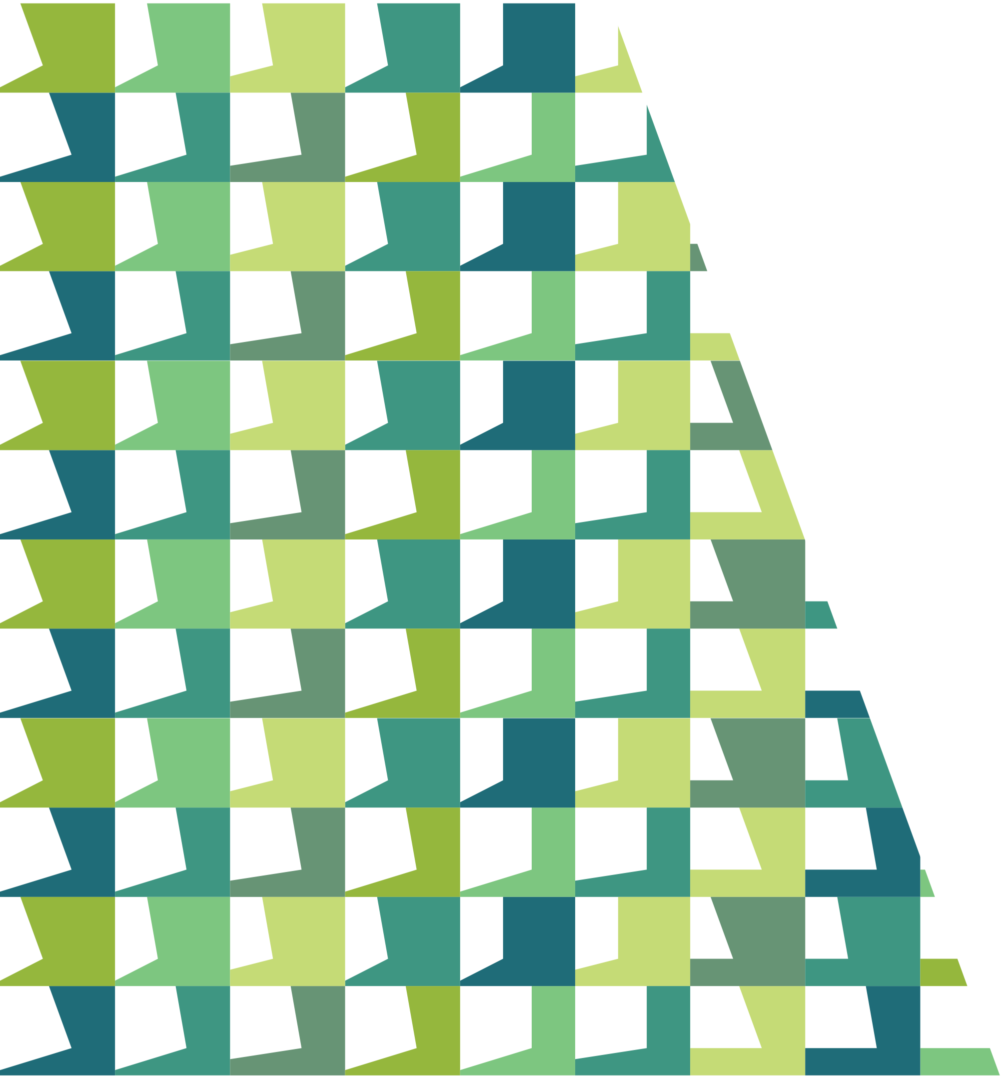

ACOUSTIC PERFORMANCE-BASED DESIGN:

EXPLORATION OF THE EFFECTS OF DIFFERENT GEOMETRIES AND ACOUSTICAL PROPERTIES OF AN URBAN FAÇADE ON THE MITIGATION OF CHATTING NOISE IN A STREET CANYON.

Elena Badino

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Master Degree in "Architecture Construction City"
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A Giovanni.

