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IRRELEVANT SPEECH NOISE IN SHARED AND OPEN-PLAN OFFICES: design of acoustic solutions for noise reduction

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ABSTRACT

Over the years, many studies have been conducted on the efficiency of open-plan offices both in relation to the degree of subjective satisfaction of the occupants, and in relation to the performance reached in an open-plan environment. In particular, a focus has been made on "Irrelevant Speech Noise" (ISN) and its effects on health, well-being and performance of employees, as it is the most distracting noise source in open-plan offices.

According to the definition of Di Blasio S. et al., ISN is the noise that is generated from conversations between colleagues, telephone calls and laughter. Therefore it negatively influences well-being, health, comfort, productivity and atmosphere between colleagues.

Literature studies of Haapakangas et al. (2008), Pejtersen et al. (2006) and Danielsson (2005), comparing many office layouts, showed that dissatisfaction with noise and privacy is very high, especially in large open-plan offices. Furthermore, from the results of these studies emerged that there is a correlation between the noise annoyance in open-plan offices and its effects on health and comfort, such as absenteeism at work, hearing impairments, hypertension, discomfort and difficulty to concentrate.

The aim of this thesis is to investigate whether - and in what way - the acoustic design of an office can influence the acoustic parameters defined by the ISO 3382-3:2012 and therefore the well-being and comfort of the occupants.

The study begin with five case studies of shared and open-plan offices within the Politecnico di Torino. First of all, in-situ measurements of reverberation time (T_{20}) and background noise have been made. Measurements are performed using a

Sound Level Meter (*SLM XL2, NTi Audio).* Measurements have been made in unoccupied conditions.

The results of these measurements showed that two out of five offices do not meet the T_{20} limits defined by the NF S31-080 - French standard on acoustics of office and associated areas. Therefore, two acoustic improvement projects have been proposed for these two offices: then, acoustic projects have been verified through Odeon (version 13.0), an acoustic simulation software.

The 3D models of the two offices have been designed on SketchUp - a 3D geometric modeling software - and they have been then uploaded in Odeon in order to verify the acoustic parameters at the state of the art and, then, after the acoustic improvement project.

For the simulations, the following parameters have been taken into account:

- **$D_{2,S}$** ie the spatial decay rate of A-weighted SPL of speech;

- $\mathbf{L_{p,A,S,4m}}$ ie the weighted sound pressure level (A) at 4 m;

- $\mathbf{L_{p,A,B}}$ ie the A-weighted SPL of speech at 4 meters;

- **STI** (Speech Transmission Index);

- $\mathbf{r_D}$ ie the distraction distance.

Once the results defined by the standard ISO 3382-3:2012 have been reached, the effects that different acoustic design layouts have on the simulated parameters have been studied. In particular, the effect that sound masking, absorbent wall panels, screen dividers and ceiling panels have on the STI, $D_{2,S}$ and r_D values has been studied.

Different acoustic design conditions of both offices have been investigated. The differences between the different design acoustic conditions are in the addition of both sound masking and moquette on the floor. From the comparison of these conditions, emerged that the addition of both acoustic treatments have beneficial effects on the results of simulated acoustic parameters.

In conclusion, room acoustic parameters defined by ISO 3382-3:2012 standard for open-plan offices behave differently when the acoustical conditions of the room change in absorption, screens or background noise. The results also show a correlation between sound masking in open-plan offices and its effects on the values of acoustic parameters: that is, adding sound masking in an office, the acoustic parameters have better values, especially regards to STI, $D_{2,S}$ and $r_{D.}$.

SOMMARIO

Nel corso degli anni sono stati condotti numerosi studi sull'efficienza degli uffici open space sia in relazione al grado di soddisfazione soggettiva degli occupanti, sia in relazione alle prestazioni raggiunte in un ambiente open space. In particolare, l'attenzione è stata rivolta all’"Irrilevant Speech Noise" (ISN) e agli effetti che quest’ultimo ha sulla salute, sul benessere e sulle prestazioni dei dipendenti, in quanto è considerato, secondo la letteratura, la fonte di rumore più distraente negli uffici open space.

Secondo la definizione di Di Blasio S. et al., l’ISN è il rumore che viene generato dalle conversazioni tra colleghi, telefonate e risate. Pertanto influenza negativamente il benessere, la salute, il comfort, la produttività e l'atmosfera tra colleghi.

Studi di letteratura di Haapakangas et al. (2008), Pejtersen et al. (2006) e Danielsson (2005), confrontando molti layout di ufficio, hanno dimostrato che l'insoddisfazione per il rumore e la privacy è molto alta, specialmente nei grandi uffici open space. Inoltre, dai risultati di questi studi è emerso che esiste una correlazione tra il disturbo del rumore negli uffici open space e i suoi effetti sulla salute e il comfort, come l'assenteismo sul lavoro, problemi uditivi, ipertensione, discomfort e difficoltà di concentrazione.

Lo scopo di questa tesi è di indagare se - e in che modo - la progettazione acustica di un ufficio possa influenzare i parametri acustici definiti dalla norma ISO 3382-3:2012 e quindi il benessere e il comfort degli occupanti.

Lo studio inizia con cinque casi studio di uffici condivisi e uffici open space all'interno del Politecnico di Torino. Gli uffici condivisi sono uffici con un numero di occupanti che va da due a cinque dipendenti per stanza, mentre gli uffici open space sono uffici con più di cinque dipendenti.

Prima di tutto, sono state effettuate misurazioni in campo del tempo di riverbero (T_{20}) e del rumore di fondo. Le misurazioni sono state eseguite utilizzando un fonometro (*SLM XL2, NTi Audio*). Le misurazioni sono state effettuate in condizioni di uffici non occupati

I risultati di queste misurazioni hanno mostrato che due uffici su cinque non rispettano i limiti T_{20} definiti dalla norma francese sull'acustica degli uffici e aree associate NF S31-080. Pertanto, due progetti di miglioramento acustico sono stati proposti per questi due uffici: poi, i progetti acustici sono stati verificati tramite Odeon (versione 13.0), un software di simulazione acustica.

I modelli 3D dei due uffici sono stati progettati su SketchUp - un software di modellazione geometrica 3D - e sono stati poi caricati in Odeon per verificare i parametri acustici allo stato di fatto e, quindi, dopo il progetto di miglioramento acustico.

Per le simulazioni, sono stati presi in considerazione i seguenti parametri:

- $\mathbf{D_{2,S}}$ cioè il tasso di decadimento spaziale di SPL ponderato A del parlato;
- $\mathbf{L_{p,A,S,4m}}$ cioè il livello di pressione sonora ponderato (A) a 4 m;
- $\mathbf{L_{p,A,B}}$ ovvero il rumore di fondo ponderato A;
- **STI** (Speech Transmission Index);
- $\mathbf{r_D}$ cioè la distanza di distrazione.

Una volta raggiunti i risultati definiti dalla norma ISO 3382-3:2012, sono stati studiati gli effetti che i diversi layout di progettazione acustica hanno sui parametri simulati. In particolare, è stato studiato l'effetto che i trattamenti acustici, quindi, il sound masking, i pannelli assorbenti a parete, i pannelli divisori tra le postazioni di lavoro e i pannelli a soffitto, hanno sui valori STI, $D_{2,S}$ e r_D.

Sono state studiate diverse condizioni di progettazione acustica di entrambi gli uffici.

Le differenze tra le differenti condizioni di progetti acustici riguardano l'aggiunta sia del sound masking, sia della moquette sul pavimento. Dalla comparazione di tali condizioni è emerso che l'aggiunta di entrambi i trattamenti acustici sovracitati ha effetti benefici sui risultati dei parametri acustici simulati.

In conclusione, i parametri acustici definiti dalla norma ISO 3382-3:2012 per gli uffici open space presentato risultati diversi quando le condizioni acustiche dell’ambiente analizzato cambiano in termini di assorbimento, schermi o rumore di sottofondo. I risultati mostrano anche una correlazione tra il sound masking negli uffici open space e i suoi effetti sui valori dei parametri acustici: cioè, aggiungendo il sound masking in un ufficio, i parametri acustici hanno valori migliori, soprattutto per quanto riguarda i parametri di STI, $D_{2,S}$ e r_D.

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Introduction

1. Origin and development of shared and open-plan offices

    1.1 Acoustic as a driving factor in the development of different office layouts

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1. ORIGIN AND DEVELOPMENT OF SHARED AND OPEN-PLAN OFFICES.

This chapter deals with the development of shared and open-plan office layouts from the early 1900s to nowadays.

According to Hongisto V. et al [5], conventionally offices are divided according to their layout and number of occupants: shared offices (from two to e.g. five employees per room), and open-plan offices (more than e.g. five employees).

In the second part of the chapter various examples have reported to understand how acoustics has been a predominant factor in the change and development of office layouts over time, up to the layouts of today's offices.

Over time, the layout of the office has changed shape, design and size according to several needs.

Before 1900 offices were not designed according to specific rules, but they were always mixed with other functions and they were obtained from residences of important personalities, dignitaries, nobles and merchants. In this scenario offices were characterized by small and confined rooms, furnished with domestic furniture or with workshop shelves [23]. The structure itself of these buildings did not differ from those of residential buildings. For example, the internal distribution of the spaces followed the scheme of rooms and corridors typical of bourgeois residences. For a long time office buildings maintained a mixed use destination: housing and commercial activity. Only in the early 1900s there was an effective specialization in the design of the office building and its furnishings. For the first time in history, the division into rooms and corridors was abolished, the interior walls were eliminated and the desks were located into a single large room called "open-plan office" [23].

The factors that led to the consolidation of the open-plan office typology were varied: the increase in the demand of work, the development of new communication systems, the technological progress, the diffusion of electricity and new office equipment. For these reasons there was the need to concentrate a large number of employees in buildings that were extended in height rather than in width, that namely multi-storey buildings. The internal distribution of the office in these buildings was closely related to the role/task of the occupants: the lower, dark and cramped floors were assigned to apprentices and employees, the central floors were occupied by medium-level employees, while the executive managers of the company were located in a private and more comfortable office in the upper floors.

The "open-plan" offices were born in the United States and they were diffused towards other industrialized countries [23].

Frank Lloyd Wright designed the Larkin Administration Building in New York, in 1906, that was conceived as an open-plan factory, with a large central atrium and few walls. It was considered the first ultramodern office building in the USA [9],[1]. The interior consisted of a five-storey central nave (fig. 1) [33]. The upper floor contained a kitchen, a bakery, dining rooms, classrooms, a public library, a hanging garden, and a winter garden. The office galleries were developed on all floors, served by stairs and corner elevators. All employees worked together in one large space, without private offices or separate spaces. Each workstation was composed of a chair and a small desk and all of them were disposed one behind the other, suggesting the classroom space (fig. 2).

The peculiarity of this architecture was given by the fact that furniture were designed by Wright himself to improve well-being inside the building. Another innovation adopted by Wright concerns the use of magnesite[1] for floors, stairs, doors, window

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[1] Floors consisted of a cement base, padded with a mixture of wood fiber and magnesite, then covered with sheets of magnesite. Magnesite is a mixture of concrete, sawdust, pigment and sometimes asbestos.

sills, partitions, work surfaces, in order to improve acoustic comfort using absorption materials. The interior walls of the building were made of semi-vitreous, hard bricks. Windows and doors were characterized by double glazing so that the building was well sealed in order to avoid the passage of dust and noise [29].

Lark Administration Building was the first open-plan office building designed in terms of well-being and acoustic comfort.

Fig. 1: The large internal nave of the Larkin Administration Building

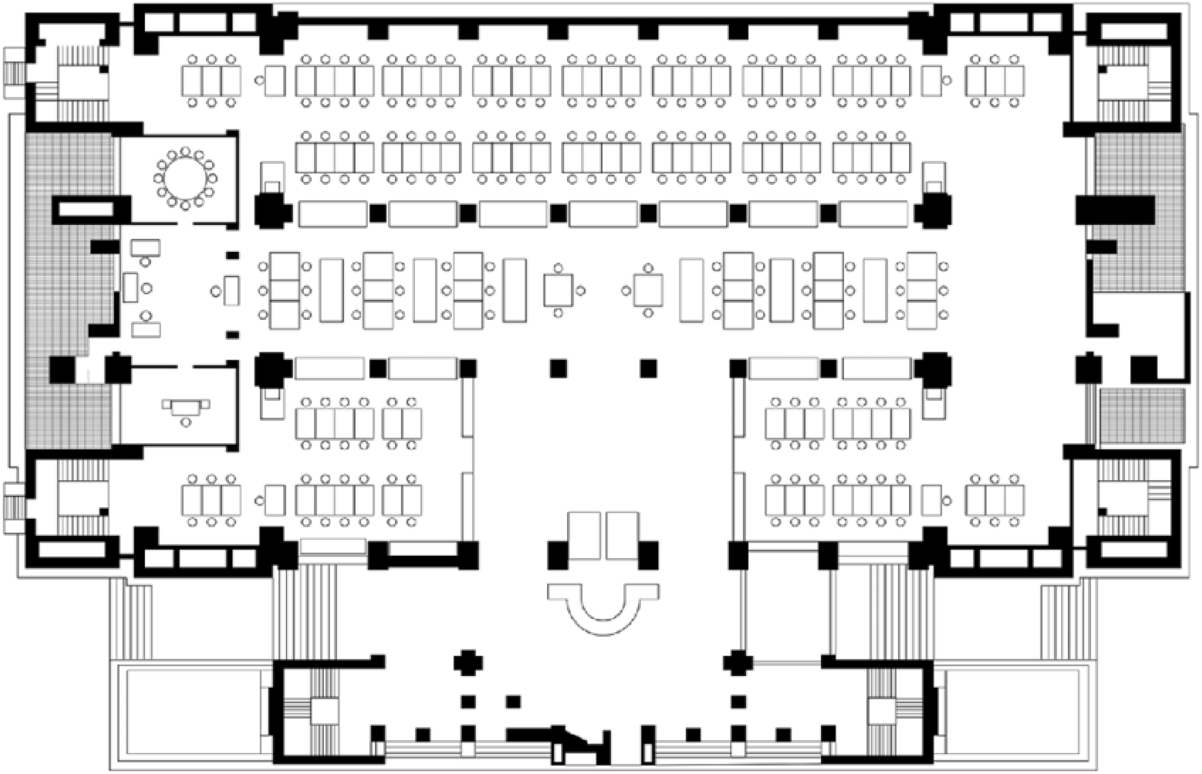


Fig. 2: First floor of Larkin Administration Building, 1904-1945, Frank Lloyd Wright [4]

1.1 ACOUSTIC AS A DRIVING FACTOR IN THE DEVELOPMENT OF DIFFERENT OFFICE LAYOUTS

Over the years acoustics has been a determining factor for the changing of the office layout. Below it is reported an historical overview of how acoustics led to the development of different office layouts from 1900 to today.

The Tayloristic office

Engineer Frederick Winslow Taylor[2], in the early 1900s, noticed that workers did not work efficiently due to interruptions and conversations between colleagues. Therefore, he defined an open-plan office, where each employee had its own workstation and they were seated in front of a supervisor, thus they could be constantly monitored (see figg. 3 and 4).

From the architectural point of view, the offices were brighter and more spacious, but also more uniform and noisier. Therefore, the office proposed by Taylor was a

[2] Frederick Winslow Taylor, (born March 20, 1856, Philadelphia, Pennsylvania, U.S. – died March 21, 1915, Philadelphia), American inventor and engineer who is known as the father of scientific management. His system of industrial has influenced the development of virtually every country enjoying the benefits of modern industry.

failure because the workers were constantly distracted by noise coming from machinery and conversations between colleagues.

Moreover the furniture became simpler, without paying proper attention to ergonomic aspects.

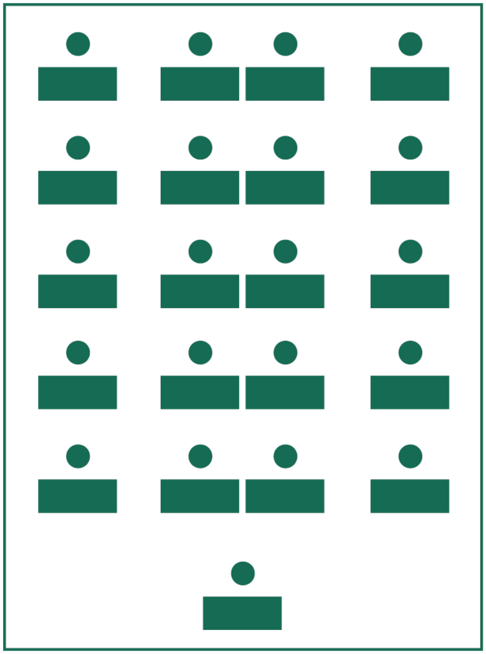


Fig. 3: Schematic representation of the Taylorist office layout

Fig. 4: A typical office according to the Taylorist layout

The work-stations office

An alternative to the Taylorist model was a hybrid type between the "open-plan" and the offices with light walls, so-called " work-stations layout".

This type of environment was still characterized by absence of walls, but with partitions about one and a half meters high that divided a series of boxes occupied by one or maximum two employees (see figg. 5 and 6).

This type of office layout guaranteed greater privacy and more concentration. Moreover, it guaranteed an improvement in terms of acoustic, indeed each worker, surrounded by three "light walls" – of reflective material -, was less distracted by the conversations of the colleagues sitting close to him.

The workstations were obtained by assembling containers for archives and shelves, coupled with traditional desks. However, this was an expensive solution because many containers were used.

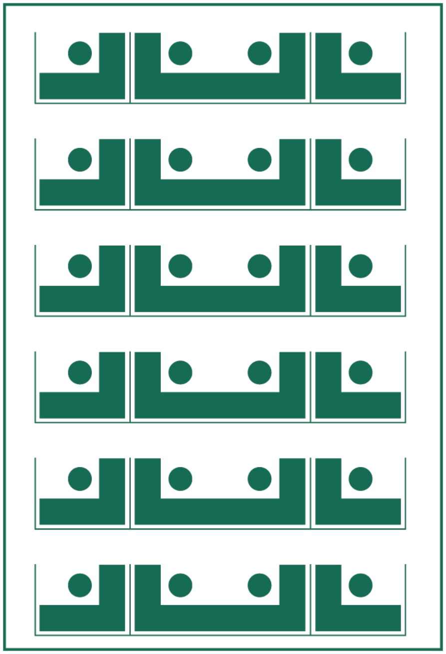


Fig. 5: Schematic representation of the work-stations office layout

Fig. 6: A typical office according to the work-stations layout

The office landscape

An innovation of the office layout was implemented by a group of business organization experts the *Quickborner Team*[3]. in the late 50s in Europe.

In this period two factors led to the change in office layout: 1) the growth in the number of employees and companies and 2) the attention of the psychophysical well-being of the worker in the workplace.

[3] The Quickborner Team, named for the town of Quickborn, a suburb of Hamburg, was founded in 1956 and it was headed by the two brothers Eberhard and Wolfgang Schnelle.

The founders of the Quickborner Team, *the* two brothers Wolfgang and Eberhard Schnelle, were the first to realize that the aspect and characteristics of the workplace had an important impact on the psychophysical state of employees, and that their productivity depends on these [23].

On one hand Quickborner Team recognized the economic and logistical advantages of the open-plan office, on the other hand they realized that the casual arrangement of the workstations caused feelings of discomfort, stress and dissatisfaction for work. Therefore Quickborner Team developed a new office layout called "Bürolandschaft" or "office landscape" [23].

They redesigned the open-plan office in a large space free of walls, corridors and partitions in favor of screens and plants used as dividers between people and departments. In this perspective the name "office landscape" is suggested by a naturalistic view of the office, given also by use of green plants as screens (see figg. 7 and 8).

In this framework the hierarchy of space of the office was abolished, thus managers and employees were placed at the same level and seated on the same floor. In this type of layout furniture was arranged tidily, paying attention to details that have been neglected until now: *"the use of carpeted floors was frequent, a sound-absorbing ceiling was used to limit noise in the environment, use of anti-glare lamps, full air conditioning was used, and also the chromatic study for interior design for the first time was scientifically studied"* [23].

Each floor was capable to accommodate up to 80-100 workers and the office buildings were very large and with few floors.

Everything was reduced to the essentials and only the useful furniture was maintained. For example, the old desks were deprived of drawers and were reduced to simple tables with furniture for archives. The sound-absorbing panels and barriers had been made flexible and movable.

The environmental conditions - lighting, air temperature and humidity, and acoustic conditions - should have been carefully studied to provide comfort. The Quickborner Team developed a short list of guide line for office occupancy. Among these the acoustic component was mentioned as follows:

<u>Acoustics</u>: *"Conditions would be made ideal by the provision of sufficient sound-absorbing materials to reduce noise to a low level, but one still well above the extreme quiet that makes every "pin drop" sound stand out. In practice this meant*

acoustic treatment of ceilings and the carpeting of all floors. Solid furniture masses and any surfaces that might reflect sound were to be minimized or eliminated" [10].

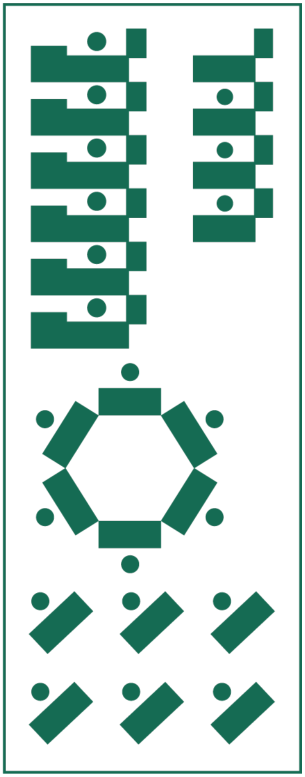


Fig. 7: Schematic representation of the office landscape layout

Fig. 8: A typical office according to the office landscape layout

The action office

An evolution of the office landscape layout was represented by the "Action Office" designed by Robert Propst[4] [26]. Propost's proposal was an individual space for employees within the open-plan environment without causing obstacles to the workflow.

The initial idea was to create an "open fence" with panels, connected together. On these panels worktops and shelves have been placed according to a scheme that depends on the needs of individual employees. This system consisted of a hybrid space - closed space mixed with open space. This solution of semi-open cells, connected to each other, generated a physical order that made it possible to differentiate individual areas, group areas and paths (see figg. 9 and 10).

[4] Robert Propst (1921 - 2000) was a researcher and inventor who was let to an interest in furniture when he took up a post as a researcher for Herman Miller, Inc., in 1960.

The arrangement of furniture based on equipped panels was more expensive than the previous landscape office layout theory. The action office began to diffuse when the weaknesses of the office landscape were evident. In fact, after 1970 many industries were converted to the concept of the action office layout. Some planning companies (such as JFN., Inc., in New York and Chicago) adopted Action Office with great fervor [12].

In any case, the use of the Action Office had positive and negative outcomes:

positive outcomes given by the possibility of having more storage space, unique workstations, a higher level of privacy and less noise disturbance;

negative outcomes because the need to schematize each individual-based workstation became a complex load; moreover, the use of panels to support components led to a wider division of the really useful one, generating a costly expense for the company.

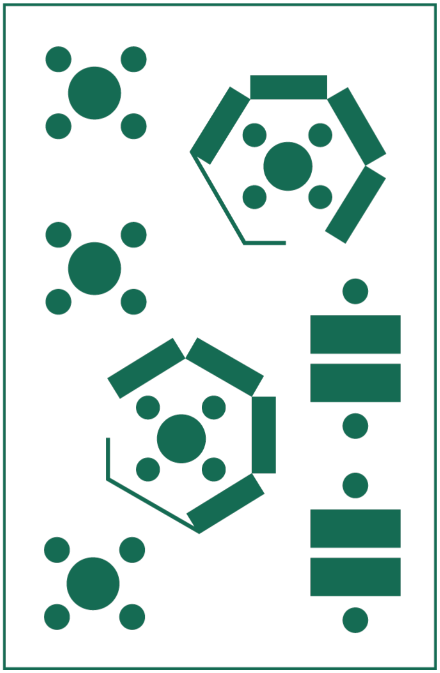


Fig. 9: Schematic representation of the action office layout

Fig. 10: A typical office according to the action office layout

The cube farm

In the 1980s, a new layout was designed called cubicle or cubic farm. Its aim was to create a situation of total privacy for the employee. It was a very cheap accommodation that consisted of a large hall in which a series of workstations were arranged tidily. Within each there was only one worker, with his own personal desk, surrounded by three vertical partitions. This organization of the workplace guaranteed a high level of privacy and a reduction of distraction because an

employee is not distracted by what a colleague is doing in the nearby cubicle [21] (see figg. 11 and 12).
Over the years the cubicle was severely criticized since they led to a standardization of the workplace and to a dehumanization of the staff.

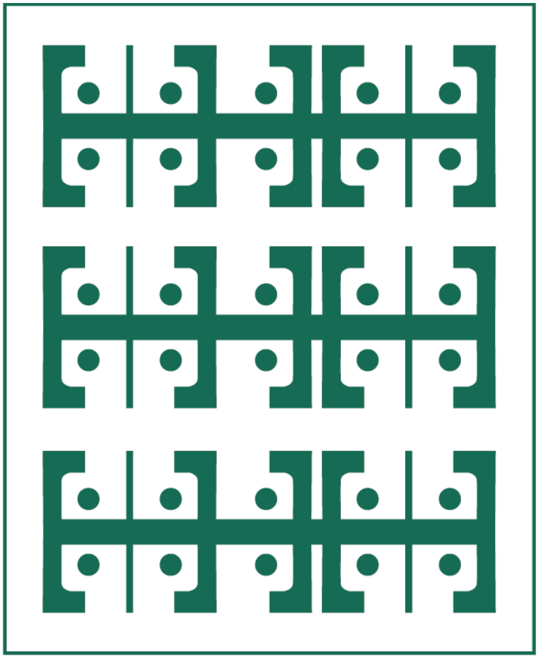


Fig.11: Schematic representation of the cube farm layout

Fig. 12: A typical office according to the cube farm layout

The post-modern office

From the 90s onwards, with the advancement of technologies and the information revolution, verbal and written communications are increasingly lacking, in favor of cable communications dictating the rules of the internal distribution of the office layout. The redefinition of space is based on the hybridization of the two opposite models discussed so far: the closed space and the open space.

The new millennium has introduced a new way of conceiving space. People do not necessarily want to work in many different places and prefer to convene and work together in one place.

The introduction of refreshment areas, cafeterias, relaxation areas and social gathering spaces, has led to a place in which working and leisure time coexist. This innovation in the world of work has led to an improvement in the physical, social and emotional conditions of employees, but above all, working conditions, performance and productivity have increased thanks to a better condition of well-being and comfort [22].

The purpose of the 21st century offices is to improve the community and the collaboration between the employees. Therefore, there is a return to the open-plan, in which there are no hierarchies or divisions anymore according to the office landscape developed in the late 50s in Europe (see figg. 13 and 14).

Nowadays open-plan office is widespread especially because its supporters think that it promotes cooperation, social relations, communication, solidarity and knowledge-sharing between workers [13]. They are adopted by large companies such as Facebook, Google, Microsoft where the space is fragmented according to the tasks to be performed: wide open spaces, smaller team spaces for work-team and pods for private conversations, in order to meet the needs of privacy or team collaboration.

