,37

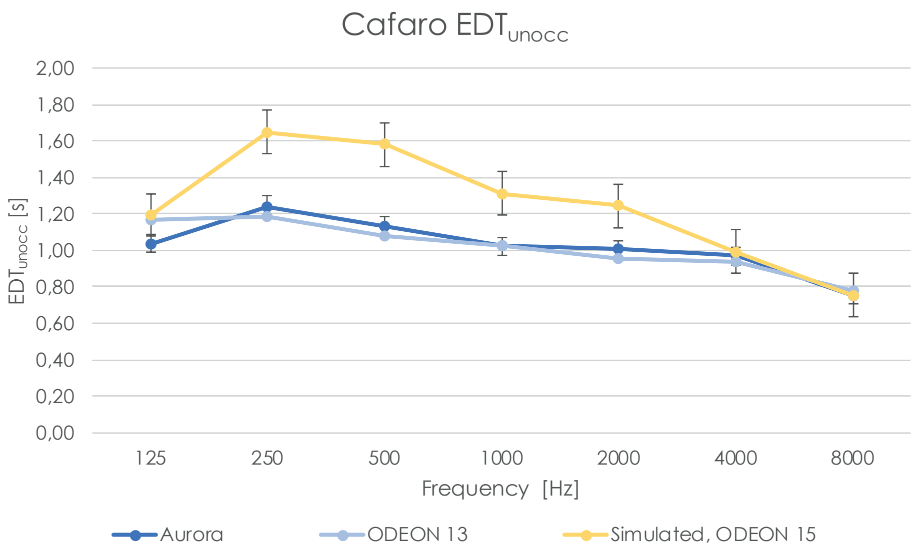


In the Educarium open plan office the measurements were taken using just the method offered by SoundBook: the achieved results were interesting to understand how the acoustic treatment of the room, carried out with absorbent panel on the front and rear walls affects the whole aocustic perception in the indoor space. One of the main requirements for an open place office is the speech privacy, in order to avoid disturbing other employers; the *objective parameters* (such as Reverberation Time, Early Decay Time, etc...) point out an optimal acoustic quality, because the reflected sound is just a very small part of the waves reflections, but the *subjective* perception of the sounds is quite bad. Indeed, speech privacy is not much respected.

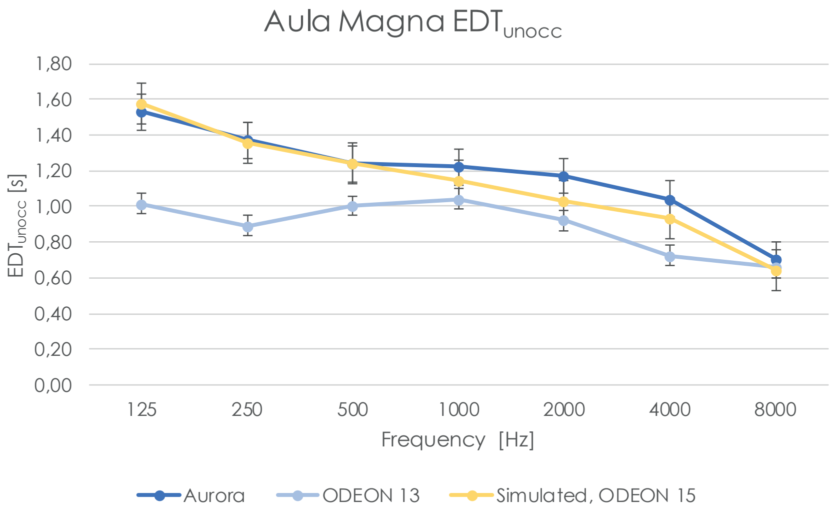
	125	250	500	1000	2000	4000	8000
$EDT_{medio,\ Aurora}$	1,79	1,87	1,70	1,75	1,59	1,48	1,00
$EDT_{medio,\ ODEON13}$	1,81	1,93	1,67	1,68	1,62	1,48	0,97
$EDT_{medio,\ ODEON15}$	2,18	1,94	1,57	1,31	1,28	1,11	0,74



Cafaro	125	250	500	1000	2000	4000	8000
$EDT_{medio,\ Aurora}$	1,04	1,24	1,13	1,02	1,01	0,97	0,75
$EDT_{medio,\ ODEON13}$	1,17	1,19	1,08	1,02	0,96	0,94	0,78
$EDT_{medio,ODEON15}$	1,19	1,65	1,58	1,31	1,25	0,99	0,75



Aula Magna	125	250	500	1000	2000	4000	8000
$EDT_{medio, Aurora}$	1,53	1,37	1,24	1,22	1,17	1,04	0,70
$EDT_{medio, ODEON13}$	1,02	0,89	1,00	1,04	0,92	0,72	0,66
$EDT_{medio, ODEON15}$	1,58	1,36	1,24	1,15	1,03	0,94	0,64



The results achieved from the study cases measured in Turin return a more noticeable range between the measurements methods' lines, if compared to data in graphs obtained from the Finnish rooms. This happens because ODEON tends to underestimate also the measured Early Decay Time, compared to Aurora's results: on the other hand, the simulation differs, looking at some frequencies, from the two blue lines. In Galfer meeting room the gap is more visible at middle and high frequencies; in Cafaro meeting room, at low and middle frequencies; in Aula Magna the room acoustic prediction given by ODEON 15 appears on average between the blue lines of the measurements' results.

Clarity, C50 (dB)

The Clarity parameter, expressed in decibels, is related to the subjective listener aspect of the perceived quality of sound: in indoor environments used for speech an interval of 50ms is enough to ensure a correct evaluation of the perceived speech quality. A typical range is pointed out between -5dB and +5dB: referring to Farina (2001) optimal values of the Clarity index vary between -1 and 1dB. The UNI 11367: 2010-15 indicates as optimal a value greater than or equal to 0 dB.

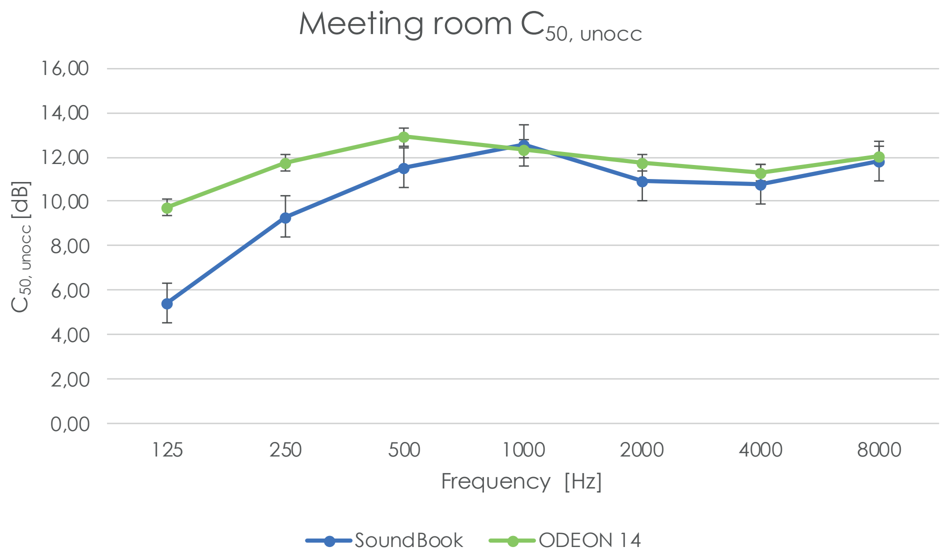
Not in each study case analyzed in this research the clarity values were fit in the above-mentioned range: the clarity parameter depends also on the geometric volume and shape of the rooms, besides the architectural features and the materials present in each indoor environment.

For example: in the Finnish cases, there's a strongly noticeable difference between the clarity values returned by measuring rooms: indeed, while looking at the Data City meeting room (first case), almost an anechoic room, and at the Educarium open plan office (last room measured in Finland), presenting an acoustic treatment designed through absorbent panels, the clarity values are all above 0 dB and, on average, quite high, presenting a very good perception and understanding of speech (within the 50ms), in some reverberant and huge spaces, like the Reverberant room (measured as a second case study in Turku, FI) and the Turku Concert Hall, where the indoor space is very reflective, less absorbent, the clarity values descend even below -1 dB, but always remaining in the reference range pointed out by UNI 3382-1: this latter tyipical range is particularly specific for the Turku Concert Hall, which is a space used for music.

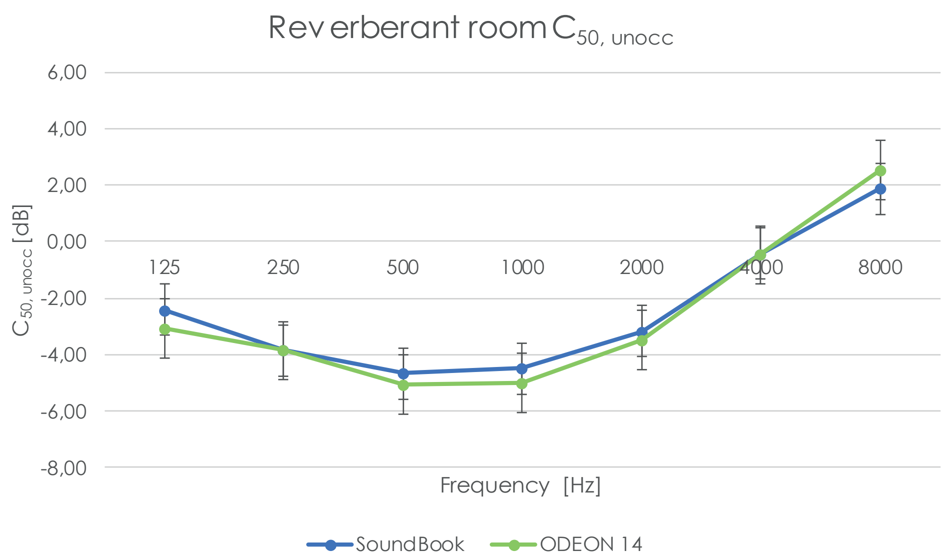
The cases studied in Torino presents, on the other hand, a deeper gap between the two blue lines of the measurements: there is a general underestimation of the clarity values by measures carried out with ODEON, higher values given by Aurora.

The simulation's yellow line is placed on average in the Aula Magna; it presents higher values than the measurements in the Galfer meeting room and lower values in Cafaro room.

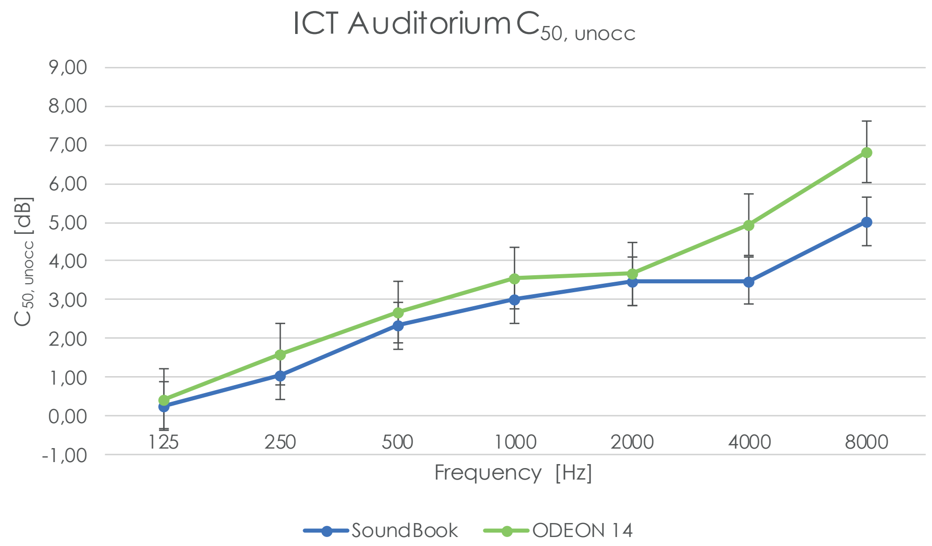
Meeting room	125	250	500	1000	2000	4000	8000
$C_{50, \text{SoundBook}}$	5,42	9,33	11,50	12,52	10,93	10,80	11,81
$C_{50, \text{ODEON14}}$	9,72	11,75	12,90	12,37	11,77	11,30	12,07



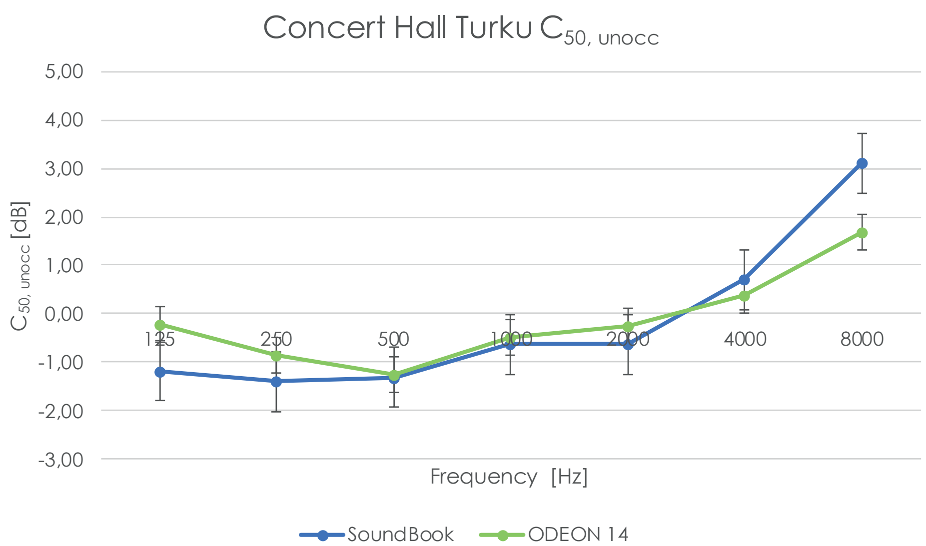
Reverberant room	125	250	500	1000	2000	4000	8000
$C_{50, \text{SoundBook}}$	-2,41	-3,84	-4,67	-4,48	-3,16	-0,42	1,88
$C_{50, \text{ODEON14}}$	-3,08	-3,85	-5,07	-5,00	-3,48	-0,47	2,52



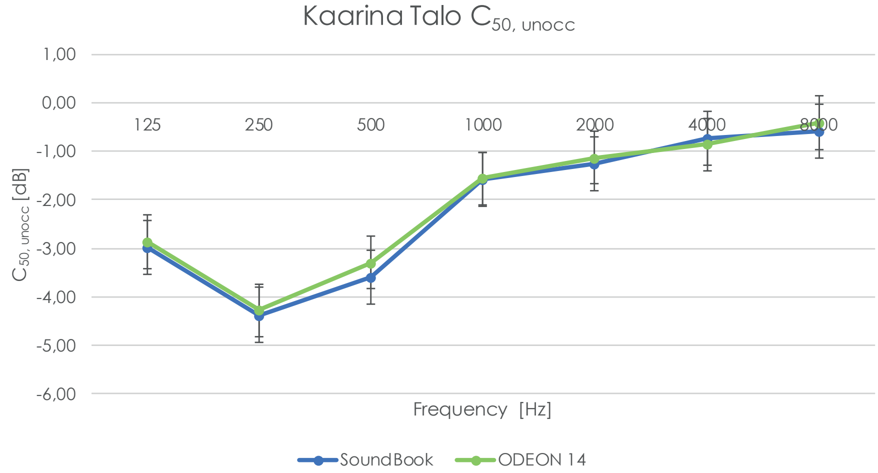
ICT Auditorium	125	250	500	1000	2000	4000	8000
$C_{50, SoundBook}$	0,28	1,04	2,35	3,01	3,48	3,49	5,02
$C_{50, ODEON14}$	0,44	1,60	2,68	3,57	3,67	4,93	6,81



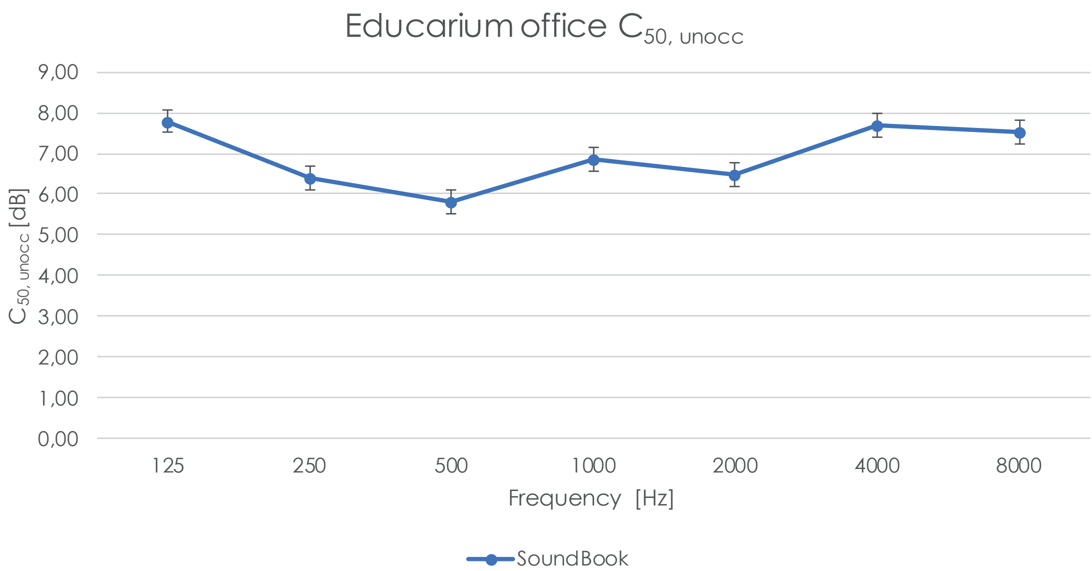
Concert Hall Turku	125	250	500	1000	2000	4000	8000
$C_{50, SoundBook}$	-1,17	-1,40	-1,30	-0,63	-0,62	0,70	3,11
$C_{50, ODEON14}$	-0,21	-0,85	-1,24	-0,48	-0,25	0,37	1,69



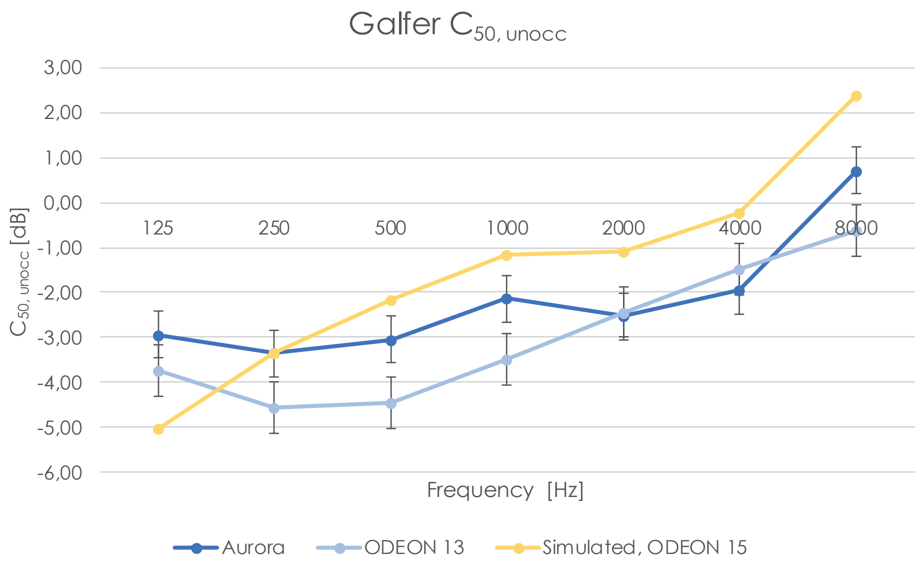
Kaarina Talo Auditorium	125	250	500	1000	2000	4000	8000
$C_{50, SoundBook}$	-2,98	-4,37	-3,59	-1,58	-1,26	-0,74	-0,59
$C_{50, ODEON14}$	-2,87	-4,27	-3,29	-1,56	-1,13	-0,86	-0,42



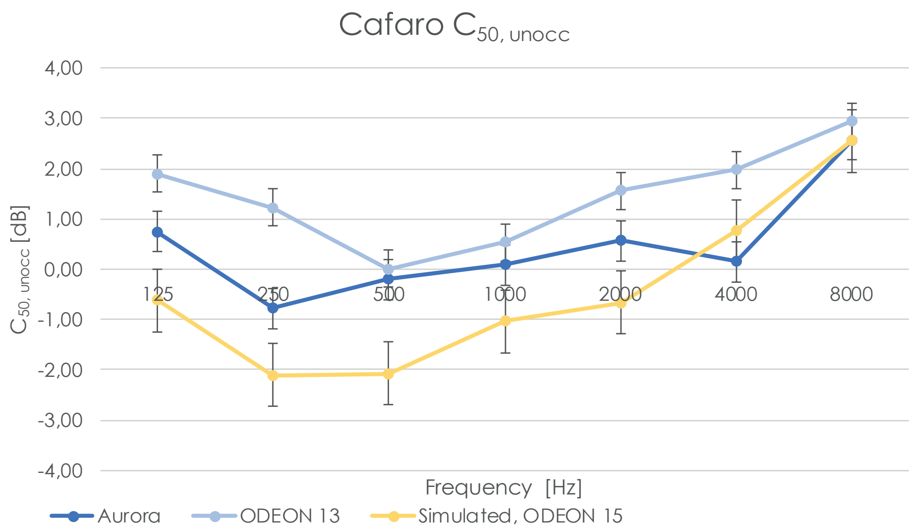
Educarium office	125	250	500	1000	2000	4000	8000
$C_{50, SoundBook}$	7,79	6,40	5,80	6,86	6,49	7,68	7,51



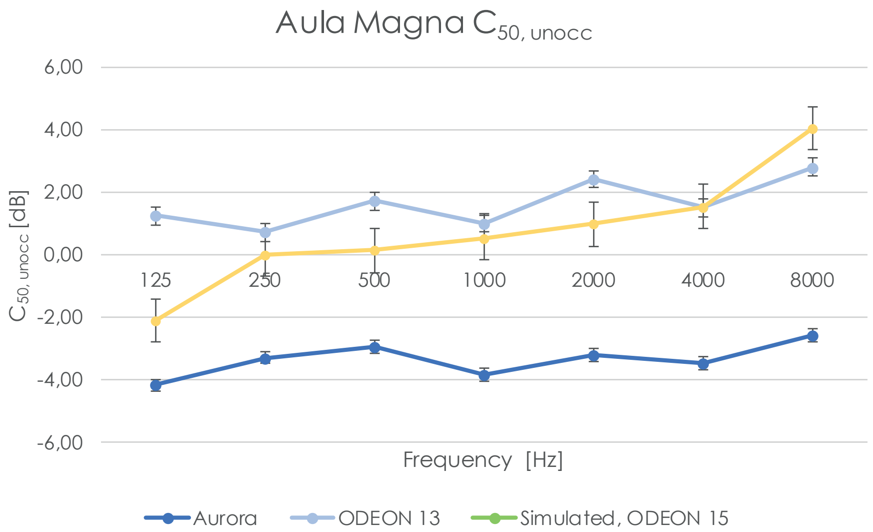
Galfer	125	250	500	1000	2000	4000	8000
$C_{50,\ Aurora}$	-2,94	-3,35	-3,04	-2,13	-2,52	-1,96	0,71
$C_{50,\ ODEON14}$	-3,73	-4,57	-4,44	-3,48	-2,43	-1,49	-0,63
$C_{50,\ sim.ODEON15}$	-5,01	-3,33	-2,17	-1,18	-1,08	-0,23	2,37



Cafaro	125	250	500	1000	2000	4000	8000
$C_{50,\ Aurora}$	0,75	-0,78	-0,07	0,09	0,57	0,15	2,58
$C_{50,\ ODEON13}$	1,90	1,23	0,00	0,54	1,57	1,98	2,94
$C_{50,\ ODEON15}$	-0,63	-2,11	-2,08	-1,04	-0,66	0,77	2,55



Aula Magna	125	250	500	1000	2000	4000	8000
$C_{50,\ Aurora}$	-4,18	-3,30	-2,95	-3,86	-3,20	-3,47	-2,60
$C_{50,\ ODEON13}$	1,23	0,71	1,71	1,00	2,40	1,50	2,79
$C_{50,\ ODEON15}$	-2,11	-0,01	0,13	0,53	0,96	1,53	4,03



In the cases study analyzed in Torino, there is a gap between values measured using Aurora and those measured by ODEON: differently from the previous considered parameters, both related to the reverberation time, in the clarity evaluation results given by ODEON 14 appear higher than those returned by Aurora, showing an overestimation in the perception and understanding of speech in the studied rooms.