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Chapter 0

INTRODUCTION

Noise pollution in urban areas is a rising concern, due to the growing number of vehicles and other sound sources located in the streets. The building fronts reflect the sounds multiple times, preventing them to leave the urban environment: this phenomenon, known as “street canyon” effect, exacerbate the perception of noise in the cities. These undesired sounds are reported to have a damaging effect on the well-being and health of the city inhabitants, and new solutions to address these issues are required.

This Master thesis project aims to investigate the capability of building facade design in mitigating the adverse acoustical effect of street canyons.

Given the multipurpose nature of architectural problems, the design of building facades does imply the consideration and the conciliation of a number of different and often conflicting criteria. Visual aspects, energetic performance, city regulations need to be conjugated within the particular cultural and social context of the projects.

The present work attempts to explore the potentiality of the inclusion of acoustical aspects during the design phases of an urban front. In particular, during early design phases, the project is not jet defined and is still open to major changes: a number of possible design options are being considered and either discarded from implementation. In this framework, the consideration of acoustic performances during this “search” process is expected to enhance the acoustical quality of the final outcome, especially in cases in which the project is located in an acoustically-critical environment. It is indeed reported that design decisions taken in early phases have the greatest impact over the final outcome and are less costly than those pursued later (Paulson Jr., 1976).

Consequently, it is assumed that the consideration of acoustical criteria in the design process of building facades can prove effective in addressing the acoustical issues in urban areas, enhancing the acoustic comfort of the dwellers and pedestrians.

The present thesis research project aims to:

1. Identify a design methodology that features the introduction of acoustical aspects at the early design phases, allowing to orient design decisions on the basis of preliminary predictions of the performance of the project.
2. Explore how different geometrical and material features of a building facade located in acoustically-critical urban scenario can contribute in enhancing the acoustic quality for dwellers and pedestrians.
3. Define a series of ground rules to support architectural designers involved in the design of building facades, to promote the awareness of the acoustical consequences of the design options proposed.
4. The guidelines drafted are intended to provide general insights over the acoustical consequences of a set of reference geometrical and material options, without limiting the creativity and the sensitivity of designers.
5. Understand to what extent each of the two figures that are mainly involved in the design urban areas, namely architectural designers and public administrations, can contribute in addressing acoustical issues within the city.

THE STRUCTURE OF THE THESIS

This thesis work is divided into two parts: the first explores the tools and design methods already used by designers and acousticians, while in the second part a case study is considered in order to test and put into practice the topics highlighted in the previous..

The first part, that ranges from Chapter 1 to Chapter 4, is theoretical and explores the design tools and methods empowered by computers. This part focuses on performance-based design, in which the design procedures in which the simulation of the performances orients the design decisions toward the most favorable design options.

In the second part, from Chapter 5 to Chapter 8, the themes considered in the previous steps are applied to the design a reference building facade. A set of geometrical and material options for the façade elements (eg. balconies and ceilings of the ledges) is proposed. The acoustic effect of each variation is investigated using an acoustic simulation software integrated in the design software, that allowed to measure the variation of sound quality within the street canyon for each variation proposed.

FIRST PART

IDENTIFICATION OF A SUITABLE DESIGN METHODOLOGYTO BE FOLLOWED IN PROJECTS IN WHICH ACOUSTIC QUALITY IS A CONCERN

The first chapter focuses on the potentialities offered by the introduction of the use of computers in architectural practice: it focuses on the modeling and simulation tools and on the design method that exploits the potentialities of computers. In this framework, performance-based design method is identified as the most appropriate approach to develop a project in which acoustic performance is considered as an important concern.

Performance simulation systems are used as design tools: the assessment of performance is indeed the driving factor of the design process. Nonetheless, performance-based design is still rarely applied in the acoustic field. In chapter 3, a collection of case-studies is gathered to understand which are the possible limitations that restrict the application of acoustic performance-based design in current practice.