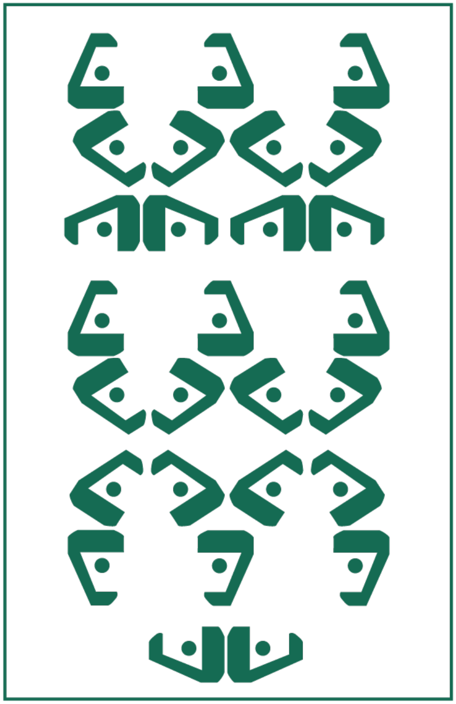


Fig. 13: Schematic representation of the post-modern office layout

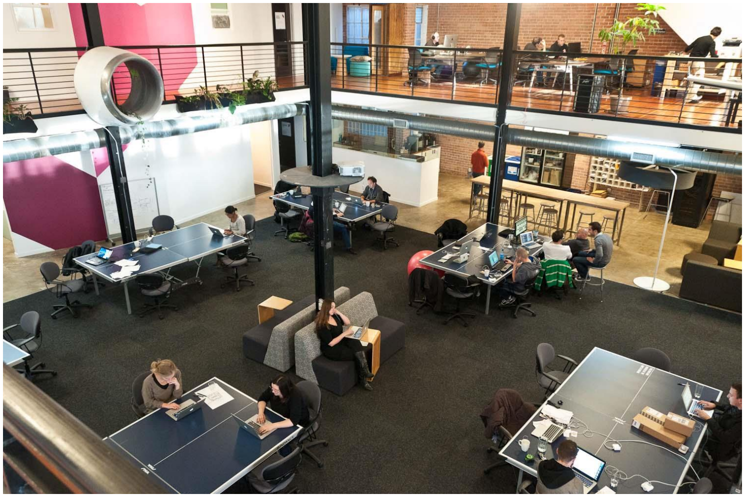


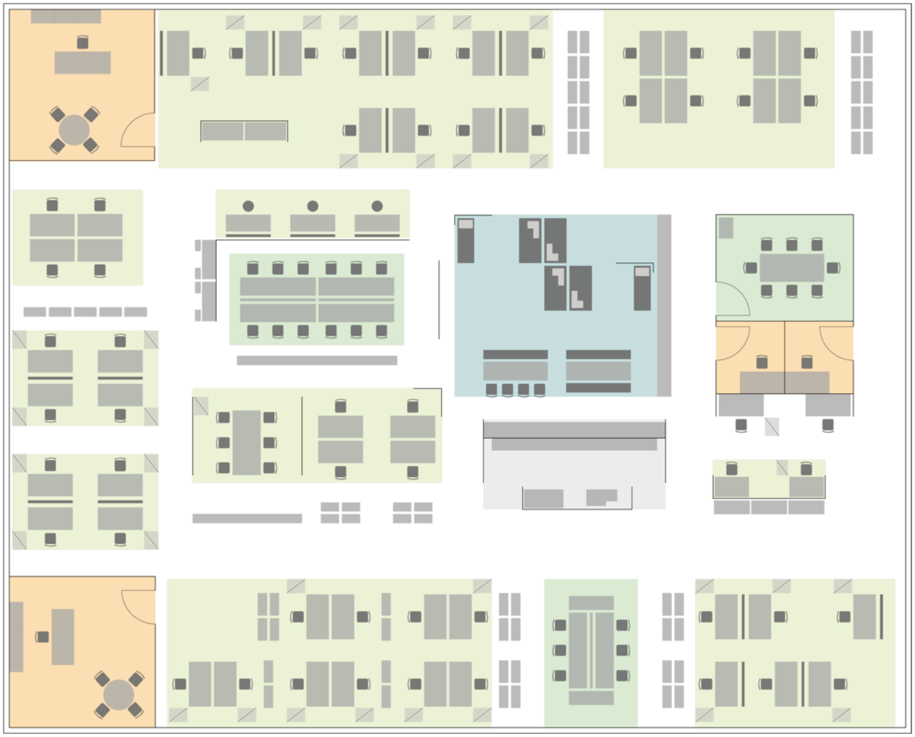
Fig.14: A typical office according to the post-modern office layout

1.2 OFFICE LAYOUT NOWADAYS

The main argument for an open-plan office is to improve communication and knowledge-sharing between workers, and therefore promote performance [7]. The open-plan office can be organized in a variety of areas and these can be dislocated and used for a variety of purposes and for a variety of occasions. These include elements that form self-sustaining units within a person can do their job without interruptions, or they can be used for group meetings, exchange of ideas and informal discussions. But this also includes the aspect of modernity: create a communication environment without barriers, easily accessible by everyone [25].

The post-modern office layout includes both the concept of **co-working office layout** and that of **activity-based office layout**.

OPEN-PLAN OFFICE LAYOUT



Discussion
Team
Private offices/manager
Lounge area
Technical Equipment

From the distribution and organization of spaces point of view, co-working and activity-based office are very similar. The difference is in the users:
co-working spaces are occupied by self-employed workers who are not part of the same company, such as freelancers, startuppers, small businesses, and employees of large companies who work from remote locations; while activity-based office are mainly occupied by workers of the same company who decided to adopt this type of layout.

CO-WORKING OFFICE LAYOUT

Co-working is a new philosophy of work born in the 21st century. The term co-working was first coined by Bernie DeKoven[5] in 1999. He associated the term with a web resource capable of sharing several online services simultaneously through a single interface. In 2005 the concept was taken up by Brad Neuberg who uses the term to describe a physical space shared by independent and dynamic workers.

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[5] Bernie De Koven is a multidisciplinary professional: writer, theorist, humorist, but above all he has devoted much of his life to the virtual world of video game design.
This last role led him to formulate the central approach that gave birth to the concept of co-working in the 90s: to look for that collaborative work that has a personal benefit, but also a common one.

Neuberg founded the first co-working space, Hat Factory, in a loft in San Francisco [27].

According to *oxford dictionaries* the definition of co-working is as follows: *"the use of an office or other working environment by people who are self-employed or working for different employers, typically so as to share equipment, ideas, and knowledge"* [31].

In a study of collaborative production in Berlin [15], Bastian Lange provides another definition of co-working: *"spaces as bottom-up spaces participated by workers who strive for independence, collaborative networks and politics, and that share a set of values in a collective-driven, networked approach of the open source idea translated into physical space"*. The idea behind this concept is that productivity depends mainly on social relationships in co-working spaces, conceived as spaces where freelancers work in non-hierarchical situations.

However, noise is a persistent problem in a co-working office. Being an open environment and, often, without the right acoustic design, people who occupy a coworking office are bothered by the speech of other co-workers. In this context it is difficult to find silent/private spaces or soundproofed booths that could reduce noise, or allow workers to temporarily isolate themselves [20].

From a practical point of view, co-working involves renting a workstation in an open-plan environment for a variable period of time. In the co-working spaces professionals can share a large office and take advantage of a wide range of services: conference rooms, coffee machines, hot-desking, small group offices, living room.

An example of a co-working office layout is showed in figg. 15 and 16.

Fig. 15: Impact Hub, Oakland, designed by Flynn Architecture.

Fig. 16: Impact Hub, Oakland, designed by Flynn Architecture.

ACTIVITY-BASED OFFICE LAYOUT

Activity-based workplaces (ABW) design consists by creating multiple areas tailored to work tasks such as "hubs", that are common areas allowed for greater opportunities to collaborate, for team working and collaborative areas for brainstorming and meetings. This layout model gives workers the choice of choosing the workstation based on the needs of the current activity. Rather than forcing people to do all their work in a specific setting, people are allowed to physically locate where it is best suited for them to complete their task. A clear difference between open-plan offices and activity-based offices is office use. The open-plan offices applies assigned workstations while the activity-based offices applies a non-territorial workplace concept with flexi-desking [8].

Depending on the type of activity, ABW is usually divided into three different zones; quiet, middle and active zones [19]. Quiet zones, usually small offices with physical partitions, are suited for focused work. Intermediate areas are suitable for collaboration between employees. Active zones facilitate virtual or physical meetings. The different zones can be interconnected, or strictly separated and defined by physical partitions (such as acoustic panels, furniture). The furniture in

the office is an important part of the design because it can help the user understand what kind of zone it is, and what type of activity that is to be carried out [19].
In this type of office layout, a series of acoustic solutions can be adopted to ceiling, wall, or through dividing panels and furniture. They will be explained in chapter 3.
An example of an activity-based office layout is showed in figg. 17 and 18.

Fig. 17: Eneco Headquarters, Rotterdam, designed by Hofman Dujardin Architects and Fokkema&Partners.

Fig. 18: Eneco Headquarters, Rotterdam, designed by Hofman Dujardin Architects and Fokkema&Partners.

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2. Pros and cons of shared and open-plan offices

2.1 Irrelevant speech noise (ISN)

2.1.1 Definition

2.1.2 Effects of ISN on annoyance, health, well-being and performance of employees

2. Pros and cons of shared and open-plan offices

The contents of this paragraph deal with the themes of advantages and disadvantages of open-plan office planning. There has always been a great debate about how the perfect office environment should be set. There are two currents of thought: on the one hand, there are those who think that an open-plan design encourages teamwork, on the other hand there are those who think that such an environment is a source of disturbance. Therefore here's a recap of the main advantages and disadvantages of open-plan layout [**Errore. L'origine riferimento non è stata trovata.**].

Open planning can offer some advantages listed below. Most installations fully achieve some of these positive aspects, others to a more limited measure.

BETTER COMUNICATION

When an office is free of physical barriers, employees feel more involved in the work.

By working all in the same room, no one feels less important than the others: even managers and business leaders choose to work alongside their employees. In this way people feel all at the same level, automatically increasing well-being and involvement. People can talk to each other, use visual cues and pass documents from hand to hand without crossing separate spaces and corridors.

FLEXIBILITY OF SPACES

Offices, in general, due to the clutter of desks and partition panels, minimize spaces and movements, limiting the number of employees who can comfortably work in the building.

With open-plan offices, furnishings such as desks, wardrobes, chairs can easily be moved from one place to another, according to the needs of the workers, thus favoring an increasing number of staff.

This is a positive aspect for those companies that need to accommodate more staff and have the opportunity to move the furniture according to needs. For this reason it is easier to plan changes in the arrangement of both the workstations and furniture, as there is no partition to be demolished and rebuilt [20].

REDUCTION OF COSTS AND SPACES

Open offices are more cost-effective than traditional cubicles or private offices. By not buying large desks and walls of the cubicles, there are fewer overheads, and at the same time it is possible to guarantee to each employee a desk and the necessary equipment to carry out the tasks.

If the company wants to redesign the layout, this can be done day by day with no construction costs and lost work days. Thus, in terms of savings, open planning is economically preferable.

BETTER AESTHETICS = GREATER WELL-BEING

The open-plan offices have clean and sober lines and atmospheres that are not found in the cubicles. When you choose to work in an open room, there is more space to breathe, which provides more creativity and health to employees. A greater care of the aesthetics of the open-plan office layout, such as more natural lighting, natural furnishings such as plants and flowers, makes the workplace more livable and comfortable. Nowadays, green spaces in offices are widespread as these generate positive physiological responses [6], such as increased brain activity and lowering stress levels. Good planning and a good location of equipment leads employees to prefer open-plan offices rather than closed cubicles. "*This leads to an improvement in morale, a reduction in absenteeism and employee turnover and the improvement of total office productivity*" [12].

Despite this series of potential advantages, it is natural to wonder why this type of layout can still be questioned about its validity. Opposing the use of the open plan derives from situations in which the open-plan office layouts have been poorly designed.

This negative reaction is based on negative aspects described below.

LACK OF PRIVACY

Lack of privacy is one of the strongest environmental factors producing dissatisfaction in open-plan offices [1]. This is caused by the absence of rooms that could be used for private discussions, group meetings or demanding jobs that require more concentration [**Errore. L'origine riferimento non è stata trovata.**].

To obtain good acoustic privacy it is necessary to consider the masking sound, the height of the screen and the absorption of the architectural environment (ceiling, walls, screens). Furthermore, there are many other things that affect speech privacy such as the distance between workstations, amount of speech and speech levels.

According to a study by Valtteri Hongisto [10] on the relationship between the quality of the physical environment and the satisfaction of employees, it emerges that the results are in line with the idea that the bad design of the open-plan office and the lack of privacy constitute a stress factor for the individual worker.

If the intervention studies are well designed they could have positive effects on the acoustic privacy of the occupants, and consequently on their degree of satisfaction.

STRESS

In relation to the lack of privacy, there is another disadvantage of the layout of an open office: the possibility for employees to be more stressed. Stress in an open-plan office has negative effects on people's health, but it can also cause paranoia to workers because they feel like someone is always looking behind them.

Stress also increases the ability to distract and be interrupted while performing a task; it means that for every break, to which workers are subjected, there is a waste of time which is detrimental to the economic productivity of the company. According to a study by Loewen and Suedfeld [6] submitted to some university students, it emerged that the latter said they had a more negative mood and felt more disturbed and stressed than the participants in the quiet condition of confrontation. The effects of intelligible speech in open-plan environments have negative effects on long-term occupants due to the stress caused by the poor acoustic conditions of the environment [19].

Intelligible speech must be controlled in open-plan office environments to avoid the long-term negative effects of stress [14].

GREATER RISK OF ILLNESS:

Without partitions or walls and with more people working closely together, employees are at greater risk of getting sick because an employee who fights a cold has a greater chance of spreading it to neighboring colleagues. As a result, companies are more prone to a high rate of absenteeism at work and of claims for illness, as well as a decrease in productivity [19].

The insecure and unhealthy working environment in terms of poor ventilation, inappropriate lighting, excessive noise, etc. affects the workers' productivity and health [5].

Several researchers (Pejtersen et al., 2006 [11]; Haapakangas et al., 2008 [8]) studied how noise has adverse health effects, comparing the declared health of people working in an open office and that of people working in a private office .

They found that the percentage of noise-complaining occupants was 10 times higher in open-plan offices than in private offices. The most common symptoms are headaches, fatigue, fatigue and difficulty concentrating.

For example, Bodin Danielsson et al. [2] have shown, in a recent study, that there is a higher prevalence of short periods of sick absenteeism among employees working in open-plan offices, compared to those who occupy a private office.

NOISE AND DISTRACTION

But the most problematic aspect of the open-plan office is the high amount of noise, caused mainly by the chatter of colleagues, but also by electronic devices, computers, machine systems, which compromise workflow and concentration. This is given by the fact that often the acoustic component is not treated in the same way as the thermal, ventilation and other architectural and engineering considerations:

probably because the causes and consequences of a poor acoustic design is not adequately understood by designers and owners of offices buildings.

2.1 IRRELEVANT SPEECH NOISE (ISN)

2.1.1 Definition

The open-plan office, for its conformation, is an environment that allows the diffusion of sounds and noises more easily. Among these phones ringing, people speaking on the telephone, people speaking to each other, computer keyboards, office equipment, musical ambience or background noise, ventilation or air-conditioning system, noise outside the building, etc... (SBiB 2010).

Noise in open-plan offices is considered to be the main source of distraction and dissatisfaction on the part of workers. In particular, the *irrelevant speech noise (ISN) is the noise that is generated from conversations between colleagues, telephone* *calls and laughter* [4]. Since the level of background noise due to the conversations of workers is very high, it means that it negatively affects the mental and physical conditions of colleagues.

2.1.2 Effects of ISN on annoyance, health, well-being and performance of employees

Over the years a multitude of surveys have been carried out concerning the effects that the ISN has on annoyance, health, well-being and performance of employees. Surveys were performed on the different office layouts: e.g. Becker et al. (1983), Danielsson (2005) [3], Pejtersen et al. (2006) [11] and Jensen et al. (2005), have shown that the most unsatisfactory factor causing discomfort in office is noise. Danielsson (2005), comparing many office layouts, has reported that dissatisfaction with noise and privacy was very high especially in large open-plan offices [3].

Another study by Pejtersen et al. (2006) [11] found that the percentage of occupants who rated noise as the main source of annoyance was ten times greater in large open offices than in cellular offices.

The same study showed an association between office size and numerous symptoms, including fatigue, headaches and difficulties in concentration.

Haapakangas et al. in 2008 [8] also remarked that people who work in open environments have almost negative perceptions; they consider the acoustic quality as well as the thermal quality, lighting and air quality of the offices to be significantly lower.

Therefore, the perception of the working environment and job satisfaction depend on the physical conformation of the work space: hence the layout of the office.

Exposure to noise in a closed environment is a risk in terms of hearing impairment, hypertension, discomfort and sleep disorders [17], [18].

Furthermore, there is evidence regarding the correlation between absenteeism at work and exposure to noise.

Analyzing some subjects exposed to the condition of office noise and other subjects exposed to the condition of stillness, it was found a greater concentration of the stress hormone among the first, although these did not declare a particular state of stress [6]. Although the results of other studies are conflicting, noise exposure is more prevalent in open environments and particularly in open-plan offices.

An explanation of the office-noise correlation could be that occupants in shared offices are more likely to be exposed to viruses than occupants in closed/private offices. A study has shown that this is mainly due to ventilation and air movement in open buildings: this leads to a more rapid spread of infectious diseases [15].

Another explanation has to do with the presence of other people sharing the same workspace. Working in an open-plan office can reduce employee autonomy, since the absence of physical barriers increases the likelihood that people will interfere with the discretion of their colleagues.

Lack of autonomy can be a stress factor, as it is related to exhaustion, and therefore can be a factor contributing to sickness absenteeism.

Studies [7] have shown that working in coexistence with others can lead to social facilitation, but if employees are subject to an assessment by managers, this could lead to inhibition rather than social facilitation. This stress factor can therefore also be a factor contributing to a greater demand for rest days by employees.

As Sonja Di Blasio et al. report in "A subjective investigation on the impact of irrelevant speech noise on health, well-being and productivity in open-plan offices": “*Regarding the work productivity, previous researches have found a self-estimated loss in performance caused by open-plan office noise. A recent number of laboratory experiments suggested that cognitive performance is negatively affected by irrelevant speech noise*” [4].

Therefore, the negative effects of the open-plan office layout can compromise both the health of workers, in psychic and physical terms, and their productivity and performance. For this reason many researchers have stated that working in open-plan environment is not recommended [16].

The workplace environment plays a vital role in terms of employees productivity. The heads of companies must force themselves to design an environment in which the operators perform their tasks in a favorable and comfortable mood, both to avoid problems related to the health of employees, and to avoid delays in achieving tasks (performance).

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3. Acoustic solutions for different office layouts

3. Acoustic solutions for different office layouts

In this chapter the topic of the different acoustic solutions that can be adopted within an open-plan office is treated.

More people in the same office means more noise to contend with. Employees, to compensate for this high noise, increase their tone of voice when they talk to each other, which in turn means a further increase in noise levels in the room. In addition, many open-plan offices are derived from old buildings, with high ceilings and concrete surfaces - or other hard surfaces - that tend to reflect noise. For this reason, absorbent materials and elements are widely used in order to reduce reverberated sound energy.

Today there are many different acoustic solutions in open-plan offices that can be applied through many different methods, preserving the layout of the room and optimizing the sound quality. Among these there are:

1. **acoustic solutions for ceilings, walls and flooring;**
2. **screens between workstations;**
3. **acoustic furniture.**

1. Acoustic solutions for ceilings, walls and flooring

The ceiling is a reflective surface that must be treated in open-plan offices. The use of sound-absorbing materials for ceiling has its advantages because excessive reverberation and the disturbing propagation of sound via reflections off the ceiling are avoided [5].

The ceiling is a reflective surface that must be treated in open-plan offices. The use of sound-absorbing materials for ceiling and walls has its advantages because excessive reverberation and the disturbing propagation of sound via reflections off the ceiling are avoided.

Sound absorption in these materials occurs through the conversion of part of the incident energy into heat. This process occurs in different ways depending on whether one of the three fundamental sound absorption mechanisms is chosen: by porosity, by membrane resonance, by cavity resonance.

Sound absorption in materials occurs through the conversion of part of the incident energy into heat. This process occurs in different ways depending on whether one of the three fundamental sound absorption mechanisms is chosen: by porosity, by cavity resonance, by membrane resonance.

ABSORPTION BY POROSITY[6]

Porous materials consist of an open-pore structure (pore size less than 1 mm). The acoustic wave that affects the porous material causes the vibration of air molecules inside the pores; the vibration produced causes a transformation of the incident sound energy into heat due to friction in the microcavities of the material.

ABSORPTION BY CAVITY RESONANCE

Resonance absorbers consist of a volume of air in a cavity with rigid walls, connected to the external environment through an opening called "neck of the resonator". The sound wave that affects the neck of the resonator causes the vibration of the air inside it and it undergoes compressions and rarefactions. So the air behaves like a vibrating mass.

[6] Porosity is defined as the ratio between the volume occupied by the pores and the total volume. Sound absorption increases with increasing porosity. The materials that absorb sound most effectively have porosity over 90% [10].

A very common application of cavity resonators is represented by perforated acoustic panels. The perforated panels consist of a perforated structure, at a certain distance from the wall, and porous material in the interspace.

ABSORPTION BY MEMBRANE RESONANCE

It occurs when a panel, placed at a low distance to a rigid wall, behaves like a vibrating mass, while the air in the cavity acts as an “acoustic spring”. The effectiveness of the sound absorption of this system can be increased by inserting porous material into the cavity.

The choice of ceiling materials was once limited to plaster, gypsum board and mineral or fiberglass tiles [4]. These types of ceiling materials have a very low sound absorption coefficient. For example, a gypsum board ceiling has a Noise Reduction Coefficient (NRC)[7] of about 0.05.

To ensure a high degree of noise attenuation, ceilings and walls must be highly absorbent in open-plan offices. To do this, materials with better acoustic

[7] NRC (Noise Reduction Coefficient) measures how much sound materials can absorb. The NRC is the percentage of sound that a surface absorbs. So a carpet on rubber underlay could easily have an NRC of about 0.4 (it absorbs 40% of the sound hitting it and 60% bounces back), while a glass window might score only about 0.05 (it reflects 95% of the sound hitting it straight back again).

characteristics than plasterboard or plaster are used, such as rockwool, mineral wool, polyester fiber, glass wool, fiberglass with fabric covering. Moreover, a factor that influences the absorption of the acoustic panel is the thickness. The thicker the panel, the higher the absorption.

For example, fiberglass tiles with a fabric covering have the highest scores. In fact, a fiberglass tile with a thickness of 19 mm has an NRC value of about 0.90 and with a thickness of 38 mm its value can reach a value of 1.0 [4].

Mineral tile ceilings have NRC values, ranging from 0.55 to 0.65. This value depends on both the thickness and the surface treatment. An example of how the thickness of the material affects the sound absorption is shown in fig. 1.

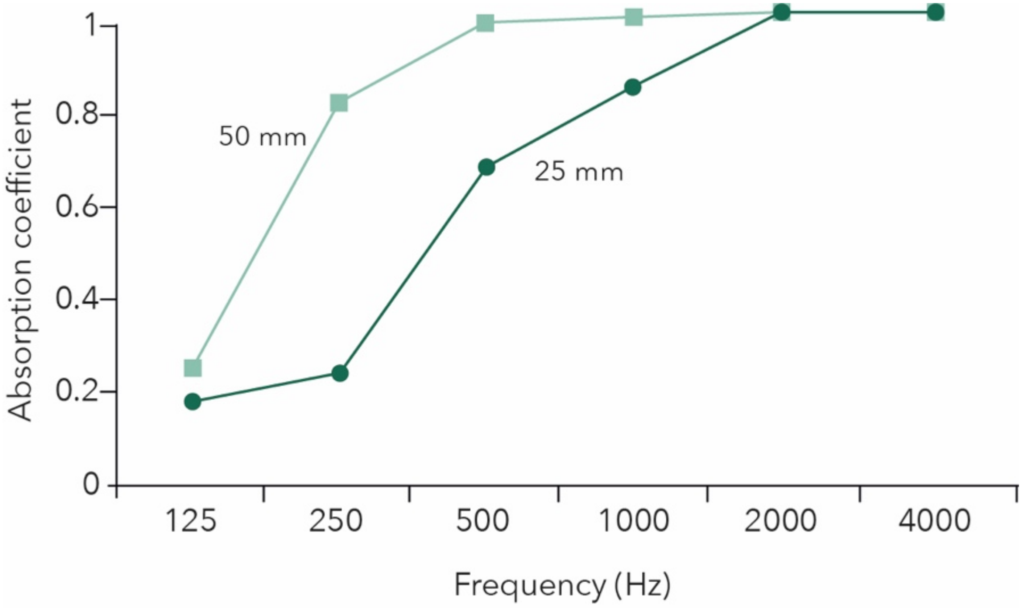

Fig. 7: Random incidence absorption coefficient for mineral wool of two different thickness on a rigid backing.[8]

When it is not possible to install acoustic ceilings, the absorbent elements can be represented by single objects arranged in rows, as in the case of baffles (see fig. 2). They are elements designed to absorb and/or interfere with sound waves that prevent them from dispersing in a closed space and they are installed hanging from the ceiling. The two extruded sides of the acoustic baffle, generally covered in fabric. Their composition allows them to effectively damp the sound waves and become an aesthetic element within the office [2].

The absorbent properties of the baffles are expressed as an equivalent absorption area, deduced from the variation induced by the presence of the material on the reverberation time of the empty chamber. By decreasing the interaxle spacing of the panels, the number of panels increases and therefore also the area of equivalent absorption [10].

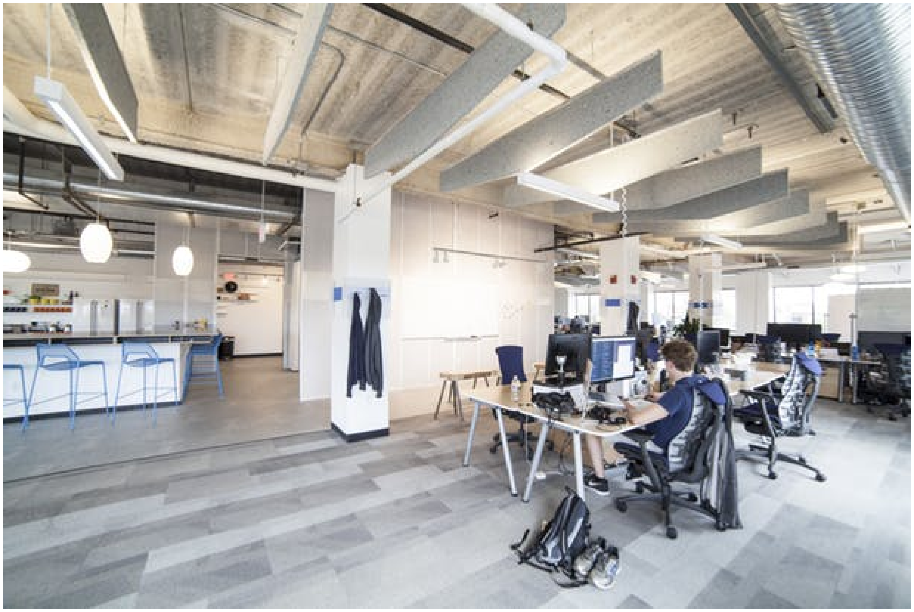

Fig. 8: Example of applications of baffles on ceiling.

Regarding the flooring, carpet can be applied to the floor to dampen sounds at high frequencies, but it does not prevent sound propagation inside the room [5] (see fig. 3). An advantage of carpet is the reduction in the transmission of impact sound, in particular the noise of footsteps, in neighboring rooms.

Fig. 9: Example of a floor covered with carpets.