This is valid both for Cafaro meeting room and Aula Magna multipurpose auditorium, while in the Galfer meeting room the situation is opposite: Aurora returns higher clarity values than ODEON.

The simulations results of the prediction, achieved by ODEON 15's room acoustic system, appear quite on average between the two blue lines if looking at Aula Magna, very lower than the measurements in Cafaro meeting room and very high compared to the blue lines (of ODEON and Aurora measurements) in the Galfer meeting room.

Definition, D_{50} (a-dimensional)

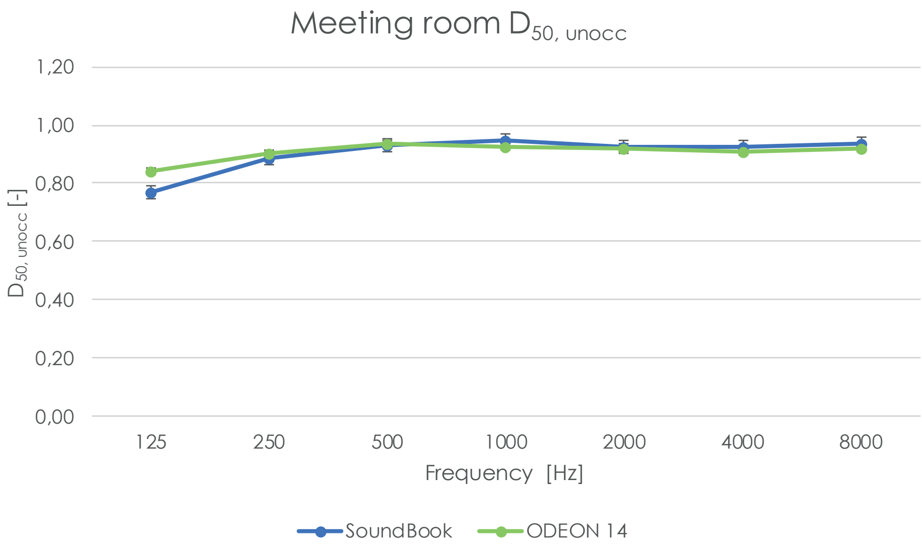
The Definition parameter, in this research expressed and analyzed as a-dimensional coefficient, evaluates as well the subjective perception of clarity of a sound: this is quite similar to Clarity parameter, and the typical range indication is normally between 0,3 and 0,7. Its values can be expressed both in index form and in percentage. It represents a similar criterion for evaluating the perceived speech quality to the C_{50} and has a very sensitive just noticeable difference of 0,05. In the measured and studied cases carried out in Finland, like other evaluated parameters, the lines showed in the following graphs, representing measurements taken both with ODEON 14 and with the portable compact pc SoundBook, are very close to each other and they stay always within the tolerated error range, showed in graphs using vertical grey bars.

This reveals that the ODEON measurements' system is also reliable in the evaluation of the definition of speech and its clear understanding. The situation readable from the Definition's graphs returned by the study cases measured and simulated in Torino appears quite similar to the one seen for the Clarity evaluation, in the same indoor environments: in Galfer meeting room there is an underestimation of the values pointed out by ODEON, while in Cafaro room and in Aula Magna multipurpose auditorium this software return an overestimation if compared to values given by Aurora measurements' system.

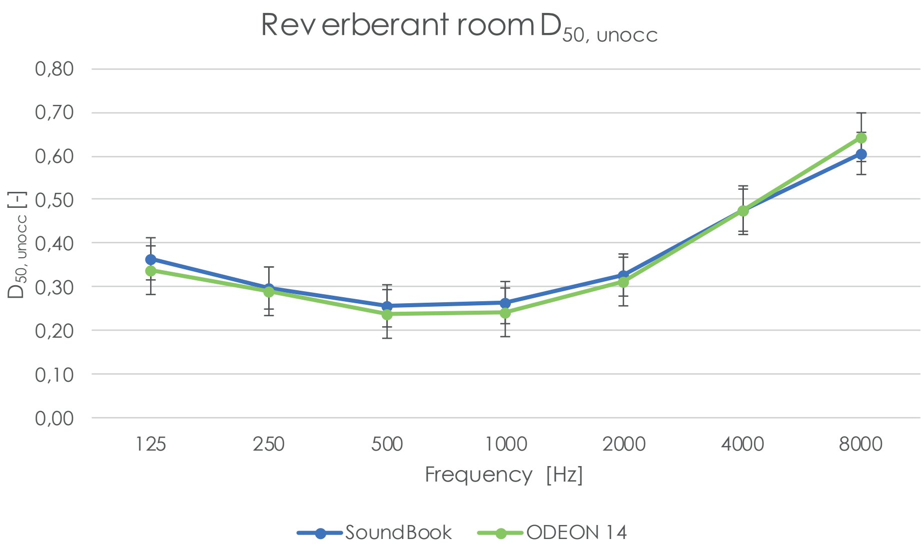
The same happens in the evaluation of the room acoustic simulation made by ODEON 15: the yellow line in Galfer is placed over the blue lines, in Cafaro under them and in Aula Magna appears on average between the measurements' lines gap.

Comparing achieved results to the above-mentioned typical range pointed out by ISO 3382-1, it seems clear that rooms with high absorbtion power return higher values in Definition (like already found in the Clarity evaluation), while reverberant environments present lower values of speech perception and understanding, also due to their volume and shape.

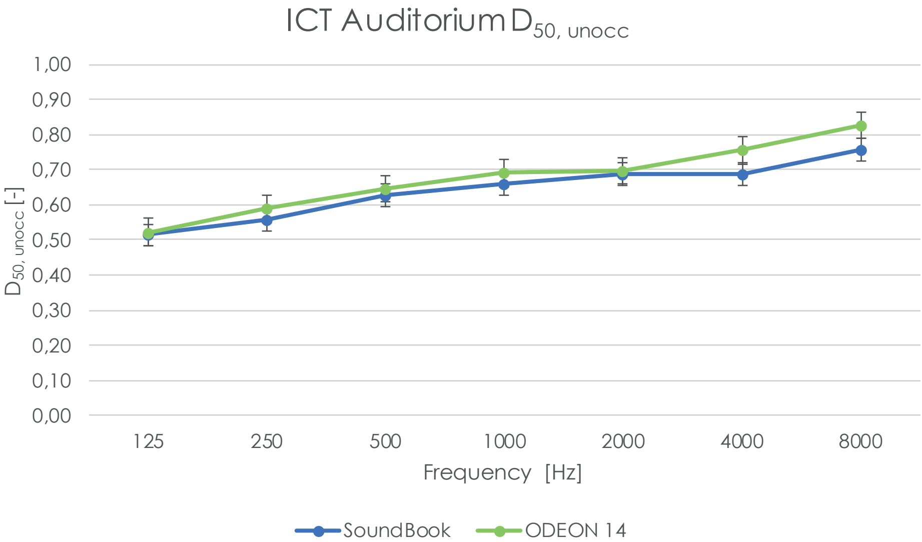
Meeting room	125	250	500	1000	2000	4000	8000
$D_{50, SoundBook}$	0,77	0,88	0,93	0,95	0,92	0,92	0,94
$D_{50, ODEON14}$	0,84	0,90	0,94	0,93	0,92	0,91	0,92



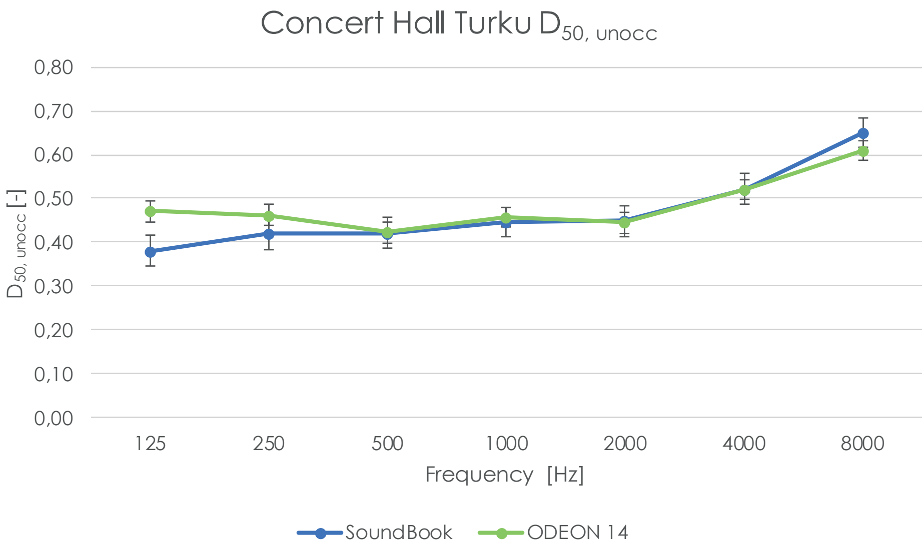
Reverberant room	125	250	500	1000	2000	4000	8000
$D_{50, SoundBook}$	0,37	0,30	0,26	0,26	0,33	0,48	0,61
$D_{50, ODEON14}$	0,34	0,29	0,24	0,24	0,31	0,48	0,64



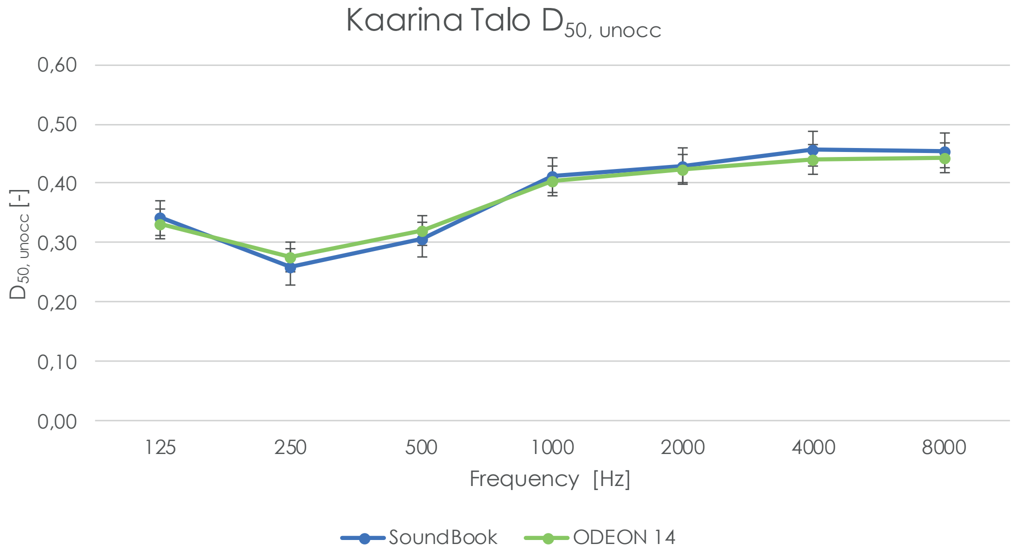
ICT Auditorium	125	250	500	1000	2000	4000	8000
$D_{50,\ SoundBook}$	0,51	0,56	0,63	0,66	0,69	0,69	0,76
$D_{50,\ ODEON14}$	0,52	0,59	0,65	0,69	0,70	0,76	0,83



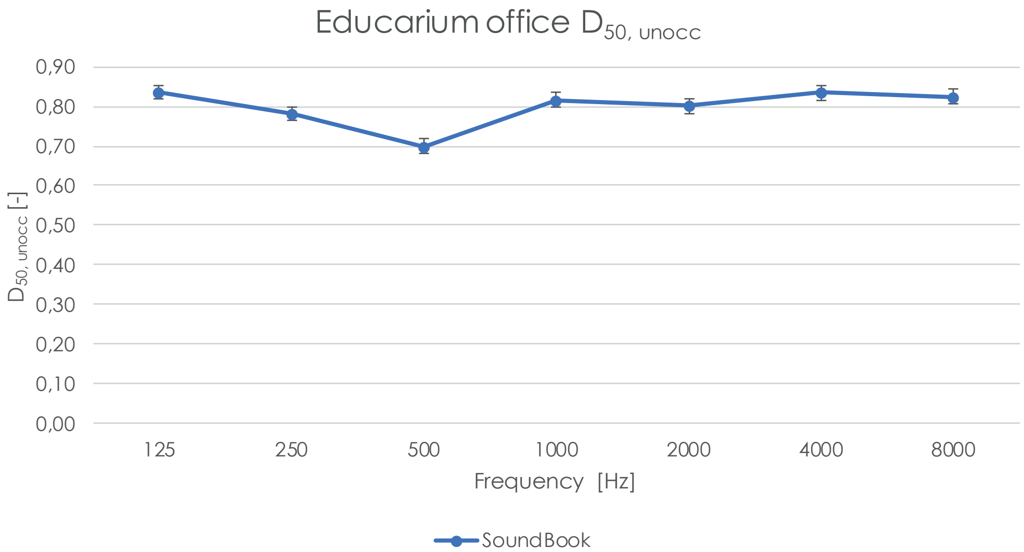
Concert Hall Turku	125	250	500	1000	2000	4000	8000
$D_{50,\ SoundBook}$	0,38	0,42	0,42	0,45	0,45	0,52	0,65
$D_{50,\ ODEON14}$	0,47	0,46	0,42	0,46	0,45	0,52	0,61



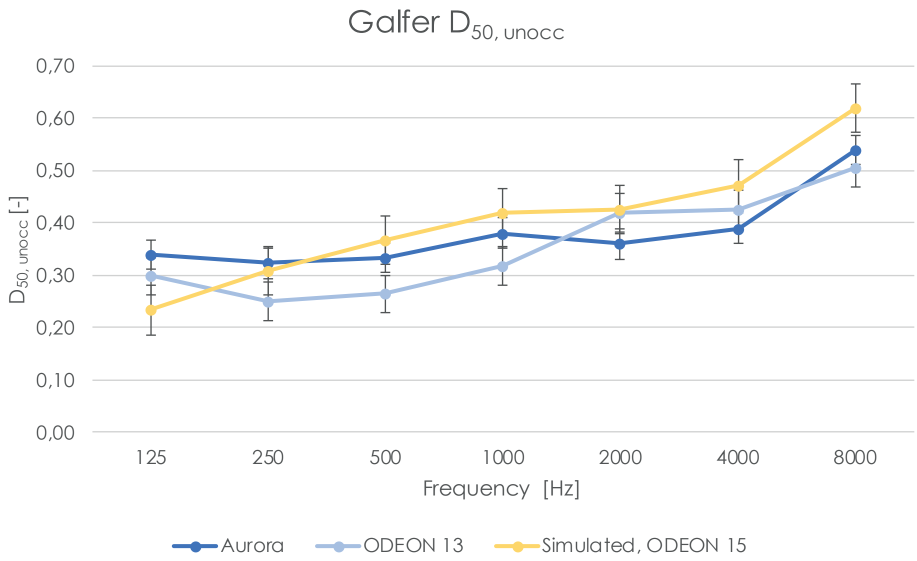
Kaarina Talo Auditorium	125	250	500	1000	2000	4000	8000
$D_{50, SoundBook}$	0,34	0,26	0,31	0,41	0,43	0,46	0,46
$D_{50, ODEON14}$	0,33	0,28	0,32	0,40	0,42	0,44	0,44



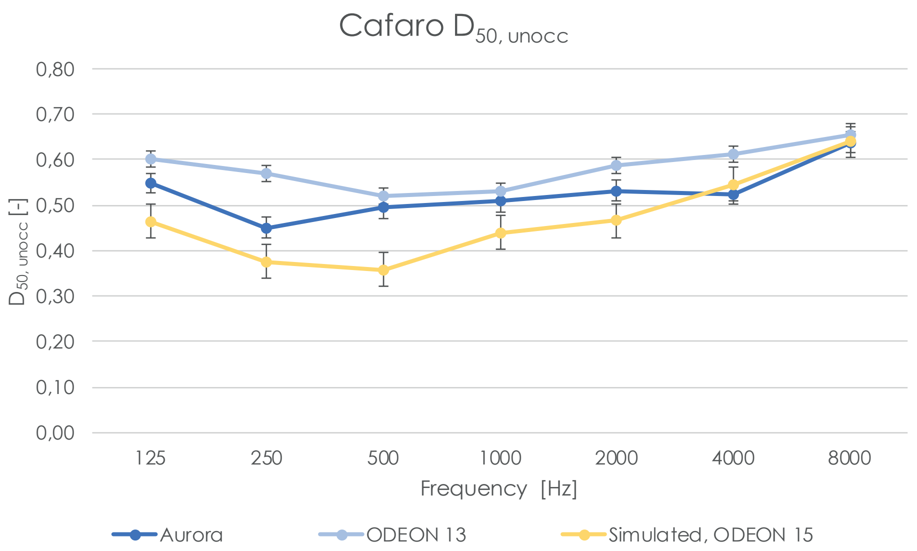
Educarium office	125	250	500	1000	2000	4000	8000
$D_{50, SoundBook}$	0,84	0,78	0,70	0,82	0,80	0,83	0,82



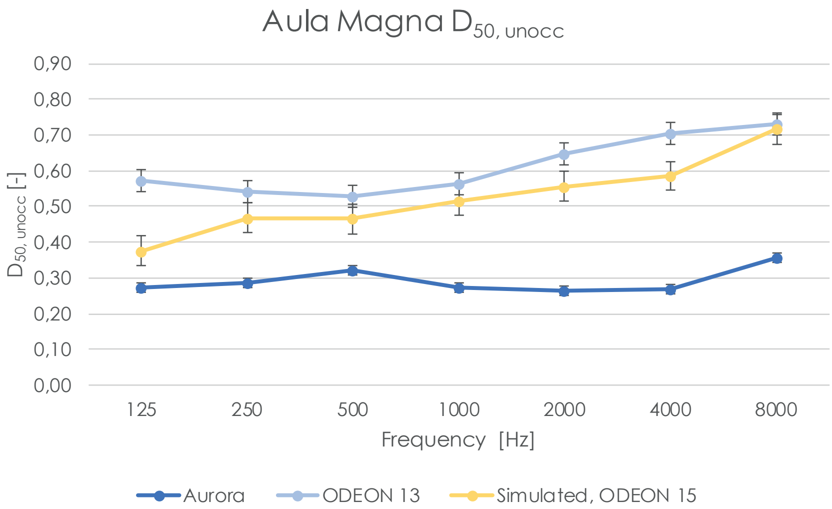
Galfer	125	250	500	1000	2000	4000	8000
$D_{50, Aurora}$	0,34	0,32	0,33	0,38	0,36	0,39	0,54
$D_{50, ODEON13}$	0,30	0,25	0,26	0,32	0,42	0,42	0,50
$D_{50, ODEON15}$	0,23	0,31	0,37	0,42	0,43	0,47	0,62



Cafaro	125	250	500	1000	2000	4000	8000
$D_{50, Aurora}$	0,55	0,45	0,49	0,51	0,53	0,52	0,64
$D_{50, ODEON13}$	0,60	0,57	0,52	0,53	0,59	0,61	0,65
$D_{50, ODEON15}$	0,47	0,38	0,36	0,44	0,47	0,55	0,64

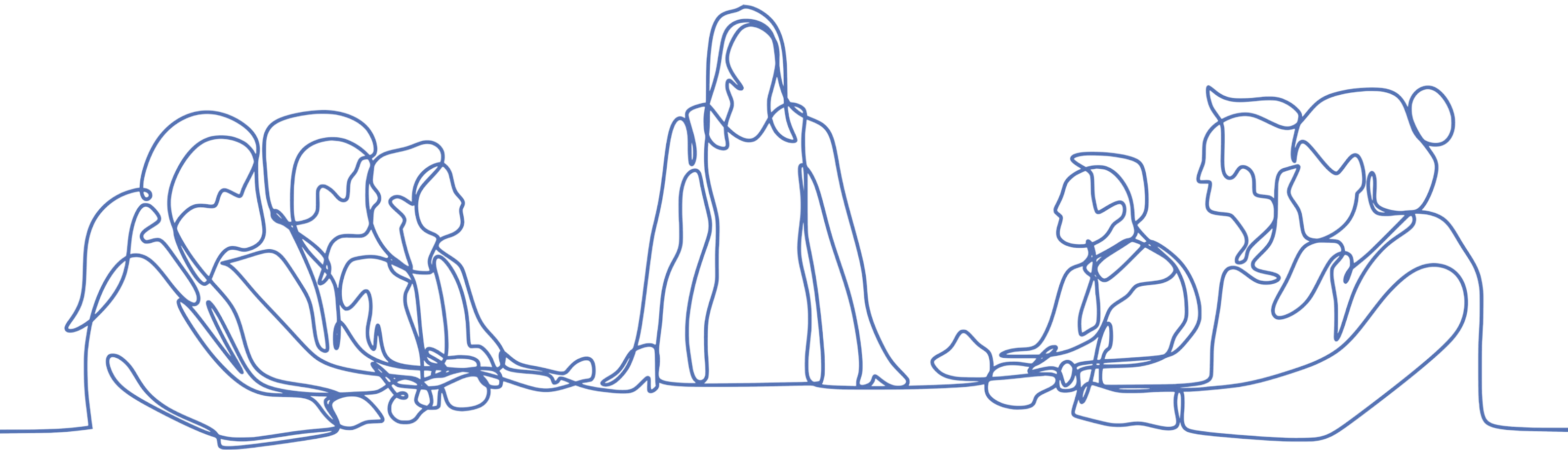


Aula Magna	125	250	500	1000	2000	4000	8000
$D_{50, Aurora}$	0,27	0,29	0,32	0,27	0,26	0,27	0,36
$D_{50, ODEON13}$	0,57	0,54	0,23	0,57	0,65	0,71	0,73
$D_{50, ODEON15}$	0,38	0,47	0,47	0,52	0,56	0,59	0,72



Reading the above-reported graphs it appears clearly how both the Clarity and the Definition parameters, included in the *subjective parameters* list, are strongly depending on the physical and architecturale features of the rooms: the volume, shape, geometry and specially the materials of the surfaces in the rooms affect in a deep way all the speech quality results achieved through measurements or room acoustic simulations and predictions.

In the cases study measured in Torino it is noticeable a difference between the measurements methods, the lines of which present a deep gap in each analyzed room, although the different disposition (situations of underestimation or overestimation by Aurora and ODEON).



7.

INDOOR ACOUSTIC DESIGN

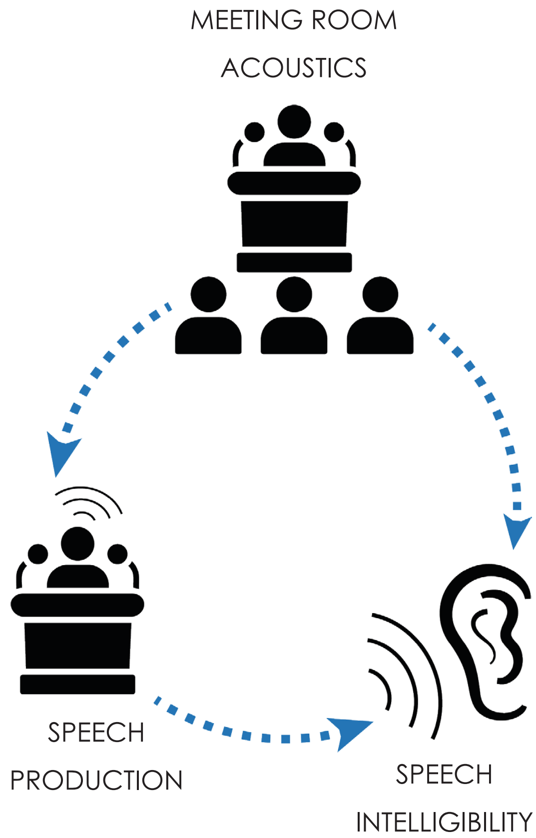
7. INDOOR ACOUSTIC DESIGN

7.1 Acoustic requirements and needs

The conditions for optimal transmission of sound messages in a closed environment, whether it is spoken or music, have been summarized by Sabine in these simple rules:

1. The sound must reach sufficiently intense in all the listening points of the room;
2. The sounds that follow each other with rapid emission must reach the listener clear and distinct maintaining their individuality;
3. The spectral components of a complex sound must maintain their intensity unchanged related.