Chapter four is dedicated to an overview of the acoustic materials, as a preparatory step to proceed to following phases of the thesis. In this part the operating principles of the most common sound absorptive and diffusing devices are described, along with a series of guidelines intended to guide designer in the choice of the most appropriate acoustical treatments in accordance to both acoustic and installation requirements dictated by the projects.

Finally, the fifth chapter is dedicated to the acoustic effect known as “street canyon”. In this phase, a literature research has been pursued to identify which are the most effective solutions to treat the acoustics of these urban environments and collect publications regarding the contribution of façade design in enhancing the acoustic comfort in the street.

SECOND PART

ACOUSTICAL ASSESSMENT OF THE ADVANCED DESIGN OPTIONS

With these premises, a building facade located in the city of Turin is taken as case study to investigate the effect of a series of design options. In the specific case, the neighborhood is characterized by high levels of noise during night times, generated by people chatting in the street. At the same time, the morphology of the context exacerbates the perception of the noise for the dwellers and pedestrians.

The thesis project focuses on the introduction of acoustical concern in early design phases: several façade design configurations were compared on the basis of the assessment of the acoustic performances, allowing to identify the most favorable ones. The acoustical effect of each variation was assessed by recording the sound pressure level over the façade of the reference building, at the ground level and on the façade of the building across the street.

A set of geometrical variations was proposed, featuring various balcony shapes and surface inclinations. The effect of these configurations was firstly assessed considering the sole effect of the geometrical variations. In total, 21 geometrical options were considered, and their acoustical effect analyzed: 18 options were referred to balcony geometries and three affected the inclination of the ceilings of the loggias.

The following phase features the combination of the geometrical options with a series of material variations featuring opposite acoustical properties. In this phase 1152 combinations of geometrical and material option were analyzed. In this step, four materials featuring opposite acoustic properties were applied to the parapets of the balconies and the boundary surfaces of the loggias of a set of geometrical options. It is expected that the effect of the application of different materials to these surfaces may vary in accordance to the geometrical configuration considered.

For material and geometrical options advanced in the mentioned simulations, the sound pressure level was measured in three different locations: the reference façade, the street level and the façade of the building across the street. In particular, all measurements are expressed in dB(A) that accounts for the relative loudness perceived by human ear.

The results were further analyzed in accordance to the pertaining floor and, in case of the reference façade, by distinguish between the microphones located within the loggias and those placed in the balconies.

By comparing the results obtained to those of the reference case it was possible to investigate the SPL variations trend plotted by each group of receivers for the design options advanced.

DESIGN GUIDELINES FOR ARCHITECTURAL DESIGNERS FOR THE DEVELOPMENT OF BUILDING FRONTS PROJECT IN URBAN AREAS

A set of design guidelines is set on the basis of the comparison of the results obtained, to support architectural designers in defining the most favorable design choices for building front in case of chatter noise pollution. The geometrical features of the urban context of the case-study are encountered in various zones of the city and can therefore be considered representative of the Turin cityscape. Consequently, the soundness of the guidelines proposed can be extended to a wide range of urban areas.

The advanced ground rules were drafted as general insights over the acoustic performances of the design options considered. The guiding principles proposed are intended to support both the development of ex-novo projects and the retrofit interventions over existing buildings. Their aim is to promote the awareness of the acoustical consequences of a series of reference design options, without limiting the creativity of designers with the imposition of fixed geometrical and material alternatives.

CONSIDERATIONS REGARDING THE POSSIBILITIES OF DESIGNERS AND PUBLIC ADMINISTRATIONS TO IMPROVE ACOUSTIC QUALITY IN URBAN AREAS

To conclude, a set of manual material changes are pursued for the street paving and for the parts of the façade that was not affected by geometrical and material changes in the previous steps. In particular, the surfaces of the building façade affected by these material variations are the surfaces delimiting the ground floor and the external side of the façade. In façade facing was divided in two parts: the first two floors above ground and the upper level, to investigate the effect of material changes pursued in each of the two portions.

The objective of this analysis is to define to what extent the design of the façade is able to lower the sound pressure level within the street canyon.