2. Screens between workstations

Another acoustic element in open-plan offices is screening - in the form of movable partitions. These elements are installed between workstations in a height range between 1.30 m and 1.70 m from the floor as reported by V. Hongisto [11] et al. [3].

Placing acoustic screens between workstations is important because speech of nearby colleagues is often the main problem inside an open-plan office [11]. Such screens can guarantee different levels of screening depending on their position. For example, if they are positioned to face the corridor, full-height screens ensure a degree of privacy and reduce distractions due to persons passing, slamming doors, ecc.

As previously mentioned for acoustic panels, the acoustic absorption of the these elements depends on their thickness.

Moreover, depending on weighted sound attenuation, $\Delta L_{s,w}$, screens can be classified in different screen sound attenuation class as showed in tab. 1:

Screen sound attenuation class	**Requirement**
A+	$\Delta L_{s,w} \leq 19$
A	$15 \leq \Delta L_{s,w} \leq 18$
B	$12 \leq \Delta L_{s,w} \leq 14$
C	$9 \leq \Delta L_{s,w} \leq 11$
D	$6 \leq \Delta L_{s,w} \leq 8$
Not classified	$\Delta L_{s,w} \leq 5$

Tab. 1: Classification of screen sound attenuation [6]

Generally acoustic screens are covered with noise reducing materials such as felt wool or polyester fabric. They can be installed in a number of different applications including: as a freestanding element (see fig. 4), desktop separator (see fig. 5) and or workstation divider (see fig. 6).

Fig. 4: Example of an acoustic screen as a freestanding element.

Fig. 5: Example of an acoustic screen as a desktop separator.

Fig. 6: Example of an acoustic screen as a workstation divider.

3. Acoustic furniture

With acoustic furniture or furnishings made with acoustic materials, the necessary sound absorption is exactly where it is needed, without interrupting the flow through the design of the office. Sound-absorbing furniture helps effectively manage noise problems in open-plan offices.

Furniture elements found within this category can include high back acoustic sofas, acoustic meeting pods, privacy lamp shades, acoustic chairs. If there is a lack of meeting rooms, a space can be defined with soft acoustic seats or creating a mobile room with meeting pods.

Among the different acoustic furnishings, the concept of the acoustic chair is one of the most innovative uses of space in an open-plan office (see fig. 7). Employees can use cocoon hoods to make a phone call or simply to isolate themselves, blocking disturbing noises. The high, upholstered structure absorbs ambient background noise providing complete privacy from the surrounding environment without the need for interior sub structures. The external and internal hoop are in fabric, while the seat and cushion upholstered are in fabric, leather or vinyl.

Fig. 7: Cocoon acoustic chair

Another expedient belonging to the "acoustic furniture" family is the acoustic chair (see fig. 8). This type of seating is quite flexible; it can be easily moved from one position to another in the office, depending on the needs of the employees. This acoustic chair is particularly useful if an employee wants to make a privacy call within an occupied space. In this way the employee is not disturbed by office noise and the other employees are not disturbed by the phone call. In this way, employees can concentrate better and work more productively.

Fig. 8: A model of an acoustic chair.

Nowadays in the open-plan offices a specific space is often required to isolate themselves from the rest of the office, to make calls in absolute privacy, without disturbing the colleagues of the nearby workstations. In this regard, the best solution is represented by the so-called "phone boxes" (see fig.9).
It is a sound isolated workspace ideal for private phone calls, video conferences and demanding tasks. It cuts down the noise in open-plan offices and improves the everyday life of entire organizations by freeing the potential of individuals. The phone box can be easily placed and relocated around the office according to an existing floor plan providing people a quick escape from the noise.
Regarding materials, the external surface is usually painted sheet metal of brushed stainless steel; while the internal surface is composed of a sandwich element of sheet metal, birch plywood, recycled acoustic foam and acoustic felt.

Fig. 9: Acoustic phone box

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Case study

4. Shared and open-plan offices at Politecnico di Torino

   4.1 Acoustic characterization

4. Shared and open-plan offices at Politecnico di Torino

The first part of this chapter deals with the description and explanation of the offices taken as case studies. More specifically, in the second part the characterization of the offices from the architectural and acoustic point of view is dealt with.

Within the Politecnico di Torino, some offices have been selected with the predominant feature of being shared offices or open-plan offices. Shared offices are offices with a number of occupants ranging from two to five employees per room, while open-plan offices are offices with more than five employees [1].

On site photographic investigations were made of seven offices: of these seven, five were chosen as case studies.

By convention shared offices will be indicated with the name "SH office n° #", while open-plan offices will be indicated with the name "OP office n° #".

The selected offices differ from each other in a number of factors: dimension, number of occupants, acoustic characteristics and tasks performed within the office.

OFFICE	NUMBER OF OCCUPANTS	VOLUME	DESIGNATED USE
OP OFFICE 1	20	580 m^3	Research office
OP OFFICE 2	21	487 m^3	Research office
SH OFFICE 1	6	157 m^3	Office open to the public Administrative office
SH OFFICE 2	6	135 m^3	Administrative office
SH OFFICE 3	5	51.50 m^3	Technical/administrative office for teachers and researchers

Table 10: Characteristics of the offices where measurements were done.

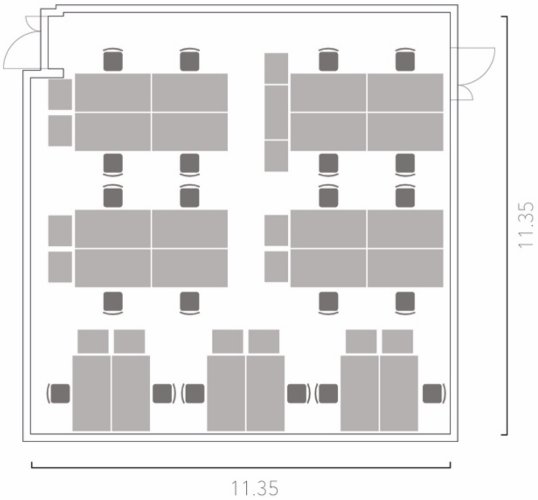
Each office has been analyzed on architectural and acoustic characteristics. On site investigations defined the location of the office, the dimensions of the room - area and volume -, materials and surfaces.

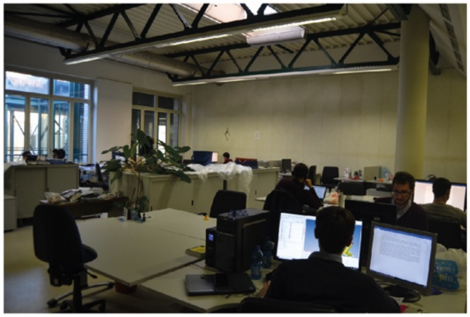
Regarding the materials and surfaces, these have been analyzed for acoustic evaluation purposes.

4.1 Acoustic characterization

What follow are the characterization sheets with a brief description of each office. The knowledge of these characteristics helps to understand the different acoustic behaviors, in order to subsequently choose the method of field measurements.

OP OFFICE 1





Characteristics of the office

Average ceiling height: 3.96 m

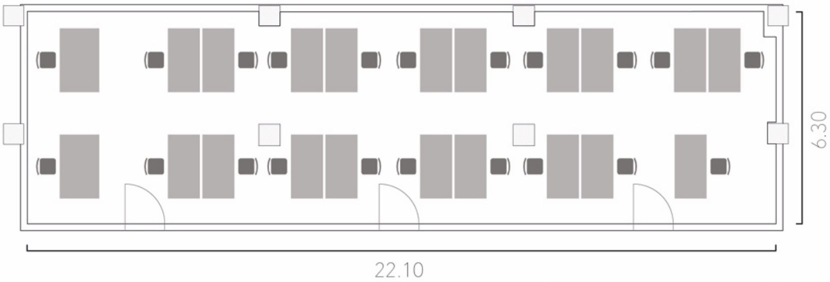
Area: 130 m²

Volume: 580 m³

Surfaces and materials:
Office surfaces are characterized as follows:
wooden desks; metal cabinets; moderately padded chairs; acoustic door with steel frame, double seals, absorbant in airspace; two glazed surfaces (windows) - area = 6.5 m²; plastered walls; steel trapeze profile ceiling.

Acoustic:
Two walls opposite the entrances are covered by a layer of vibrating panels;
six bosex of air ventilation grille along the wall to the left of the entrance.

OP OFFICE 2



Characteristics of the office

Average ceiling height: 3.50 m

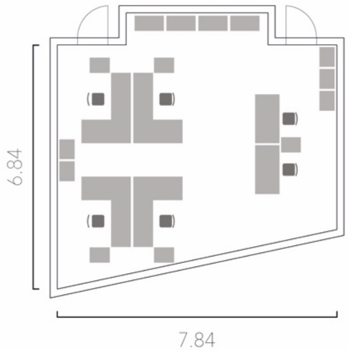
Area: 137.20 m²

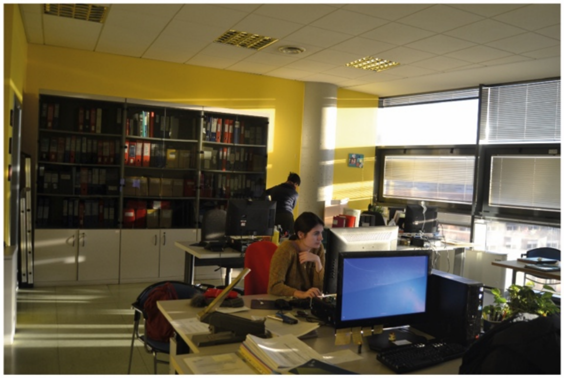
Volume: 487 m³

Surfaces and materials:
The office is characterized as follows:
long walls are covered by glass elements - full-height windows with roller blinds, alternated with plaster elements, on one side, and glass doors and walls on the other; short walls are plastered. Wooden desks and cabinets; chairs padded.

Acoustic:
False ceiling is made with acoustic panels with an acoustic absorption coefficient able to guarantee good acoustic comfort.

SH OFFICE 1





Characteristics of the office

Average ceiling height: 3.10 m

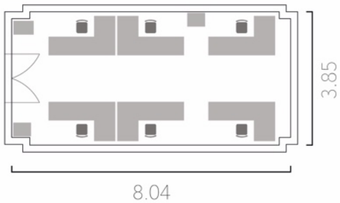
Area: 50.65 m²

Volume: 157 m³

Surfaces and materials:
Located on the third floor of the headquarters of the Politecnico di Torino in the part that runs along Corso Castelfidardo. The office is characterized as follows:
plastered walls with the exception of the oblique wall, characterized by 12 glazed elements in blocks (size of the single glazed element = 1.98 x 1 m) with darkening Venetian blinds.
Wooden desks; metal cabinets; moderately padded chairs.

Acoustic:
False ceiling is made of 600 x 600 x 40 mm absorbent panels.

SH OFFICE 2



Characteristics of the office

Average ceiling height: 4.60 m

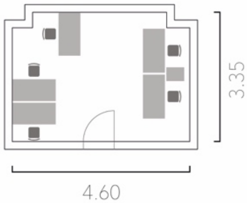
Area: 30 m²

Volume: 135 m³

Surfaces and materials:
The office is characterized as follows:
all the walls are plastered, including the ceiling; floor is covered in marble; in the entrance wall there is a wooden door; in the wall opposite to the entrance there is a glass window of dimensions 3.43 x 2.20 m with vertical banded curtains; wooden desks and cabinets; moderately padded chairs.

Acoustic:
No particular acoustic expedient adopted.

SH OFFICE 3



Characteristics of the office

Average ceiling height: 3.50 m

Area: 14.72 m²

Volume: 51.50 m³

Surfaces and materials:
The office is characterized as follows:
walls and ceiling are plastered, with the exception of the entrance wall covered with opaque glass; in the wall opposite to the entrance there is a glass window with an area equal to 6.5 m²; wooden desks and cabinets; moderately padded chairs.

Acoustic:
No particular acoustic expedient adopted.

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Case study

5. Acoustic measurements

The acoustic survey of the five offices included room acoustic measurements of background noise level and reverberation time T_{20}. Measurements were carried out in December 2018. In accordance with the availability of the occupants of the offices, two persons were responsible for transporting the technical equipment for data acquisition in the various offices. The methodology adopted for carrying out the acoustic measurements was previously agreed upon and studied so as to always use the same methodology for all offices.

5.1 Measurement protocol

Measurements of background noise level and reverberation time T_{20} were made in accordance with ISO 3382-3[8]. Measurements were performed both during working hours (1.00 pm - 2.30 pm), and out-of-work hours (after 6pm), when workers were out of the office.

[8] The standard specifies the methods for the measurement of the acoustic properties of the "open-space" type environment. It specifies the measurement procedures, the necessary equipment and the methods for data evaluation. The measurement results can be used to evaluate the acoustic properties of the "open space" type environment.

According to ISO 3382-3, measurements must be carried out in furnished rooms, but without the presence of people, with the exception of the persons necessary for carrying out the measurements themselves. This is done because the noise from people talking in the office should not be included in the measurement of the background noise level [1].

Furthermore, ISO 3382-3 states that an omnidirectional source for different reasons must be applied. First of all because the orientation of the people who speak in an open-plan office may not be well defined. Secondly, because it would be technically complicated to make realistic and sufficiently precise specifications for the directivity of a directive sound source, while the omnidirectional sound source is well established in acoustic measurements of the environment.

Regarding the measurement positions, these must be performed along a line that runs through the workstations. The optimal number of measurement positions ranges from 6 to 10: the minimum number is 4 [5].

The standard states that the source and receiver should be positioned at least 0.5 m from the desks and more than 2m away from walls or other reflecting surfaces [1].

This was not possible to fulfill due to the office layouts. Therefore a minimum distance of 1 m from the walls or other reflective surfaces has been set [8].

The height of the sound source and receiver was 1.5 m and 1.2 m, respectively, above the floor.

5.2 Acoustic parameters

The **background noise level** and **reverberation time (T_{20})** of the offices were measured. The measurements of the two parameters were carried out in different times and ways.

Measurements of **background noise level** were made in accordance with ISO 3382-3. They were made one time and in a time range that varied from 30 to 90 seconds for each position, in every office.

In particular in OP OFFICE 2, measurements of background noise level were done twice: the first time at the start of measurements, when the ventilation/heating systems were switched on, the second time at the end of the measurements when the ventilation/heating systems were switched off. This was done to understand how much the background noise level could vary in relation to plant noise.

Though *as recommended by ISO 3382-3 systems for heating, ventilation and conditioning, and other sources of sound should be driven with the same effect as during working hours*[9].

Measurements were made using a hand-held sound level meter (SLM), *SLM, XL2, NTi Audio.* The SLM was positioned at 1.2 m above floor level and the measurements were conducted while the office spaces were unoccupied, as recommended by N. Che Din et al. [6].

Before the measurements, the sound level meter was calibrated using a calibrator. Then the average background noise level was calculated.

The number of measurement points of the background noise level in the specific case study varied from 2 to 5, depending on the size/layout of the office to be measured.

Measurements of **reverberation time (T_{20})** were conducted using clapper as sound omnidirectional source (Fig. 1) [4]. The clapper was positioned at one selected point at the height of 1.5 m. The sound energy released by each impact of the clapper is

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[9] Svensson P., *Comparing measurements and simulations for acoustics in open-plan office spaces*, Norwegian University of Science and Technology, Department of Electronic Systems, 2017, p. 19.

able to excite rooms up to 200 m^3 in size with 1/3 octave levels ranging from 80 to 100 dB [2].

The clapper is characterized by two wooden boxes placed on the upper half of each of the two planks and closed towards the outer side with a 4 mm rubber layer; the aim is to obtain a greater energy concentrated in the frequency spectrum between 100 Hz and 500 Hz. The inner volume of each of the wooden boxes is filled with spongy polyurethane absorbent material to spread the effect of cavity resonances. The outer edges are strengthened by the continuation of the wooden strip that closes the sides of the wooden boxes. [2]

Fig. 11: 2009 version of the clapper used in acoustic measurements.

Regarding sources and receivers, the number of sound sources varied from 3 to 4, depending on the size/layout of the office to be measured. The same concerns the number of receivers, ranging from 4 to 9. Receivers points were also located in the manner that they apply to the whole room.

All measurements were performed by two persons.

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Case study

6. Acoustic simulations

6. ACOUSTIC SIMULATIONS

In this section the Odeon software was used to simulate two of the six offices where the acoustic measurements were performed. The calculation method using Odeon is described in this section. Then, the configuration of the offices, the construction model with a 3D modeling software, the calibration procedure - with related sound absorption coefficients used - and the simulated acoustic parameters will be explained.

6.1 ACOUSTIC SIMULATIONS IN ODEON VERSION 13.0

Simulations was done using ODEON Room Acoustic Simulation Software Version 13. ODEON is an energy based room acoustic modeller, meaning that sound waves are represented by rays. A ray can be understood as a straight line connecting a source and a receiver. Reflections are represented by image and secondary sources where still the sound to the receiver can be seen as a line – ray. These simplifications make it possible to calculate the acoustic response in large spaces [2].

This software calculates the early reflections using a combination of the image source method and ray tracing, while the late reflections are calculated by a special ray tracing process that generates diffuse secondary sources [13].

6.2 CALIBRATION PROCEDURE

First of all, the 3D models of the offices were made using Sketchup 3D design software. Then, 3D models were imported in Odeon, using Odeon's plugin SU2Odeon. For each of the offices all the furnishings were modeled - desks, chairs, cabinets. Absorption and scattering coefficients of all the materials present in the offices have been assigned: they were gathered from the literature. Odeon has a large library of measured absorption coefficients for different materials; this has also been used as a guide line for input values. These values, for each material, were chosen and adjusted in such a way that the simulated reverberation time was adapted to the measured reverberation time.

In addition, sources and receivers have been placed in the 3D model in order to simulate people who have performed acoustic measurements. The positions of sources and receivers changed in each simulation, as many times as the number of measurements, as recommended in the Odeon Application Note of open-plan offices [11].

Then the calibration procedure started. The calibration procedure consists in assigning the absorption and scattering coefficient values to all surfaces of the virtual model. The calibration ends when at each octave band frequency (125 Hz - 4 kHz) the simulated reverberation time (T20) value is equal to the measured reverberation time (T20) [13]. Many regulations establish limit values of the reverberation time (T20) for open-plan offices as follows:

SOURCE	**OFFICE DESCRIPTION**	**Rt LIMIT VALUES**
UNI 11532	Open-plan offices for less than 20 people	$T_{20} \leq 0{,}5$ s
NF S31-080	Open-plan offices	$0{,}6 < T_{20} < 0.8$ s
EN 12354-6	Open-plan offices	$T_{20} \leq 0.6$ s

Several attempts were made before reaching the final calibration, so that the simulated results fall within the limit value defined by the standards mentioned above.

6.3 ROOM ACOUSTIC PARAMETERS IN OPEN-PLAN OFFICES (ISO 3382-3:2012).

For the simulation of acoustic parameters, ISO 3382-3: 2012 standard has been taken into consideration. The parameters can be divided into two groups: three parameters based on the A-weighted SPL (Sound Pressure Level) and three other parameters based on STI (Speech Transmission Index).

The A-weighted SPL based parameters are:

- **$D_{2,S}$** , ie Spatial decay rate of A-weighted SPL of speech. $D_{2,s}$ parameter is the rate of spatial decay of A-weighted sound pressure level of speech per distance doubling in an open plan office [8]. In Annex A of ISO 3382-3 is expressed that a spatial decay rate of speech with a value equal to or greater than 7 dB is suggested as a target value for good acoustical conditions.

  $D_{2,s}$ is expressed in dB;
- **$L_{p,A,S,4m}$** , ie A-weighted SPL of speech at 4 meters. $L_{p,A,S,4m}$ parameter shows how much the source level is influenced by nearby reflecting surfaces [14]. For the simulations with Odeon software the receivers and the sources were located as

reported by the ISO 3382-3 definitions, and the same conditions were maintained to assess $D_{2,S}$.

According to Annex A of ISO 3382-3, If $L_{p,A,S,4m}$ > 50 dB, an open plan office has bad acoustic conditions. In this case, acoustic comfort is affected negatively by the intensive furnishing of the office, the small distance between the desks and the cabinets, the reflectivity of the close materials. An open plan office with good acoustic conditions must have a $L_{p,A,S,4m}$ equal or lower than 48dB [15];

- **$L_{p,A,B}$** , ie A-weighted background noise. $L_{p,A,B}$ is the average background noise level in 1/3 octave band from 125Hz to 8kHz at each measurement position. According to ISO 3382-3 the background noise shall represent the heating ventilation and air conditioning devices and other noise sources operating as during typical working hours. In these case studies the $L_{p,A,B}$ was first measured and then simulated with Odeon software to compare the results. $L_{p,A,B}$ is expressed in dB.

The STI based parameters are:

- **STI** in nearest workstation. The STI is a physical measurement that quantifies the quality of transmitted speech with regards to speech intelligibility. The result is a number from 0 to 1, where 1 means perfect transmission and 0 means no speech can be recognized [8]. The background noise level averaged over the measurement positions of the measurement line is used for the determination of STI. This is used because spatial variation of background noise level can cause strong variations in STI and the determination of distraction distance and privacy distance may not always be unambiguous [8]. STI is a dimensionless parameter. Table 1 shows the speech intelligibility and speech privacy for different STI values;

STI	Speech intelligibility	Speech privacy
0.00 – 0.05	very bad	confidential
0.05 – 0.20	bad	bad
0.20 – 0.40	poor	reasonable
0.40 – 0.60	fair	poor
0.60 – 0.75	good	bad
0.75 – 0.99	excellent	very bad

Table 1: STI, Speech intelligibility and speech privacy [7].

- **r_D** , ie distraction distance. The distraction distance, r_D, is the distance from the speaker at which the STI falls below 0,50. For distances above the distraction distance, concentration and the experience of un-distractedness quickly improves [6]. Distraction distance is expressed in meters;
- **r_P** , ie privacy distance. The privacy distance, r_P, is the distance from the speaker at which the STI falls below 0,20. Above the privacy distance, concentration and privacy are experienced very much the same as between separate office rooms. STI values less than 0,20 are difficult to achieve in offices with poor speech privacy or small volume. Also privacy distance is expressed in meters.

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Results

7. Acoustic measurements

7.1 Open-plan offices

7.2 Shared offices

7. ACOUSTIC MEASUREMENTS

In-situ acoustic measurements concern the reverberation time (T_{20}) and the background noise level.

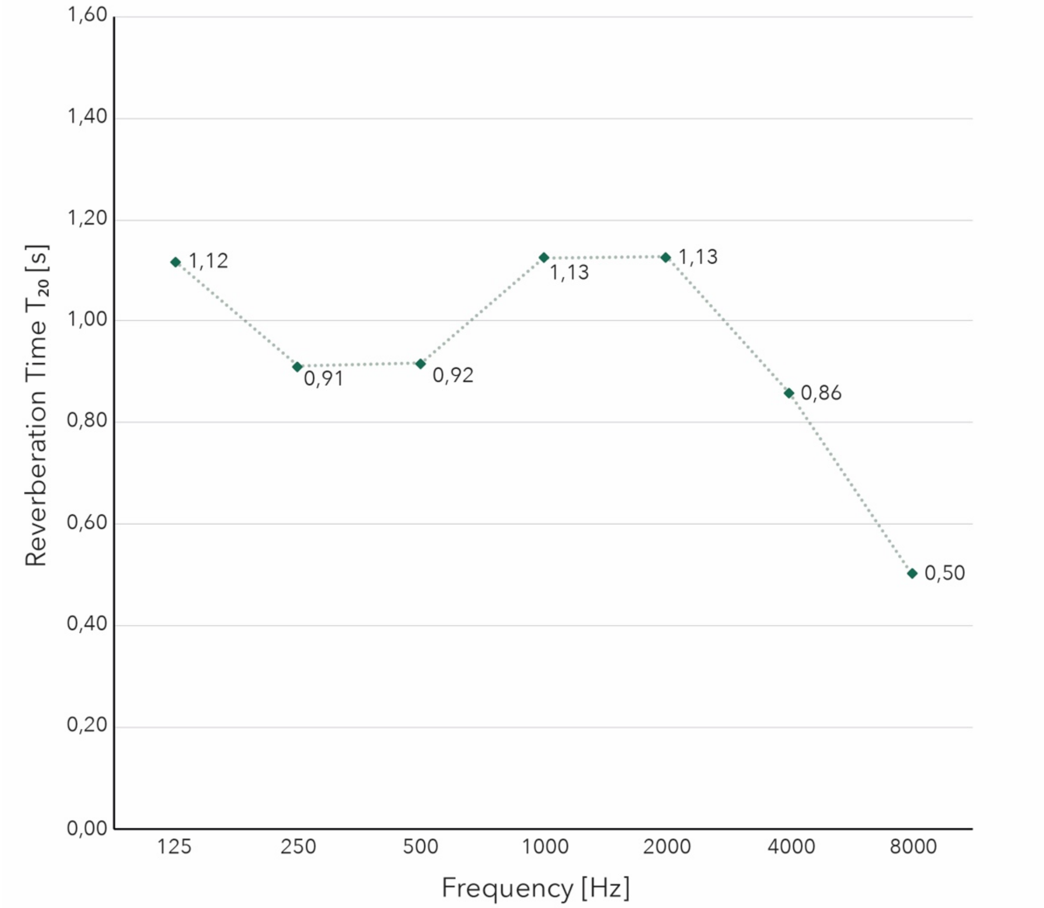
The measurement results will be presented for each of the open-plan and shared offices. They were performed by two persons following a measurement plan decided in advance. As previously mentioned in chapter 5, according to ISO 3382-3 [1], measurements were carried out in furnished offices, but without the presence of people, with the exception of the persons necessary for carrying out the measurements themselves.

Tabs with the graphical representation of the various measurement points for each office are presented in the attachements.

7.1 OPEN PLAN-OFFICES

OP OFFICE 1

REVERBERATION TIME (T_{20}) RESULTS OF OP OFFICE 1



f (Hz)	63	125	250	500	1000	2000	4000	8000	Average (500 - 1000 Hz)
T20 (s)	**-**	**1,12**	**0,91**	**0,92**	**1,13**	**1,13**	**0,86**	**0,50**	**1,02**

Value corresponding to 63 Hz has been removed due to lack of detection by SLM.