The reverberation of a room is often controlled by installing sound absorption panels to the ceiling and on the walls. The reduced reverberation is particularly important in open-plan offices to make spaces more pleasant and in auditoria, or performance spaces, to maximize the speech intelligibility.



The main acoustic elements employed in the control of sound fields are sound absorbers, reflective surfaces, and diffusers. The latter two are mainly used to preserve and distribute sound energy, whereas the role of sound absorbers is the reduction of sound levels and control of reverberation

(Springer Handbook of Acoustics, Thomas D. Rossing, 2007).

The effect of diffusers depends on scattering properties, as well as on the position of the source, the receiver and the diffuser (Shtrepi et al., 2016). In addition to prevention of echoes and focusing effects, diffusers can also be used to reduce sound levels and control reverberation. This is because diffusers can be placed strategically to disperse incidence sound energy to areas with greater absorption.

An adequate selection and placement of acoustic elements is essential to achieve optimal acoustic conditions with minimal costs. Optimal conditions are determined by the destination of use of a room.

“Meeting rooms are spaces of communication and therefore acoustic performance is of critical importance (Peters et al., 2019)”: in meeting situations speech intelligibility is the most relevant room acoustic parameter. High speech intelligibility is achieved by increasing signal-to-noise ratio (SNR) and reducing reverberation time.

The former requires reducing noise and increasing speech levels, whereas the latter involves eliminating the late sound reflections, reflected sound arriving at the listeners after 50ms. Early reflections, on the contrary, are beneficial for speech intelligibility as they reinforce direct sound, resulting in an increase in SNR (Bradley et al., 2003).

In the Cucharero, Hanninen and Lokki’s study in 2019, the influence of sound-absorbing material placement was investigated by both performing measurements of sound absorption coefficients in a reverberation room and in a furnished mockup classroom characterized by a considerably lower degree of diffusion.

The purpose of the research, in that case, is to evaluate variations on the main acoustical parameters for speech as the same amount of sound-absorbing material is displaced from the middle of the room to the corners. The results show the worst placing for sound absorbers that should be avoided to achieve target acoustic conditions with the minimum amount of sound-absorbing material (Cucharero et al, 2019).

7.2 Influence of the sound absorbing and diffuser panels placement on indoor acoustic parameters

When the materials are applied to the walls of the rooms to be treated it is necessary to bear in mind that the alternation between zones absorbent and reflective will improve sound diffusion.

It is good practice to place the material more absorbent towards the back of the room and leaving the part close to the sound sources quite reflective in order to favor reflections towards the public and thus improve the distribution and sound level.

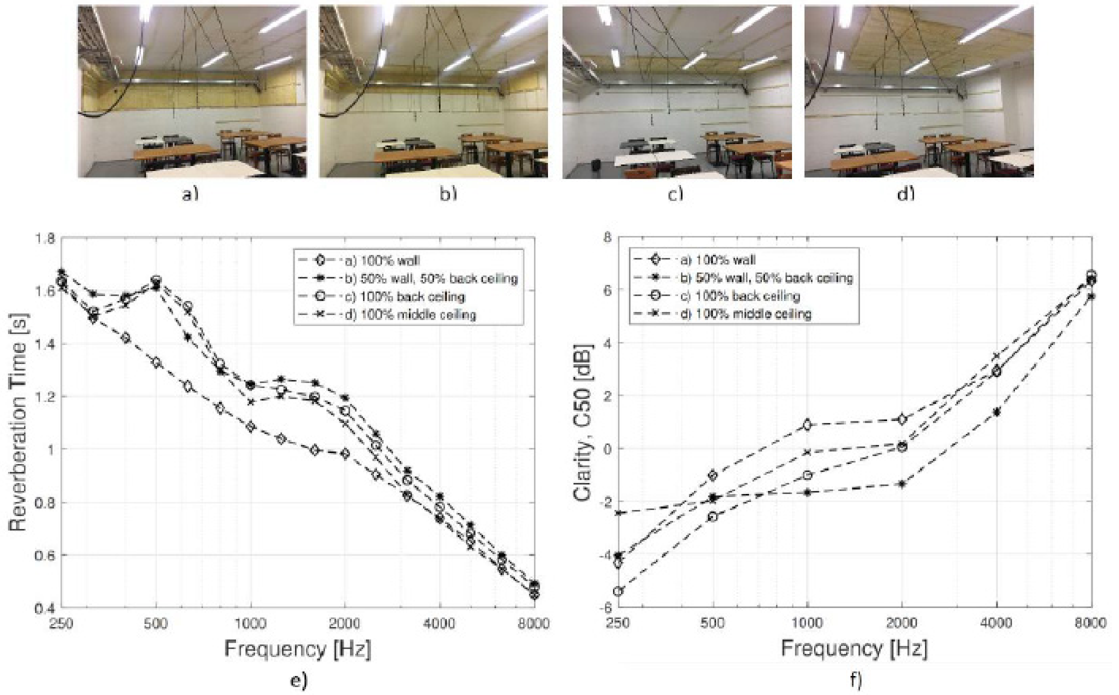
The Cucharero et al. experiment's results demonstrated that corners, followed by any edge between two surfaces of the room, are the less efficient placements in terms of reduction of reverberation time.

The following four arrangements of sound-absorbing materials were tested in the above-mentioned research.

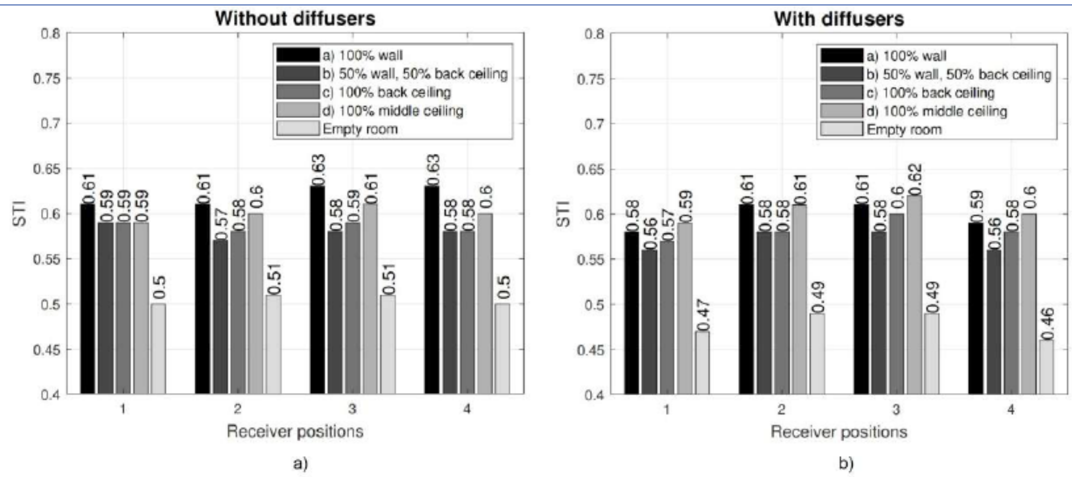
- 100% at the upper part of the rear and back side walls;
- 50% at the upper part of the rear and back side walls and 50% at the back part of the ceiling;
- 100% at the back part of the ceiling;
- 100% at the middle of the ceiling.

These considerations would be detectable to lower frequencies for materials with higher sound absorption at low frequencies, following the trend observed between the two measured materials. The efficiency of porous materials to dissipate sound energy is reduced over 20% when the material is moved from the middle of the room to a corner.

As consequence, placing porous sound absorbers at boundaries of walls and ceiling, particularly at corners, may lead to the use of larger amount of sound-absorbing material to achieve a specific reverberation time. The most efficient material arrangement, in terms of reverberation time (T_{20}) and clarity (C_{50}), is given by the acoustic treatment where 100% of the material is placed at the upper part of the walls (Cucharero et al, 2019).



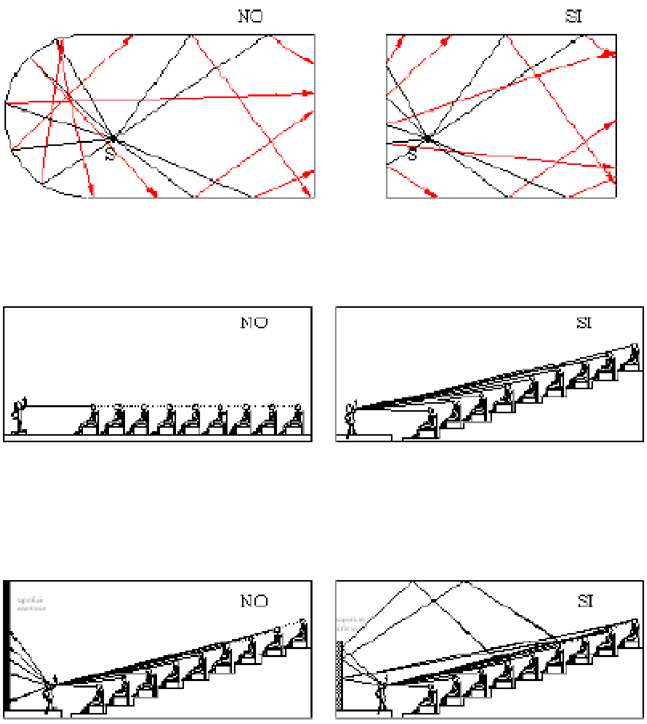
Cucharero et altri's (2019) experiments results and acoustic treatment's materials placements: *Reverberation time* T_{20} (e) and speech *Clarity* C_{50} (f) measurements measured in the mockup classroom with 5 cm glass wool panels distributed at the upper part of the back and side walls (a), at the upper part of side and back walls, and back part of ceiling (b), at the back part of the ceiling (c), and at the middle of the ceiling (d).



STI calculated in four microphone positions in the classroom for four arrangements of sound-absorbing material and for the empty room (no absorbing material inside the room).
(a) No diffusers inside the classroom; (b) Diffusers set in the classroom (Cucharero et al., 2019).

Therefore, according to Moretti's study, an important shrewdness is to avoid covering any surfaces with sound-absorbing panels: materials constitute useful reflectors for a good listening such as the wall listening behind the source, in case of a room intended for the dissemination of speech (classroom school or conference room). Indeed, the reflected sound will be little delayed compared to the direct sound and will help to raise the useful sound level.

Regarding the rear wall of the room, it should not send the sound in the same direction of the source, to avoid dangerous echoes if the room is large and however undesirable effects of interference with the direct sound. If this wall is reflective it must be re-inserted in order to send the sound back to the last places in the room, or it has to be covered with absorbent and diffusing material (Moretti, 2011).

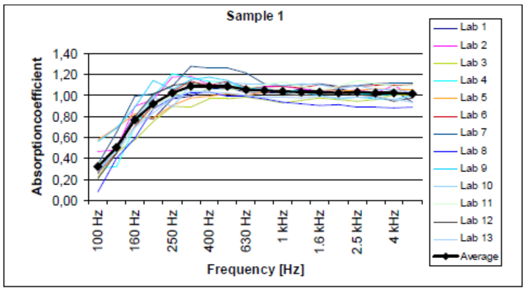


Moretti's (2011) suggestions for acoustic design and treatment of an auditorium, basing on its shape and geometry: Room shape and absorption characteristics and acoustic reflection of the walls, considering the main architectural features.

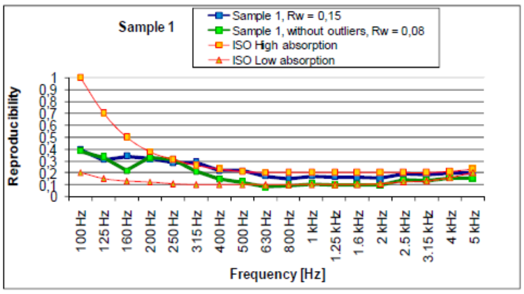
In Vercammen's 2010 experiment, the accuracy of sound absorption measurement, according to ISO 354, was investigated: sound absorption measurements of building materials, such as suspended ceilings and other products, are performed in a reverberation chamber according to the above-mentioned standard. It is known that the inter laboratory reproducibility of these measurements is not very well: the differences of results between laboratories are much larger than can be accepted, e.g. from a jurisdictional viewpoint in case of building contracts and liability. Actions should be taken to reduce the spread. Due to the insufficient diffuse sound field in a reverberation chamber with the test sample, the shape of the reverberation room and the placing of diffusers will influence the result.
A round robin research containing 13 laboratories is performed to get information on the spread and if it is possible to reduce this by correcting for the mean free path or by application of a reference material. It is not clear how to determine the 'right' absorption coefficient. The conclusions of this research reveal that:

- The measured sound absorption of a high absorbing material is larger than 1,0, both for the lower frequency range, where this can be attributed to the edge effect, as for the higher frequencies.
- The Reproducibility of the absorption measurement is rather poor.
- A limited number of 'outliers' is responsible for this Reproducibility.

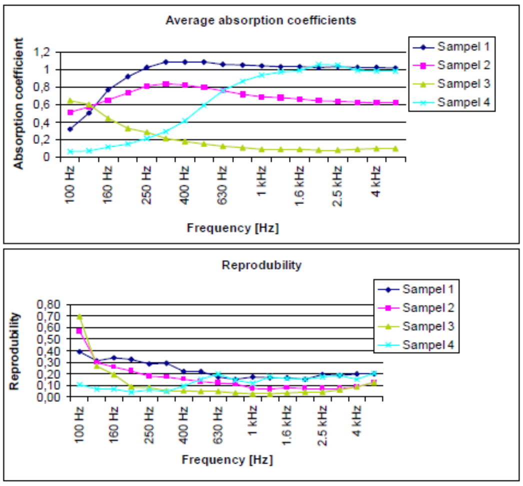
The use of volume diffusers instead of free suspended diffusers may create a more defined situation, the volume of the diffusers can be subtracted from the volume of the room and applying these on the walls may give a better diffuse field situation (Vercammen, 2010).



Vercammen's (2010) results from the Round Robin Test experiment carried out: Measurement results of the sound absorption in 13 labs. The black solid line gives the average result.



Reproducibility of sample 1. Experiments involving 13 labs (blue line) and for 9 labs (green line).
Also indicated are the indications for the Reproducibility of a high and a low absorptive sample.



Average measured absorption (upper graph) and Reproducibility (lower graph) of sample 1 to 4.

When using a standard absorber the average result may be used as a reference for correcting measurement results of other samples, based on the difference of the measured absorption of the reference absorber and the average absorption of this absorber. The results of sample 1 will be used as reference absorber, to correct the measurement results of sample 2 and 4.

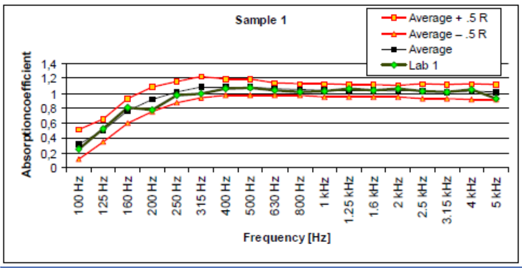
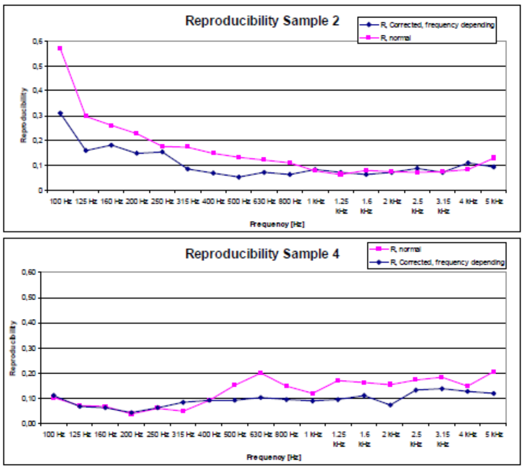


Illustration of the average and spread (±½R) of sample 1 and the indvidual result of one laboratory (green).



The effect of correcting for the reference absorber (sample 1) on the Repoducibility of sample 2 (upper graph) and sample 4 (lower graph).

Since acoustic diffusers and absorbers are important components in room acoustic design and treatment to control unwanted reflections or to increase sound diffusiveness (both of which may enhance subjectively perceived sound quality) a research in this field was carried out by Sanavi et al., in Dubendorf's Federal Laboratories for Material Science and Technology. To date, little is known about whether the treatment with diffusers or absorbers is more favorable for the subjectively perceived qualities. The aim of the study was twofold: the first purpose was to investigate the effect of an acoustic diffuser on the subjectively perceived quality of speech in a meeting room; the second point was to determine if and in which measure there are perceptual differences if the used diffuser is replaced by an acoustic absorber.

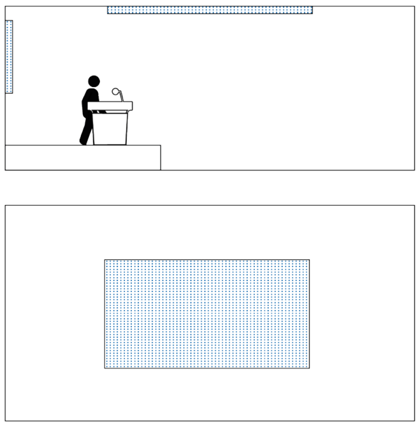
The results, after two listening tests carried out, confirmed that, despite the already excellent speech intelligibility and low values of the early decay time, speech quality can be further improved by introducing diffusers or acoustic absorbers: that means with respect to the subjectively perceived speech quality the room selected for the experiment equipped with diffusers outperforms the original without diffusers. Indeed, diffusers are a remedial measure to control flutter echoes, while uniformly dispersing the energy to improve the quality spoken speech. The perception of the investigated transmission path of the room equipped with absorbers is better than the same room equipped with the specific diffusers, with absorbers improving the subjectively perceived speech quality slightly more than the diffusers (Sanavi et al., 2017). The described research leads to a fundamental and very useful fact for the acoustic design of a meeting room, like the case study of the Cafaro room in Politecnico di Torino: the use of absorbers reduces diffuseness.

By using acoustic absorbers, indeed, the unwanted reflections are substantially suppressed and do no longer contribute, positively or negatively. This fact seems to enhance the rating of quality when it is compared with the quality provided by diffusers.

In the specific design measures pointed out by DIN 18041: 2004-05 standard, there are some sound absorptive surfaces calculations, based on the reverberation theory, for different volume rooms: the type and extent of the sound absorptive surfaces to be installed in existing rooms where acoustic improvements are required, the actual reverberation times should be measured in accordance with UNI EN ISO 3382, as the basis for planning. Such measurements can also be used for checking the effectiveness of the measures carried out.

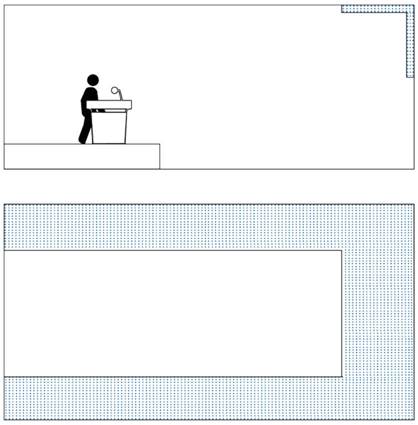
As a rule, the absorptive surfaces should be distributed evenly throughout the room: the size of the absorption surface can be predicted referring to the DIN 18041: 2004-05, where the required additional sound absorption surface area in m2, in rooms having low sound absorption furnishings and with linoleum floor (no sound absorbing covering), is estimated basing on the volume of the evaluated room. For rooms having an about 250 m3 volume, a sound absorption surface area of 34 m2 is corresponded. As a rule, textile floor coverings absorb sound only at high frequencies and are not sufficient as the sole measure to improve room acoustics.

Sound absorbers which are primarily effective in the low frequency range are particularly effective near the sound source and in corners or angles of the room. To avoid the risk of disturbing flutter echoes in spaces having a rectangular ground plan and the walls are plane and not interrupted by furniture, a central sound reflecting area in the ceilings is recommended: the walls are to be partially sound absorptive, as compensation.

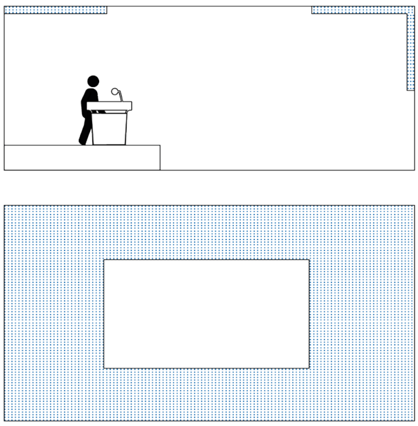


A. Unfavourable absorber panels position (DIN 18041: 2004-2005).

A ceiling with a fully sound absorptive surface can be used in combination with a similarly sound absorptive rear wall.



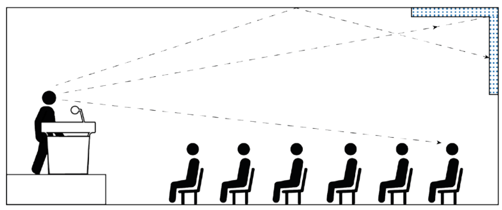
B. Favourable absorber panels position (DIN 18041: 2004-2005).



C. Favourable absorber panels position (DIN 18041: 2004-2005).

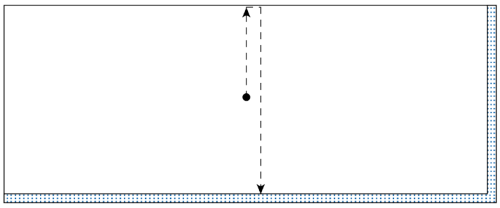
The proportions of larger rooms are less critical even at low frequencies because of the higher density of natural frequencies. Wall surfaces that are parallel to each other and untreated are just as unfavourable as concave curved or angled surfaces, which in areas occupied by people (or, possibly, microphone positions) can lead to flutter echoes or focusing of the sound.

In rooms with a length of more than about 9 m, time-delayed sound components can be deflected from the rear wall into the front area of the room, either directly or via angle reflections. This leads to a reduction in the level of speech intelligibility. In this case the sound reflecting surfaces shall either be covered with a sound absorptive material.



Direct sound and early reflection paths with absorber panels positioned in the ceilings and corner of the room (DIN 18041: 2004-2005).

In case of parallel surfaces at least one of the opposing surfaces shall be sound absorptive or sectioned. This works in particular way in larger rooms that do not have tiered seating. An inclination of the surfaces by at least 5° is also favourable.



Sound reflection paths in rooms with parallel walls: one of those must be treated with absorber panels, to avoid flutter-echoes phenomena (DIN 18041: 2004-2005).

The above reported situation avoids flutter echoes in the room and disturbing late sound reflections. A suitable arrangement and alignment of reflecting surface areas is needed to amplify beneficial sound at larger distances, also improving speech intelligibility. The wall behind the speaker should be sound absorptive at low frequencies. The central part of the ceiling, from which the first reflections reach listeners, should be sound-reflecting in the medium and high frequency ranges, and configured as a low frequency sound absorber.
A slight use of absorbent materials can lead to "tonal unbalance" is necessary instead try to balance the sound levels reflected at different frequencies. This is achieved by putting in operates different materials in order to obtain the same number of absorbent units in the different bands of the sound spectrum (DIN 18041: 2004-05).

There is also a need to be able to quantify how sound is reflected from a surface, in terms of how it is spatially dispersed. In recent years, diffusion and scattering coefficients have been developed to enable room acoustic prediction models to be more accurate, and designers to evaluate the worth of diffusing surfaces.
The development of the modern diffuser can be traced back to the 1970s and Schroeder's revolutionary designs that try to achieve diffuse reflection. The invention of Schroeder diffusers coincided with the development of small room design concepts, involving temporal reflection free and diffuse zones.
Temporal reflection free zones around the listening position are created by absorbing or diffusing the first order reflections. Diffusers are used on the rear wall to provide uniform, enveloping diffuse reflections,

creating passive surround sound. The use of diffusers can reduce coloration effects due to strong early reflections that naturally occur in small rooms. For this reason, there is widespread use of Schroeder diffusers in small critical listening environments.