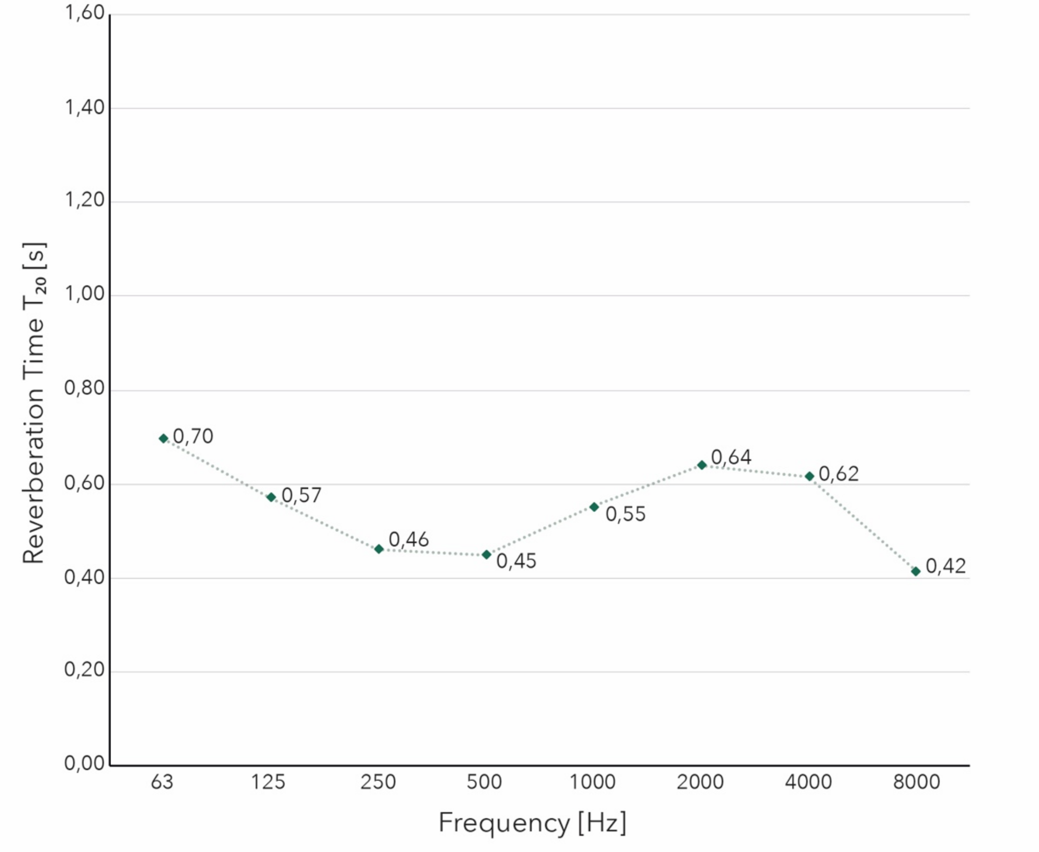
BACKGROUND NOISE LEVEL RESULTS OF OP OFFICE 1

Measuring point	Start time	End time	Duration [s]	LAeq [dB]	LA_{50} [dB]	LA_{90} [dB]
Lf_1	20:53:09	20:54:40	92	41,8	41,6	41,3
Lf_2	20:56:41	20:58:14	94	42,2	42,1	41,8
Lf_3	21:00:41	21:02:08	88	41,5	41,3	41,0
Lf_4	21:03:05	21:04:33	89	43,0	42,7	42,2

Average	41,9	41,6
Stand_dev	0,6	0,5

OP OFFICE 2

REVERBERATION TIME (T_{20}) RESULTS OF OP OFFICE 2



f (Hz)	63	125	250	500	1000	2000	4000	8000	Average (500 - 1000 Hz)
T20 (s)	**0,70**	**0,57**	**0,46**	**0,45**	**0,55**	**0,64**	**0,62**	**0,42**	**0,50**

BACKGROUND NOISE LEVEL RESULTS OF OP OFFICE 2

Measuring point	Start time	End time	Duration [s]	LAeq [dB]	LA_{50} [dB]	LA_{90} [dB]
Lf_1	Missing values					
Lf_2	18:44:23	18:45:24	62	34,5	34,4	34,0
Lf_3	18:46:11	18:47:12	62	33,2	32,9	32,5

Average	33,7	33,3
Stand_dev	1,1	1,1

Measuring point	Start time	End time	Duration [s]	LAeq [dB]	LA_{50} [dB]	LA_{90} [dB]
Lf_4	19:40:23	19:41:11	49	31,2	28,2	27,8
Lf_5	19:42:29	19:43:16	48	30,1	29,1	28,2
Lf_6	19:43:41	19:44:28	48	27,2	24,8	24,5

Average	27,4	26,8
Stand_dev	2,3	2,0

$Lf_{1,2,3}$ = background noise level at start of measurements

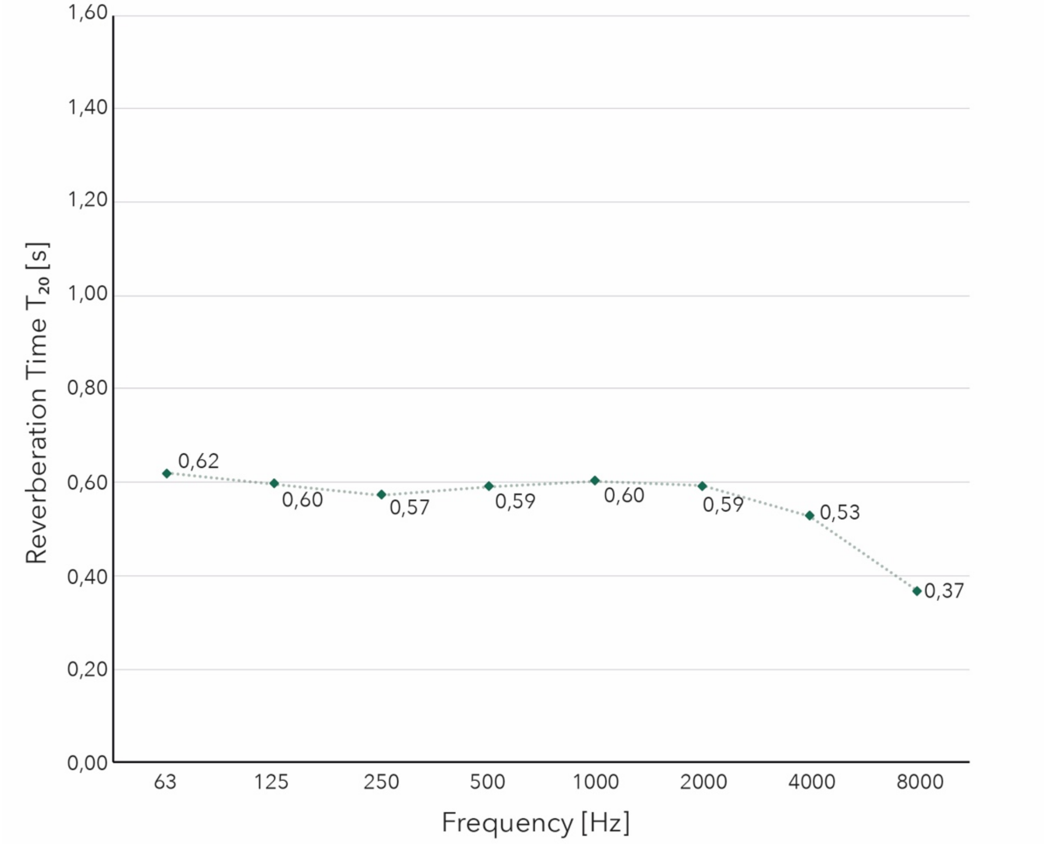
$Lf_{4,5,6}$ = background noise level at the end of measurements

Missing values = values not detected by SLM

7.2 SHARED OFFICES

SH OFFICE 1

REVERBERATION TIME (T_{20}) RESULTS OF SH OFFICE 1



f (Hz)	63	125	250	500	1000	2000	4000	8000	Average (500 - 1000 Hz)
T20 (s)	**0,62**	**0,60**	**0,57**	**0,59**	**0,60**	**0,59**	**0,53**	**0,37**	**0,60**

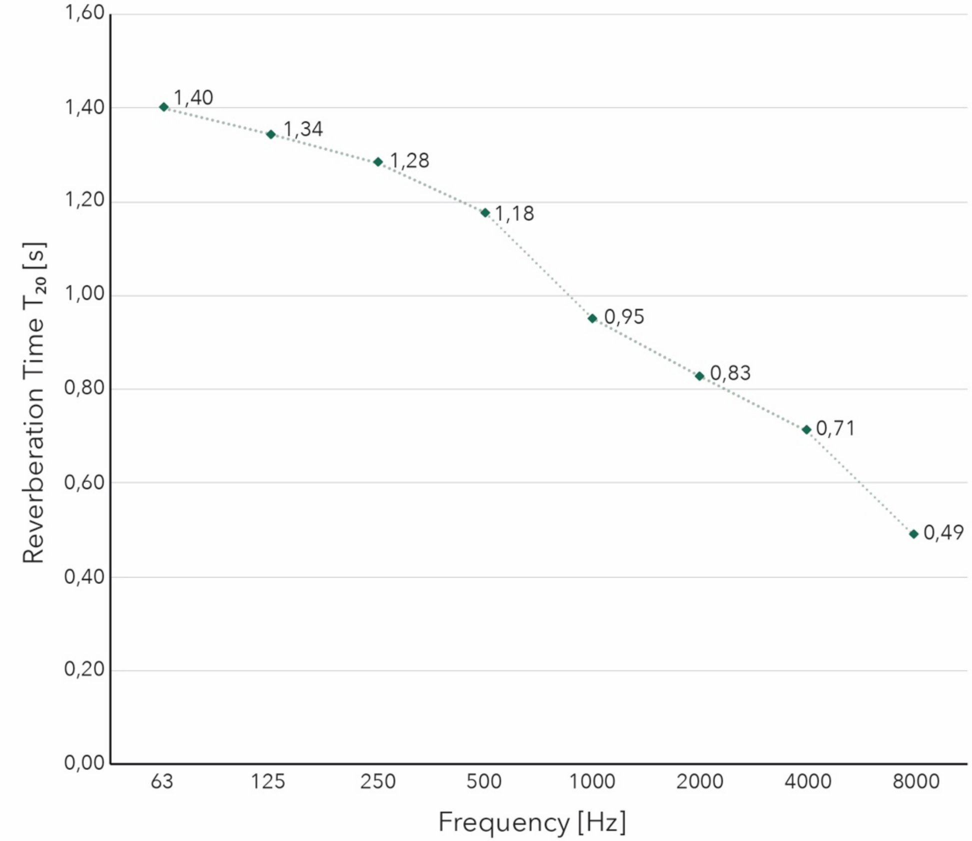
BACKGROUND NOISE LEVEL RESULTS OF SH OFFICE 1

Measuring point	Start time	End time	Duration [s]	LAeq [dB]	LA_{50} [dB]	LA_{90} [dB]
Lf_1	18:29:57	18:30:57	61	39,6	39,4	38,8
Lf_2	18:32:31	18:33:33	63	41,7	41,7	41,2
Lf_3	18:34:49	18:35:50	62	40,9	40,9	40,4
Lf_4	18:36:35	18:37:37	63	39,8	39,7	39,2

Average	40,4	39,9
Stand_dev	1,1	1,1

SH OFFICE 2

REVERBERATION TIME (T_{20}) RESULTS OF SH OFFICE 2



f (Hz)	63	125	250	500	1000	2000	4000	8000	Average (500 - 1000 Hz)
T20 (s)	**1,40**	**1,34**	**1,28**	**1,18**	**0,95**	**0,83**	**0,71**	**0,49**	**1,06**

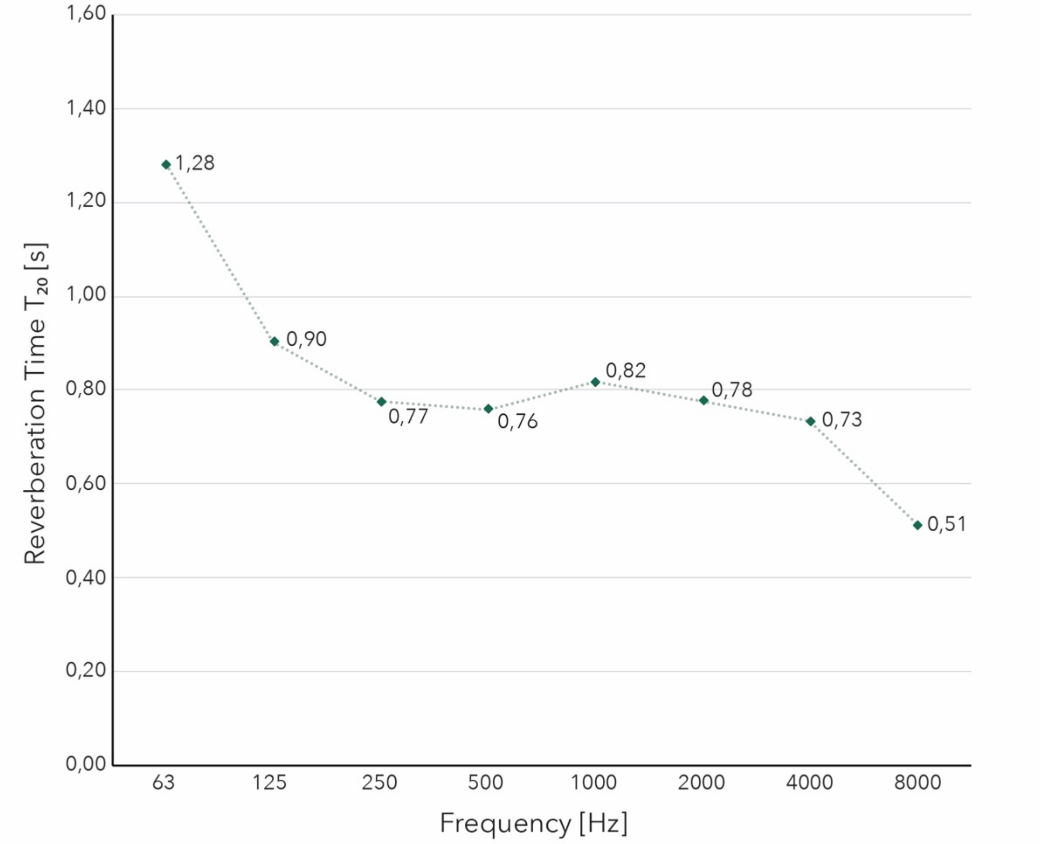
BACKGROUND NOISE LEVEL RESULTS OF SH OFFICE 2

Measuring point	Start time	End time	Duration [s]	LAeq [dB]	LA_{50} [dB]	LA_{90} [dB]
Lf_1	19:05:29	19:06:30	60	30,0	29,4	29,0
Lf_2	19:00:33	19:01:34	60	29,4	29,2	28,8
Lf_3	18:58:31	18:59:32	60	30,8	30,2	29,6
Lf_4	19:02:21	19:03:22	60	29,6	29,0	28,6
Lf_5	19:03:47	19:04:48	60	33,1	29,9	29,2

Average	29,5	29,0
Stand_dev	0,5	0,4

SH OFFICE 3

REVERBERATION TIME (T_{20}) RESULTS OF SH OFFICE 3



f (Hz)	63	125	250	500	1000	2000	4000	8000	Average (500 - 1000 Hz)
T20 (s)	**1,28**	**0,90**	**0,77**	**0,76**	**0,82**	**0,78**	**0,73**	**0,51**	**0,79**

BACKGROUND NOISE LEVEL RESULTS OF SH OFFICE 3

Measuring point	Start time	End time	Duration [s]	LAeq [dB]	LA_{50} [dB]	LA_{90} [dB]
Lf_1	18:09:05	18:09:37	33	33,6	28,2	27,3
Lf_2	18:10:15	18:10:47	33	32,0	30,0	28,5

Average	29,1	27,9
Stand_dev	1,3	0,8

The NF S31-080 standard defines limit values for reverberation time both for shared offices and open-plan offices as follows:

	"Standard" level	**"Efficient" level**	**"Highly efficient" level**
Shared offices	Tr ≤ 0,6 s	Tr ≤ 0,6 s	Tr ≤ 0,5 s
Open-plan offices	Tr ≤ 0,8 s	0,6 < Tr < 0,8 s	Tr ≤ 0,6 s

Table 1: Acoustic requirements for shared and open-plan offices defined by NF S31-080 [2].

From the results of the measurements it is clear that only two out of five offices comply with the standard with regard to the T_{20} limit values within the offices. It's the case of OP OFFICE 2 and SH OFFICE 1. Then, of the three offices that have values that do not respect the standard, two case studies have been taken: an open-plan office (OP OFFICE 1) and a shared office (SH OFFICE 2). So of the three offices that have values that do not respect the standard, two case studies have been taken: an open-plan office and a shared office. These two case studies were chosen for calibration on Odeon software and, therefore, for the acoustic project, as we will see in chapters 8, 9 and 10.

REFERENCES:

1. Acoustics – Measurements of room acoustic parameters – Part 3: Open-plan offices (EN ISO 3382-3:2012).
2. NF S31-080, Janvier 2006, AFNOR Association Française de Normalisation.

8. Acoustic simulations

8.1 Calibration

8.1.1 Open-plan office

8.1.2 Shared office

8.2 Room acoustic parameters

8.2.1 Open-plan office

8.2.2 Shared office

8. ACOUSTIC SIMULATIONS

The results of the simulations are presented in this chapter, first for the OP OFFICE 1 and then for the SH OFFICE 2.

This chapter is divided into two parts concerning two different methods of acoustic simulations. Paragraph 8.1 presents the results of the reverberation time (T_{20}) calibration process measured in-situ; while in paragraph 8.2 the results of the simulations of the acoustic parameters defined by the ISO 3382-3 [1] standard for offices are presented.

8.1 CALIBRATION

The calibration process on Odeon software consists in assigning to each surface of the 3D virtual model the absorption and scattering coefficients related to the real material, according to the literature [2], [3]. The calibration is stopped when at each octave band frequencies (125 Hz - 4 kHz) the value of reverberation time (T_{20}) calculated is equal to reverberation time (T_{20}) measured.

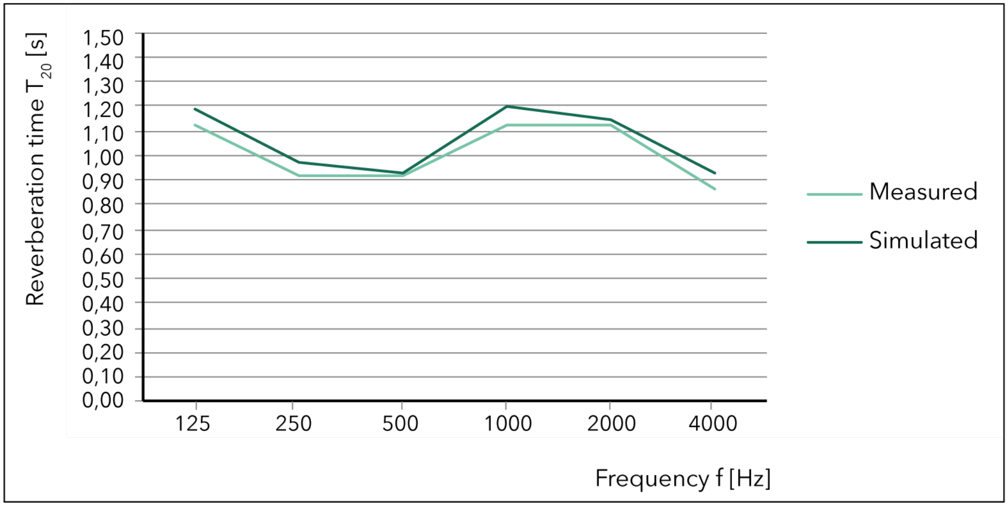
8.1.1 OPEN-PLAN OFFICE (OP OFFICE 1)

The open-plan office calibration was performed by assigning absorption and scattering coefficients shown in table 1.

Surface/Material	Reference	Area [m2]	Values of acoustic absorption coefficients of surfaces/materials, a [-]					
			125	250	500	1000	2000	4000
Plaster	*BB93_Plaster on solid wall*	157,66	0,04	0,05	0,06	0,08	0,04	0,06
Window glass	*BB93_4mm glass*	11,39	0,3	0,2	0,1	0,07	0,05	0,02
Window frame	*BB93_4mm glass*	3,26	0,3	0,2	0,1	0,07	0,05	0,02
Door	*BB93_Acoustic door*	5,74	0,35	0,39	0,44	0,49	0,54	0,57
Chair	*Odeon_Audience, lightly upholstered seats*	7,04	0,51	0,64	0,75	0,8	0,82	0,83
Desk	*Odeon_classroom wood desk*	21,13	0,05	0,08	0,1	0,12	0,12	0,12
Floor	*BB93_Floor tiles, plastic or linoleum*	121,66	0,03	0,00	0,03	0,00	0,05	0,05
Vibrating panels	*File excel*	68	0,36	0,19	0,13	0,09	0,06	0,05
Ceiling	*Odeon_Steel trapez profile*	104,65	0,30	0,25	0,2	0,1	0,1	0,15
Cabinets	*Odeon_classroom wood desk*	41,55	0,05	0,08	0,1	0,12	0,12	0,12
Ventilation grille	*Manuale Rockwool_Griglia dell'aria, area aperta 50%*	1,8	0,30	0,50	0,50	0,50	0,50	0,50
Scattering coefficient ceiling	0,17							

Table 2: Absorption and scattering coefficients of open-plan office based on the literature database.

After assigning the aforementioned acoustic coefficients, the calibration process was started. After several attempts, the best – calibrated - option was reached which results are shown in fig. 1.



Measured	Reverberation time calculation T20						
f (Hz)	125	250	500	1000	2000	4000	500-1000
plus 10%	1,17	0,96	0,96	1,18	1,18	0,90	
T20 (s)	**1,12**	**0,91**	**0,92**	**1,13**	**1,13**	**0,86**	**1,02**
minus 10%	1,06	0,87	0,87	1,07	1,07	0,81	

Simulated	Reverberation time simulation T20						
f (Hz)	125	250	500	1000	2000	4000	500-1000
T20 (s)	**1,19**	**0,97**	**0,92**	**1,20**	**1,15**	**0,93**	**1,06**
DELTA	-0,07	-0,06	-0,01	-0,07	-0,02	-0,07	

Fig. 1: Comparison between T_{20} values measured and T_{20} values pre and after calibration.

8.1.2 SHARED OFFICE (SH OFFICE 2)

The shared office calibration was performed in the same way as OP OFFICE 1. Absorption coefficients of SH OFFICE 2 are shown in table 2.

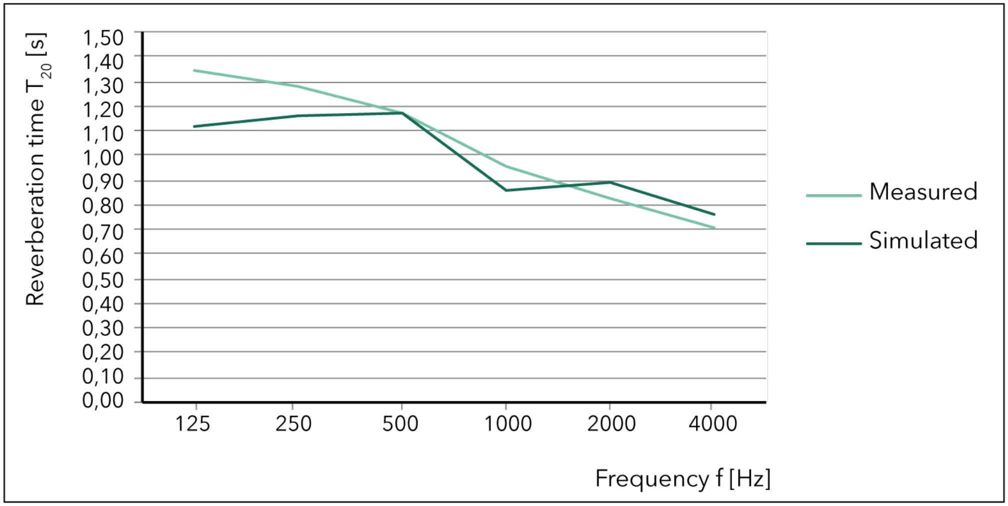
Surface/Material	Reference	Area [m2]	Values of acoustic absorption coefficients of surfaces/materials, a [-]					
			125	250	500	1000	2000	4000
Plaster	BB93_Plaster on solid wall	122,08	0,04	0,05	0,06	0,08	0,04	0,06
Window	BB93_4mm glass	8,23	0,30	0,20	0,10	0,07	0,05	0,02
Wooden door	BB93_Solid timber door	3,3	0,14	0,10	0,06	0,08	0,10	0,10
Chair	http://mapleintegration.com/sound_ab.php	2,56	0,15	0,19	0,22	0,39	0,38	0,30
Desk	https://patchbay.wordpress.com/2011/01/	12,24	0,44	0,33	0,22	0,34	0,33	0,32
Floor	BB93_Smooth marble or terrazzo slabs	30,54	0,01	0,01	0,01	0,01	0,02	0,02
Marble	BB93_Smooth marble or terrazzo slabs	1,6	0,01	0,01	0,01	0,01	0,02	0,02
Ventilation plant	Manuale Rockwool_Griglia dell'aria, area aperta 50%	1,12	0,30	0,50	0,50	0,50	0,50	0,50
Wooden furniture	http://driftwoodaudio.com/blog/media/refe	3,27	0,14	0,17	0,20	0,35	0,34	0,27
Plastic	BB93_Floor tiles, plastic or linoleum	2,50	0,03	0,00	0,03	0,00	0,05	0,05
Curtains	https://cds.cern.ch/record/1251519/files/9	8,16	0,03	0,09	0,24	0,46	0,79	0,76

Table 3: Absorption and scattering coefficients of shared office based on the literature database.

During the calibration of this office, problems were found with the absorption coefficients of the desks, as during the measurements these latter were covered with office accessories - sheets, computers, telephones - so the absorption coefficients taken from the literature were not able to perform calibration. For this reason, an experiment in a reverberating room was performed, with Dr. Louena Shtrepi, simulating a model desk model of SH OFFICE 2 as close to reality as possible.

A picture of the experiment is shown in fig. 2. Therefore new absorption coefficients of the desks were obtained and the calibration was performed correctly. Results of the calibration are shown in fig. 3.

Fig. 2: Experiment of the measurement of absorption coefficients of desks of SH OFFICE 2.



Measured	Reverberation time calculation T20						
f (Hz)	125	250	500	1000	2000	4000	500-1000
plus 10 %	1,48	1,41	1,29	1,05	0,91	0,78	
T20 (s)	**1,34**	**1,28**	**1,18**	**0,95**	**0,83**	**0,71**	**1,06**
minus 10%	1,21	1,15	1,06	0,86	0,75	0,64	

Simulated	Reverberation time simulation T20						
f (Hz)	125	250	500	1000	2000	4000	500-1000
T20 (s)	**1,12**	**1,16**	**1,17**	**0,86**	**0,89**	**0,76**	**1,02**
DELTA	0,23	0,13	0,01	0,09	-0,06	-0,05	

Fig. 3: Comparison between T_{20} values measured and T_{20} values pre and after calibration.

8.2 ROOM ACOUSTIC PARAMETERS

In the international standard ISO 3382-3, in addition to the description of the measurement procedure of the open-plan offices, new acoustic parameters are also defined for the objective evaluation. These parameters have been previously described in chapter *6.3 - Room acoustic parameters in the open-plan offices (ISO 3382-3: 2012)*.

With room acoustic simulation software measurements can be simulated, thus providing a tool for the acoustical design of open-plan offices.

The principle is to calculate the sound propagation from a sound source to a number of receivers that are located in different distances from the source [4]. An omnidirectional sound source is used, and the spectrum and sound power is defined in order to represent speech at normal vocal effort [5]. The spectrum is based on ANSI 3.5 [6].

In this case the directivity of a talking person is not considered, so it is not necessary to consider the sound pressure level in the frontal direction [5]. The source data are included in Odeon in the predefined sound source ISO3382-3_OMNI.SO8, as can be seen from Fig. 4.

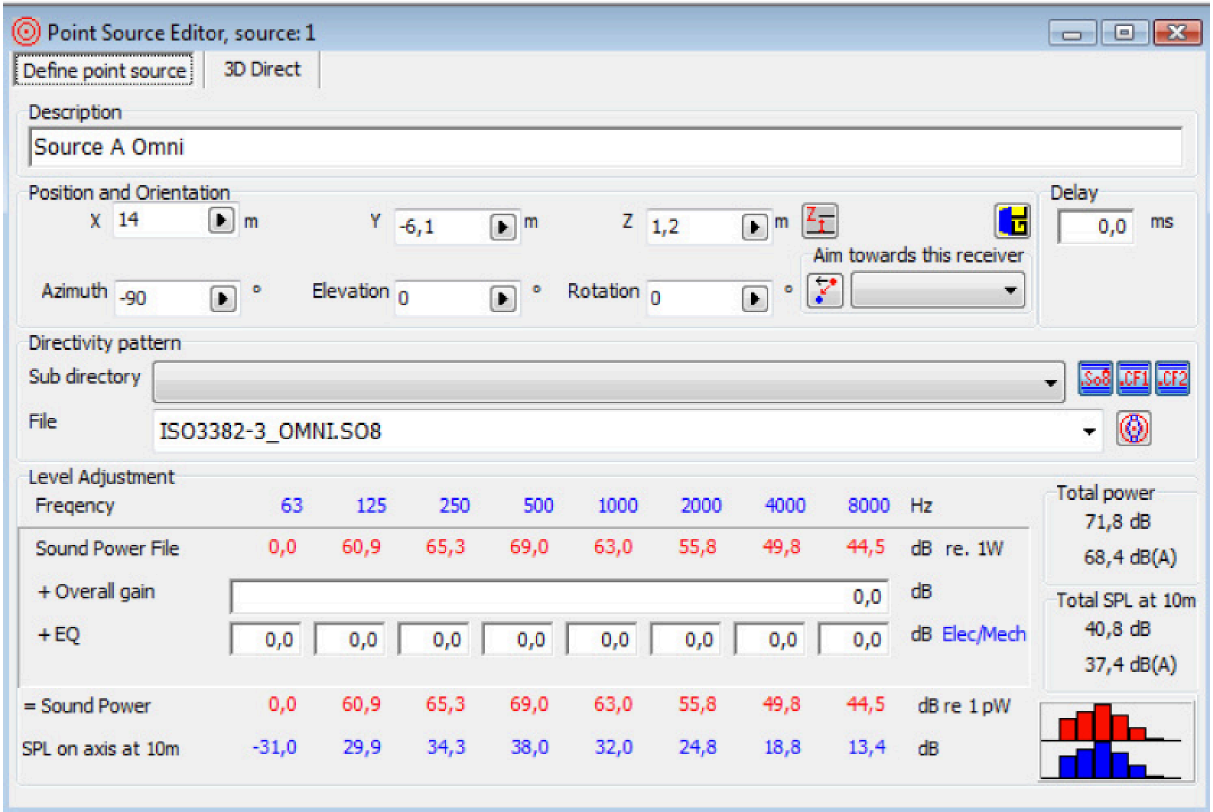


Fig. 4: The source definition menu in Odeon; the source with the name ISO 3382-3 OMNI.SO8 has the spectrum and sound power of normal speech as specified in the standard. The A-weighted sound power level is 68,4 dB(A).

Then the simulation of acoustic parameters is started.

Annex A of ISO 3382-3 provides the limit values of acoustic parameters for open-plan offices for correct acoustic design. Offices with poor acoustical conditions have typical values like $D_{2,S} < 5$ dB, $L_{p,A,S,4m} > 50$ dB, and $r_D > 10$ m. As examples of target values for good acoustical conditions are mentioned $D_{2,S} \geq 7$ dB, $L_{p,A,S,4m} \leq 48$ dB, and $r_D \leq 5$ m [1].

Furthermore Virjonen et al. [7] have made a classification of the parameters that goes from "A" to "E", where "A" is the best value, and "E" is the worst value as follows:

ACOUSTIC CLASS	**r_D**	**$D_{2,S}$**	**$L_{p,A,S,4m}$**
A	< 5	> 11	< 48
B	5 | 8	9 | 11	48 | 51
C	8 | 11	7 | 9	51 | 54
D	11 | 15	5 | 7	> 54
E	> 15	< 5	

Class “A” is the equivalent of the highest level of speech privacy; vice versa class “E” is the equivalent of the lowest level of speech privacy.

While H.O. Olufsen [8] has drawn up a classification of the values of the STI in relation to the speech privacy, as follows:

STI	**Speech privacy**
0.00 – 0.05	confidential
0.05 – 0.20	bad
0.20 – 0.40	reasonable
0.40 – 0.60	poor
0.60 – 0.75	bad
0.75 – 0.99	very bad

8.2.1 OPEN-PLAN OFFICE (OP OFFICE 1)

Results of OP OFFICE 1 are shown as follows:

	STATE OF THE ART												
	C0												
		LINE 1		LINE 2		LINE 3		LINE 4		LINE 5		LINE 6	**AVERAGE**
T20 [s]		1,45		1,43		1,44		1,44		1,45		1,43	**1,44**
STI	**1,80 m**	0,60	**2,30 m**	0,63	**2,10 m**	0,56	**2,40 m**	0,58	**1,05 m**	0,73	**2,00 m**	0,62	**0,62**
	7,50 m	0,52	**7,50 m**	0,53	**7,50 m**	0,53	**7,50 m**	0,53	**9,05 m**	0,55	**9,05 m**	0,54	**0,53**
rD [m]		8,21		8,33		11,71		9,70		8,50		11,26	**9,62**
D2,S [dB]		1,27		1,54		0,85		1,11		1,25		1,14	**1,2**
Lp,A,S,4M [dB]		55,75		56,18		55,85		56,00		55,91		55,96	**55,9**
Lp,A,B [dB]		34,68		34,68		34,68		34,68		34,68		34,68	**34,7**

Table 4: Results from the six different measurement lines.

As can be seen from the results of the simulations, all the simulated acoustic parameters do not comply with the ISO 3382-3 Annex A, especially with regard to the $D_{2,S}$, highlighted in red colour in table 3.

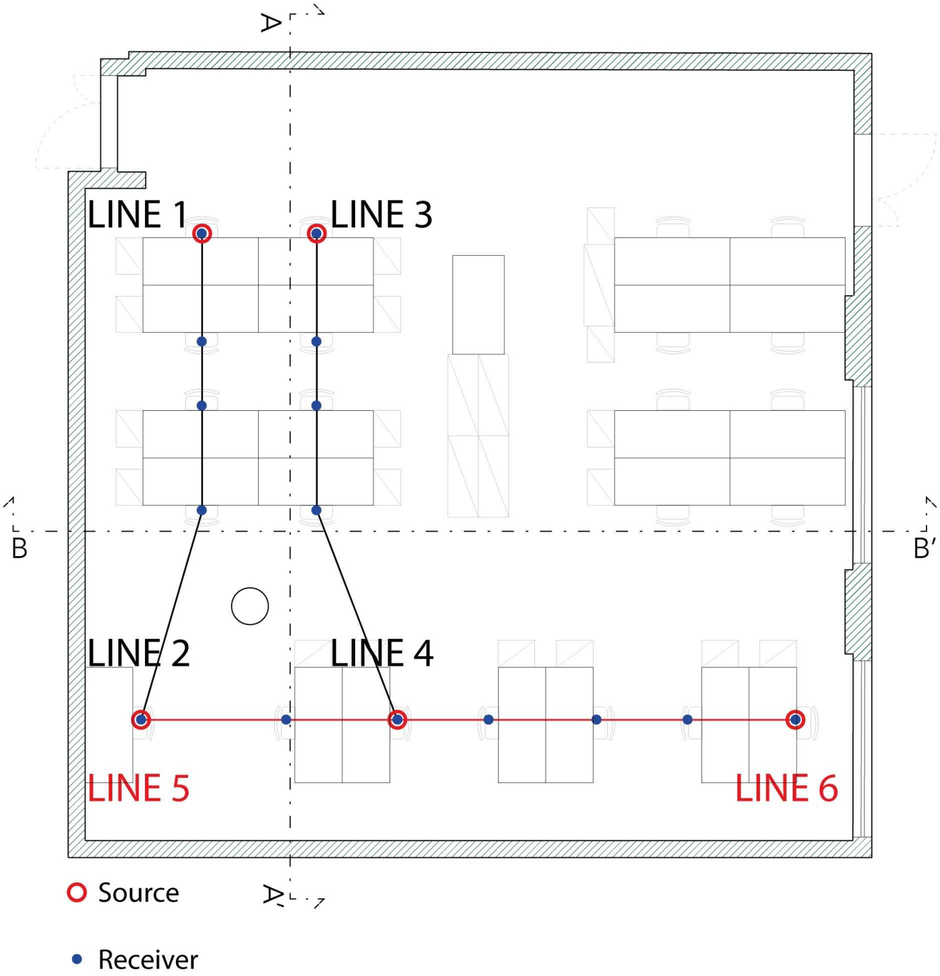
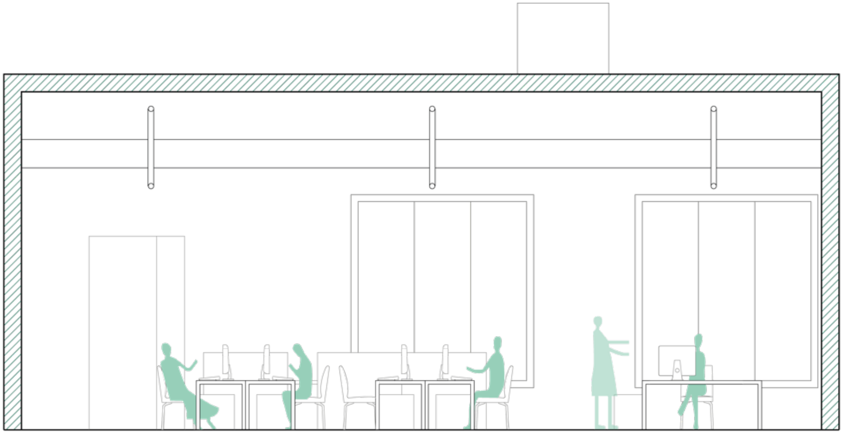


Fig. 1: Plan of OP OFFICE 1 (scale 1:100) with source and receiver positions. Four measurement lines are used, each associated with a point source.



SECTION AA’

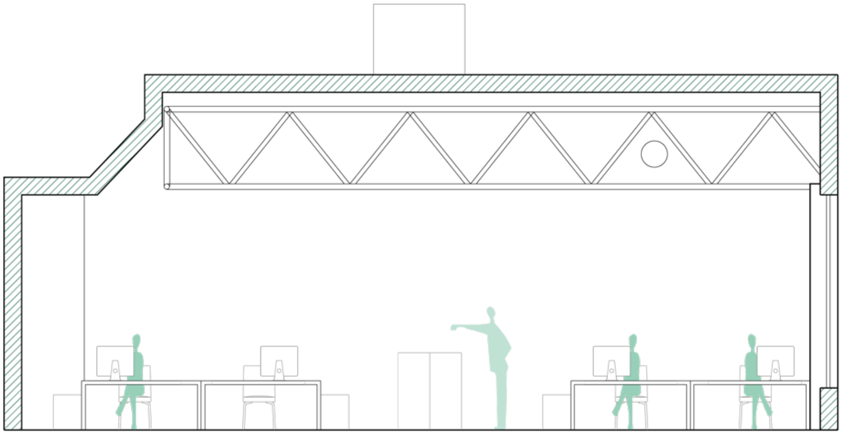


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Fig. 2: Sections (scale 1:100) of OP OFFICE 1

8.2.2 SHARED OFFICE (SH OFFICE 2)

Results of SH OFFICE 2 are shown as follows:

	STATE OF THE ART				
	C0				
		LINE 3		LINE 4	**AVERAGE**
T20 [s]		0,99		0,99	**0,99**
STI	**2,75 m**	0,62	**1,90 m**	0,62	**0,62**
	4,65 m	0,62	**4,65 m**	0,61	**0,62**
rD [m]		208,36		104,93	**156,65**
D2,S [dB]		1,19		-	**1,2**
Lp,A,S,4M [dB]		59,80		-	**59,8**
Lp,A,B [dB]		22,17		22,17	**22,2**

Table 5: Results from the two different measurement lines.

As can be seen from the results of the simulations, no parameters meet the requirements of the ISO3382-3 Annex A, highlighted in red colour in table 4.

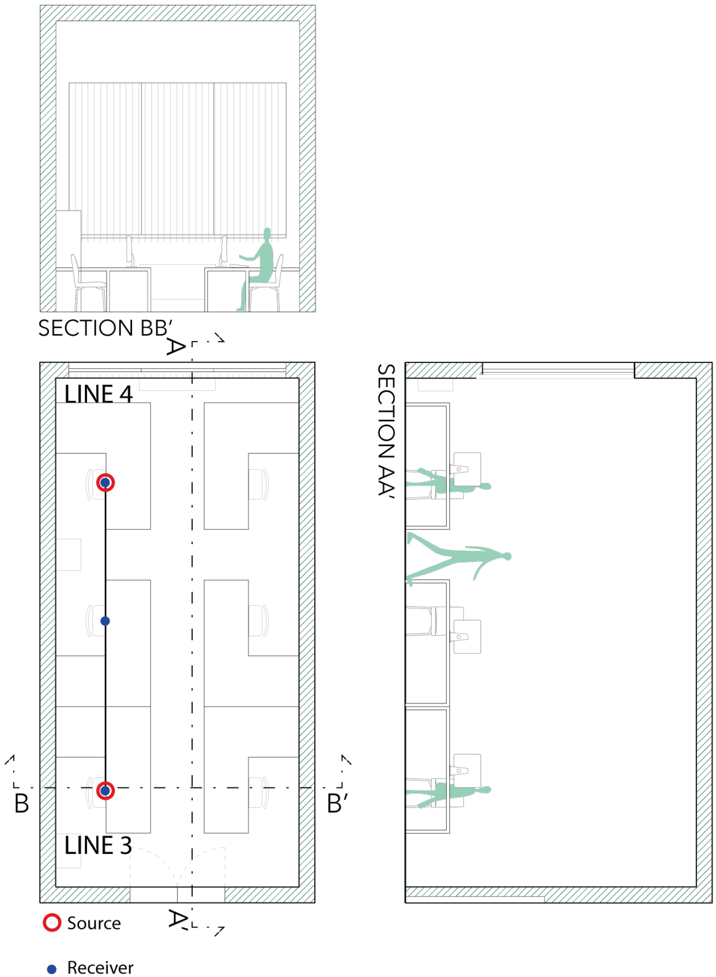

Fig.3: Plan and sections of SH OFFICE 2 (scale 1:100) with source and receiver positions. Four measurement lines are used, each associated with a point source.

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1. Acoustics – Measurements of room acoustic parameters – Part 3: Open-plan offices (EN ISO 3382-3:2012).
2. Building Bulletin 93 (BB93).
3. Arianna Astolfi e Maria Giovannini (a cura di), Acustica delle aule scolastiche, Rockwool, 2008.
4. Rindel, Jens & Christensen, Claus. (2012). Acoustical simulation of open-plan offices according to ISO 3382-3.
5. ODEON APPLICATION NOTE – ISO 3382-3 Open-plan offices, JHR, December 2012
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7. Virjonen et al. 2009 Acta Acust united Ac RIL 243-3-2008 Sisäilmastoluokitus 2008.
8. H.O. Olufsen, Comparing measurements and simulations for acoustics in open-plan office spaces, Norwegian University of Science and Technology, Department of electronic systems, 2017.

Acoustic solutions: proposals and results

9. PROJECT PROPOSALS

In this chapter the acoustic projects of the two offices will be described in detail. At the end of the chapter there are the technical data sheets of all the acoustic treatments adopted in both open-plan (OP OFFICE 1) and shared office (SH OFFICE 2).

9.1 Open-plan office

The project is based on the modern concept of activity-based office layout, in which different tasks of different degrees of concentration can be performed simultaneously in the same environment.
So the OP OFFICE 1 is marked by two distinct areas: a FOCUS AREA in which a high degree of concentration on the job is required, making sure not to be disturbed by colleagues in adjacent workstations; a TEAM-WORKING AREA based on the concept of co-working, collaboration between colleagues and exchange of ideas. The employee is able to choose the workstation according to the needs of the current activity.

As previously mentioned in chapter 3, it is useful to differentiate the different acoustic solutions adopted in the OFFICE 1 OP into 3 sections:

1) acoustic solutions for walls, flooring and ceiling;

2) screens between workstations;

3) acoustic furniture.

1) J.S. Bradley argues that where there are large area of **wall**, these should be covered with sound-absorbent material with an SAA[10] > 0,70 [3].

For this reason, acoustic panels are placed on the walls, covering the surfaces of reflective plaster and vibrating panels as much as possible. In the state of the art, plaster surface counted 158 m^2. After introducing the acoustic panels on the walls, this was reduced to 126,8 m^2.

A total of 24 panels are applied to the four perimeter walls, for a total area of 31,2 m^2.

[10] SAA is the average of the absorption coefficients in the 1/3-octave frequency bands from 250 Hz to 2,5 kHz. It replaces the older *Noise Reduction Coefficient (NRC)* measure and has similar values for the same material.

The linoleum **flooring** is instead entirely covered with moquette in order to reduce the footsteps noise produced by the occupants. Astolfi A. [4] claims that acoustic absorption of floor must be at least equal to 0,20[11]. In this case a moquette with an average absorption of 0.55 was chosen.

The metal **ceiling** is covered with ceiling-hanging acoustic panels exactly above the workstations, at heights of 3,0 and 3,5 m above the floor. A total of 17 panels were placed inside the office, for a total absorbing area of 34 m^2.

The metal ceiling was covered by ceiling-mounted acoustic panels exactly above the workstations, at heights of 3.5 m from the floor in the part adjacent to the windows, and 3.0 m from the floor in the team-working area side. A total of 17 panels were placed inside the office, for a total absorbing area of 34 m^2.

As recommended by J.S. Bradley [3] ceiling absorption with SAA > 0,90 is required in order to have a good design of open-plan offices.

2) To control speech sound transmission through workstation, screens must be put in the three sides of the workstation. These panels must be high at least 1,7 m from

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[11] Average value of sound absorption coefficients for a 1/3-octave frequency bands from 200 Hz to 3.15 kHz.

floor, as recommended by J.S. Bradley [3] and must have a SAA ≥ 0,70. In the project of OP OFFICE 1 screens 1,7 m high above the floor with SAA = 0,70 are used.

It should be noted, as reported by V. Hongisto [4], that the dividing panels between workstations must be used where privacy is needed; In fact these panels in the OP OFFICE 1 project are used only in the team-working area.

3) A predominant feature of the activity-based office layout concerns acoustic furniture. Their presence within the office makes it easier to concentrate, if an employee requires concentration to perform a particular task.

Two different types of acoustic furniture are used in the project:

- **Haven pods** is a solution for desk based individual focussed work. It provides a defined space for individual focused work. They can simply be erected, plugged in, taken down and relocated according to the needs of the employees;
- **Cocoon acoustic chair/sofa** is a solution that can be used for team meetings, collaborative tasks or as a breakout area. The high sides, back and roof provide noise reduction and reduces peripheral vision, increasing privacy and productivity, whilst also highly enhancing an office’s business interiors.

The layout of all the acoustic expedients of OP OFFICE 1 is visible in plan (see fig.1), sections (see fig. 2) and 3D axonometric exploded (see fig. 3).

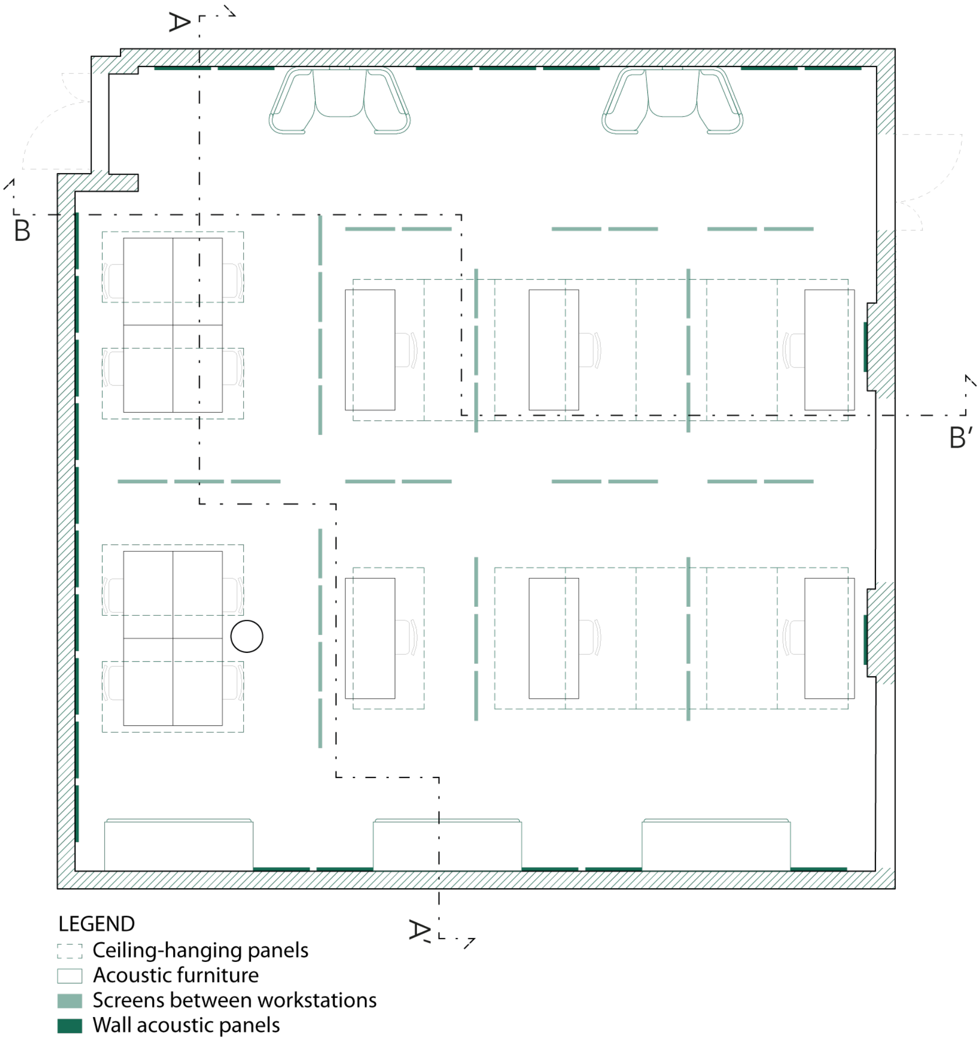
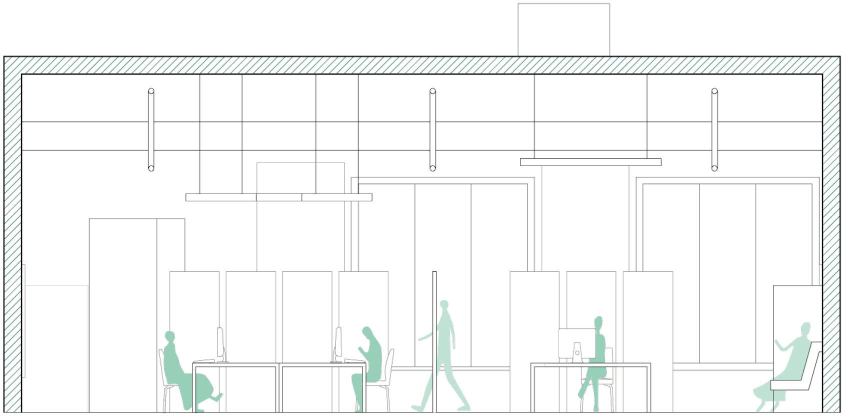
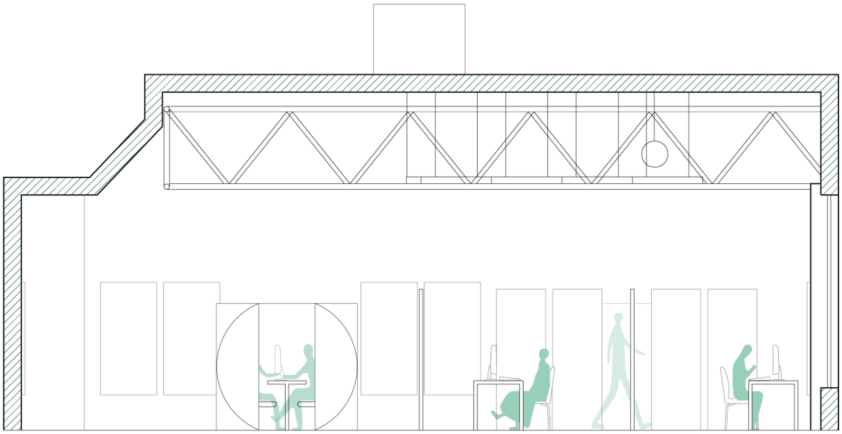


Fig. 12: Plan of acoustic project of OP OFFICE 1 – scale 1:100



SECTION AA’



SECTION BB’

Fig. 13: Sections of acoustic project of OP OFFICE 1 – scale 1:100

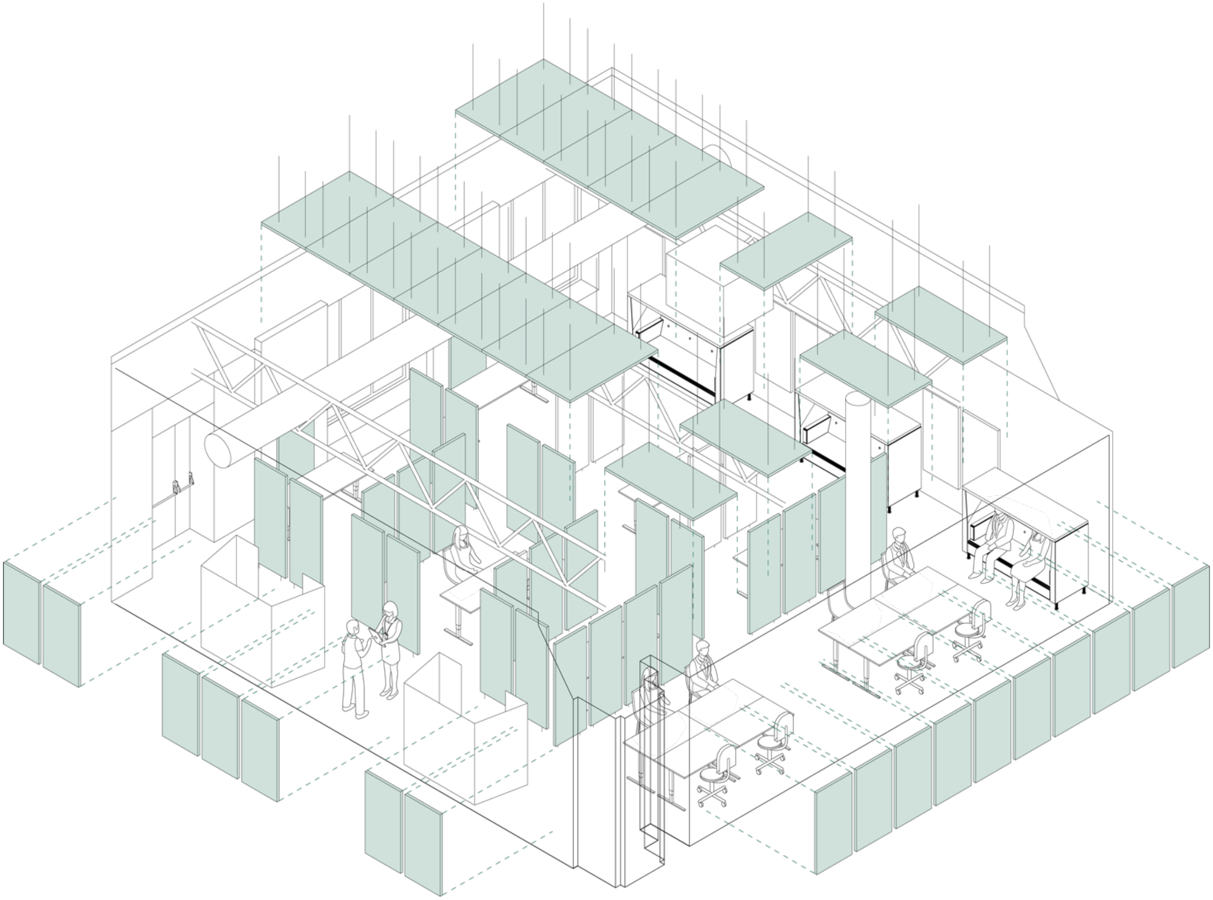


Fig.3 : 3D axonometric exploded OP OFFICE 1.