The recent frequent use of diffusers appears to be a reaction to the dominant mid-late twentieth century architectural forms. Sometimes this can cause problems of coloration and echoes, which can be corrected by absorbers or diffusers.

When a designer requires absorbing surfaces in a space, a performance specification in terms of the absorption coefficient will be used to ensure quality and compliance with design requirements. One of the aims of research into diffusion coefficients was to facilitate the use of defined scattering ability in performance specifications; this can now be done by specifying diffusions coefficients measured or predicted, according to AES-4id-2001. It appears that diffusing surfaces are often applied in a haphazard fashion because there is an incomplete understanding of when and where to apply diffusers.

According to the interpretation of the polar distribution of the scattered sound is not necessarily useful, since the details of the distribution, the lobes and nulls, are spatially smeared with incoherent excitation. Instead, an adequate quantity for describing broadband scattering on rough surfaces is a scattering coefficient.

The scattering coefficient is defined as the ratio of the non-specularly reflected sound energy to the totally reflected energy. The coefficient is used to decide whether a reflection is diffuse or specular in a room model. The diffuse reflection's spatial distribution may then be Lambert's law, or any other distribution depending on the energy balance between specular and scattered parts and on the angle of incidence. In this sense, the scattering coefficient has the same importance as the absorption coefficient. Like the absorption coefficient, the scattering coefficient varies with frequency and so is given in one-third octave or octave frequency bands (Cox et al, 2006).

In this research's Odeon simulation case, the scattering coefficient is used as input, given to relevant diffusor materials taking from reference values listed in literature.

The *diffusion coefficient* is intended to be a measure of quality, as the primary goal in developing the coefficient was to enable the worth of surfaces to be determined. This is then a single number which gauges the uniformity of the polar response. If the same energy is scattered in all directions, then the diffusion coefficient is one; this is termed complete diffusion. If all the energy is scattered in one direction, then the diffusion coefficient is zero. The diffusion coefficient is evaluated in one-third octave bands and is frequency dependent.

Comparisons between diffusion and the scattering coefficients have rarely been undertaken; they have been developed in relative isolation. Comparisons are hindered because by definition many surfaces that could be tested using the diffusion coefficient cannot be tested using the scattering coefficient and vice versa. Scattering coefficients give a quick and rough estimate of the scattering process, they should not be used to evaluate the worth of surfaces when designing or specifying diffusers.

The scattering coefficient, *s*, is only concerned with how much energy is moved from the specular direction, it does not measure the quality of dispersion. For this reason, diffusing surfaces need to be evaluated using the diffusion coefficient when quality is being assessed (Cox et al, 2006).

In other words, a diffusion coefficient measures the similarity between the scatter polar response and a reference uniform distribution. A diffusor that scatters sound uniformly in all directions will have a diffusion coefficient of 1. When the scattered level is concentrated in one angular location (even if different from the specular direction), the diffusion coefficient approaches zero.

On the other hand, the scattering coefficient is a measure of the amount of sound scattered away from a particular direction or distribution. If s=0, then a pure specular reflection takes place; however, if s=1, then all reflected power is scattered according to some kind of “ideal” diffusivity. One weakness of the definition is that it does not say how the directional distribution of the scattered power is; even if s=1 the directional distribution

could be very uneven. This coefficient has the greatest similarity to the coefficients required as inputs to geometric acoustic models (Inacio, 2005).
As simplification, according to Astolfi (2017), a surface is defined as diffusing when the scattering coefficient *s* is ≥ 0,5.

7.3 Acoustically designed rooms: before and after the treatment

The acoustical characteristics of the surfaces of a room, described by the mentioned coefficients, can be used in an appropriate combination in order to beneficiate a specific acoustical application. For example, for concert halls and auditoria where high reverberation times are expected, there is a more need for specular and diffuse reflections than sound absorption. However, rooms for cinema or recording studios require a high degree of sound absorption combined with some diffuse reflections. When noise control is the problem, then the emphasis is most entirely given to sound absorption (Inacio, 2005).
The process characterizing the acoustic design of the Cafaro meeting room in Politecnico di Torino was then divided in phases:

1. Characterization of the current state through a campaign of measurements of the main acoustic descriptors of the room (Reverberation Time, Definition Indices, Clarity, Background Noise Level);
2. Calculation of the required equivalent absorption area to add;
3. Planning of interventions;
4. Simulations of the project status (using Odeon 15), in order to predict the acoustic state after the realization of the acoustic corrections;
5. Verification measures of the main acoustic descriptors of the room (Reverberation Time, Definition Indices, Clarity, Background Noise Level) after completion of the work.

Before
The first step to move to apply an acoustic design and treatment to a measured room is calculating its **optimal reverberation time** values, on frequency.
This parameter is defined as the value

of the reverberation time that combines the two good opposing requirements intelligibility and sufficient level of intensity, expressed in seconds. It must assume, depending on the listening conditions, a value that offers the best compromise due to the influence of the reverberated sound field on the quality of the listening.
Values for listening to speech are found of T_{60} shorter, all other conditions being equal, than for the rooms intended for the performance of music programs. The shortest values of T60 are found in the rooms where the direct sound comes privileged compared to the reverberated one.
The optimal value of T_{60} grows slightly with increasing room volume, for a given destination of use. This intuitively corresponds to the fact that, as the volume of the room increases, a slight deterioration of intelligibility in favor of the sound level is accepted, together with the subjective feeling of greater vastness of the environment that is spontaneously associated to a longer sound tail.

Method

In real rooms the reverberant field is only approximately diffuse, with reflections arriving from several directions with a similar pattern in most of the audience positions. Usually, the degree of diffusiveness depends on the homogeneity of distribution of absorption surfaces into the room.
The received sound in a room can be divided into three components: *direct sound, early reflections and late reverberant sound*.
The first reflections include limits depending on the size of the room: this part of the received sound presents higher values as the room size increases (Inacio, 2005).

In **Galfer and Cafaro meeting rooms'** acoustic design, the optimal reverberation time was calculated in order to understand how the treated room's reverberation time values should appear after applying absorbent and diffusing panels.
The calculation was made using the method suggested in the UNI 11532 standard (2019), referring to rooms having a volume included between 30-5000 m^3 range and are designed as interaction rooms: indeed, the Cafaro meeting room is about 298 m^3.

The following equation, referred to rooms occupied for 80% of their volumes and for class A3 in the standard classification, is used. The A3 category, in the UNI 11532 standard, refers to interaction rooms having a volume included between 30 and 5000m^3.
It represents a function of the room volume, leading to calculate the optimal reverberation time at the central frequency of 1000 Hz:

$$T_{60,ott,A3} = (0,32 \log V - 0,17)\ [s]$$

(UNI 11532)

Where V points out the global volume of the room.
The empirical achieved value of optimal reverberation time is equal to 0,63 s. In order to obtain the on-frequency values (expressed in the octave bands range of 125-4000 Hz), a further equation is applied, involving both the absorption a-dimensional coefficients of the surfaces (α, walls and chosen panels) and the equivalent absorption area of the people (A), expressed in m^2.

	125	250	500	1.000	2.000	4.000
α_{pers}	0,10	0,15	0,20	0,25	0,25	0,25
A_{pers}	0,90	1,36	1,81	2,26	2,26	2,26

Absorption coefficients used for people.

These equivalent absorption area values were obtained considering a total surface of 9,04m2 for people occupying the room, calculated from a chair's area multiplied with the number of these latter.
The method used to calculate the optimal reverberation time in the unoccupied room is found in the same UNI 11532, where a graph showing the curves (the first one for the room used for speech, the second for sports hall) of T60, ott is presented calculated between 500 and 1000 Hz. The above-mentioned global value of 0,63 in this frequency range is found.
A further equation is then applied in order to obtain the reverberation times for unoccupied room conditions:

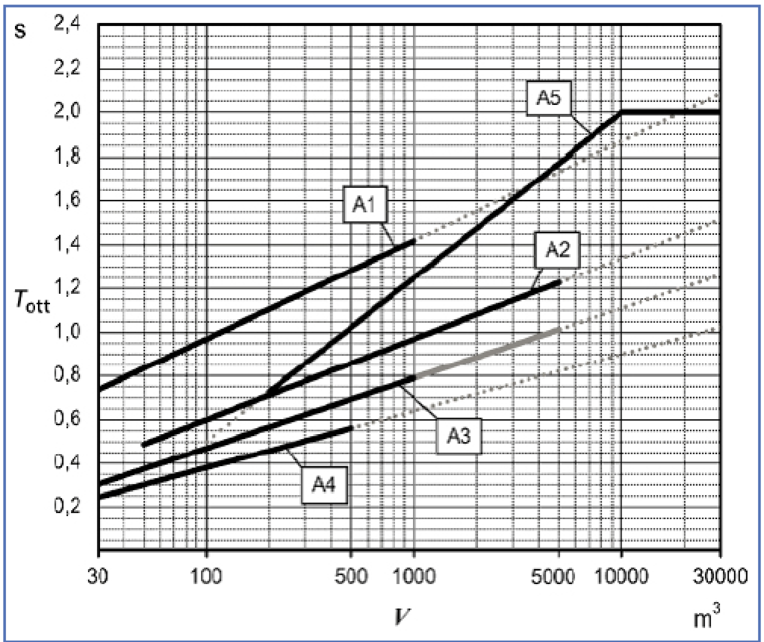
$$T_{unocc} = \frac{T_{occ}}{1 - T_{occ}\dfrac{A_{pers}}{0,16}V}\ [s]$$

(UNI 11532)

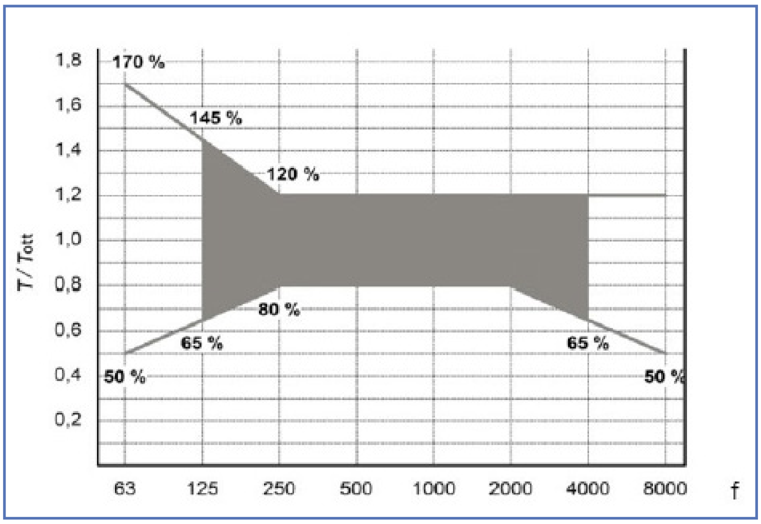
The results of this last equation's application are listed in the table below:

	125	250	500	1.000	2.000
T_{unocc} [s]	0,63	0,63	0,64	0,64	0,64

Optimal reverberation time values with coefficients applied, for each octave band in the 125-4000 Hz range, unoccupied room.



UNI 11532: Dependence of the Optimal Reverberation Time T_{ott} from the volume and the mode of use. In this research the class A3 is considered, including *teachers' rooms and similar* environments.



UNI 11532: Target range for Optimal Reverberation Time, as a function of frequency for the categories from A1 to A4. The graph shows how the range of tolerance, that extends within 0,8 and 1,2s in the mid-frequency range of 125-2000 Hz, becomes wider for low and high frequencies, including even higher values than 1,2 at low frequencies (63-125 Hz).

Calculating an average between these reverberation times, a similar-to the predicted global value is achieved. They are then used as a reference for the further 3D simulations with the acoustic panels applied.

The acoustic correction chosen in the Cafaro meeting room case study is applied in too reverberant environment condition: the reverberation time is indeed higher than the optimal one. This is the most common case, in which absorbent units must be added. The choice, in order to achieve better speech understanding and perception, is to include both absorbent and hybrid (absorbent + diffusing) panels. The needed surface of such panels was calculated using the equation reported below:

$$S_{panels} = \frac{A_{tot,ott} - A_{tot,1}}{\alpha_{panels} - \alpha_{plaster}} \; [m^2]$$

Once found the global surface of treating panels necessary, appears easy to calculate the number of panels, dividing the m2 achieved values for the area of one single panel.

After

One way to get the best performance from acoustic panels is by placing in a *staggered* position to the open space on the opposing wall. For example, in case of placing the panels on each wall right across from each other, not as many reflective paths are eliminated as would happen if the panels were inserted with an offset of one panel on the other (or "*checkerboard*").

The use of acoustic diffuser panels, combined with the absorption ones, is very useful for the general indoor environment acoustic perception.

Well-designed Acoustic Diffusers, indeed, spread the sound over the entire three-dimensional space in front of themselves. In the acoustic sound graph, the arcs of the diffused field generated should be homogeneous, because the variations from a homogeneous arc bring variations and fluctuations in volume. The goal of diffusion is to *redistribute* the sounds of medium and high frequencies uniformly throughout the space without absorbing them; therefore, the aim is to obtain a diffuser panel whose reflections at the various frequencies (indicated by the polar diagram) are:

A. as homogeneous as possible and without focused lobes in the

graph;
B. all showing the same shape at different frequencies: this feature indicates that the panel is providing a uniform diffusion at all frequencies.
A method similar-to Peters, Hoban, Yu and Xian's experiment was used: in their research they firstly aimed to improve the acoustic performance of their case study rectangular meeting room, designing new architectural surface geometries. a meeting room was measured before and after the installation of acoustic surfaces and the final results were compared to simulation, taken with Odeon room acoustics simulation system.
According to Sanavi et al.'s research, absorbers and diffuser panels were applied in strategic way: "to control unwanted reflections, diffusers are not the only solution. An alternative approach could be to use acoustic absorbers".
Absorption panels act on part of the acoustic energy of the incident sound. In relatively small spaces, like the Cafaro and Galfer meeting rooms, absorbers form a possible solution to control echoes. The rear wall, opposite to the speaker, works better if the sound is absorbed, avoiding diffusers in order to exclude disturbing reflections of the arriving late sound; the wall behind the orator should instead left untreated, because excessive absorption causes difficulties in speaking and a too heavy vocal effort: using absorber panels, a reduction in the whole environment sound's diffuseness is caused (Sanavi et al., 2017). The lateral walls shall be in the most part reflective, in order to encourage speech coming from the sound source and let the audience listen in a homogeneous way.
Regarding the ceilings' treatment, according to Astolfi and Shtrepi (2017) the best position to place absorbers is along the internal perimeter of the room, leaving the central part untreated and reflective: in this way the sound energy is centered in the middle of the room and let both early and late reflections reach the listeners' ears, form the first to the furthest row of chairs.
A combination of diffusers and absorbers is usually recommended, as a treatment, in small volume rooms where reflections between parallel walls may cause colouration and

flutter-echoes: in these spaces the first reflections are the main source of sound colouration.

In the projects carried out in this research, two studied parameters were used as assessment meters to evaluate the acoustic quality of the designed indoor environments:

- the **Reverberation Time (T_{20})**;
- the **Speech Transmission Index (STI)**.

The first parameter, Reverberation Time, expressed in seconds and extrapolated in 20ms, was already seen and analyzed in the measurements' phase, as a main tool of evaluation for the acoustic quality of the rooms.

The **STI** is an a-dimensional coefficient, called **Speech Transmission Index**. It is "a metric ranging between 0 and 1, representing the transmission quality of speech with respect to intelligibility by a speech transmission channel". With the expression *speech intelligibility* the reference is to the rating of the proportion of speech that is undestood by listeners, from a speaker (IEC 60268-16, 2011).

The STI concept is based on the empirical finding that the fluctuations in speech signals carry the most relevant information relating to speech intelligibility. These fluctiations, while speaking, result from the acoustic separation of sentences, words and phonemes, which are the fundamental elements in the speech: indeed, they (termed *modulations*) can be quantified as a function of modulation frequency *F*, producing the whole spectrum.

As a typical range reference, according to the specific STI standard IEC 60268-16-2011, for clear speech the modulation frequencies typically extend from 0,5Hz up to 16Hz, with maximum modulation at around 3Hz.

The parameters analyzed in this part of the research, dedicated to the acoustic design of interactions and presentation rooms, are significant in terms of acoustic features evaluation, because in the carried out simulations made in Odeon 15 they return an objective feedback of the sound and speech perception and understanding.

In the end, the above-mentioned part of the research outlined a design workflow, useful for architects and engineers to design better sounding, more performing and pleasant meeting rooms (Peters et al., 2019).

Examples between STI qualification bands and typical applications

In the below-reported table a qualification in STI classes is reported, referring to the Annex E of the EN IEC 60268-16 standard, specific for the STI parameter. In the Annex G of the standard just the categories were listed, mentioned with an alphabet capital letter, while in this reference table also examples of the type of message, of typical applications and STI comments are described, in order to help distinguish each case of usage (EN IEC 60268-16, 2011(E)).
The STI is always calculated by the ODEON software considering the background noise levels, previously measured with a sound level meter. This helps to obtain more reliable values of the parameter, strongly depending also on the materials that the indoor environment in case presents.

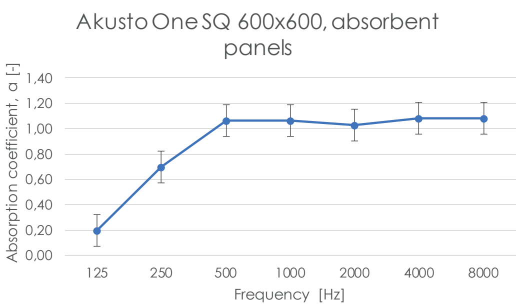
Table G.1 – Examples between STI qualification bands and typical applications

Category	Nominal STI value	Type of message information	Examples of typical uses (for natural or reproduced voice)	Comment
A+	>0,76		Recording studios	Excellent intelligibility but rarely achievable in most environments
A	0,74	Complex messages, unfamiliar words	Theatres, speech auditoria, parliaments, courts, Assistive Hearing Systems (AHS)	High speech intelligibility
B	0,7	Complex messages, unfamiliar words		
C	0,66	Complex messages, unfamiliar words	Theatres, speech auditoria, teleconferencing, parliaments, courts	High speech intelligibility
D	0,62	Complex messages, familiar words	Lecture theatres, classrooms, concert halls	Good speech intelligibility
E	0,58	Complex messages, familiar context	Concert halls, modern churches	High quality PA systems
F	0,54	Complex messages, familiar context	PA systems in shopping malls, public buildings' offices, VA systems, cathedrals	Good quality PA systems
G	0,5	Complex messages, familiar context	Shopping malls, public buildings' offices, VA systems	Target value for VA systems
H	0,46	Simple messages, familiar words	VA and PA systems in difficult acoustic environments	Normal lower limit for VA systems
I	0,42	Simple messages, familiar context	VA and PA systems in very difficult spaces	
J	0,38		Not suitable for PA systems	
U	<0,36		Not suitable for PA systems	

Chosen acoustic panels and materials

The proposed solutions were treated using both absorber and diffusive panels: having as a main purpose the absorption of excessive reflective sounds on the environment's surfaces, both design using only absorbers and an alternation of them with hybrid-diffusive panels were realized.

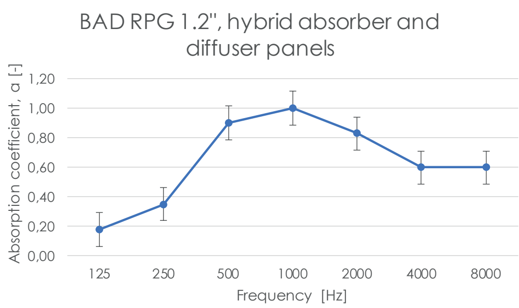
As phonoabsorbers, the **Akusto One SQ** panels by **Ecophon** were chosen: the Politecnico di Torino already had several panels of this kind, previously used for another room's acoustic treatment: this may lead to a money saving in the whole design. Their dimensions cover 60*60cm and the thickness is 4cm: this products result very manageable and can easily be installed on the surfaces, with no need of special tools. These panels absorb more at the mid and high frequencies, in the considered frequency range of 125-8000 Hz.



As a completion of the design, to give better efficacy in acoustics to the room, also diffusive panels were used. The chosen products were the **B.A.D.** hybrid panels by **RPG**: they were applied mostly on the ceilings and the back wall (referring to the directional speaker in the room), in order to encourage the sounds reflections in favorable directions for listeners.

These panels' dimensions are the same standard as the Akusto One SQ (60*60cm, but only 3cm thick), in order to allow a good alternation of the different products and, thanks to their straight edges, they can be easily fit one beside another with no untreated surface left between the panels.

The **Binary Amplitude Diffsorbor (B.A.D.)** panels have a different absorption spectrum from the Akusto One SQ: they are better absorbers of middle frequencies, while in the low and high they leave more sound reflections act.



Galfer meeting room Acoustic Design

The Galileo Ferraris meeting room, in Lamsa department, is a space use for interaction, meetings and presentations in public.

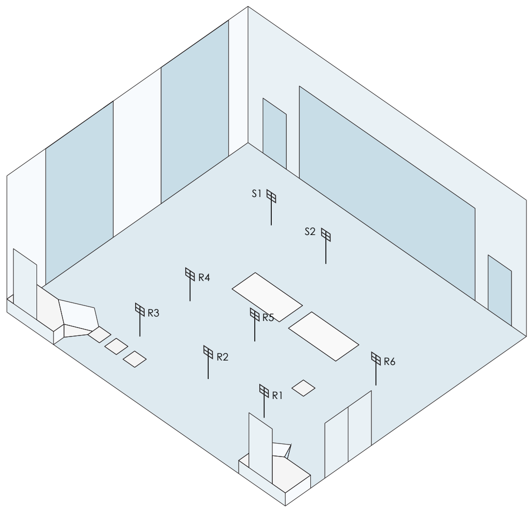
The main acoustic feature of this room is the *coupled-environment* effect: this is mainly due to the back wall (considering a directional speaker as a sound source), built in drywall and presenting a huge screen occupying the most part of the whole wall's area. Just this partition allow sounds to pass also in the adjacent environments, with no insulation of the analyzed meeting room. Sounds can be clearly audible by the offices besides the room, causing distraction and annoyance to employers, and a reverberation effect is noticeable in all the points of the room: this leads to a lack in the acoustic quality of the room, often generating also flutter-echoes phenomena.

In this research, 3 different solutions were studied, considering both the absorption and the diffusivity of the produced sounds, in order to guarantee the best performance to listeners:

1. The first solution foresees **Akusto One SQ panels installed only on the vertical walls**: this experiment was made in order to evaluate the effective influence of the panels' placement in a meeting room, referring to suggestions by DIN 18041: 2004-05 standard;
2. The second idea for acoustic treatment also forsees the application of both **Akusto One SQ absorbers and BAD diffusers just on the walls of the room**, leaving the ceilings untreated: differently from the first solution, this experience was realized exploiting a functional combination of absorber and diffusive panels, alternating them side by side. The main purpose was to compare this model to the previous and understand the way the sounds perception is influenced by the diffusive materials positioning in a room;
3. A third alternative is proposed: the **Akusto One SQ absorber panels** are fit on the room's walls, while the **BAD hybrid-diffusive materials** are positioned on the

ceilings. This situation aims to evaluate how the different panels act if placed in separate positions.

All the solutions are designed referring to the calculated Galfer's Oprimal Reverberation Time ($T_{60,ott}$), according to UNI 11532 standard's method and typical range, expressed in seconds: its values on frequency are reported below, considering frequencies within 125 and 8000 Hz.



f [Hz]	125	250	500	1000	2000	4000	8000
T_{60}, ott [s]	0,70	0,71	0,71	0,71	0,71	0,71	0,71

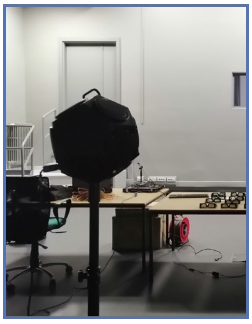
3
Axonometry explosed view of the Galfer meeting room in its *as built* conditions, with no treatment. The positions of speakers (sources, *S*) and microphones (receivers, *R*) used for measurements and in 3D model used in Odeon, for the room acoustic simulations of the design projects, are pointed out.