9.2 Shared office

In the acoustic project of SH OFFICE 2 the same acoustic expedients adopted for the OP OFFICE 1 are used, with the exception of acoustic furniture, due to the reduced size of the office. As in the previous case, the acoustic solutions adopted are indicated below:

1) In the state of the art, **walls** are plastered covering an area of 95.5 m^2. To reduce the surface of reflective material, a number of 16 acoustic wall panels are added, covering the plastered surface for 22%, for an area equal to 20.8 m^2. So now the walls covered with plaster have a reduced area of 74.7 m^2.

Also in this case **flooring** is entirely covered by moquette with an average absorption of 0.55.

Ceiling is plastered, but in the project is expected to be covered with ceiling-hanging acoustic panels at a height of 2,7 m above the floor. In the state of art plastered ceiling was 30 m^2: with the addition of 8 ceiling panels, the reflective plastered surface is reduced by more than 50%. In fact the panels cover a total absorption area of 16 m^2 and they are positioned in correspondence of the workstations to prevent the propagation of the speech noise produced by the occupants.

2) In SH OFFICE 2, given the small size of the office (area = 30 m2), the absorbent screens between the workstations are positioned to avoid any visual contact between the employees and, therefore, to provide a high level of privacy within the office. They are positioned at a height of 1,7 m above the floor, as recommended by J.S. Bradley [3].

The layout of all the acoustic expedients of SH OFFICE 2 is visible in plan, sections (see fig. 4) and 3D axonometric exploded (see fig. 5).

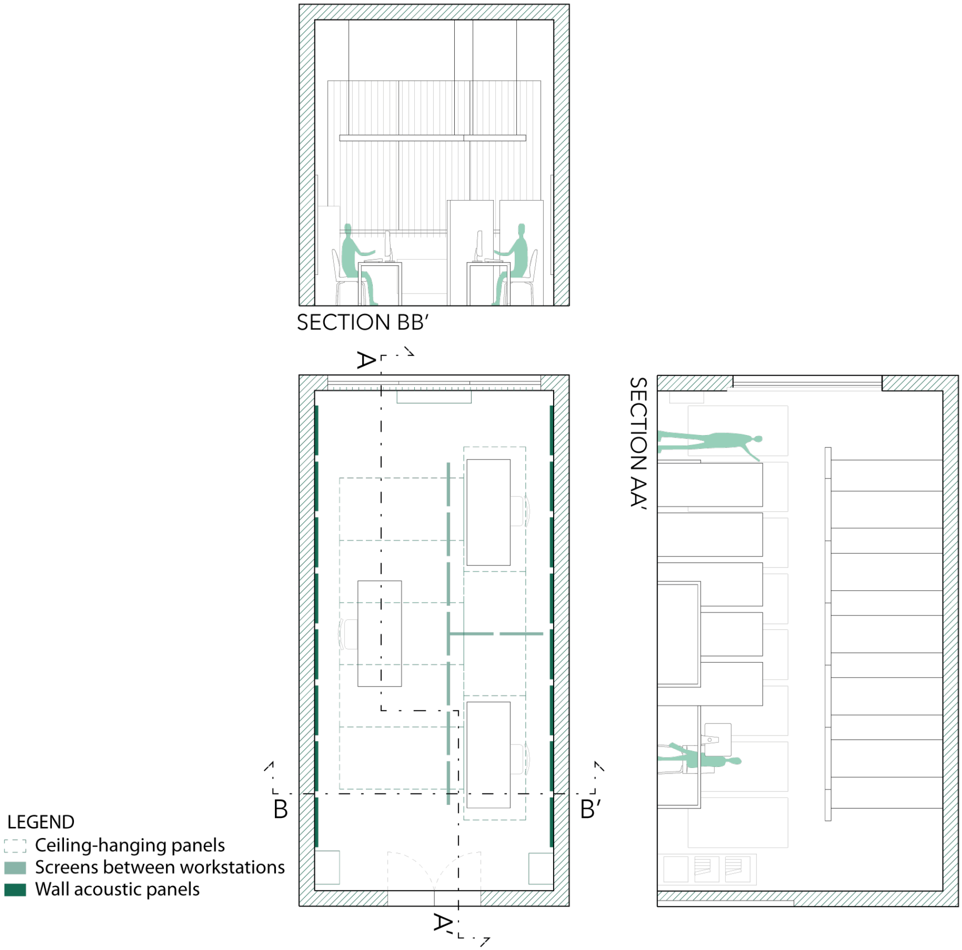


Fig. 4: Plan and sections of acoustic project of SH OFFICE 2 – scale 1:100

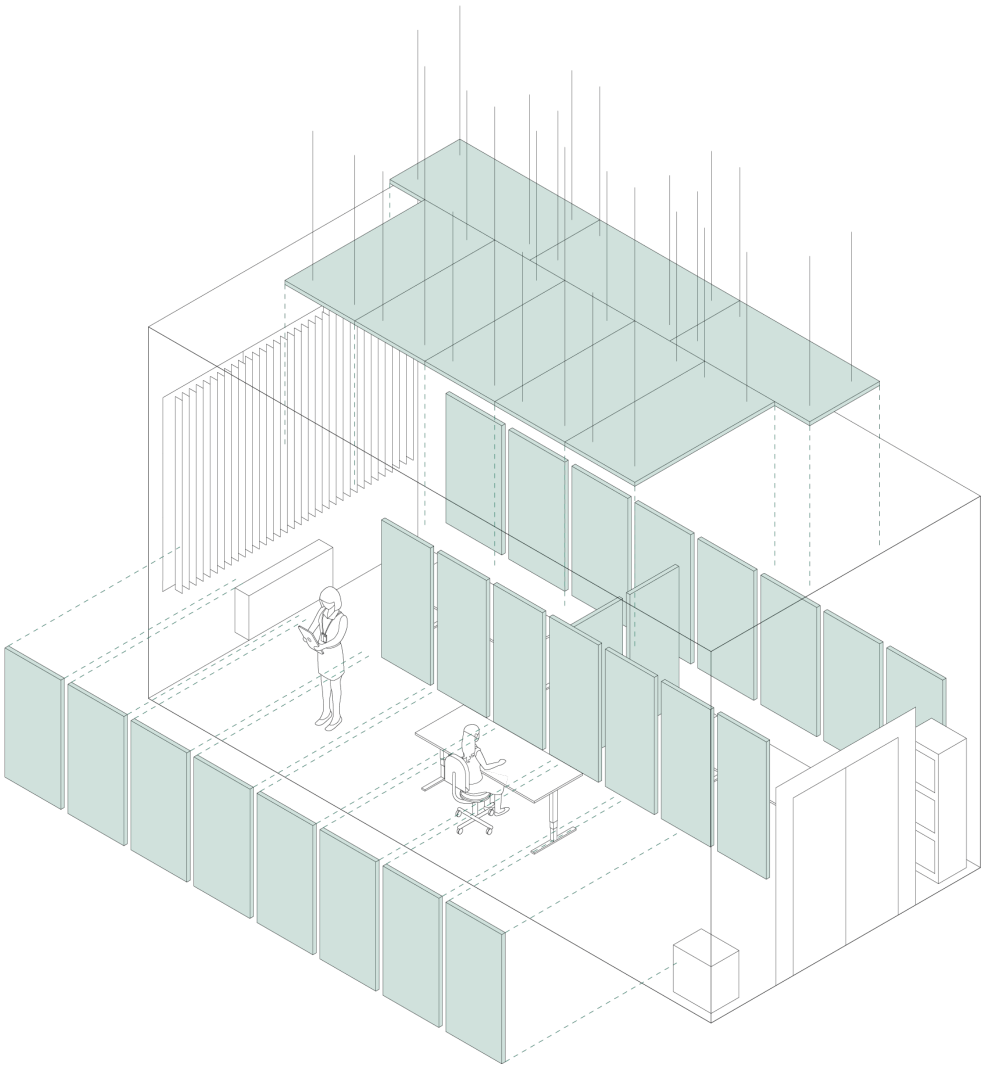


Fig. 5: 3D axonometric exploded of SH OFFICE 2.

TECHNICAL DATA SHEETS

WALL ACOUSTIC PANELS

SYSTEM AND PRODUCT DESCRIPTION

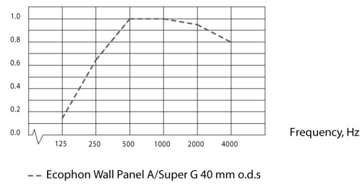
The system consist of Ecophon Wall Panel A panels and Ecophon Connect grid systems, with an approximate weight of 4 kg/m². The panels are manufactured from high density glass wool. The visible surface has a glass fibre fabric (Super G).
The back of the tile is covered with glass tissue. The edges are natural. The grid is manufactured from galvanized steel·

Format: panels

Application: walls

Material: glass wool

ACOUSTICS:
SOUND ABSORPTION: Test results according to EN ISO 354.
o.d.s = overall depth of system



Classification according to EN ISO 11654, and the single value ratings for NRC and SAA according to ASTM C 423.

ACOUSTIC PERFORMANCE

Sound Absorption Coefficient - Ecophon wall panels								
Frequency (Hz)	125	250	500	1000	2000	4000	SAA	Sound Absorption Class
Ecophon wall panels	0.15	0.65	1.00	1.00	0.95	0.80	0.90	A per ISO 11554

Fig. 6: Technical data sheet of Ecophon Wall Panels.

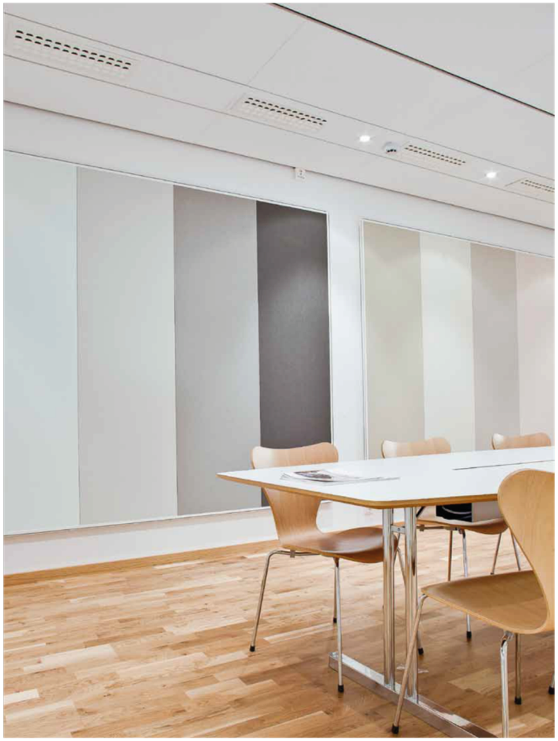


Fig. 7: Example of application of Ecophon Wall Panels.

MOQUETTE

SYSTEM AND PRODUCT DESCRIPTION

Floors can be covered with sound absorbent carpeting, which is easy to install and maintain (especially synthetic vinyl fabrics). These are the ideal flooring solutions for open-space offices, meeting rooms and executive spaces as they offer simple but effective soundproofing.

Format: carpet

Application: floor

Material: synthetic vinyl fabric

ACOUSTIC PERFORMANCE

Sound Absorption Coefficient - Ecophon wall panels							
Frequency (Hz)	125	250	500	1000	2000	4000	SAA
Moquette	0.10	0.20	0.50	0.60	0.80	0.80	0.55

Fig. 8: Technical data sheet of Moquette on the floor.

Fig. 9: Examples of application of Moquette on the floor..

CLOUDSORBA SUSPENDED ACOUSTIC PANELS

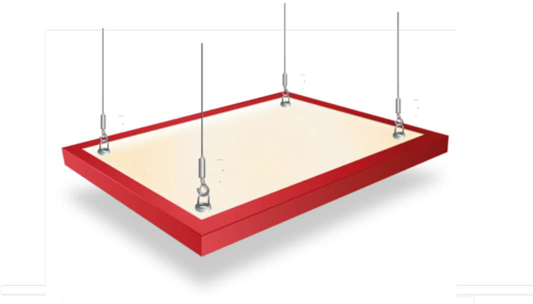
SYSTEM AND PRODUCT DESCRIPTION

Soundsorba Glass fibre sound absorbing boards consist of recovered household glass and recycled glass fibre.
The fabric range used is made from 100% recycled materials saving virgin raw materials, reducing waste to landfill.
Made using sustainable manufacturing techniques, including green electricity, comprehensive energy and effluent management, borehole water and on-going waste saving initiatives, Second Nature fabrics leave a lighter environmental footprint.

Format: panels

Application: ceiling only

Material: glass fibre



ACOUSTIC PERFORMANCE

Sound Absorption Coefficient - Cloudsorba								
Frequency (Hz)	125	250	500	1000	2000	4000	SAA	Sound Absorption Class
Cloudsorba	0.45	0.85	0.95	1.00	1.00	1.00	0.95	A

Fig. 10: Technical data sheet of Cloudsorba suspended acoustic panels..

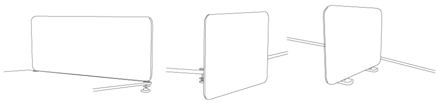
Fig. 11: Examples of application of Cloudsorba suspended acoustic panels..

STEELCASE DIVISIO SCREENS

SYSTEM AND PRODUCT DESCRIPTION

Steelcase divisio scren is a movable partition covered in sound-absorbing material.
It is a modular system that adapts easily to changing work requirements.
Divisio screen has a solid steel frame covered with fabric and offers good stability.

Different combinations



<u>Format:</u> panels

<u>Application:</u> desks/floor

<u>Material:</u> PET, steel, fabric

ACOUSTIC PERFORMANCE

Sound Absorption Coefficient - Steelcase divisio screens								
Frequency (Hz)	125	250	500	1000	2000	4000	SAA	Sound Absorption Class
Steelcase divisio screens	0.25	0.45	0.65	0.80	0.85	0.85	0.70	C per ISO 11554

Fig. 12: Technical data sheet of Steelcase divisio screens.

Fig. 13: Examples of application of Steelcase divisio screens.

HAVEN PODS

SYSTEM AND PRODUCT DESCRIPTION

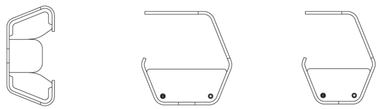
Haven Pods are designed to provide both visual and acoustic privacy within working environments.
Haven Pods are composed of a tubular steel frame fully upholstered .
The core of the screen is created using a composite of materials to provide a stable structure with enhanced acoustic properties and is fully upholstered in fabric.

<u>Format:</u> pods

<u>Application:</u> floor

<u>Material:</u> tubular steel frame
fully upholstered

Different combinations



ACOUSTIC PERFORMANCE

Sound Absorption Coefficient - Haven pods							
Frequency (Hz)	125	250	500	1000	2000	4000	SAA
Haven pods	0.49	0.66	0.80	0.88	0.82	0.70	0.79

Fig. 14: Technical data sheet of Haven Pods.

Fig. 15: Examples of application of Haven Pods.

COCOON ACOUSTIC CHAIR

SYSTEM AND PRODUCT DESCRIPTION

Comfortable and ergonomically sound, Cocoon creates the ideal meeting space for informal environments. The high, upholstered structure absorbs ambient background noise providing complete privacy from the surrounding environment without the need for interior sub structures.
Delivered on castors and having the ability to fit freely, Cocoon lends itself to being easily relocated and reconfigured.

Format: chairs/sofas

Application: floor

Material: - External and internal hoop in fabric
- Seat and cushion upholstered in any fabric, leather or vinyl

ACOUSTIC PERFORMANCE

Sound Absorption Coefficient - Ecophon wall panels							
Frequency (Hz)	125	250	500	1000	2000	4000	SAA
Moquette	0.49	0.66	0.80	0.88	0.82	0.70	0.79

Fig. 16: Technical data sheet of Cocoon Acoustic Chair.

Fig. 17: Examples of application of Cocoon Acoustic Chair.

REFERENCES:

3. J. S. Bradley, Acoustical Design for Open-Plan Offices, Published by Institute for Research in Construction, Construction Technology Update No. 63.
4. Spagnolo, R. (2015). Acustica: Fondamenti e applicazioni. Novara: UTET.
5. V. Hongisto, 10 Industrial noise control ELEC-E5640 - Noise Control P, Espoo, Finland, 25 Nov 2018.

10. Results of room acoustic parameters

10. RESULTS OF ROOM ACOUSTIC PARAMETERS

As previously mentioned in chapter 8, in the international standard ISO 3382-3, in addition to the description of the measurement procedure of the open-plan offices, new acoustic parameters are also defined for the objective evaluation. The parameters taken into account for the simulations are the followings:

- **STI** , ie the Speech Transmission Index;
- $\mathbf{r_D}$, ie distraction distance;
- $\mathbf{D_{2,S}}$, ie Spatial decay rate of A-weighted SPL of speech;
- $\mathbf{L_{p,A,S,4m}}$, ie A-weighted SPL of speech at 4 meters.

Therefore in the following paragraphs the simulated acoustic parameters for the projects of the two offices will be explained.

10.1 OPEN-PLAN OFFICE

First of all, sound absorption coefficients are chosen, based on the literature and on the technical sheet. These can be read in the table 1; the absorption coefficients of the acoustic design are highlighted in green.

Surface/Material	Reference	Area [m2]	Values of acoustic absorption coefficients of surfaces/materials, a [-]						
			125	250	500	1000	2000	4000	8000
Plaster	BB93_Plaster on solid wall	157,66	0,04	0,05	0,06	0,08	0,04	0,06	0,06
Window glass	BB93_4mm glass	11,39	0,3	0,2	0,1	0,07	0,05	0,02	0,02
Window frame	BB93_4mm glass	3,26	0,3	0,2	0,1	0,07	0,05	0,02	0,02
Door	93_Acoustic door, steel frame, double seals, absorbant in airspa	5,74	0,35	0,39	0,44	0,49	0,54	0,57	0,57
Chair	Odeon_Audience, lightly upholstered seats	7,04	0,51	0,64	0,75	0,8	0,82	0,83	0,83
Floor_Linoleum	BB93_Floor tiles, plastic or linoleum	121,66	0,03	0,00	0,03	0,00	0,05	0,05	0,05
Desk	Odeon_classroom wood desk	21,13	0,05	0,08	0,1	0,12	0,12	0,12	0,12
Pavimentazione_Moquette	http://www.bruit.fr/images/stories/pdf/B2_	121,66	0,10	0,20	0,50	0,60	0,80	0,80	0,8
Vibrating panels	Da file excel	68	0,36	0,19	0,13	0,09	0,06	0,05	0,05
Ceiling	Odeon_Steel trapez profile	104,65	0,30	0,25	0,2	0,1	0,1	0,15	0,15
Cabinets	Odeon_classroom wood desk	41,55	0,05	0,08	0,1	0,12	0,12	0,12	0,12
Ventilation grille	Manuale Rockwool_Griglia dell'aria, area aperta 50%	1,8	0,30	0,50	0,50	0,50	0,50	0,50	0,50
Ceiling panels_Cloudsorba	Cloudsorba.pdf	34,00	0,45	0,85	0,95	1,00	1,00	1,00	1,00
Screens between workstatior	Steelcase_Divisions_Pdf	33,60	0,25	0,45	0,65	0,80	0,85	0,85	0,85
Haven pods	http://www.sengpielaudio.com/calculator-R	-	0,49	0,66	0,80	0,88	0,82	0,70	0,70
Wall acoutic panels	Ecophon Wall Panel A/Super G 40 mm o.d.s	31,20	0,15	0,65	1,00	1,00	0,95	0,80	0,80
Acoustic chair	www.sengpielaudio.com/calculator-RT60Co	-	0,49	0,66	0,80	0,88	0,82	0,70	0,70

Table 6: sound absorption coefficients used for simulations in Odeon.

Three experimental conditions of OP OFFICE 1 are presented. The conditions are created by modifying background noise level with the level of masking sound, and the absorption coefficient of the flooring. For the configuration of the different conditions, recommendations by Hongisto et al. [8] are taken into account.

The conditions are:

0) C0_*at*[12]: this condition corresponds to the state of the art condition of the office, with room acoustic treatments. The ceiling is covered with ceiling-hanging acoustic panels above the workstations, at heights of 3,0 m above the floor; walls are covered with acoustic panels; screens between workstations 1,7 m high

[12] "*at*" stands for acoustic treatment.

above the floor with SAA = 0,70 are used, and floor is covered with moquette with SAA = 0,55. The background noise level is equal to 34,7 dB. This situation requires that the number of occupants (21) does not change.

1) **C1_*af***[13]: this condition is equal to C0_*at*, but with a different disposition of workstations. Now the number of the occupants is 14; 7 less than the C0_*at*.
2) **C1_*af_sm***[14]: this condition is equal to C2_*af*, but in this case sound masking system is applied and it is equal to 40,1 dB. Sound masking level values are taken from the book "Acustica: Fondamenti e applicazioni", ch. 20.3 [11]. The curve of the sound masking level is shown in fig. 1 and corresponds to the lowest dotted line.

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[13] "*af*" stands for absorbent floor.
[14] "*sm*" stands for sound masking.

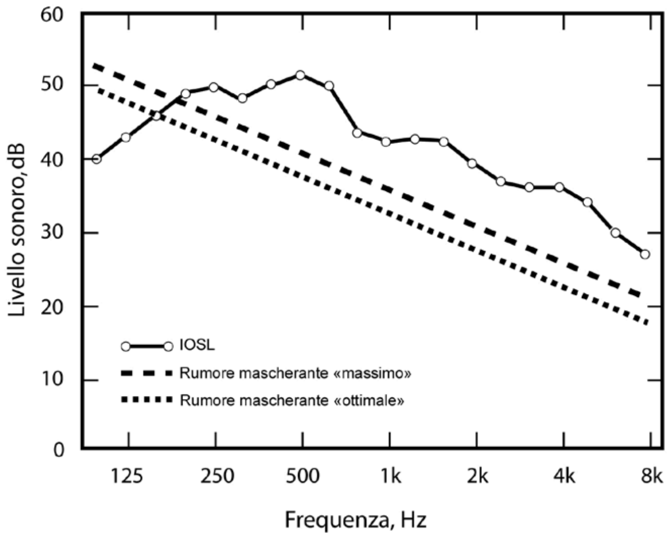

Fig. 1: curve of sound masking level.

3) **C1_*rf_sm***[15]: this condition is equal to C2_*rf_sm* without the absorbent surface of the flooring. In this case it is considered as a linoleum reflective surface. Absorption sound coefficients of the latter are shown in table 1.

[15] "*rf*" stands for reflective floor.

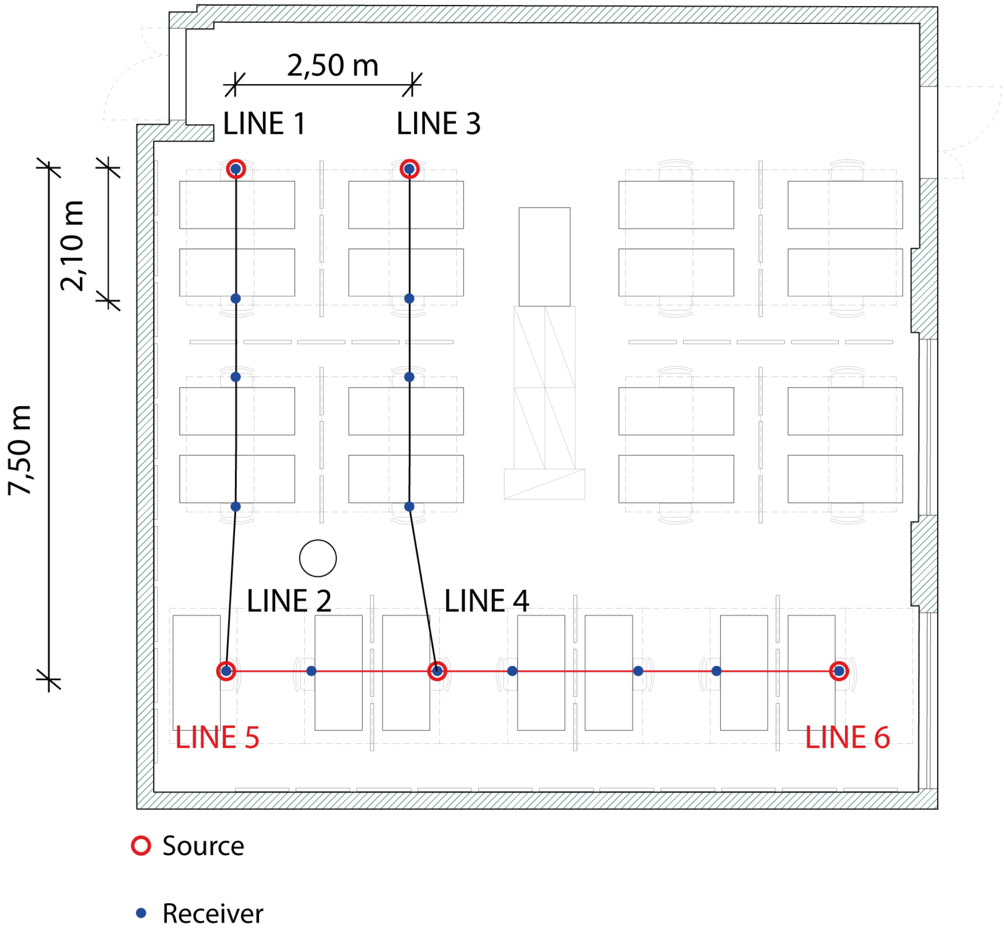

Fig.2: Plan of OP OFFICE 1, condition C0_at (scale 1:100) with source and receiver positions.

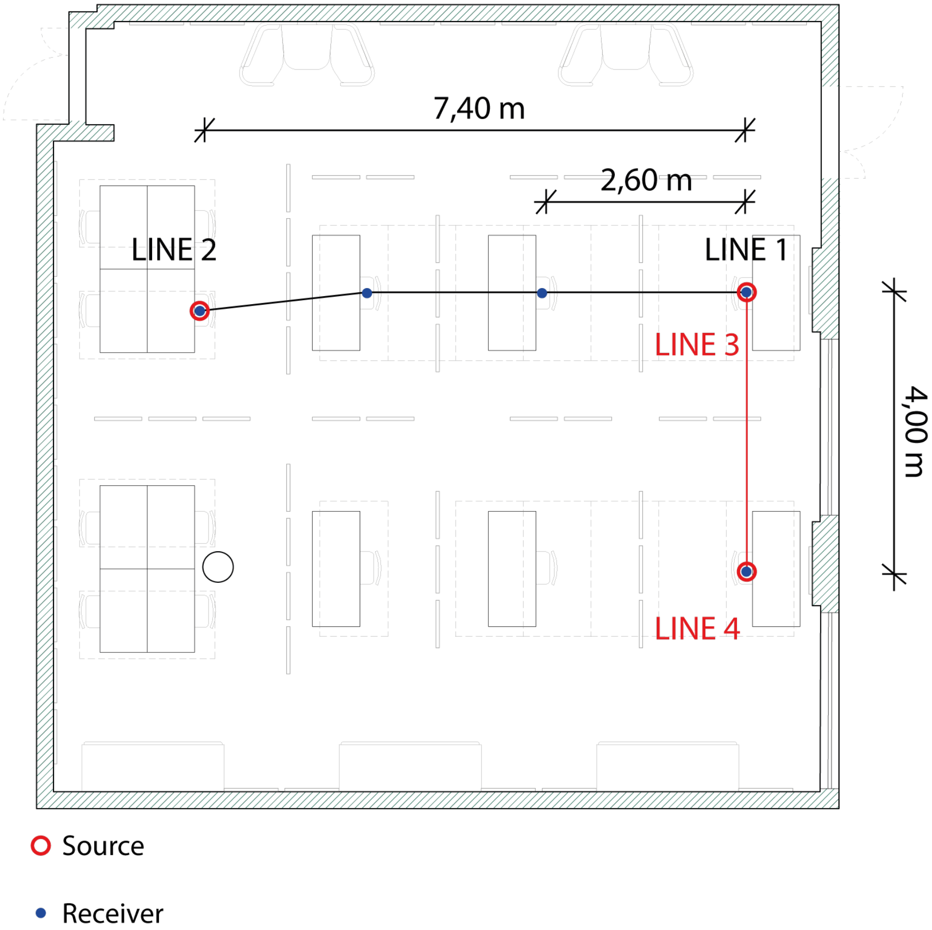

Fig. 3: Plan of OP OFFICE 1, conditions C1_af, C1_af_sm, C1_rf_sm (scale 1:100) with source and receiver positions.