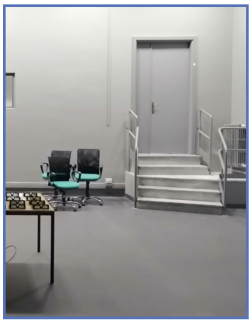
The STI parameter, in each room, is simulated through ODEON 15 room acoustic system: this coefficient leads to a prediction and evaluation of the speech's understanding in the environment.

It's a *single number quantity*, this means that, besides other acoustic parameters dealing to the speech understanding, no frequency vaues can be obtained as results after its calculation or simulation with room acoustic software.

The reported STI vaues in each acoustic design solution is achieved by averaging results from the two sound sources (positioned as shown above, a central loudspeaker and a lateral one, both in the area where usually the human speakers are placed): each source's STI is previously obtained by averaging all the 6 receivers reported in the exploded view at the top of the page. This prediction process is useful to evaluate the Speech Transmission Index in all the points in the room.

Galfer meeting room

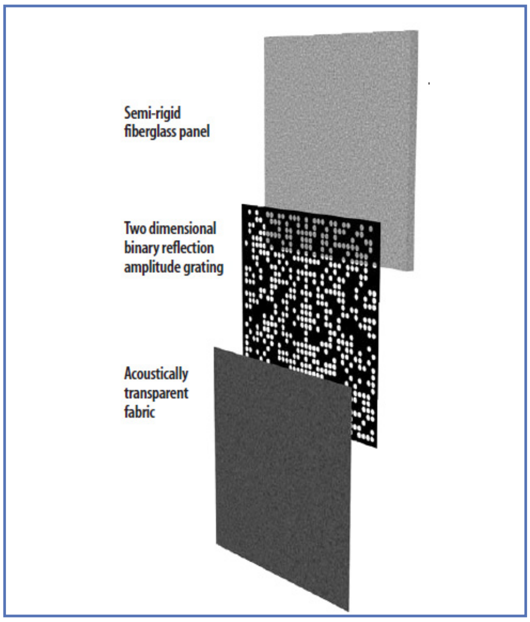




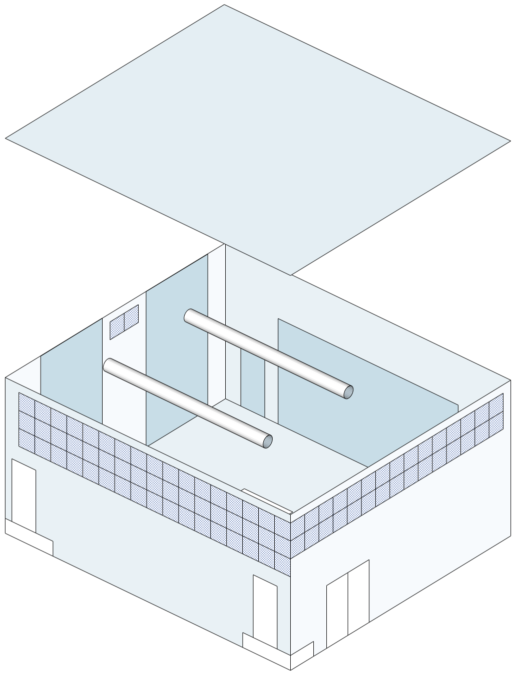
Akusto One SQ, absorber panels

Ecophon Akusto One SQ installed on the walls and ceilings of a treated room: its power in absorption is really high and the sounds in the space appear dry, almost with no reverberation.

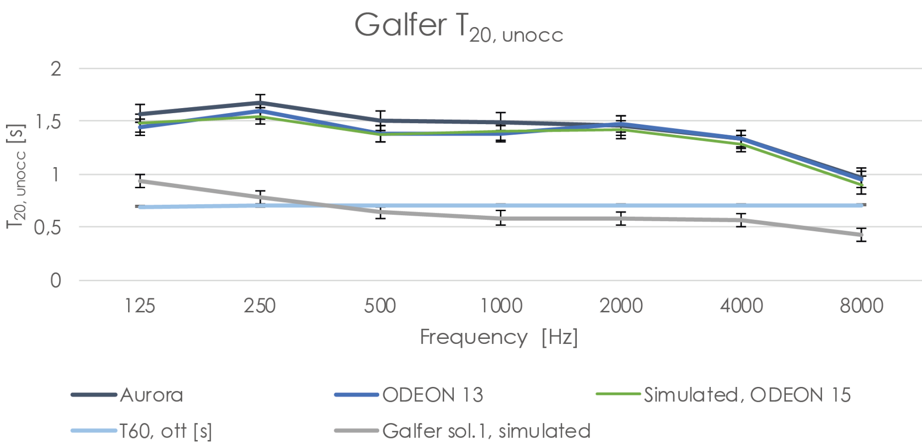
B.A.D hybrid panels, RPG



1. Akusto One SQ absorbers, only on the walls.



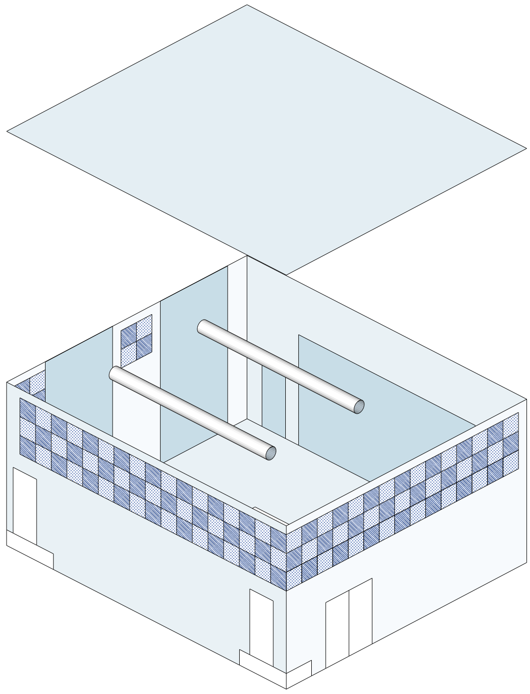
The first solution in the Galileo Ferraris meeting room was realized applying 83 **Akusto One SQ absober panels only on the walls** of the environment. This treatment leads to good results in Reverberation Time, a bit too low (that means too absorbtion in the whole environment) at the middle and high frequencies, referring to the predicted optimal reverberation time ($T_{60,ott}$). The STI is very high: referring to the table in the EN IEC 60268-16 standard, it looks included between the A and B classes (resulting 0,73), good for complex messages in speech auditoria and leading to high speech intelligibility. This is a positive result for the listeners inside the room, while it could be a problem considering the coupled-effect of the Galfer's meeting room, due to the screen on the back wall: it could cause disturbance outside.



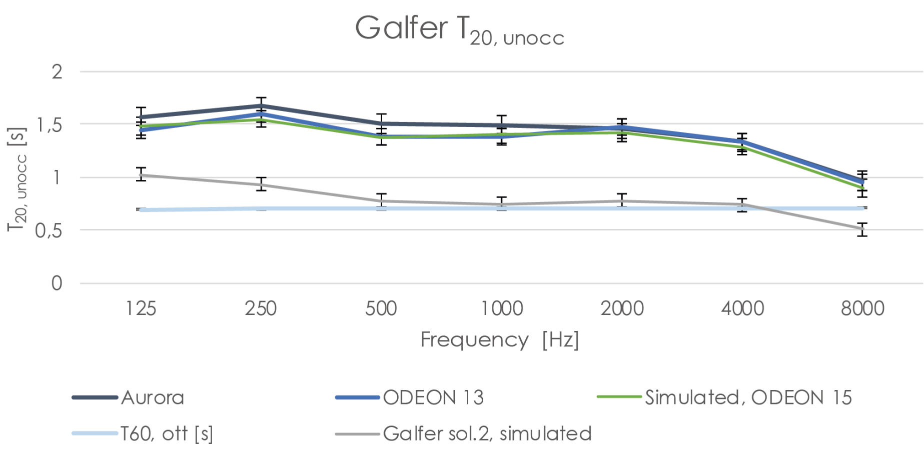
f [Hz]	STI
$T_{20,}$ Av.tot [s]	0,73

f [Hz]	125	250	500	1000	2000	4000	8000
$T_{20,}$ Av.tot [s]	0,94	0,78	0,64	0,59	0,58	0,56	0,43

2. Akusto One SQ absorbers and B.A.D. diffuser panels alternating, only on the walls.



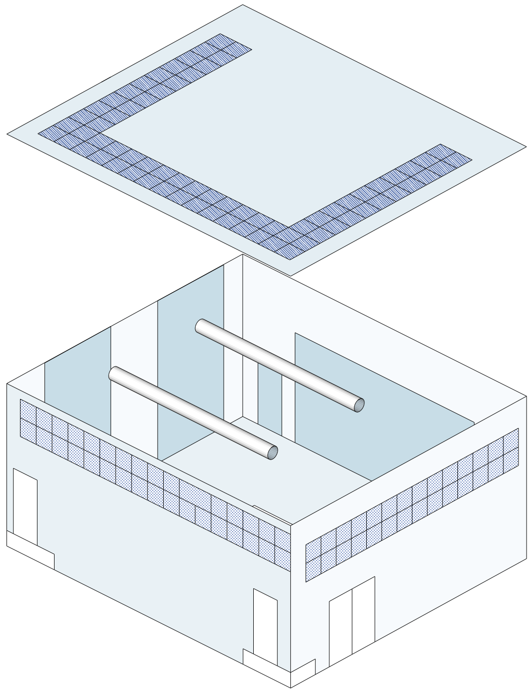
The second solution proposed for the meeting room in Lamsa (Galileo Ferraris) foresees both **absorber Akusto One SQ** and **diffuser BAD panes positioned only on the walls** of the room, leaving the whole ceilings untreated: the total number of used panels is 104. In dots pattern are pointed out the absorber panels, while in oblique hatch pattern are described the hybrid-diffuser materials, both presenting the same squared dimensions of 60*60cm. This solution looks the most suggestable in terms of number of panels (not so high) and resulting Reverberation Time values: indeed they are very close to the Optimal Reverberation Time calculated in the untreated room; the STI general value is lower than the first solution, included in class D of the Annex E table, pointing out good speech intelligibility in complex messages.



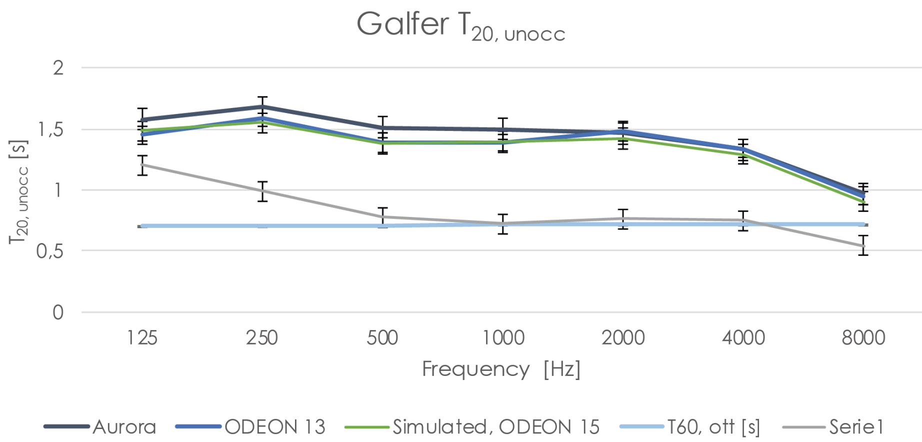
f [Hz]	STI
T_{20}, Av.tot [s]	0,62

f [Hz]	125	250	500	1000	2000	4000	8000
T_{20}, Av.tot [s]	1,03	0,93	0,78	0,75	0,78	0,74	0,51

3. Akusto One SQ absorbers, on the walls; B.A.D. hybrid-diffusive panels on the ceilings.



In the third solution the Akusto One SQ absorbers are applied on the walls, while the B.A.D. diffuser materials are placed on the room's ceilings, for a total number of 136 panels. The configuration was designed referring to DIN 18041:2004-2005 standard's suggestions. It foresees absorbers on the lateral and rear walls (considering the speaker's voice direction), with the back wall left untreated; on the ceilings, just a crown is covered with diffuser panels while the central part remains untreated. Panels in corners and conjunctions were avoided. This design solution shows good values, at middle frequencies, in the Reverberation Time graph, if compared to the calculated optimal reverberation time: at low frequencies the values rise, because in this range both absorber and hybrid panels absorb less. The STI value falls between C e D classes of the EN IEC 60268-16 table in Annex E.



f [Hz]	STI
T_{20}, Av.tot [s]	0,65

f [Hz]	125	250	500	1000	2000	4000	8000
T_{20}, Av.tot [s]	1,20	0,99	0,78	0,72	0,76	0,75	0,54

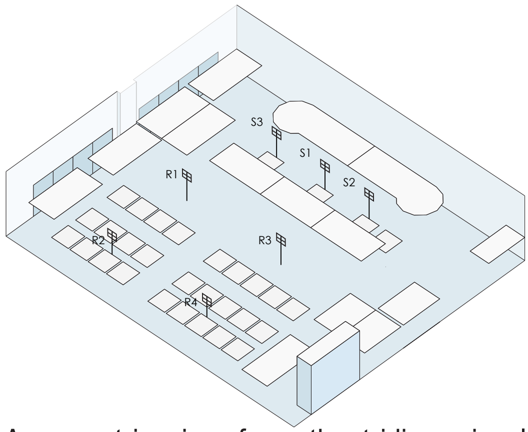
Cafaro meeting room Acoustic Design

In the Politecnico di Torino energy department there's a is a space use for interaction, presentations and PhD discussions in public: the Cafaro meeting room.
The main acoustic feature of this room is the charateristic shape of the ceilings, white painted: the architectural geometry is supported by a reticular woody beam system.
Just this ceilings could lead to high reverberation times and low values in speech intelligibility, because sounds are reflecting on the inclinated surfaces. On the other hand, many big desks, light upholstered chairs and closets are present in the room, partially absorbing sounds energy.
In this research, 3 different solutions were studied, considering both the absorption and the diffusivity of the produced sounds, in order to guarantee the best performance to listeners, avoiding the disturbing flutter echoes phenomena that actually affect the untreated Cafaro room, causing annoyance and disturbance to audience with no clear understanding of the general speeches.

1. The first solution foresees **Akusto One SQ panels installed only on the characteristic ceilings**: this experiment was made in order to evaluate the effective influence of the panels' placement in a meeting room, referring to suggestions by DIN 18041: 2004-05 standard;
2. The second idea for acoustic treatment also forsees the application of both **Akusto One SQ absorbers and BAD diffusers just on the walls and on the ceilings of the room**, where the latter was just covered with absorbers: differently from the first solution, this experience was realized exploiting a functional combination of absorber and diffusive panels, alternating them side by side. The main purpose was to compare the two models and understand the way the sounds perception is influenced by the diffusive materials positioning in a room;
3. A third alternative is proposed: both the **Akusto One SQ absorber panels** and the **BAD hybrid-diffusive materials** are positioned on the walls and ceilings of the room: on the

walls an alternated combination of absorbers and hybrid materials is chosen, while on the ceilings' panels distribution the suggestions of the DIN 18041:2004-2005 were followed, placing the diffusers in the central part of the room's covering and the absorbers in more perimetric position. This situation aims to evaluate how the different panels act if placed in separate positions.

All the solutions are designed referring to the calculated Galfer's Oprimal Reverberation Time ($T_{60,ott}$), according to UNI 11532 standard's method and typical range, expressed in seconds: its values on frequency are reported below, considering frequencies within 125 and 8000 Hz.



Axonometric view from the tridimensional exploded model of the Cafaro meeting room: R numbered positions represent the microphones, set at 1.20m height from the floor;

S numbered positions represent the sources, set at 1.50m height from the floor.

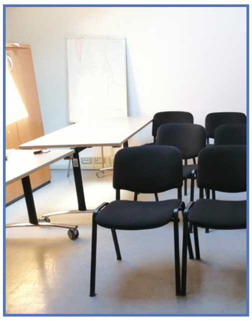
f [Hz]	125	250	500	1000	2000	4000	8000
T60, ott [s]	0,63	0,63	0,64	0,64	0,64	0,64	0,64

The STI parameter, in each room, is simulated through ODEON 15 room acoustic system: it leads to a prediction and evaluation of the speech's understanding in the environment.

It's a *single number quantity*: no frequency vaues can be obtained as results after its calculation or simulation with room acoustic software.

The reported STI vaues in each acoustic design solution is achieved by averaging results from the three sound sources (positioned as shown above, in the area where usually the human speakers are placed): each source's STI is previously obtained by averaging all the 4 receivers reported in the exploded view at the top of the page, to evaluate STI in the whole room.

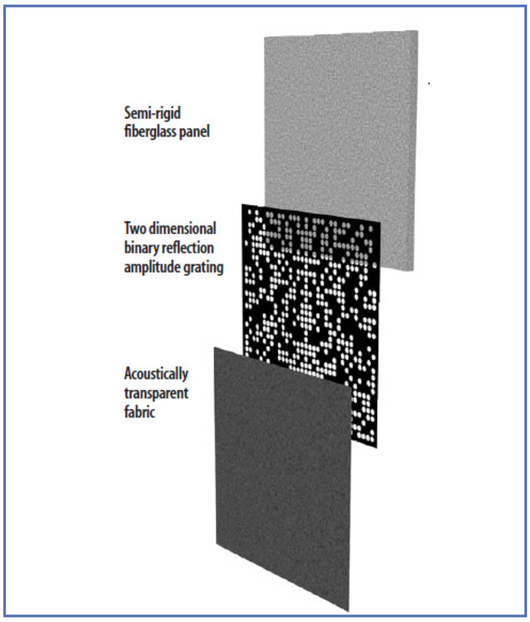
Cafaro meeting room



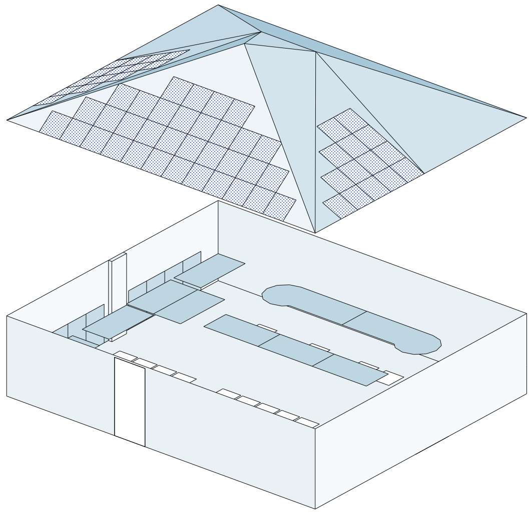
Akusto One SQ, absorber panels

Ecophon Akusto One SQ installed on the walls and ceilings of a treated room: its power in absorption is really high and the sounds in the space appear dry, almost with no reverberation.

B.A.D hybrid panels, RPG

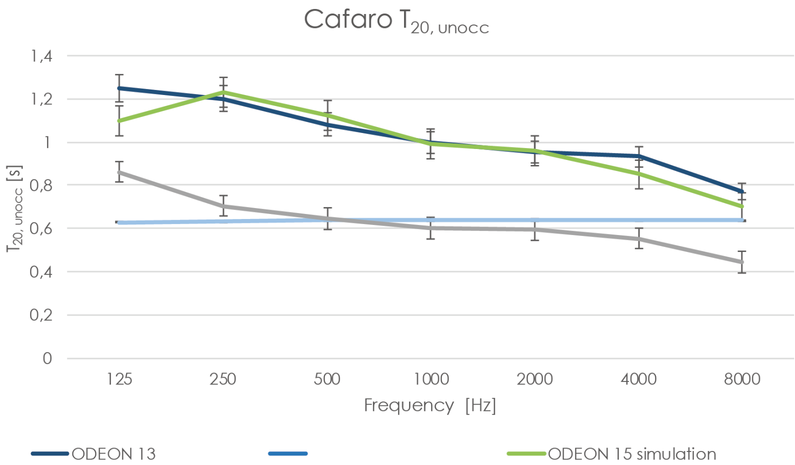


1. Akusto One SQ absorbers, only on the vaulted ceilings.



In the first soliution proposed just **Akusto One SQ absorber panels are placed on the vaulted ceilngs**, leaving the walls untreated, positioning a total number of 62 panels.

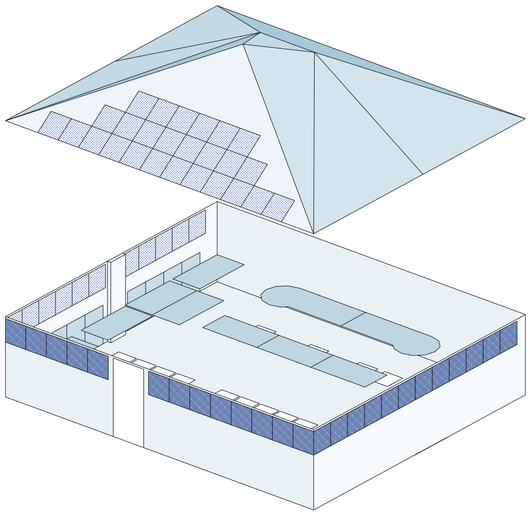
This leads to good values in Reverberation Time, specially at mid frequencies: in general both the low frequencies range and the high are a bit deviating from the line pointed out by the previously calculated Oprimal Reverberation Time. This happens because of the chosen panels: the Akusto squared panels 60*60cm work very well at mid frequencies, absorbing less at low frequencies (causing higher than average values in T_{20}), and more at high frequencies (generating lower than average values). The achieved STI is 0,70: it's included in the class B of the EN IEC 60268-16 table in Annex E, where high speec intelligibility in complex messages, calculated in speech auditoria, are the main features of this index.



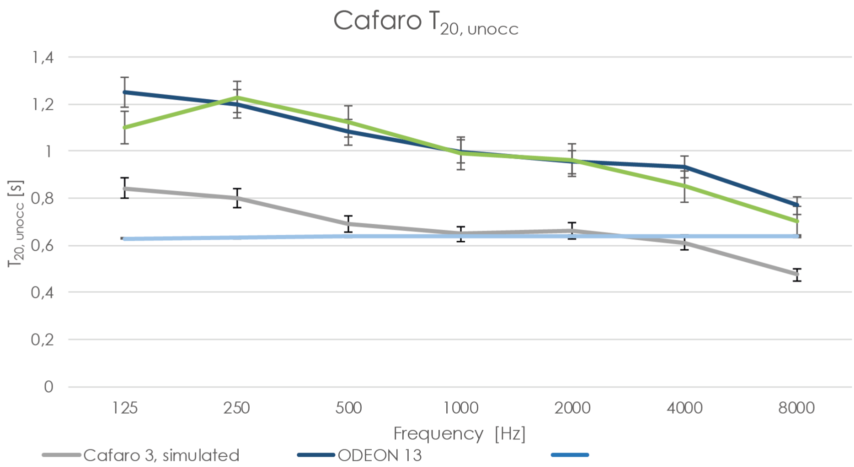
f [Hz]	STI av.
T_{20}, Av.tot [s]	0,70

f [Hz]	125	250	500	1000	2000	4000	8000
T_{20}, Av.tot [s]	0,86	0,70	0,65	0,60	0,60	0,55	0,45

2. Akusto One SQ absorbers and BAD diffuser, combined on both the walls and vaulted ceilings.



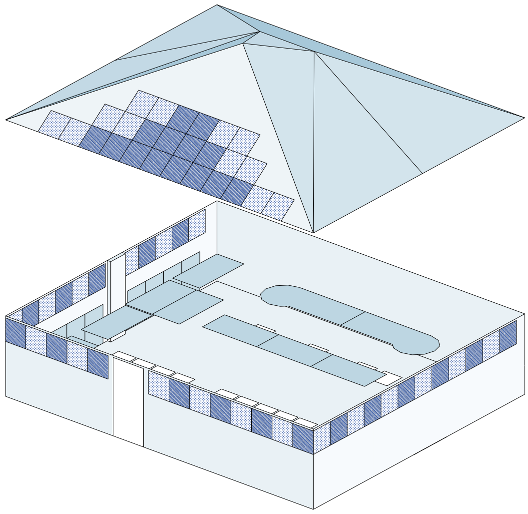
The second solution sees both **Akusto One SQ absorber and BAD hybrid diffuser panels combined in a functional configuration both on the room's walls and ceilings**, for a total number of 62 panels. In this case, the latter surface was covered using just absorbers, while just a row of those is positioned on one side wall in the room. In the rear wall and the other side one are placed BAD diffuser panels. Usually, on the rear walls, installing absorbers is suggested, in order to avoid annoying sound reflections, but here we had hybrid panels (used as diffusers), so the matter is obviated. The T_{20} values are considerable quite good, even if they remain a bit high in low frequencies; and the STI value corresponds to 0,69: it's almost included in the cathegory B, for speech auditoria presenting high speech intelligibility. The quality of the complex messages should be raised by diffusers.