Results of the simulated acoustic parameters for each of the above mentioned conditions of OP OFFICE 1 are shown below.

0) C0_*at*:

	STATE OF THE ART												
	C0_at												
		LINE 1		LINE 2		LINE 3		LINE 4		LINE 5		LINE 6	**AVERAGE**
T20 [s]		0,35		0,34		0,38		0,37		0,21		0,38	**0,34**
STI	**2,10 m**	0,91	**2,30 m**	0,90	**2,10 m**	0,86	**2,40 m**	0,89	**1,05 m**	0,97	**2,00 m**	0,77	**0,88**
	7,50 m	0,70	**7,50 m**	0,72	**7,50 m**	0,55	**7,50 m**	0,57	**9,05 m**	0,40	**9,05 m**	0,43	**0,56**
rD [m]		12,57		13,41		9,13		7,75		6,38		6,56	**9,30**
D2,S [dB]		4,70		4,69		5,49		6,81		3,58		5,25	**5,1**
Lp,A,S,4M [dB]		48,41		48,65		47,72		46,87		40,16		41,52	**45,6**
Lp,A,B [dB]		34,68		34,68		34,68		34,68		34,68		34,68	**34,7**

Average value of T_{20} is equal to 0,34. The average value of STI in the nearest workstation is 0,88; while in the furthest one it is 0,56. $D_{2,S}$ and r_D have respectively average values of 5,1 dB and 9,30. The $L_{p,A,S,4m}$ average value is equal to 45,6 dB.

1) C1_*af*:

	ACOUSTIC PROJECT						
	C1_af						
		LINE 1	LINE 2		LINE 3	LINE 4	**AVERAGE**
T20 [s]		0,37	0,34		0,35	0,38	**0,36**
STI	**2,60 m**	0,66	0,60	**4,00 m**	0,74	0,74	**0,69**
	7,40 m	0,50	0,50	**-**	-	-	**0,50**
rD [m]		5,76	5,23		11,68	7,92	**7,65**
D2,S [dB]		5,9	6,1		7,1	7,8	**6,7**
Lp,A,S,4M [dB]		41,8	40,3		46,8	46,6	**43,9**
Lp,A,B [dB]		34,7	34,7		34,7	34,7	**34,7**

Average value of T_{20} is equal to 0,36. The average value of STI in the nearest workstation is 0,69; while in the furthest one it is 0,50. $D_{2,S}$ and r_D have respectively average values of 6,7 dB and 9,30. The $L_{p,A,S,4m}$ average value is equal to 43,9 dB.

2) C1_af_sm:

	ACOUSTIC PROJECT						
	C1_af_sm						
		LINE 1	LINE 2		LINE 3	LINE 4	**AVERAGE**
T20 [s]		0,37	0,34		0,35	0,38	**0,36**
STI	**2,60 m**	0,48	0,41	**4,00 m**	0,57	0,57	**0,51**
	7,40 m	0,32	0,30	**-**	-	-	**0,31**
rD [m]		2,32	2,54		6,10	5,03	**4,00**
D2,S [dB]		6,4	6,7		7,2	7,9	**7,1**
Lp,A,S,4M [dB]		41,8	40,3		46,8	46,6	**43,9**
Lp,A,B [dB]		40,1	40,1		40,1	40,1	**40,1**

Average value of T_{20} is equal to the previous condition, 0,36. The average value of STI in the nearest workstation is 0,51; while in the furthest one it is 0,31. $D_{2,S}$ and r_D have respectively average values of 7,1 dB and 4,00. The $L_{p,A,S,4m}$ average value is equal to 43,9 dB.

3) C1_*rf_sm*:

	ACOUSTIC PROJECT						
	C1_rf_sm						
		LINE 1	LINE 2		LINE 3	LINE 4	**AVERAGE**
T20 [s]		0,43	0,43		0,40	0,42	**0,42**
STI	**2,60 m**	0,59	0,44	**4,00 m**	0,59	0,58	**0,55**
	7,40 m	0,38	0,37	**-**	-	-	**0,38**
rD [m]		3,73	2,23		6,61	5,46	**4,51**
D2,S [dB]		6,4	6,6		7,0	6,7	**6,7**
Lp,A,S,4M [dB]		43,9	41,9		48,0	47,7	**45,4**
Lp,A,B [dB]		40,1	40,1		40,1	40,1	**40,1**

Average value of T_{20} is equal to 0,42. The average value of STI in the nearest workstation is 0,55; while in the furthest one it is 0,38. $D_{2,S}$ and r_D have respectively average values of 6,7 dB and 4,51. The $L_{p,A,S,4m}$ average value is equal to 45,4 dB.

10.2 SHARED OFFICE

Sound absorption coefficients are assigned to SH OFFICE 2 in the same way as described in 10.1.

Two experimental conditions of SH OFFICE 2 are presented. The conditions are created by modifying background noise level with the level of masking sound, and the absorption coefficient of the flooring. The conditions are:

1) **C1_*sm_rf***: this condition corresponds to a situation with room acoustic treatments. The ceiling is covered with ceiling-hanging acoustic panels above the workstations, at height of 2,7 m above the floor; walls are covered with acoustic panels; screens between workstations 1,7 m high above the floor with SAA = 0,70 are used, and floor is covered with moquette with SAA = 0,55. Sound masking system is applied and it is equal to 40,1 dB.
2) **C1_*sm_af***: this condition is equal to C1_*sm_rf*, except for floor that is now considered, as it is at the start of the art, as a reflective surface covered in marble.

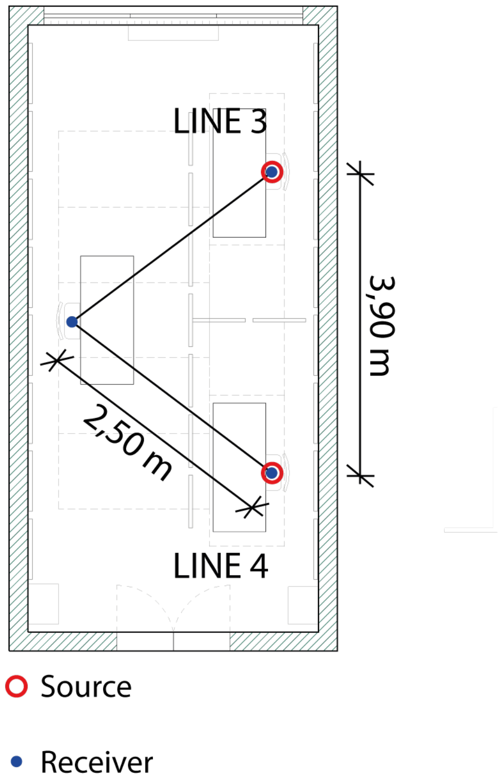

Fig. 4: Plan of SH OFFICE 2, conditions C1_sm_rf, C1_sm_af (scale 1:100) with source and receiver positions.

Results of the simulated acoustic parameters for each of the above mentioned conditions of SH OFFICE 2 are shown below.

1) C1_*sm_rf*:

	ACOUSTIC PROJECT			
	C1_sm_rf			
		LINE 3	LINE 4	**AVERAGE**
T20 [s]		0,32	0,32	**0,32**
STI	**2,50 m**	0,62	0,61	**0,62**
	3,90 m	0,48	0,49	**0,49**
rD [m]		3,70	3,75	**3,73**
D2,S [dB]		7,6	7,0	**7,3**
Lp,A,S,4M [dB]		43,6	43,8	**43,7**
Lp,A,B [dB]		40,1	40,1	**40,1**

Average value of T_{20} is equal to 0,32. The average value of STI in the nearest workstation is 0,62; while in the furthest one it is 0,49. $D_{2,S}$ and r_D have respectively average values of 7,3 dB and 3,73. The $L_{p,A,S,4m}$ average value is equal to 43,7 dB.

2) C1_*sm_af*:

	ACOUSTIC PROJECT			
	C1_sm_af			
		LINE 3	LINE 4	**AVERAGE**
T20 [s]		0,31	0,31	**0,31**
STI	**2,50 m**	0,60	0,61	**0,61**
	3,90 m	0,47	0,47	**0,47**
rD [m]		3,59	3,64	**3,62**
D2,S [dB]		7,4	7,1	**7,3**
Lp,A,S,4M [dB]		43,1	43,2	**43,2**
Lp,A,B [dB]		40,1	40,1	**40,1**

In this condition, values do not differ significantly compared to the previous condition.

Average value of T_{20} is equal to 0,31. The average value of STI in the nearest workstation is 0,61; while in the furthest one it is 0,47. $D_{2,S}$ and r_D have respectively average values of 7,3 dB and 3,62. The $L_{p,A,S,4m}$ average value is equal to 43,2 dB.

For both OP OFFCE 1 and SH OFFICE 2, results of simulated acoustic parameters are compared to optimal ones defined by Virjonen et al. [7] and by H.O. Olufsen [8], regards the STI values, as in chapter 8. Below there are tables representing these values:

ACOUSTIC CLASS	r_D	$D_{2,S}$	$L_{p,A,S,4m}$
A	< 5	> 11	< 48
B	5 | 8	9 | 11	48 | 51
C	8 | 11	7 | 9	51 | 54
D	11 | 15	5 | 7	> 54
E	> 15	< 5	

Table 2: Optimal acoustic parameters values defined by Virjonen et al.

STI	Speech privacy
0.00 – 0.05	confidential
0.05 – 0.20	bad
0.20 – 0.40	reasonable
0.40 – 0.60	poor
0.60 – 0.75	bad
0.75 – 0.99	very bad

Table 3: Optimal STI values defined by H.O. Olufsen.

10.3 DISCUSSION

Comparisons between the different conditions of the offices, has helped to understand how much the addition of acoustic treatments can influence the acoustic project and the simulated acoustic parameters. Acoustic treatments concern wall acoustic panels, ceiling panels, screens between workstations, sound masking and floor carpeting.

OP OFFICE 1

Regarding OP OFFICE 1 in ***C0_at*** all the acoustic treatments above mentioned are used, with the exception of sound masking. This condition requires that the number of occupants (21) does not change, as it is in the state of the art.

As can be seen from the results of simulated acoustic parameters, STI average values is out of the optimal values described by Virjionen et al., even if at the furthest distance the value decreases from 0,88 to 0,56. Moreover, even the r_D does not satisfy the optimal values, being 9,30 a high value. Instead the average values of $D_{2,S}$ and $L_{p,A,S,4m}$ fall within the range of optimal values.

C1_af is equal to C0_*at*. The only change is in the different disposition and different number of workstations: now they are 14. This decrease in the number of workstations has been made in order to guarantee a greater distance between occupants inside the office: the distance between two people in ***C0_at*** was 2,10 m, but now in ***C1_af*** it is equal to 2,60 m, as recommended by Hongisto [12].

The positive changes between ***C0_at*** and ***C1_af*** are clearly evident if the average simulated parameters are compared. By increasing the distance of 0,50 m between workstations, STI (in the nearest position) decreases from 0,88 of the **C0_*at*** to 0,69 of the **C1_*af***, and the STI (in the furthest position) decreases from 0,56 of the **C0_*at*** to 0,50 of the **C1_*af***. The r_D decrease from 9,30 m to 7,65 m passing from class “C” to class “B” (see table 2). Also the $D_{2,S}$ average value has improved.

Therefore the reduction in the number of workstations has brought about obvious improvements in the comparison of the simulated acoustic parameters between **C0_*at*** and the **C1_*af***.

In the condition **C1_*af***, with ceiling-hanging acoustic panels above the workstations, walls acoustic panels, screens between workstations and moquette on the floor, a good value of the STI was not reached; therefore sound masking was added in the next condition **C1_*af_sm***.

In **C1_*af_sm*** the addition of sound masking has led improvements in the results of all the simulated acoustic parameters. In fact, increasing the background noise from 34,7 dB of **C1_*af*** to 40,1 dB of **C1_*af_sm*** has a beneficial influence, decreasing value of average STI from 0,69 to 0,51, in the nearest position, and from 0,50 to 0,31 in the furthest one. It was also reported by J. H. Rindel and C. L. Christensen [9], that the addition of sound masking instead of measured background noise has positive effects on STI values.

In ***C1_rf_sm*** value of STI has increased of only 0,04 in the nearest position, and of 0,07 in the furthest one. Therefore this result does not appear to be particularly relevant in the comparison between ***C1_af_sm*** and ***C1_rf_sm***.

The average value of r_D decreases from 7,65 m in the ***C1_af*** to 4,00 m in the ***C1_af_sm***, passing from class "B" to class "A", (see table 2). However it does not present particularly improvement values in the condition ***C1_rf_sm*** with reflective floor surface. Virjonen et al. [10] suggested that distraction distance r_D would be the most suitable way to describe objective speech privacy. In fact, as also reported by Hongisto et al., [8] in his study r_D decrease considerably in condition with sound masking, compared to that one without it.

From the first condition to the third one, the average value of $D_{2,S}$ increases from 5,1 dB in ***C0_at***, to 6,7 dB in ***C1_af*** up to the maximum value of 7,1 dB in ***C1_af_sm***, then passing from class D to class C, according to optimal acoustic parameters values defined by Virjonen et al. [7]; while in the fourth condition ***C1_rf_sm*** the average value of $D_{2,S}$ is equal to 6,7 dB. So also adding moquette on the floor has beneficial impacts on the $D_{2,S}$ value if ***C1_rf_sm*** is compared to condition without sound masking ***C1_af***, but not if it is compared to the condition with sound masking and moquette on the floor ***C1_af_sm***.

Values of $\mathbf{L_{p,A,S,4m}}$ are always satisfied in all the four conditions, as they are always less than the value defined in class A (< 48,0 dB) by Virjonen et al. in table 2.

In conclusion it is clear that the condition ***C1_af_sm*** - with sound masking and moquette on the floor - is the best condition in relation to the simulated acoustic parameter output of the other three conditions (***C0_at***, ***C1_af*** and ***C1_rf_sm***).

Furthermore, it is also evident that a smaller number of occupants/workstations within the office, compared to the state of the art - 21 occupants in ***C0_at*** and 14 occupants in ***C1_af_sm*** - has beneficial influence on the results of average simulated acoustic parameters.

If the condition **C0** and the condition ***C1_af_sm*** are compared, considerable changes are evident in the values of the simulated acoustic parameters (see table 3 – chapter 8). Average value of STI decreases from 0,62 in **C0** to 0,51 in ***C1_af_sm***; average value of r_D decreases from 9,62 m in **C0** to 4,00 m in ***C1_af_sm***; average value of $D_{2,S}$ increases from 1,2 dB in **C0** to 7,1dB in **C1_*af_sm***; average value of **$L_{p,A,S,4m}$** decrease from 55,9 dB in **C0** to 43,9 dB in **C1_*af_sm***.

SH OFFICE 2

It should be noted that in the simulations of the acoustic parameters of SH OFFICE 2, the condition without sound masking was not taken into consideration for too high output values.

Two conditions are compared: **C1_*sm_rf*** with sound masking and marble reflective floor; **C1_*sm_af*** with sound masking and acoustic treatment on the floor (moquette). The differences between the two conditions are minimum and, therefore, not relevant to be reported.

Anyway, if condition **C1_*sm_af*** is compared to the condition **C0**, corresponding to the state of the art of the office, previously described in chapter 8, has significant improvements in all the simulated acoustic parameters. In fact, in **C0** all the parameters has marked in red (see table 4 - Chapter 8) because they are out of the range of optimal values described in table 2 and 3.

The only parameter that do not satisfy the optimal values (see table 3) is STI values, probably due to the small size of the office. Therefore SH OFFICE 2 may not be an office suitable for 3 occupants.

In conclusion, from these results it is clear that the set of acoustic treatments such as ceiling-hanging acoustic panels above the workstations, walls acoustic panels, screens between workstations, moquette on the floor and sound masking, lead to improvements in an open-plan and shared offices in terms of acoustic parameters.

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CONCLUSIONS

From the results of chapter 10, the conclusions of this thesis can be divided in relation to the two offices analyzed as case studies: OP OFFICE and SH OFFICE 2.

Regarding to **OP OFFICE 1**, it has been shown that at state of the art of the office (**C0**) no acoustic treatment has been done. This is evident from the in-situ measurements carried out whose outputs showed a very high reverberation time (T_{20}), 1.02 s. This value is out of the range of optimal values defined by NF S31-080 according to which the optimal value of T_{20} within open-plan offices must be at least between 0.6 s and 0.8 s.

The simulations of the acoustic parameters of STI, r_D, $D_{2,S}$ and $L_{p,A,S,4m}$ have also been carried out. Even these results are negative especially with regard to $D_{2,S}$ and $L_{p,A,S,4m}$ values.

A condition **C0_*at*** was simulated in order to maintain the same number of workstations/occupants within the OP OFFICE 1. This condition provides for an acoustic treatment as follows: ceiling-hanging acoustic panels above the workstations, walls acoustic panels, screens between workstations and moquette on the floor. Improvements are evident in the simulated acoustic parameters of this condition. In fact, if the two conditions are compared, the values of T_{20}, r_D, $D_{2,S}$ and $L_{p,A,S,4m}$ turn out to be better, but not the value of the STI that has increased.

Therefore it was necessary to reduce the number of workstations so that the results of the simulated acoustic parameters are better. This step was performed in the condition **C1_*af*** in which the only difference with the condition **C0_*at*** is in the reduction of the number of occupants, from 21 to 14, and therefore in the arrangement of workstations; while adopted acoustic treatments are almost the same in the two conditions. **C1_*af*** condition has better average values of acoustic simulated parameters, with the exception of STI and $D_{2,S}$. Distraction distance rD and A-weighted SPL of speech at 4 meters $L_{p,A,S,4m}$ are respectively in class “B” and “A” of the range of optimal values defined by Virjonen et al. (see table 2 – chapter 10).

In order to further improve the simulated acoustic parameters, another condition has been performed **C1_*af_sm*** equal to **C1_*af*** but with the addition of sound masking.

In ***C1_af_sm*** the addition of sound masking has led improvements in the results of all the simulated acoustic parameters. In fact, increasing the background noise from 34,7 dB of ***C1_af*** to 40,1 dB of ***C1_af_sm*** has a beneficial influence, decreasing value of average STI from 0,69 to 0,51, in the nearest position, and from 0,50 to 0,31 in the furthest one. It was also reported by J. H. Rindel and C. L. Christensen, that the addition of sound masking instead of measured background noise has positive effects on STI values.

Another condition has also been experimented ***C1_rf_sm*** in which the moquette of the floor is removed, and therefore the latter is a reflective surface. If this condition is compared to the previous one ***C1_af_sm***, the changes in the average values of the acoustic parameters are not particularly significant, and they do not differ much from those simulated in the condition ***C1_af_sm***, except for the following ones:

- $D_{2,S}$ which decreases from an average value of 7,1 dB in ***C1_af_sm*** to an average value of 6,7 dB in ***C1_rf_sm***;
- r_D increases from an average value of 4,00 m in ***C1_af_sm*** to an average value of 4,51 m in ***C1_rf_sm***.

Therefore the best condition of OP OFFICE 1 is the one with acoustic treatments on walls, floor and ceiling, screens between workstations, acoustic furniture and sound masking.

Two conclusions can be drawn from this office:

1) The reduction in the number of occupants/workstations within the office, compared to the state of the art - 21 occupants in **C0_*at*** and 14 occupants in **C1_*af_sm*** - has beneficial influence on the results of average simulated acoustic parameters, except for the average STI values;

2) The addition of sound masking led to improvements in all the simulated acoustic parameters, especially for the average STI values.

Regarding to **SH OFFICE 2**, it has been shown that at state of the art of the office (**C0**) no acoustic treatment has been done. This is evident from the in-situ measurements carried out whose outputs showed a very high reverberation time (T_{20}), 1.06 s. This value is out of the range of optimal values defined by NF S31-080 according to which the value of T_{20} within shared offices must be at least between 0.6 s, to reach an “efficient” level of reverberation time. The simulations of the acoustic parameters of STI, r_D, $D_{2,S}$ and $L_{p,A,S,4m}$ have also been carried out. These are simulated in **C0** condition and the average results are all out of the range of optimal values defined by Virjonen et al and H.O. Olufsen, respectively in table 2 and 3 of chapter 10.

Two conditions are simulated: ***C1_sm_rf*** with sound masking and marble reflective floor; ***C1_sm_af*** with sound masking and acoustic treatment on the floor (moquette). From the results of these two condition, there are no significant differences in the simulated acoustic parameters.

But if ***C1_sm_af*** is compared to the state of the art condition **C0**, significant improvements in all the simulated acoustic parameters are demonstrated. Results can be summarized as follows:

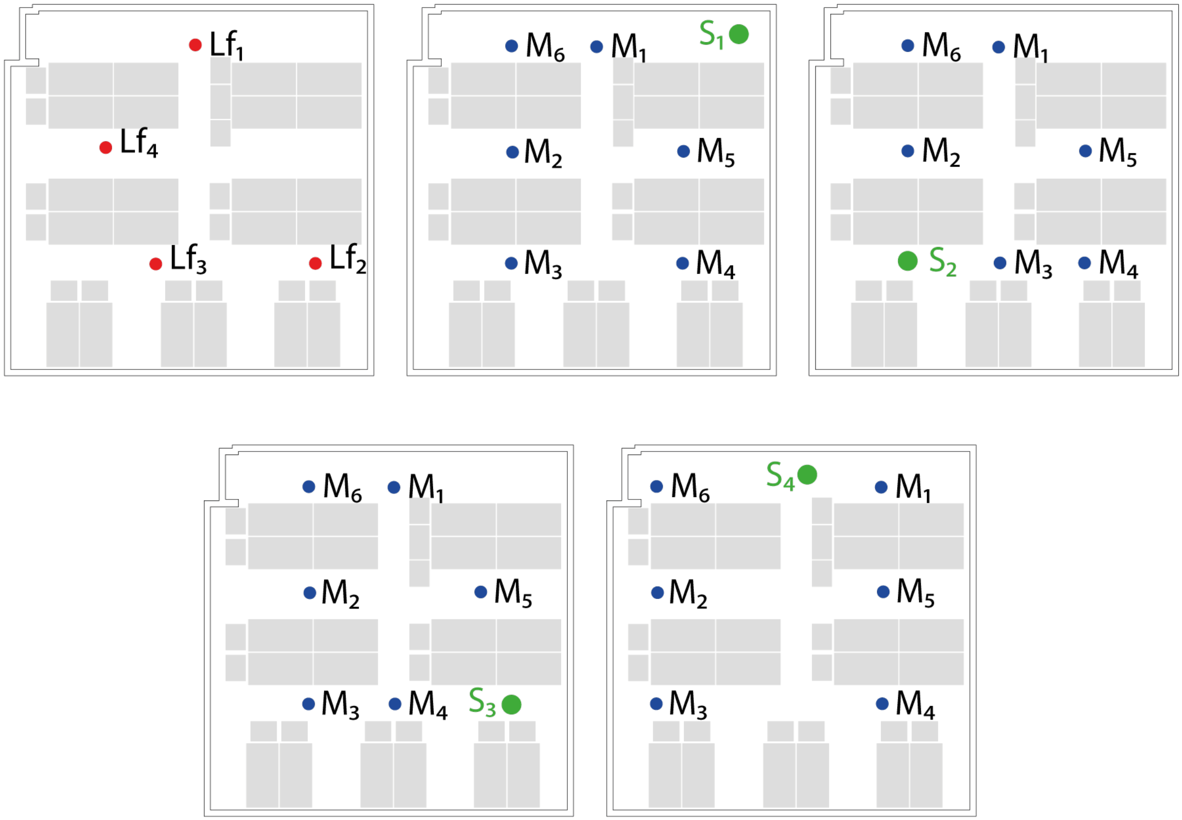
- T_{20} changes from an average value of 0,99 s in **C0** to an average value of 0,31 s in ***C1_sm_af***;
- There are no significant changes in the average STI values between the two conditions, probably due to the small size of the office;
- r_D values in C0 are too high to be compared to the ***C1_sm_af*** ones, but in the latter, r_D satisfy the optimal acoustic parameters values defined by Virjonen et al.;

- $D_{2,S}$ changes positively from an average value of 1,2 dB in **C0** to an average value of 7,3 dB in **C1_*sm_af***;
- $L_{p,A,S,4m}$ decreases from an average value of 59,8 dB in **C0** to an average value of 43,2 dB in **C1_*sm_af***, so it is in class “A” of the range of optimal values defined by Virjonen et al.

Given that the STI is the only parameter that not included into the table of optimal acoustic parameters (see table 3 – chapter 10), it can be concluded that SH OFFICE 2 may not be an office suitable for 3 occupants. In this study, sound masking turned out to be an essential acoustic treatment in order to achieve optimal acoustic parameters, especially with regard to STI values.