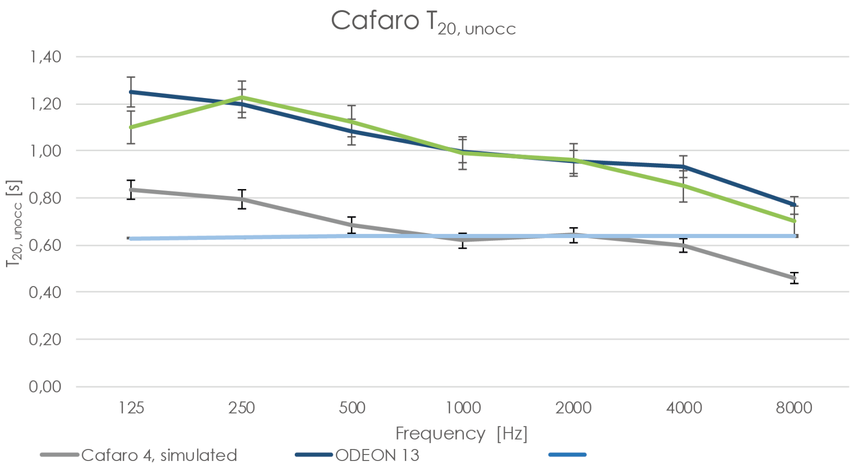
f [Hz]	STI av.
T_{20}, Av.tot [s]	0,69

f [Hz]	125	250	500	1000	2000	4000	8000
T_{20}, Av.tot [s]	0,84	0,80	0,69	0,65	0,66	0,61	0,48

3. Akusto One SQ absorbers and BAD diffusers, alternated configuration on both the walls and vaulted ceilings.



As in previous two solutions, also in the third were placed 62 panels in total, according to the pre-dimensioning calculations. In this third proposed treatment, a functional combination of alterned Akusto One SQ and BAD diffuser panels was exploited, considering the walls, and a faithful application of the DIN 18041:2004-2005 was carried out in the vaulted ceilings, where absorbers were placed on the perimetric area of the surface, while BAD hybrid (diffusers) were concentrated in the central part of the ceilings. This happens to avoid flutter echoes phenomena. The Reverberation Time values appear good in mid frequencies, while they remain a bit high in low frequencies, in the considered range.
The STI is predicted at 0,68: this value is included between the B-C classes, showing high speech intelligibility in conference rooms for complex messages.

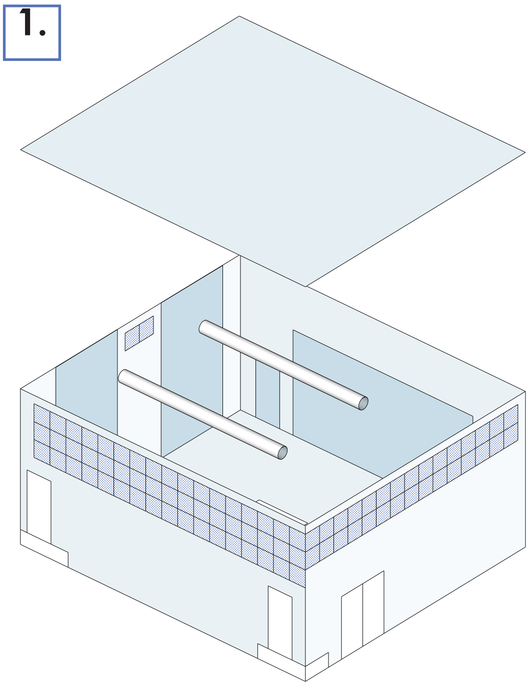


f [Hz]	STI av.
$T_{20,}$ Av.tot [s]	0,68

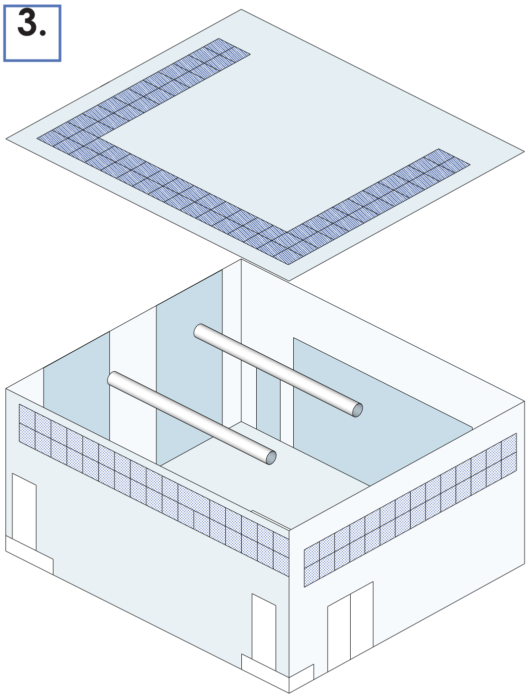
f [Hz]	125	250	500	1000	2000	4000	8000
$T_{20,}$ Av.tot [s]	0,83	0,79	0,69	0,62	0,64	0,60	0,46

Galfer meeting room acoustic solutions: comparison.

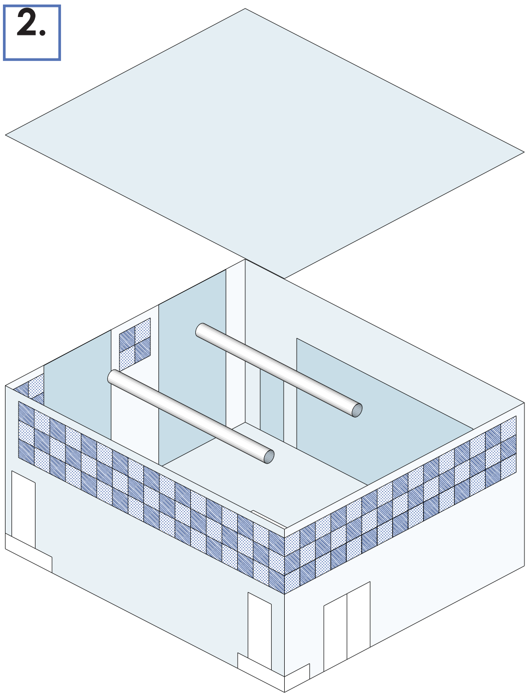
1.

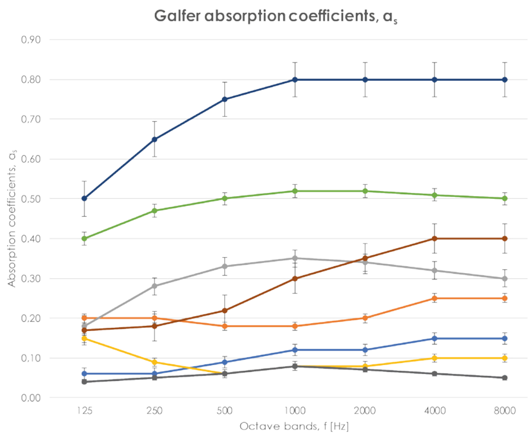


3.



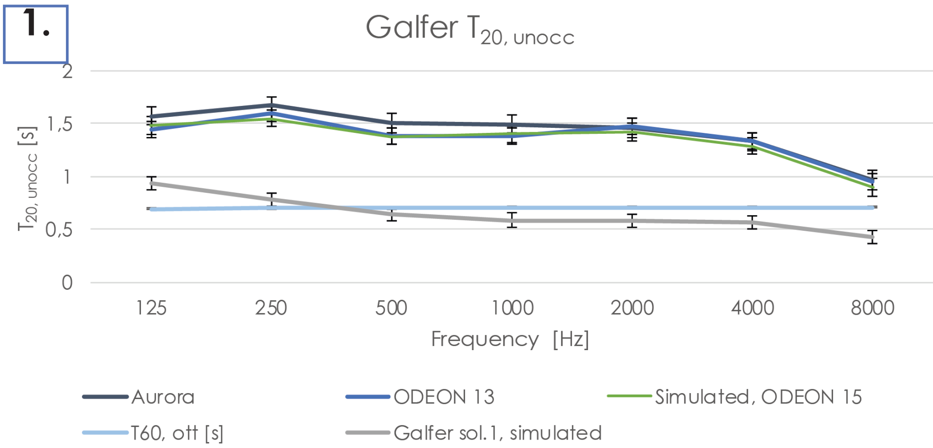
2.





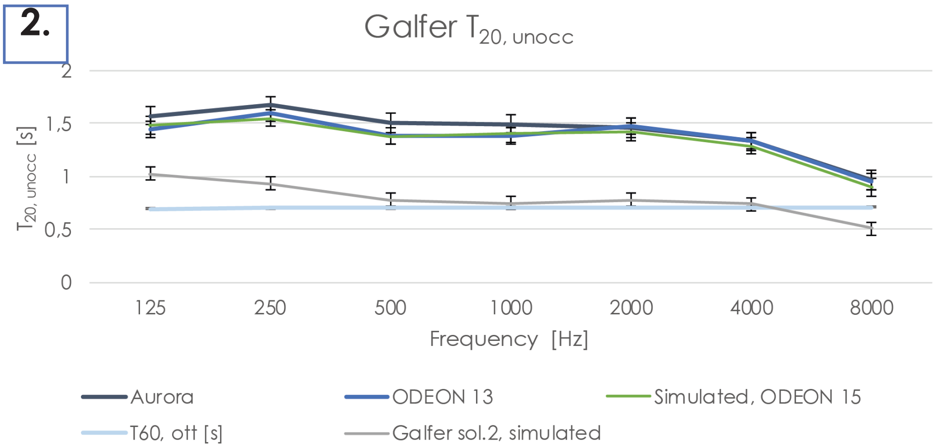
Abacus of the three design solutions proposed for the Galfer meeting room's treatment, with the absorption coefficients used for the rooms surfaces.

1.



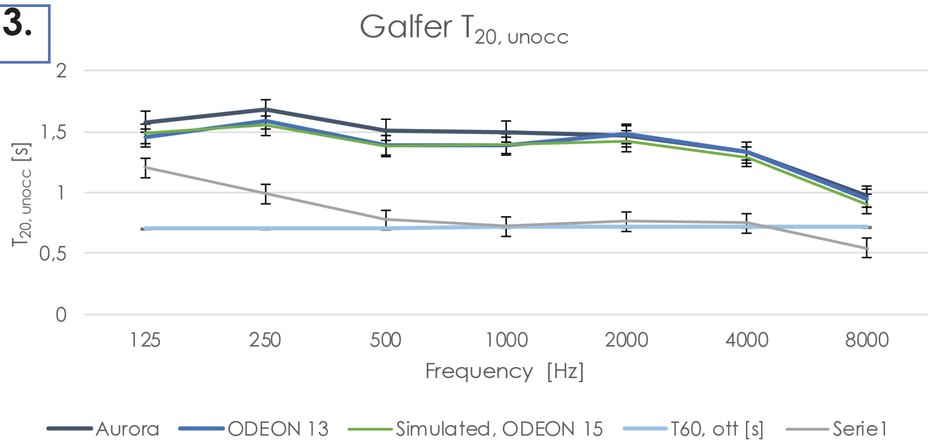
f [Hz]	STI
T_{20}, Av.tot [s]	0,73

2.



f [Hz]	STI
T_{20}, Av.tot [s]	0,62

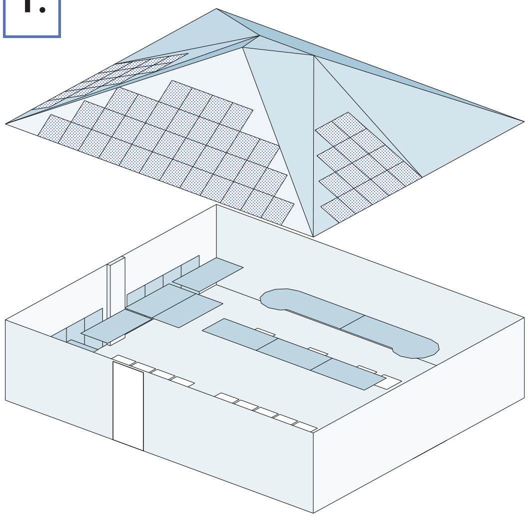
3.



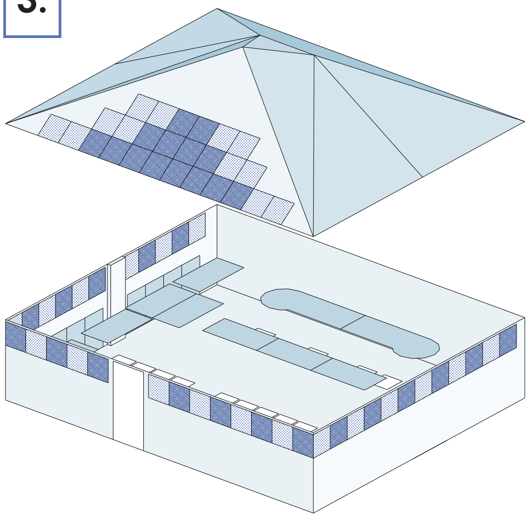
f [Hz]	STI
T_{20}, Av.tot [s]	0,65

Cafaro meeting room acoustic solutions: comparison.

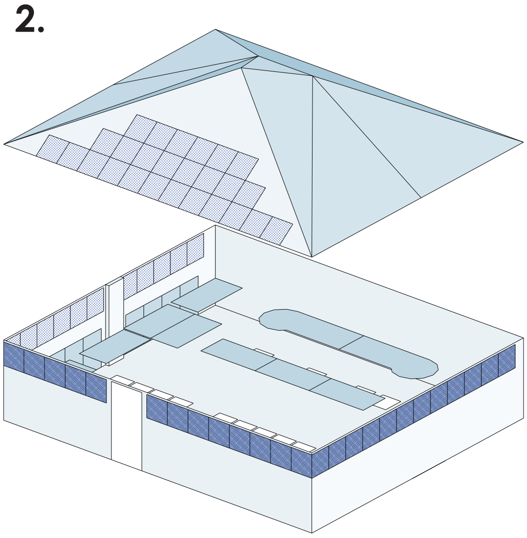
1.

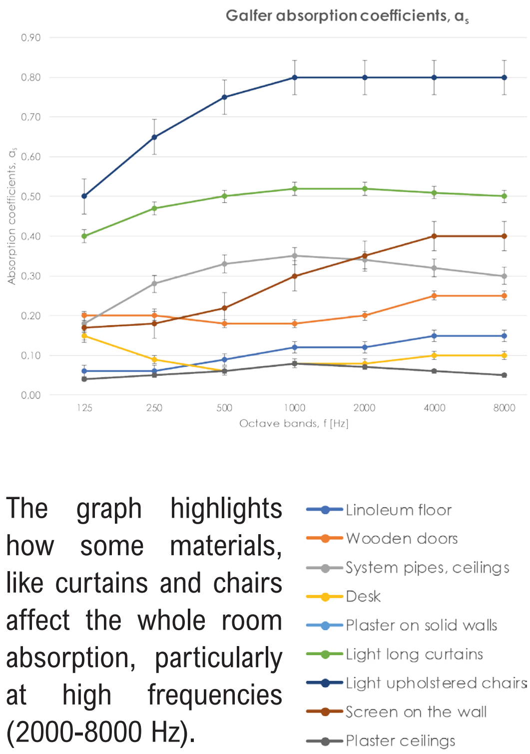


3.



2.

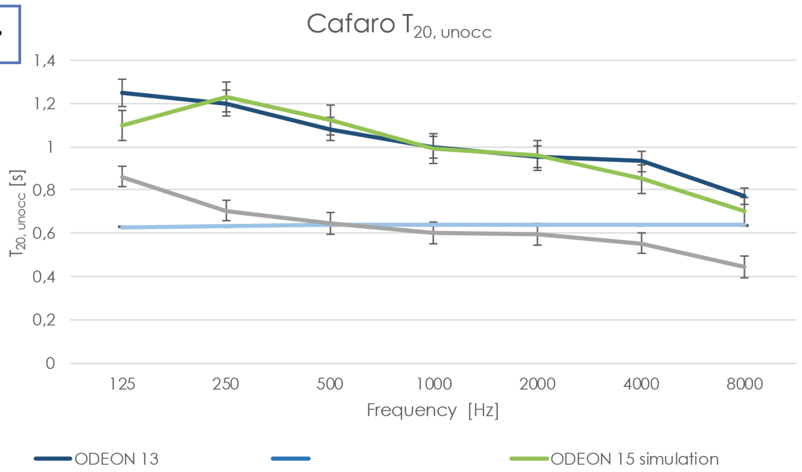




Abacus of the three design solutions proposed for the Cafaro meeting room's acoustic treatment, with the absorption coefficients used in the ODEON 15 auralizations for the existing rooms surfaces in "as built" conditions.

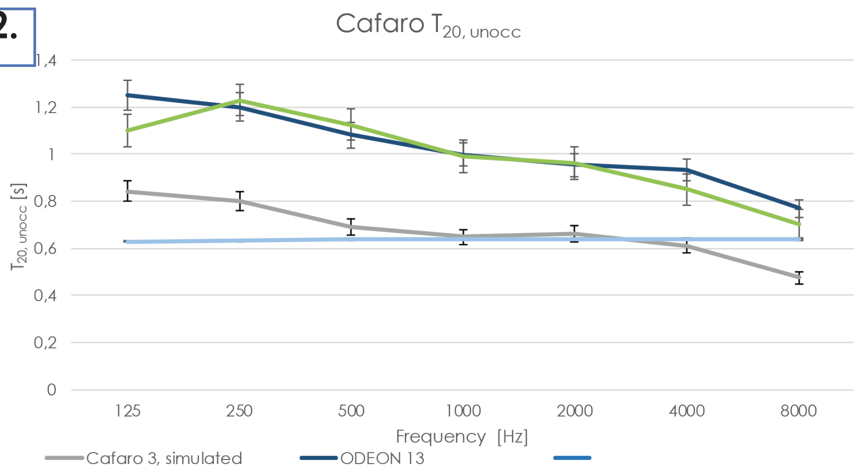
The graph highlights how some materials, like curtains and chairs affect the whole room absorption, particularly at high frequencies (2000-8000 Hz).

1.



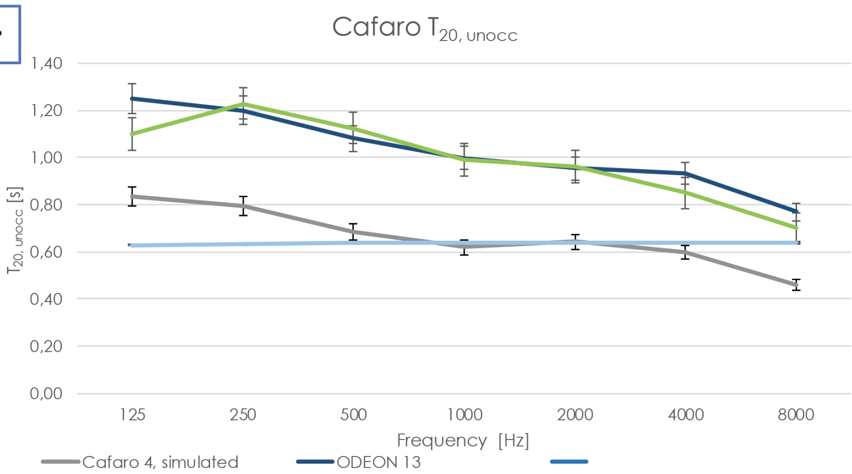
f [Hz]	STI av.
T_{20}, Av.tot [s]	0,70

2.



f [Hz]	STI av.
T_{20}, Av.tot [s]	0,69

3.



f [Hz]	STI av.
T_{20}, Av.tot [s]	0,68

8. CONCLUSIONS

8. CONCLUSIONS

The whole study aims to lead to a proper knowledge and consciousness in the acoustic treatment and possible correction of the interaction rooms, used for public speaking and for professional meetings.
The measurements carried out in **Turku** (Finland) returns good results in each described and measured parameter: both the objective ones (Reverberation Time, Early Decay Time) and the subjective qualities (Clarity, Definition of sound). The reason why this happens is found in the **acoustic correction already applied** in the large majority of the analyzed cases: the positive values though, perfectly included in the tyipical range pointed out by the mentioned literature, do not always mean an effective good perception of sounds produced inside the room. This fact reveals a still unresolved thin shade of difference between the tested results and the subjective perception by listeners.
Anyhow, the measurements taken in the Finnish environments worked as a reference to understand how to place the acoustic treating material in the most efficient way as possible, in order to guarantee the best result with the lowest budget in terms of purcase, application and maintenance costs.
Comparing ODEON and SoundBook's results, it emerged that ODEON's measurements system is perfectly reliable in terms of Reverberation Time, EDT , Clarity and Definition, while it appears weaker in the Sound Pressure Level and Speech Transmission Index evaluation, if an accurate initial calibration is missing. In both of these latter parameters, the levels of background noise measured in the analyzed room are required in order to achieve correct values.

The cases measured in **Torino** (Italy) were still **untreated**: this was an useful point to build a comparison between the Turku's sample, even if the destinations of use were diversified. The confrontation with the previously measured cases returned knowledge about the influence of the sound absorption and diffuser materials placed inside the rooms, allowing to understand which areas are the most affordable to treat in order to ensure,

to the audience, a functional comprehension of the speeches in the indoor environment and to avoid an excessive vocal effort by the speaker.
The further comparison between 3 different methods of room acoustics evaluation (ODEON's measurements system; Aurora, by Adobe Audition; ODEON's auralizations) reveals a general underestimation of the values by ODEON, while Aurora returned, on average, higher results for each measured parameter; the ODEON simulations results appear, in general, more coherent and closer to the values generated by Aurora.
This latter point could also depend on the absorption coefficients applied to each surface present in the room while carrying on the auralizations in ODEON, besides their settings of scattering coefficients.

The last part of the thesis involves the effective acoustic design of two (of three in total) studied cases in Torino: the Galfer and the Cafaro meeting rooms. This environments present, as a common line, disturbing flutter echoes and too low power in speech understanding, causing difficulties in comprehension by listeners while presentations and meetings are in progress.
Three solutions per case were proposed, one of which involved, in both the projects, the application of absorbing materials only, excluding the diffusive panels.
The results showed that the solution with alterned absorber and diffusive materials generally works at its best in the mid frequency of the considered range of 125-8000 Hz: it absorb more than necessary at low frequencies and less at high one. This is also due to the nature of the chosen panels.
The number of used panels is close to the suggested by pre-dimensioning calculations.
Solutions involving only absorbing materials are less functional than the treatment including also hybrid-diffuser panels: this appens in both case of on-walls positioning (Galfer meeting room) and in case of on-ceilings placement (like in Cafaro meeting room).
Solutions where absorbers and diffusers are placed on different kind of surfaces (walls and ceilings) appear also functional for the acoustic quality.

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10. ATTACHEMENTS

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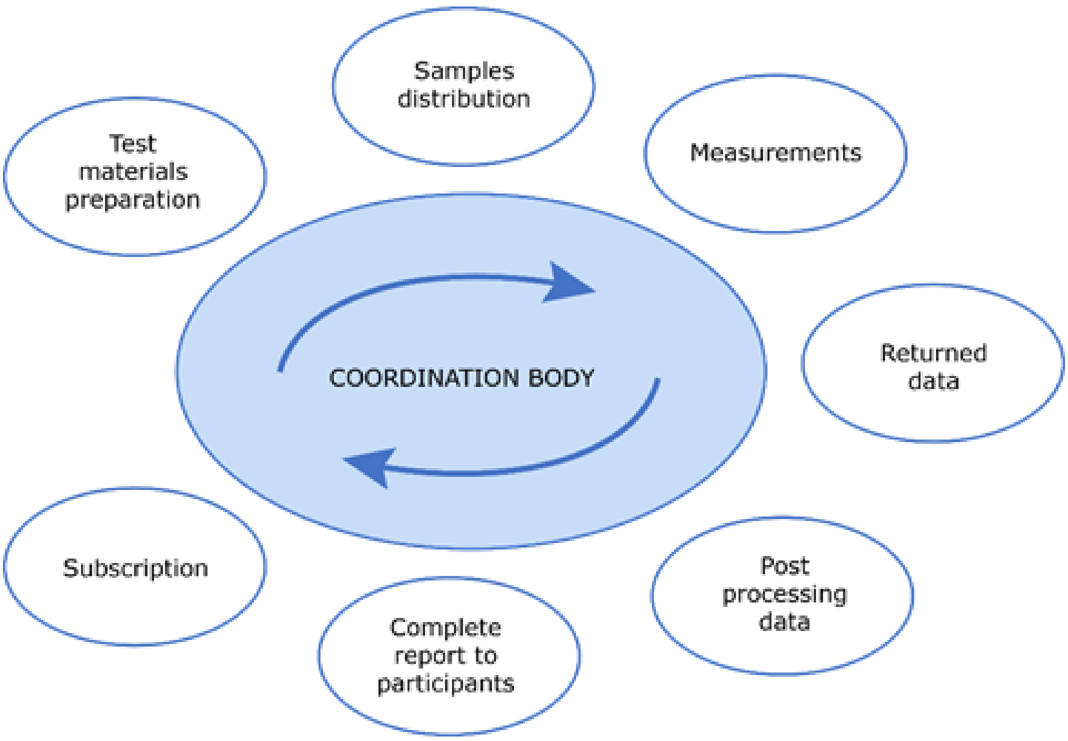
10.1 The Round Robin Test experiment

The Round Robin test is an experiment involving a decided number of operators who take part in the acoustic measurements: each operator has to carry out the measurements and to determine the room dimensions and the measurement conditions independently (Letzén & Kylliainen, 2018).

The test results are obtained with the same method, by different operators using their own equipment, on the same object in the same open plan office.

The Round Robin test carried out in TUAS involved measurements of acoustics parameters and comparison of the achieved results, according to ISO 3382-3: 2012, in a testing experiment made in an open plan office involving different companies and organized by Indoor Acoustics department in TUAS.



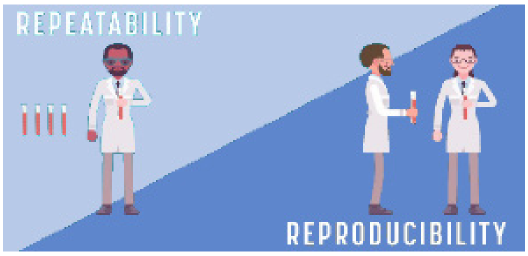
10.1.1 The purpose

The purpose of the test is to offer an opportunity to compare measurements results and to confirm their validity (Letzén & Kylliainen, 2018) for operators carrying out room acoustics conditions in open plan offices, in Finland.
There are several actors in the field of building acoustic and room acoustic measurements in Finland. However, there are fewer people who measure open room acoustics in accordance with ISO 3382-3 [1], because the standard requires the measurement of a speech transmission index, STI, which is not possible for all actors.
Generally, measurements in accordance with the standard include the uncertainty specified in the standard, but the measurement uncertainty is not reported as a numerical value in ISO 3382-2 and ISO 3382-3. There is a specific need to determine this uncertainty, since the Ministry of the Environment's Guide to Sound Environment provides guidance for both the reverberation time and the speech transmission index for a variety of modes. The aim of this study was to determine the uncertainty of the measurement results in accordance with the above standards by means of a comparative measurement involving a satisfying number of independent meters (Keranen et al., 2019).
Such inter-laboratory test is made in order to determine the uncertainty of on-site measurements of the acoustic performance of spaces.
The evaluation of the uncertainty is carried out in two different conditions, of repeatability and reproducibility.
The concepts of repeatability and reproducibility are necessary to determine the uncertainty of measurements. The general term for variability between repeated test, like the Round Robin, is precision. Two measures of precision have been found necessary to describe the variability of a test method.

- *Repeatability*: it refers to tests performed under conditions as constant as possible, with the test performed during a short interval of time in one laboratory by one operator, using the same equipment. In this way, independent test results are obtained with the same method on identical test items.

▪ *Reproducibility*: it refers to tests performed widely varying conditions, in different laboratories by different operators using different equipment. In this way, independent test results are obtained with the same method on identical test items, but the difference is between the operators themselves and their own equipment.
Repeatability and reproducibility are two extremes, the former measuring the minimum and latter the maximum variability in results (Scrosati et al., 2015).

In the Robin Round Test we are carrying out, the participants are measuring only in reproducibility conditions, without repeating measurements. In addition, the workspace location is always the same: the open plan office A319 in the TUAS campus.
The concepts of repeatability and reproducibility are necessary to determine the uncertainty of building acoustics measurements. Precision is a key driver in these measurements.



Indeed, the main scope of the Round Robin Test according to ISO 3382-3 deals with uncertainty: the aim is indeed the determination of the uncertainty of field measurement method in open plan offices described in the abovementioned standard.
According to ISO 12999, the uncertainty is a parameter that, associated with the result of a measurement, characterizes the dispersion of the values that can reasonably be attributed to the measurand. All measurements are subject to uncertainty and a measurement result is complete only when it is accompanied by a statement of the associated uncertainty, such as the standard deviation. It is a non-negative parameter.
Such inter-laboratory test is made to determine the uncertainty of on-site measurements of the acoustic performance of spaces.
Uncertainty of measurement can arise from many causes:

- Calibration uncertainty
- Resolution
- Repeatability
- Temperature
- Combined standard uncertainty.

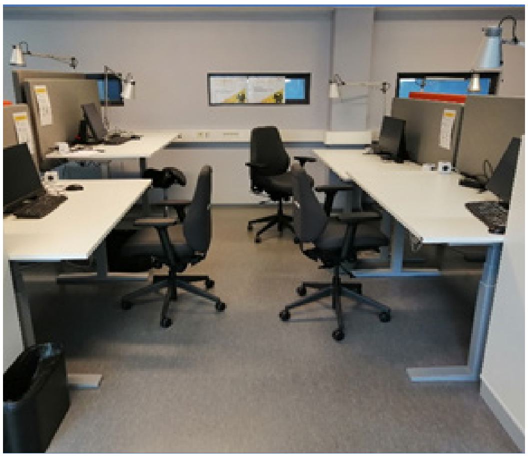
In building acoustics, single number quantities uncertainties are useful to understand the variability of a measurement method.

10.1.2 ISO 3382-3 directions

According to the ISO 3382-3 measurements procedure, in the TUAS experiment the following directions were fulfilled:

- Sound source (Loudspeaker): an omnidirectional sound source is used, since people in an open plan office do not continuously speak in any fixed directions. Verification of the sound power level of the source is performed as in ISO 3382-1, with the sound source positioned at the height of 1,2m.
- Microphone: sound pressure levels in each octave band and at each microphone position shall be measured using a sound level meter, according to IEC 61672-1's requirements. The microphone shall be omnidirectional.
- Measurement conditions: measurements shall be made in furnished rooms but without the presence of people, except the persons needed to carry out the measurements.
- The HVAC devices and other noise sources shall operate on the same power as during typical working hours. If the office is equipped with a sound-masking system, it shall be switched on during the measurement.
- The preferred number of successive measurement positions in the line is 6 to 10; the minimum number is 4.
- The measurements are carried out using source and microphone positions in workstations in the position of the person's head (height of 1,2 m).
- The position of loudspeaker and microphone is at least 0,5 m from tables and 2,0 m from walls and other reflecting surfaces.

10.1.3 The TUAS Campus case study



Open plan office A319 with 12 workstations, Turku University of Applied Sciences Campus, Kupittaa.

TUAS acoustics group organized a Round Robin Test in workspace A 319, situated at the 3rd floor of the Turku University of Applied Sciences' campus in Kupittaa, Turku.

This open-plan office includes 12 flexible workstations, divided by screens: both tables and screens are characterized by adjustable height. In addition, at the opposite end of the room from the entrance, there's a wide table for meetings with 4 provided study stations.

The measurements are made in two situations:

A. Electric tables set at the lowest position (top of the screen at a height of 117 cm)

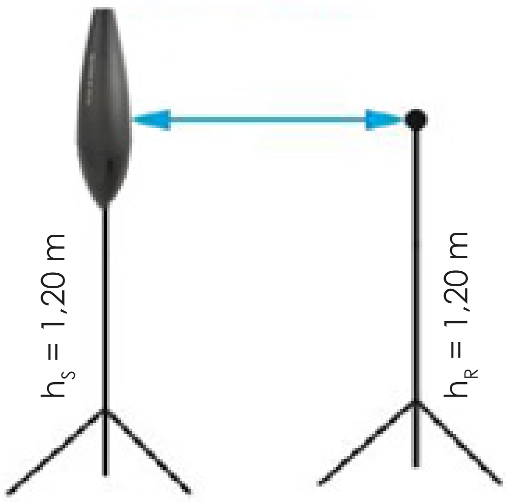
B. Electric tables set at upper position (upper scale, 183 cm)

In both situations, the measurements are done in two directions, according to ISO 3382-3 (measuring directions 1 and 2) at the measuring points selected by the participant (measuring line).

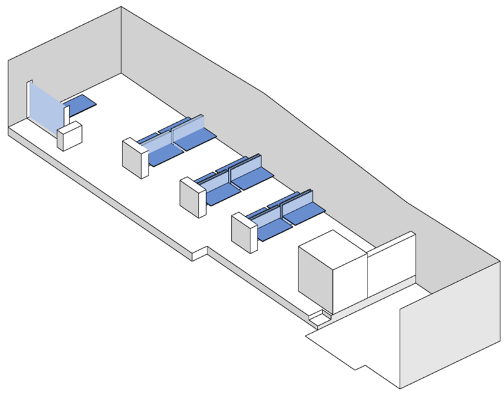
In both A and B, the height of the sound source and the microphone is 1,20 meters from the floor.

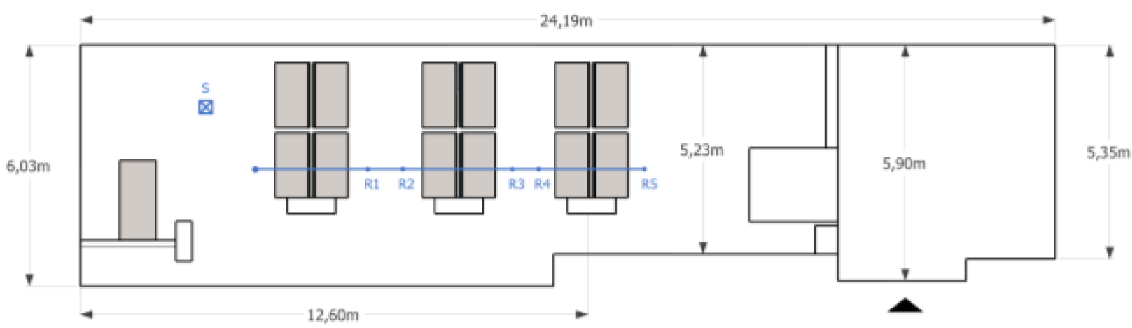
Speaker positions and measuring

points are kept the same in situations A and B. The ISO 3382-2 speaker and microphone positions are freely selected by the attendee.
Two measurement lines are used, each one associated with a sound source.
The open plan office studied case includes 12 flexible workstations divided by screens: both tables and screens are characterized by adjustable height.



Plan office with source and receiver positions, the blue line represents the path used for measurements.
The direction of the first line is from left to right in the figure and vice versa the second line. The measuring points were at work stations.





Two measurement lines are used, each one associated with a sound source.
The TUAS Indoor Acoustics department organized a Round Robin Test in the workspace A 319, at 3rd floor in the Turku University of Applied Sciences' campus in Kupittaa. This open plan office includes 12 flexible workstations divided by screens: both tables and screens are characterized by adjustable height.
According to ISO 12999 standard, a successful number of involved laboratories is at least 8 participants.
In the TUAS experiment, out of the 12 invited participants, 9 testers participated in the test. The object to be measured was an open office with 12 workstations shown in the figure above, measuring 18,5m x 5,9m x 3,5m.
The left area of the office was not included, because situated at a different level and not used for workstations.
The participants performed the test in single-person or a couple teams: the timetable for each test of reproducibility is listed in the table below.

Involved teams			Timetable
✓ 1	👤	👤	24/04/19
✓ 2	👤		29/04/19
✓ 3	👤	👤	06/05/19
✓ 4	👤		08/05/19
✓ 5	👤	👤	13/05/19
✓ 6	👤	👤	14/05/19
✓ 7	👤	👤	15/05/19
✓ 8	👤	👤	21/05/19
✓ 9	👤		23/05/19

The measurements and measurements were independently carried out by the surveyors using their own equipment. Measurements according to ISO 3382-3 were made on a single measuring line in both directions in situations A and B. The reverberation times were also measured in accordance with ISO 3382-2 in both situations A and B.
The main evaluated parameters were: the sound pressure level of speech at 4m ($L_{p,A,S,4m}$), measured in dB, the distraction distance r_D, expressed in m, the background noise pressure level at $L_{p,\ A,\ B}$, measured in dB , and the reverberation time T, expressed in seconds. While measuring the speech transmission index (STI) is necessary

to determine the distraction distance.
The ISO 3382-3 standard does not explicitly state which method should be used: this standard refers to IEC 60268-16, but its application is controversial. For example, the used speech spectra are different in standards and ISO 3382-3 does not specify whether weights for male or female speech are used in the calculation. Due to this room for interpretation, the procedures varied slightly between the surveyors.
The measurements' results were recorded in a predefined file which was emailed to the participants by the test organizer (the Turku University of Applied Sciences). The received results were returned in anonymous mode, before being reviewed. When measuring the results, microphones 1 through 9 are used.
Six surveyors placed the sound source at the end of the workstation line and measured the line at the other 5 workstations; two surveyors placed the sound source farther from the above workstation line and measured the line at all 6 workstations. One meter placed the sound source at the workstation at the end of the work dotted line and measured the red line at 5 workstations.

10.1.4 Analysis and comparison of the results

The sound pressure levels of speech were determined by each of the 9 meters in situations A and B: the related results are shown in the graphs of figures 1 and 2, in the next page, while the results of the STI calculation are presented in the graphs of figures 3 and 4, in the further page.

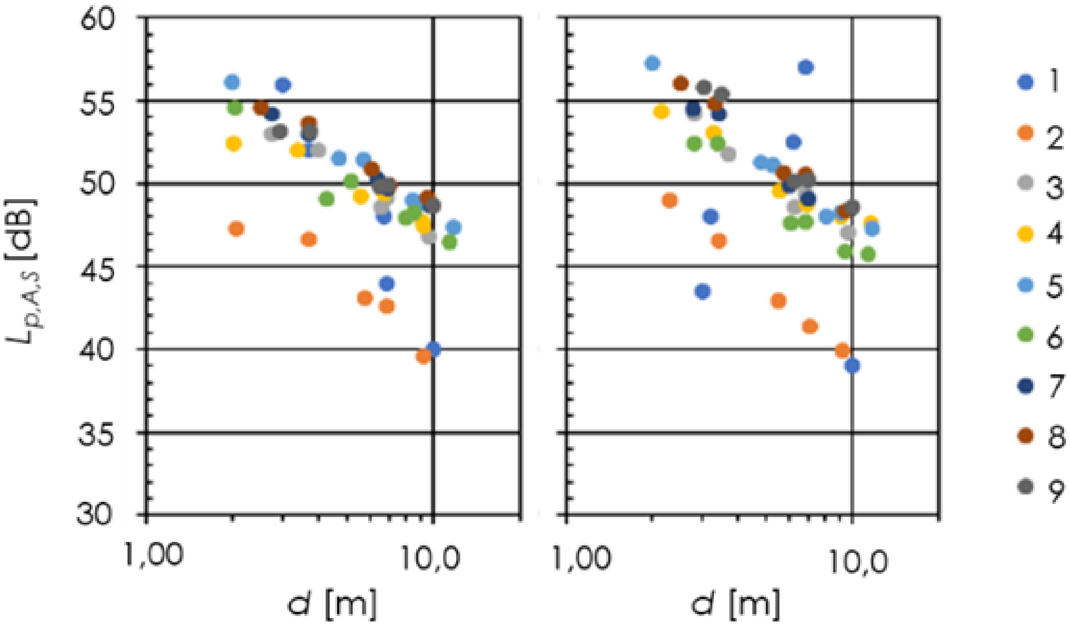


Figure 1_Sound Pressure Level of Speech (Lp,A,S), **Line 1 and 2, Situation A**.

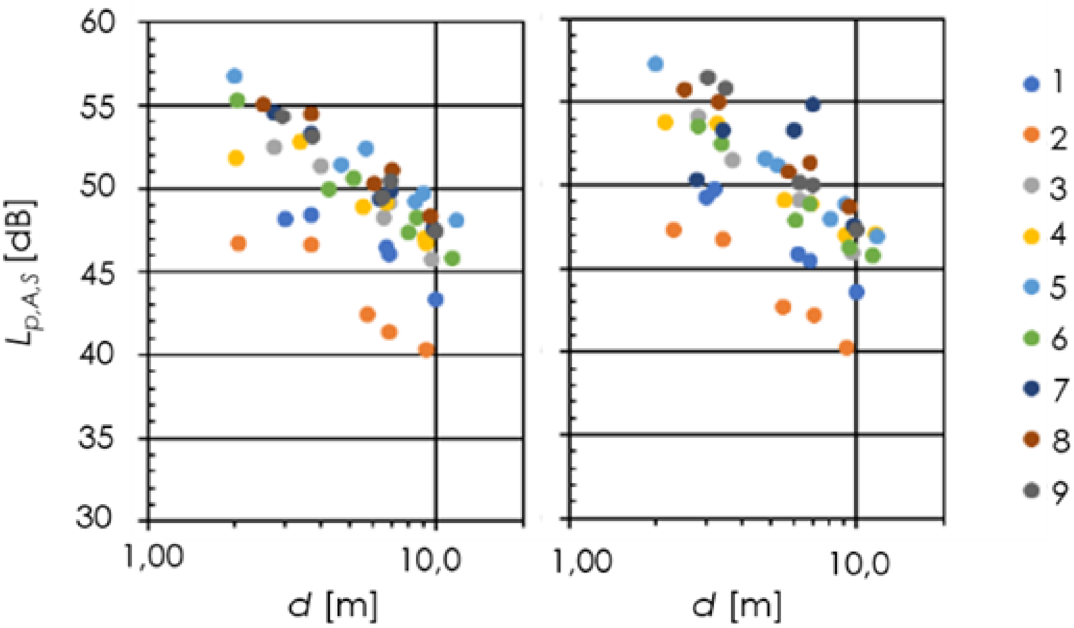


Figure 2_Sound Pressure Level of Speech (Lp,A,S), **Line 1 and 2, Situation B**.

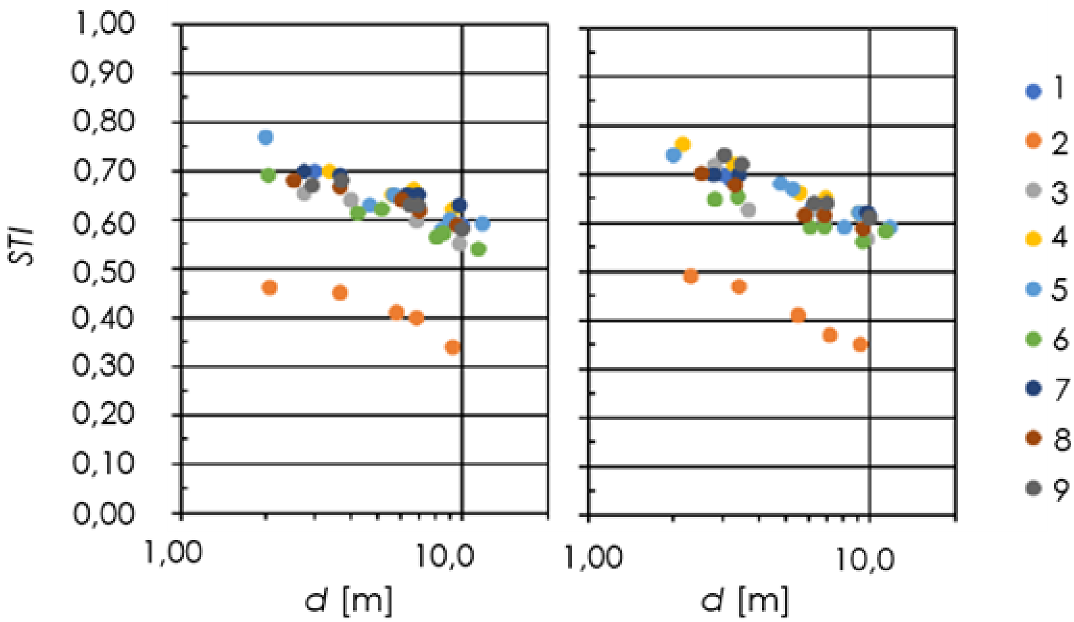


Figure 3_Speech Transmission Index (STI), **Line 1 and 2, Situation A**.

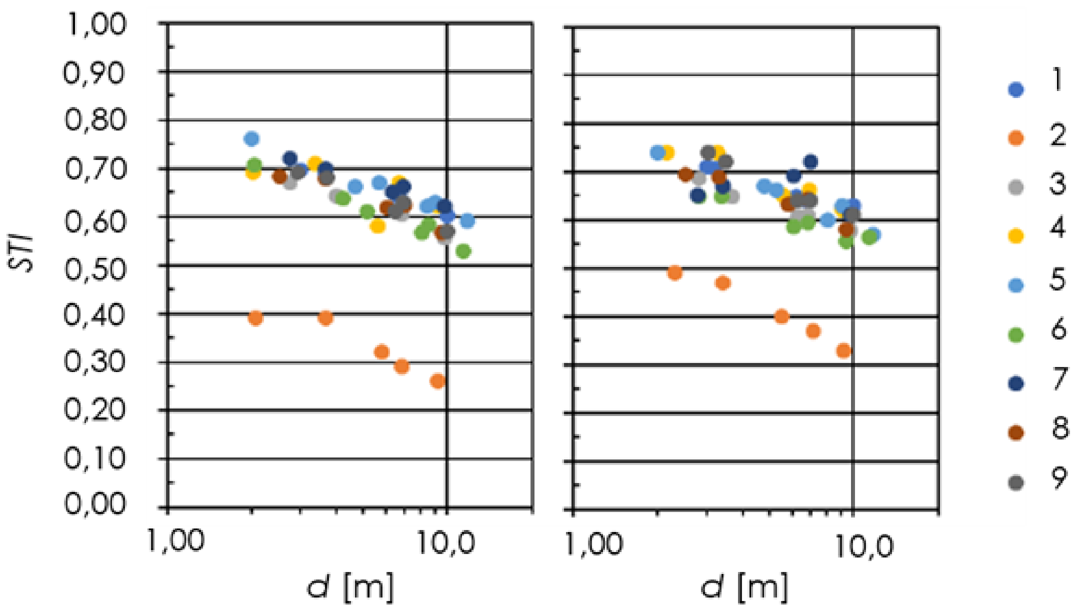


Figure 4_Speech Transmission Index (STI), **Line 1 and 2, Situation B**.

The statistical analysis of the other analyzed parameters was performed with the following depreciation:

- The 5th measurer had not determined the metric in situation B;
- for Meters 1st, 2nd and 7th, some findings are clearly different.

The results of reverberation time measurements according to ISO 3382-2 were obtained from 7 to 9 meters.