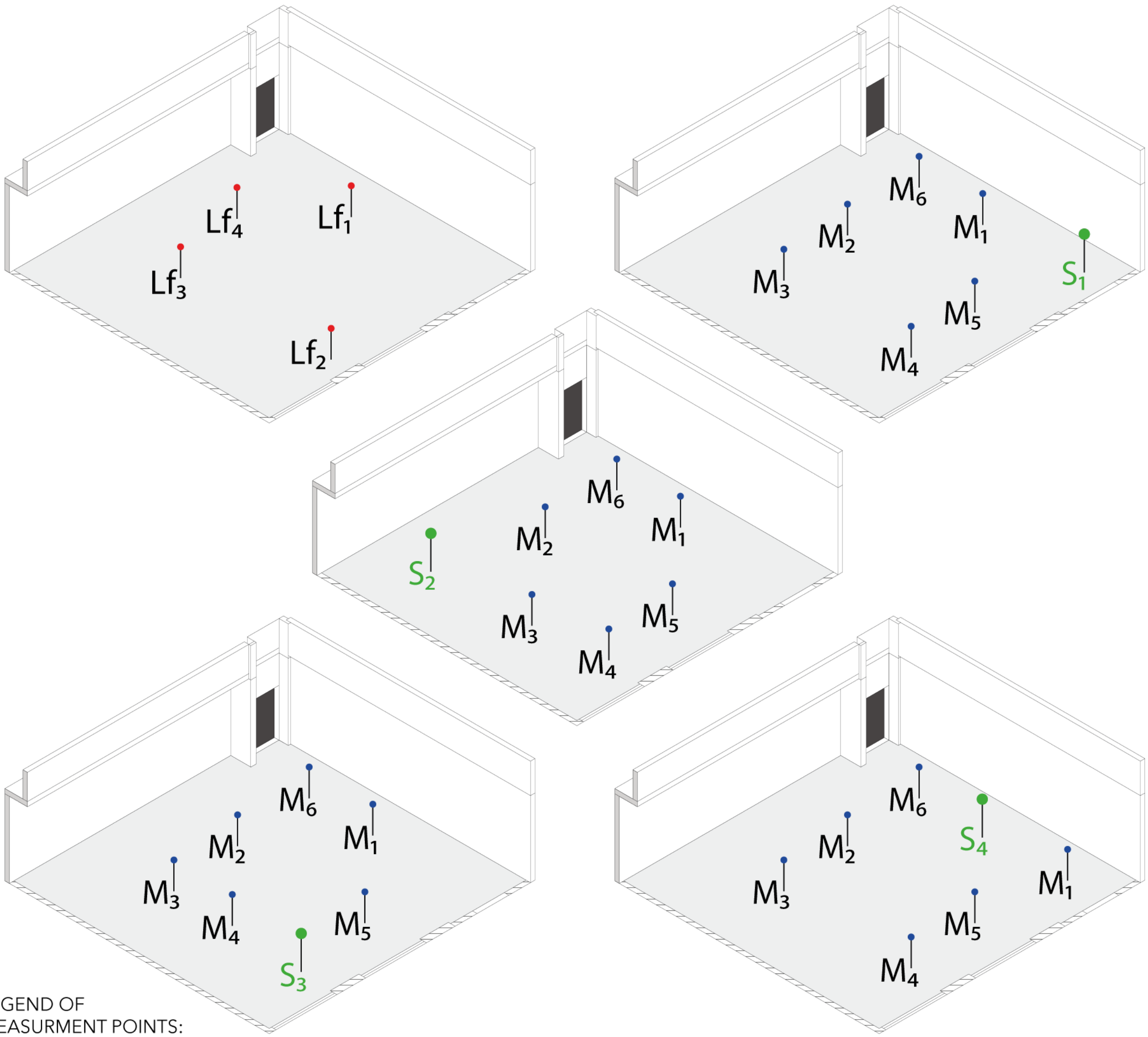
ATTACHEMENTS

OP OFFICE 1: Measuring points for acoustic measurement



LEGEND OF
MEASURMENT POINTS:
Lf = Measuring point of
background noise
S = Source - h = 1,5 m
M = Receiver - h = 1,2 m

OP OFFICE 1: Measuring points for acoustic measurement



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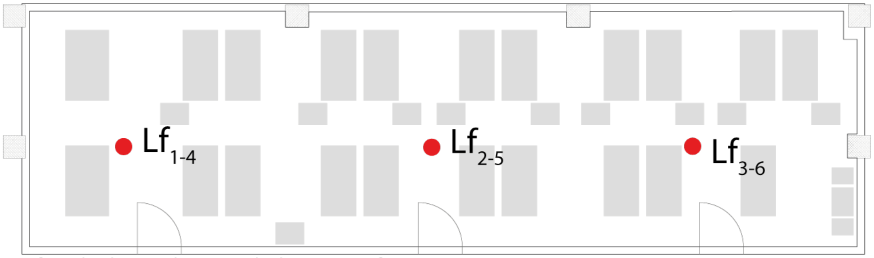
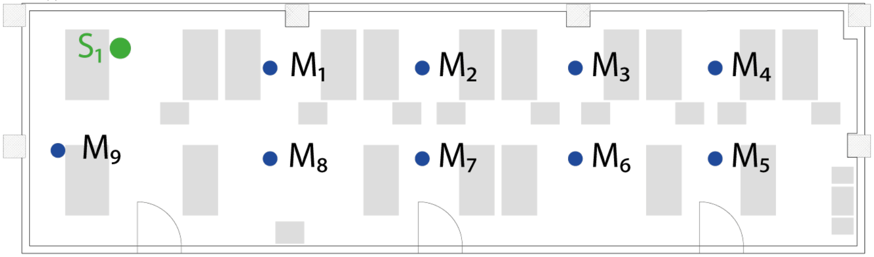
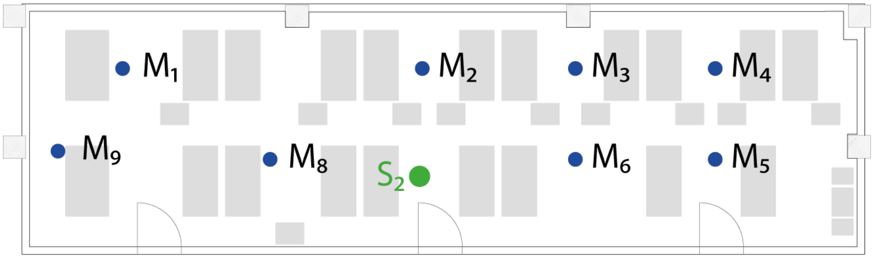
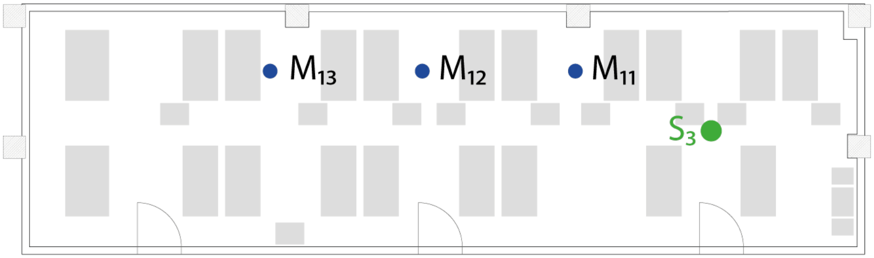
OP OFFICE 2: Measuring points for acoustic measurement



$Lf_{1,2,3}$ = background noise at the beginning of measurements
$Lf_{4,5,6}$ = background noise at the end of the measurements







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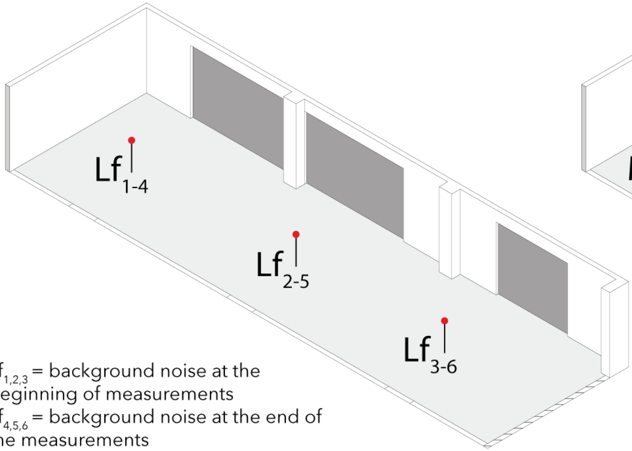

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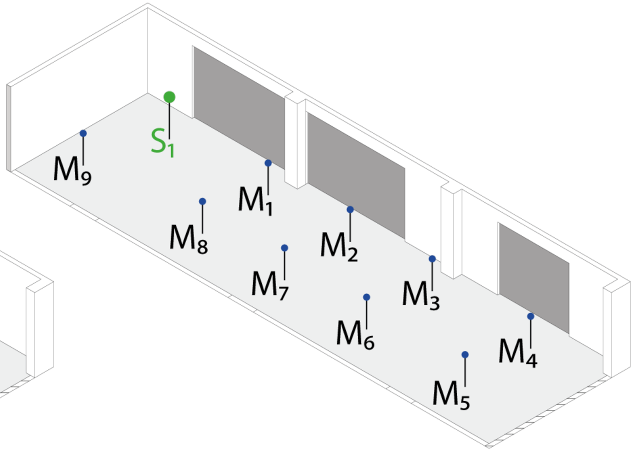

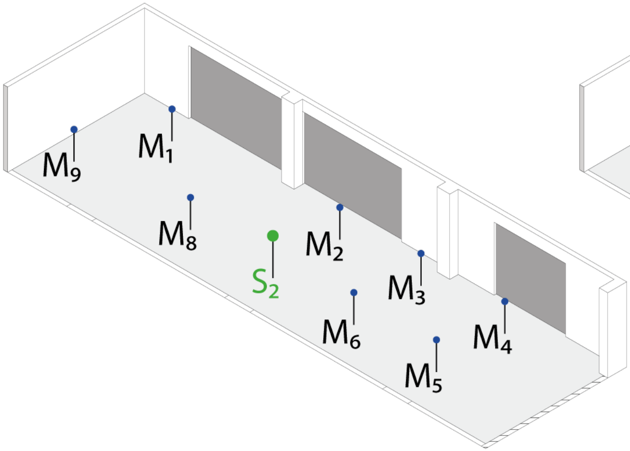

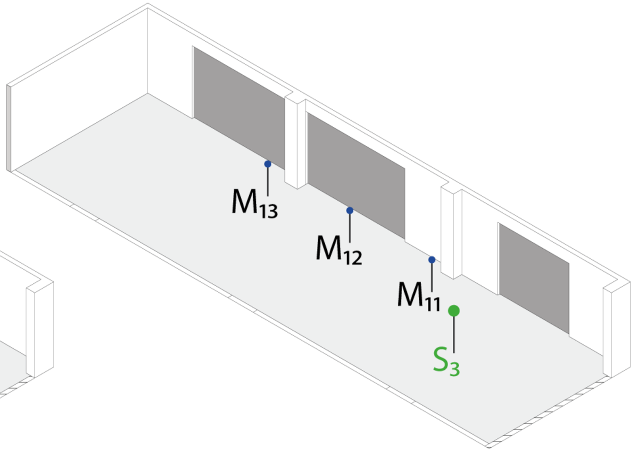

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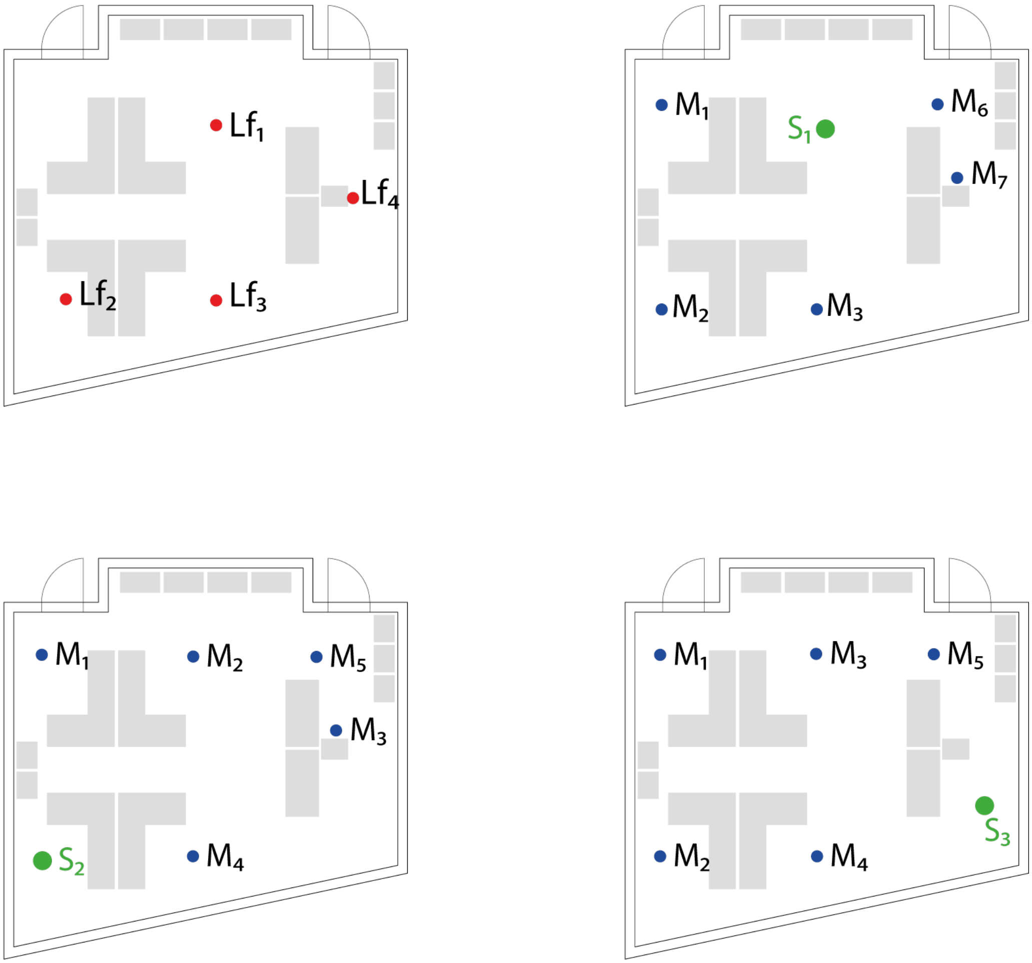

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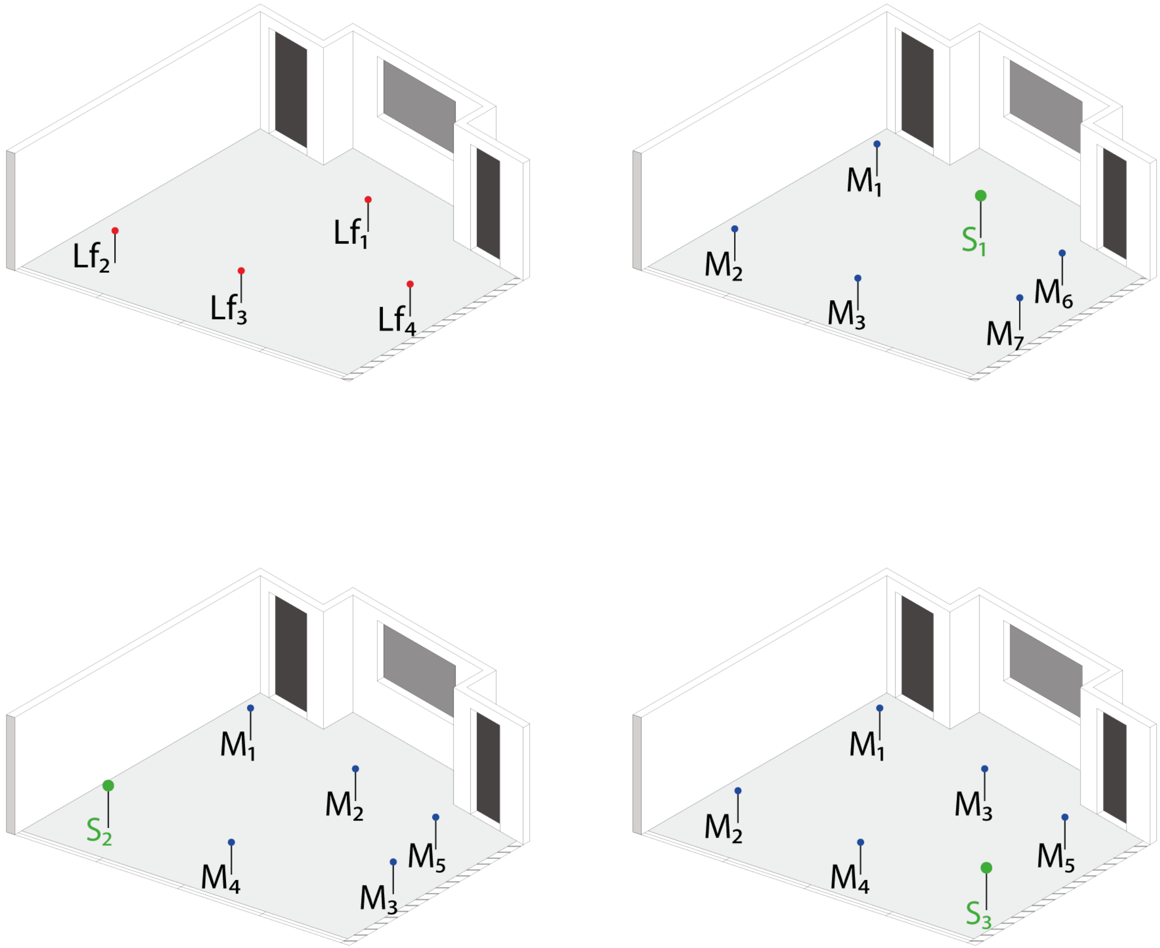

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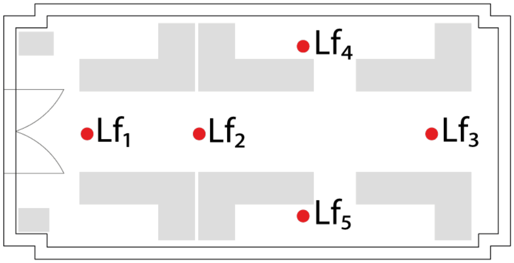
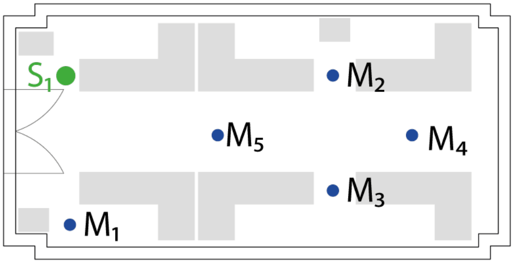
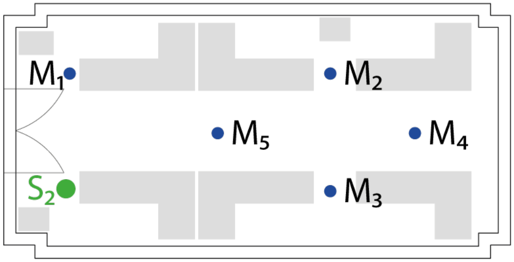
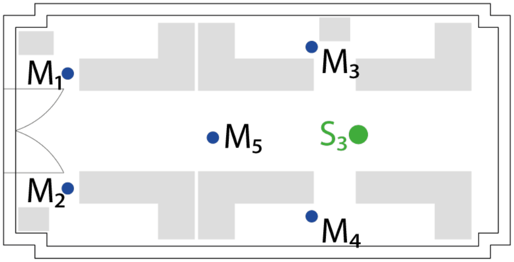
SH OFFICE 2: Measuring points for acoustic measurement









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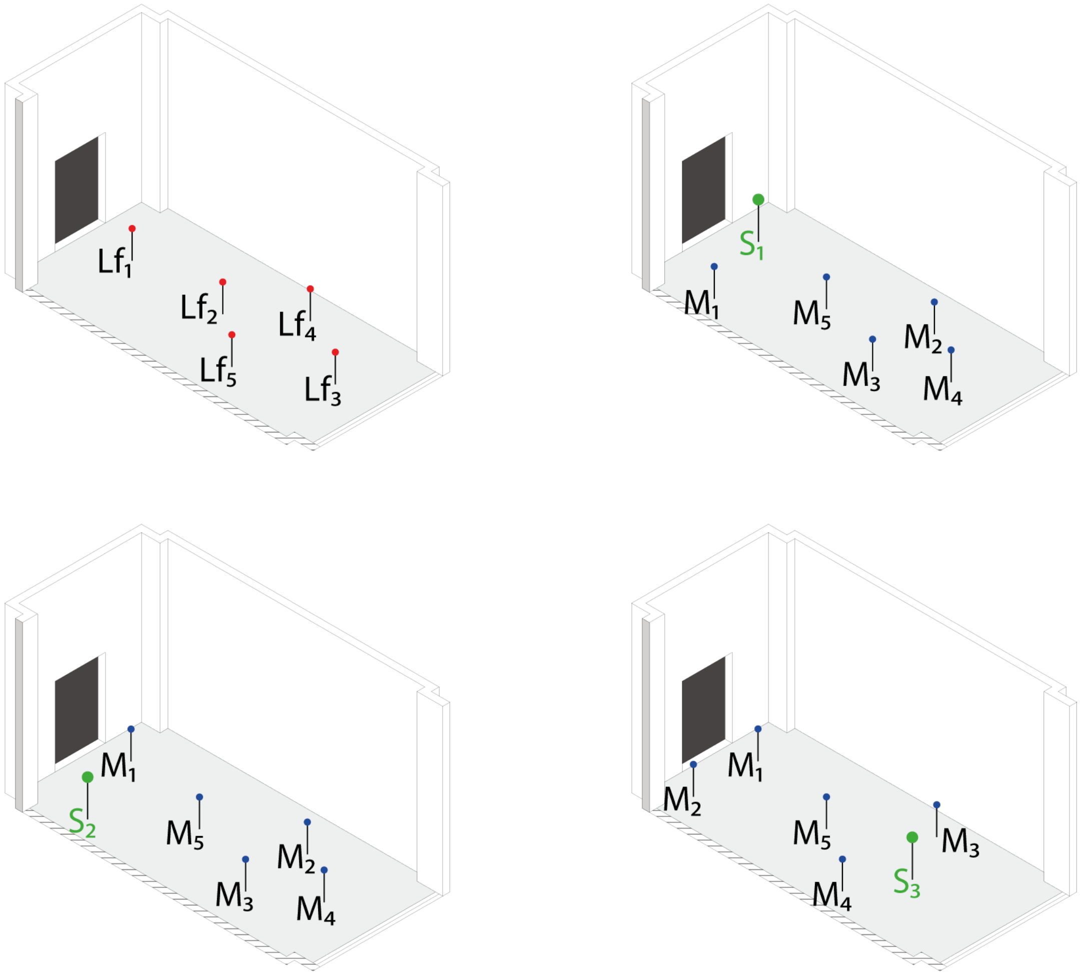

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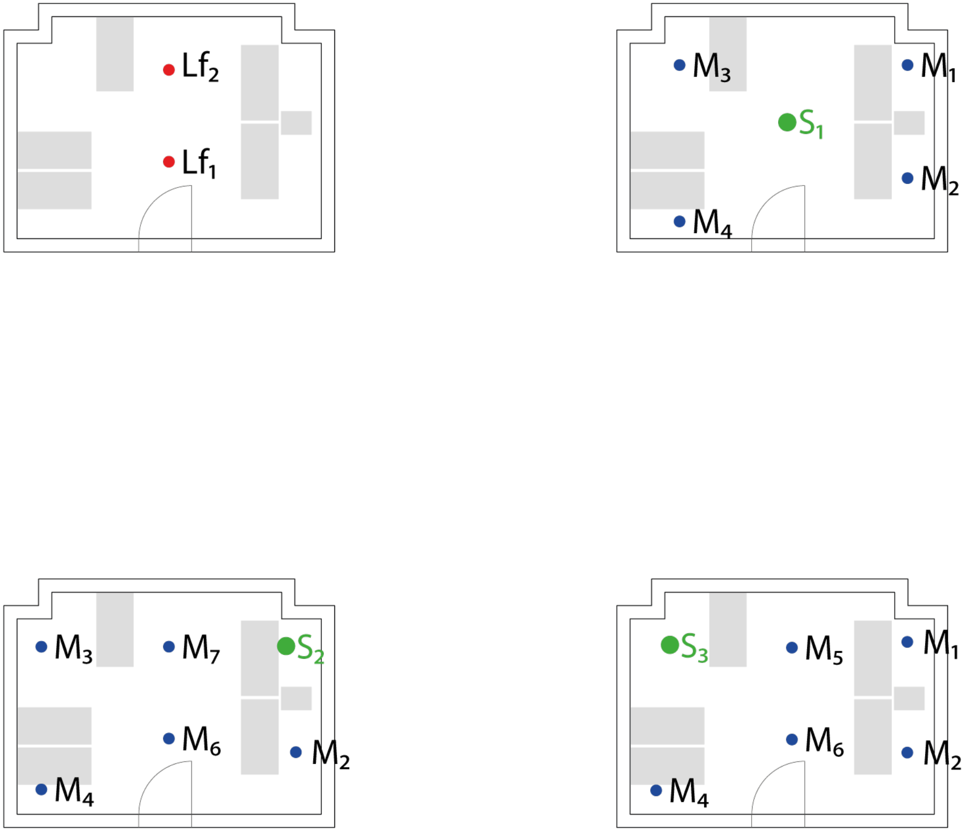
SH OFFICE 3: Measuring points for acoustic measurement



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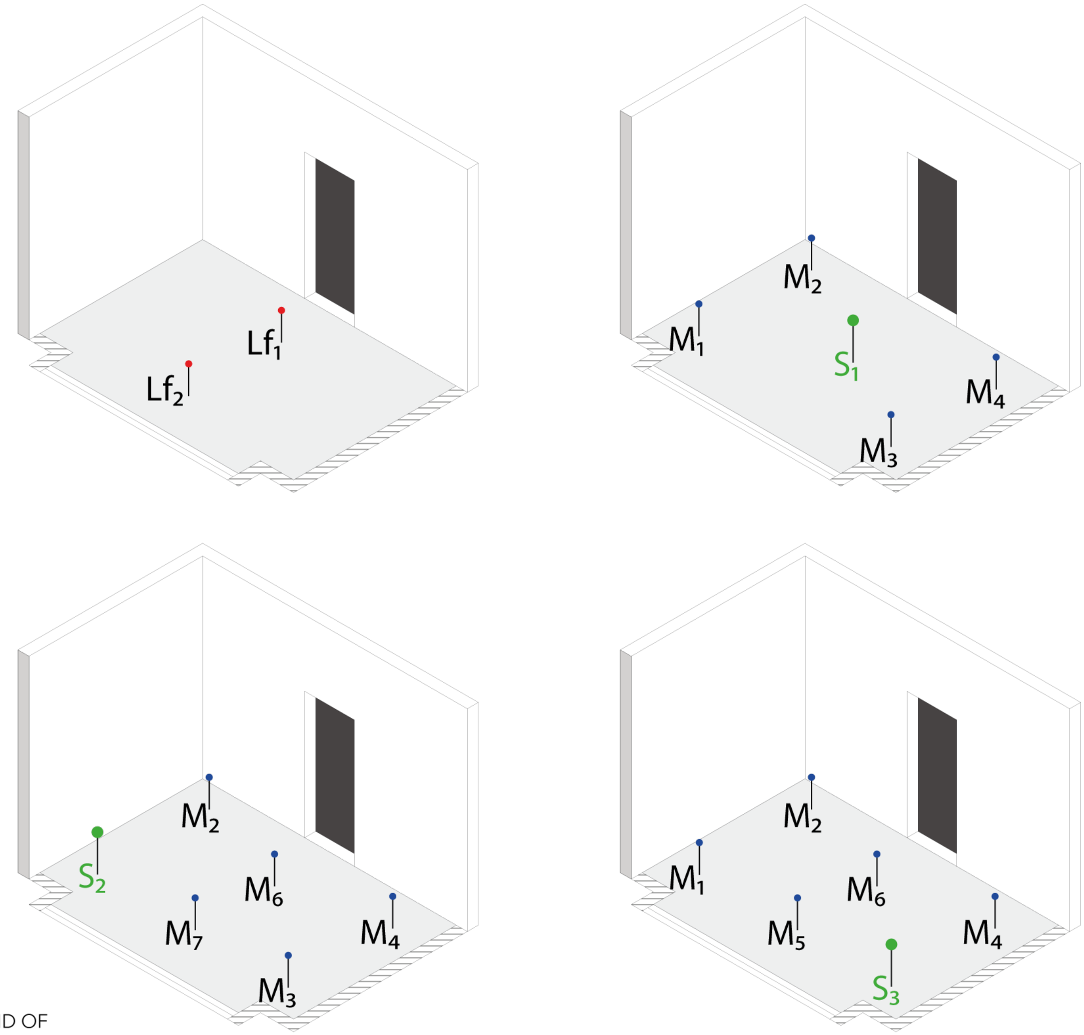
SH OFFICE 3: Measuring points for acoustic measurement



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