The uncertainty of D2, S was small. In situations A and B, the mean values $D_{2,S}$ of line 1 and 2 were 3.5 - 4.0 dB. Standard deviations were ≤ 0.5 dB in both situations.

10.1.5 Conclusions

In situations A and B, the mean values of $L_{p,A,S,4m}$ on the first line and the second were 51,7 to 52,5 dB. The standard deviations were 1,1 to 2,1 dB.

The measure uncertainty was greater than the measure $D_{2,S}$ (Level of Speech for Distance Doubling, expressed in dB).

The standard deviations of the reverberation time T in the various frequency bands were 0,02-0,07 s in situations A and B. Thus, the uncertainty in the reverberation time was surprisingly small.

The mean values for background sound pressure level $L_{p,A,B}$ were 36,7 to 37,8 dB and standard deviations 0,5 to 2,4 dB.

However, the range of measured $L_{p,A,B}$ (Background Noise Level, expressed in dB) values was higher between 31,6 and 38,6 dB. This increased the uncertainty of STI and r_D (Distraction Distance, expressed in m). Some of the large variation in the background noise level may be due to the variation in the ventilation sound level. The uncertainty would have been lower if there had been a steady 40 dB masking noise to minimize this unnecessary source of error.

The use of masking noise would also have ensured that the r_D value did not need to be extrapolated.

The r_D averages for the interference distance were 14,3-15,5 m and standard deviations 0,7-3,0 m for situations A and B. Part of the reason for this was that the value had to be extrapolated, measuring line length approximately 12 meters.

As a conclusion, the measurements' uncertainty could be determined

from standard deviations for standard metric measurements.
All surveyors made measurements in the same state with their own devices, so the test corresponded to the in-situ situation according to ISO 12999-1. Based on the results it is possible to propose measurement uncertainties based on standard deviations, according to ISO 3382-3 and ISO 3382-2. The results are valid for this open office only. Uncertainty may depend somewhat on the subject.

	$D_{2,S}$ [dB]	$L_{p,A,S,4m}$ [dB]	$L_{p,A,B}$ [dB]	r_D [m]	T_{20} [s]
Value	0,50	2,00	2,50	3,00	0,05

ISO 3382-3 and ISO 3382-2 Measurement Uncertainties.

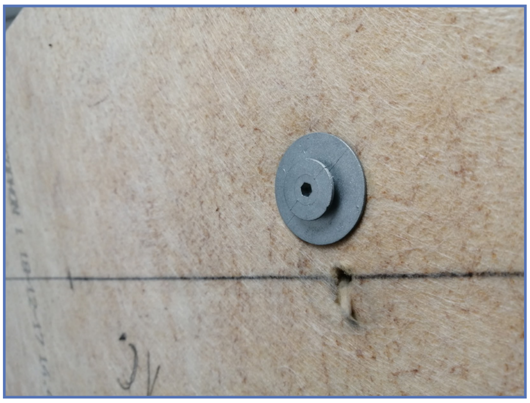
10.2.1 Ecophon Akusto One SQ, absorption panels

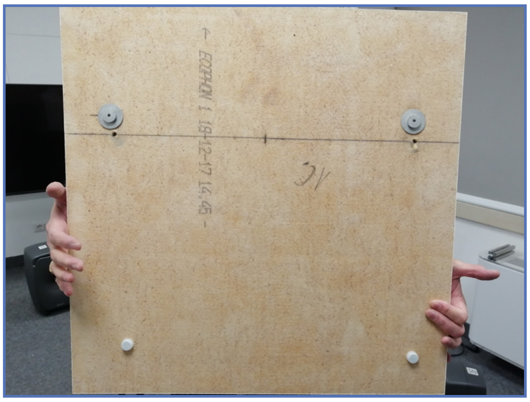
The system offers the possibility of installing Ecophon Akusto One SQ on the wall, to increase sound absorption in an environment. This kind pf absorbent panel is available in different formats with a weight between 2.0 and 4.5 kg. The used product is made of high density glass wool. The surface visible consists of a Texona fiberglass fabric and it is also available with painted surface. The back of the panel is covered with fiberglass; the edges they are straight and painted in white or gray.

In both the two acoustic design treatment realized in the second part of this research, Galfer and Cafaro meeting room, the Ecophon Akusto One SQ panels were installed: Politecnico di Torino already had several kind of these products, partly used for another room's treatment previously carried out.

The chosen size is 60*60cm, with 4cm of thickness. They were applied both on walls and on ceilings, in order to positively affect the acoustic quality of the rooms, absorbing sounds.

Ecophon Akusto One SQ installed on the walls and ceilings of a treated room: its power in absorption is really high and the sounds in the space appear dry, almost with no reverberation.

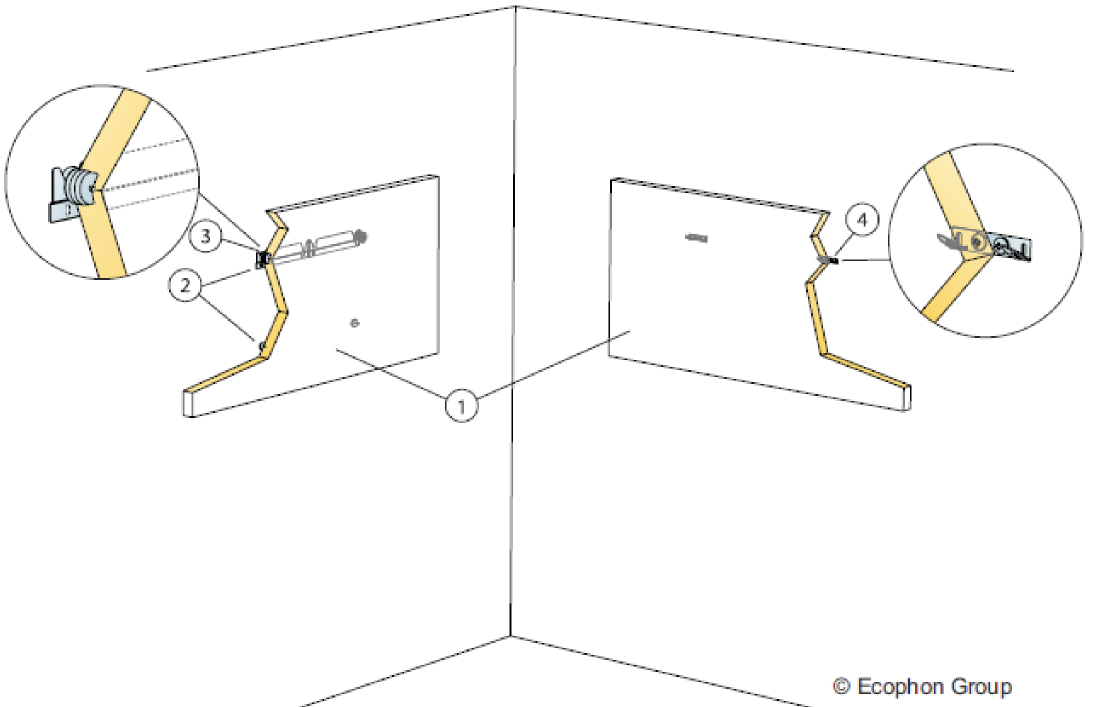




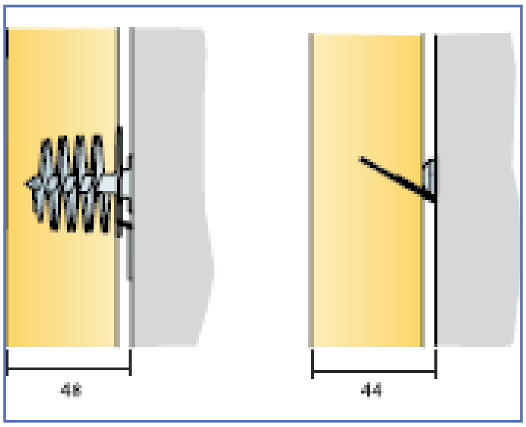
Details of the panels' assembly for positioning the Ecophon Akusto One SQ on the walls: the panels are hung on special tracks previously fixed on the walls' surface. They can be easily removed even with no specific tools.

The type of installation for Akusto panels, used for the Galfer and Cafaro design acoustic teatment, is called Connect One trim and Connect Absorber anchor one. This kind of system is very simple and could be made even by not expert technicians.
Panels are hung are hung on special tracks (showed in the first photo on the top), previously fixed on the walls' surface, on which special hooks, applied on the back of the panels, are fitted.
In this way the chosen products can be easily removed in case of need, with no use of specific tools, and then hung again with the same method. The back of the panel is covered with fiberglass. The edges are straight and painted in white or gray: in our design, white color was chosen. The straight shape of the edges works in a favorable way to fit many panels on the same surface without leaving untreated space between one and another. The dimensions of these panels are not so wide, in order to have some manageable products: their weight is light, so they cannot cause damages to the surfaces where they are applied (like walls and ceilings).

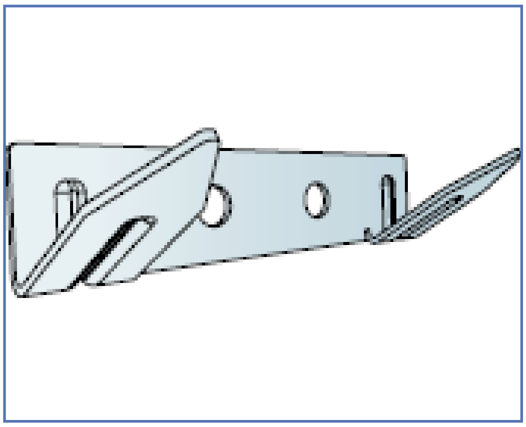
Akusto One SQ, 60x60cm, installation diagram



Installation diagram for Ecophon Akusto One SQ, using the *Connect one trim* application system.



1. Detail of the two types of anchors fixed on the back of the panels.



2. Detail of the Connect One hook fixing, tracks hung on the bearing surface before installing the whole product.

Materials	Sup, m^2	Absorption coefficients (α), adimensional						
	0,60*0,60	125	250	500	1000	2000	4000	8000
Akusto One SQ 600x600, absorbent panels	*0,36*	0,20	0,70	1,06	1,06	1,03	1,08	1,08

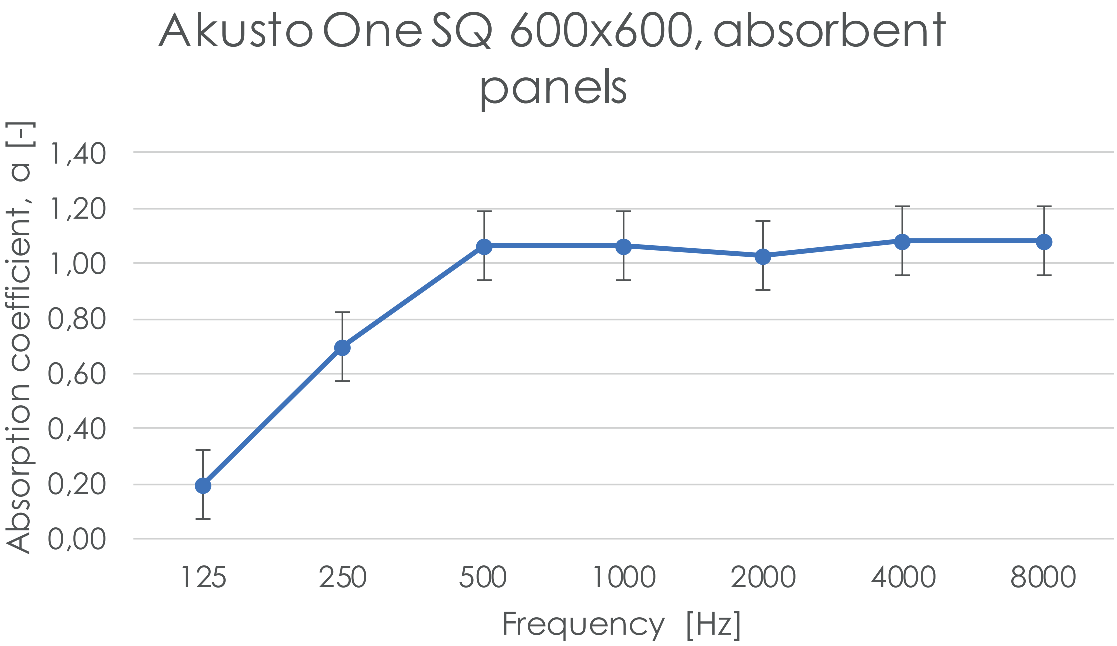
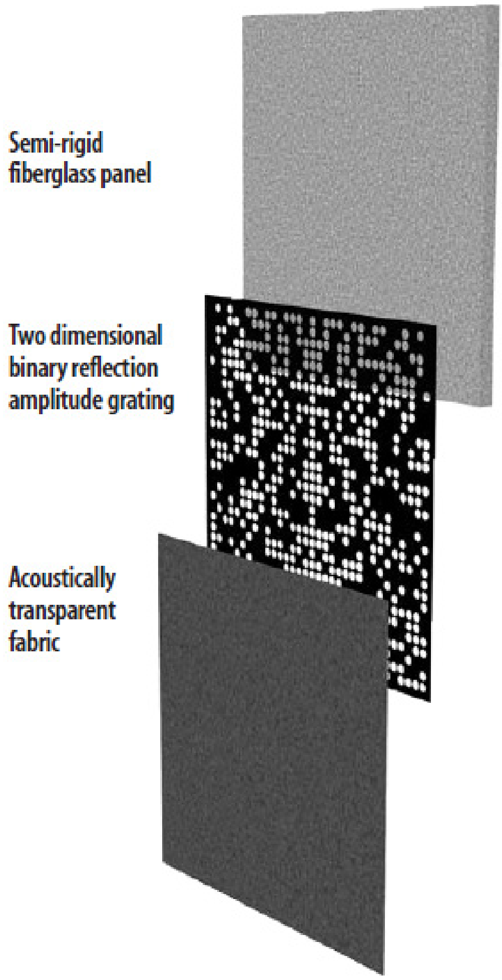


Table with values and the reported in graph representation of acoustic absorption coefficients, alpha (a-dimensional parameter).
This kind of panels absorb more at the middle and high frequencies, in the considered frequency range of 125-8000 Hz.

10.2.2 B.A.D. hybrid panels, diffuser and absorber, RPG

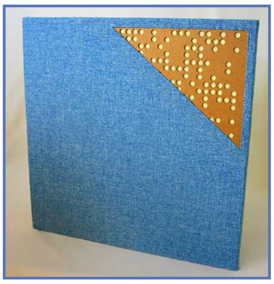


The B.A.D. acoustic panels, by RPG, have balanced acoustical designs containing an appropriate combination of absorption, reflection and diffusion. A BAD Panel simultaneously provides uniform sound diffusion at high frequencies and crosses over to pure absorption below the diffusive cutoff frequency. The energy that is *not diffused* is *absorbed*. The BAD panel allows complete tonal balance and increased speech intelligibility in gypsum board and concrete block rooms, where standard fabric wrapped panels remove the all important high frequency sound. These panels offer little sound diffusion and large area application may lead to an acoustically “dead”space.

The RPG’s BAD panels work very well on mid frequencies: in this research they are applied in the Galfer and Cafaro meeting rooms’ surfaces, on both walls and ceilings. In some proposed solutions they appeare alternate to Akusto One SQ absorbent panels by Ecophon, in order to complete the general acoustics quality effects.

The RPG developed a variable impedance panels by wrapping a resorptive binary template consisting of reflective areas and holes over a semi-rigid fiberglass panel. The resulting **Binary Amplitude Diffsorbor (B.A.D.)** flat or curved panel provides high frequency diffusion and mid frequency absorption.

The B.A.D. panels chosen for the Galfer and Cafaro acoustic design have the same standard dimensions of the Akusto One SQ, 60x60cm. This choice is made in order to easily alternate these two kinds of panels, to guarantee a better and more complete acoustic treatment to the whole indoor environment. The squared and straight shape of the products allows to fit them one beside another, to cover a wider area of the bearing surface without leaving portions of space untreated.



Details showing two kinds of Binary Amplitude Diffsorbor panels, with their characteristic texture and material.

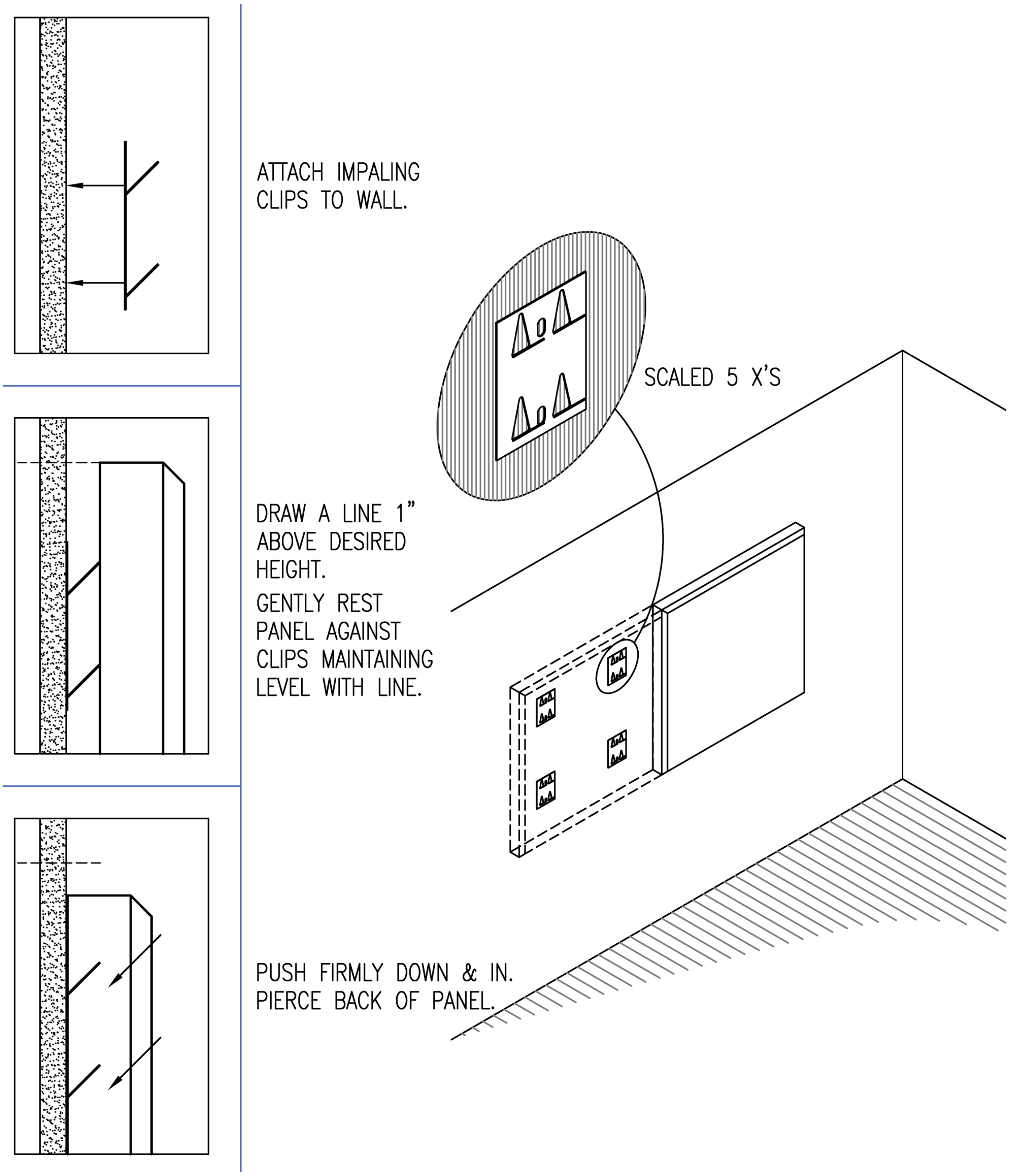
The chosen method for installing panels on the walls and ceilings of the treated rooms the impaling clips system.

The clips are previously hung on the indoor surface, then a line is drawn on the back of the 60x60cm panel, placed at the desired height in order to align all the panels between themselves: the third passage consists in gently rest the panels against clips, always mainaining the chosen level with a line. The final phase is the firmly push the back of the panels against the wall or ceilings surface.

This hanging system appear simple, just like the Akusto One SQ installation method: it does not require special tools, the panels can be easily removed from the support and then hung again, in case of need, thanks to their standard dimensions and weight, resulting very manageable. The mounting of these acoustic panels does not requires any specific technicians, they can be directly installed by users.

The thickness of the RPG products used in the acoustic designs realized in this whole research is 3cm, a bit thinner than Akusto One SQ panels.

Binary Amplitude Diffsorbor panels by RPG, 60x60cm, installation diagram



Installation diagram of panels in rooms, using the impaling clips monting system.

Materials	Sup, m²	Absorption coefficients (a), adimensional						
	0,60*0,60	125	250	500	1000	2000	4000	8000
BAD RPG 1.2", hybrid absorber and diffuser panels	*0,36*	0,18	0,35	0,90	1,00	0,83	0,60	0,60

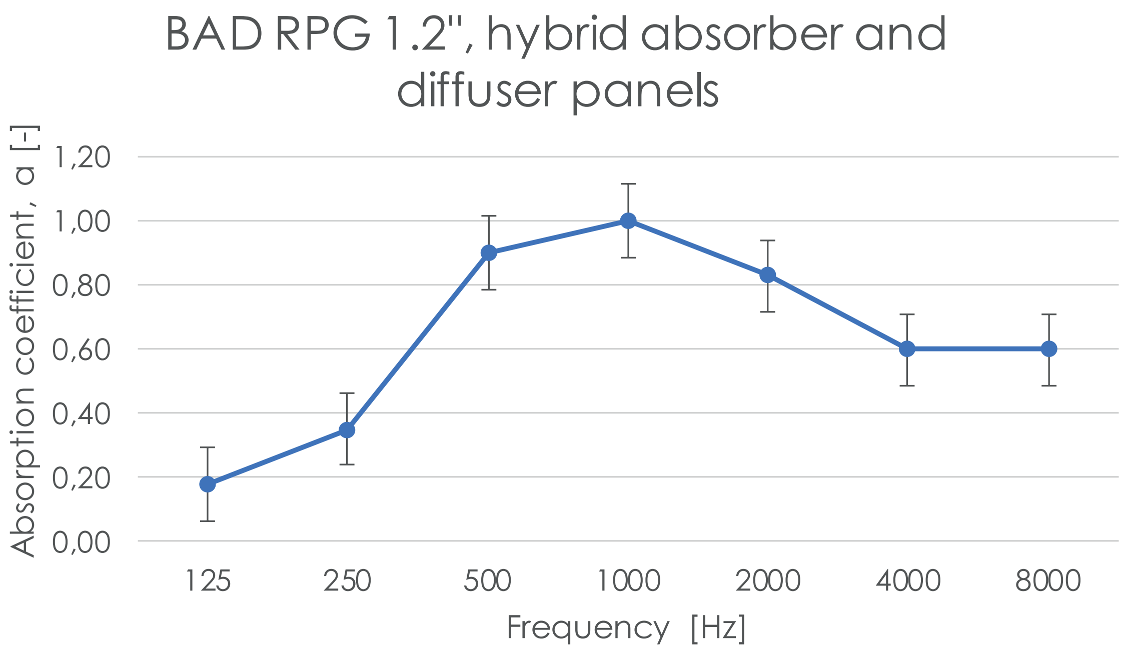


Table with values and the reported in graph representation of acoustic absorption coefficients, alpha (a-dimensional parameter).

This kind of panels absorb most at the mid frequencies, in the considered frequency range od 125-8000 Hz. The energy that is *not diffused* is *absorbed*.

THANKS TO

THANKS TO

Thanks to professor Arianna Astolfi and Louena Shtrepi for their precious suggestions and help all along the way of this involving research and for including me in this project with their passion and enthusiasm; thanks to the whole *Acousic Angels* team in Politecnico di Torino for its practical support and disposability.

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Thanks to my whole family: Paola, Domenico, Lorenzo, Marta, my grandparents and Pongo, who never stopped supporting and bearing me with their unconditional affection and for all the possibilities they always offer me.

Thanks to Samuel, who, unawares, inspires me every day with his energy and for always living by my side, even when he's not around.

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