For each material changes, the sound pressure level (SPL) recorded by the various locations is analyzed. The averaged SPL recorded by each group of receivers are then compared to the reduction of sound level provided by the application of a sound absorbing street paving, which regards the interventions made by the public administrations, to draw conclusions regarding which among the two measures is more effective.

Chapter 1

COMPUTER FORM-GENERATION

1.1 INTRODUCTION OF COMPUTER IN ARCHITECTURAL DESIGN PRACTICE

The introduction of computer in architectural offices since the 1970s radically changed the architectural practice. Since their first appearances, architectural design software experienced a continuous process of improvements and were increasingly adopted by practitioners thanks to the drop of the cost of computers and their increased processing power. By the mid-1990s, computers played such a significant role in architectural practice, to made them unavoidable. Today digital technologies are established as the predominant mean of production in architectural practice (Kotnik, 2010).

DIGITAL REVOLUTION

The widespread use of computer by architects marks what Achten calls “digital (R)evolution”. When initially introduced, Computer-aided Architectural Design (CAAD) tools, as most innovative technologies, imitated traditional tools. However, the technological advancement experienced by these systems in the following years allowed the exploration of the potentialities offered by these software, and produced major changes in architectural discipline (Achten, 2009; Grobman, 2008).

One of the most significative consequences of the use of digital technologies in architectural practice is represented by the new design possibilities allowed by computer power, able to generate, manage and analyze a huge amount of information. Computers enable designers to investigate more deeply the design proposals exploiting the information processing of the computer. Therefore it is possible to deal with issues that traditionally could not be considered, due to time constraints, lack of resources and the poor technologies available (Achten, 2009)

THREE GENERATIONS OF CAAD TOOLS

The first attempt to employ computer to support architectural design originated within academic circles: in 1963 Sutherland developed “Sketchpad”, able to draw geometries by indicating points directly on the monitor instead of using the keyboard. It is remarkable to note that at the same time Sutherland also envisaged the possibility to use computer to run numerical analysis on the model, and to assess therefore its performance. In the following years, new CAAD tools were developed and a number of international conferences were organized on the topic. The first generation of computer aided architectural design (CAAD) tools started to appear in architectural practice in the 1970s: these systems were “building design systems”, strictly architecture-oriented, and aimed to respond to specific building requirements; however, they required large and powerful computer and expensive display hardware, and therefore their application was notably restricted (Kalay, 2004).

The introduction of relatively cheap personal computer and graphic oriented input devices, as the mouse, made CAD tools affordable to the large architectural community and promoted further development of tools to support design. The second generation of CAD tools was released as simple drafting tools, and allowed elementary 2D drawings, with the goal of assisting designer by merely providing a digital alternative to traditional drawing tools. They were first developed for the Machintosh, although they were far too limited to be effectively employed to support professional architectural drafting. These tools benefited of the introduction of IBM PC, whose growing capabilities encouraged the development of more powerful and tools to be used in professional practice; these tools experienced great advancements and become increasingly more popular with the continuous growth of process power and display quality, and the parallel reduction of prices. The first 3D modeling software were developed and improved in the 1980s: in that decade the most important commercial CAD packages, among which AutoCAD, were introduced. In the 1990s, personal computers had enough processing power to support CAD software and since then they have evolved with an increasingly user-friendly interface. Notwithstanding the broad success of these tools, they were paradoxically less powerful than those of the first generation: as generic drafting tools, they did not offer any building-specific object, and was the duty of the designers to attribute a specific function to each element ("CAD: A Brief History," n.d.; Cohn, 2010; Grobman, 2008; Kalay, 2004).

Finally, the third generation of CAAD tools recovers the object-oriented approach to modeling, on the wave of the success of similar tools in other fields of application. In these software, each object come along with its geometrical features and has specific non-geometrical attributes that can be manipulated by the designer. This feature enables the computer to analyze and handle a higher amount of information and to automate some operations on behalf of the human designer. Starting from the 1980s these object-oriented tools were developed and improved: they represent a great advancement over those belonging to the second generation, boosting productivity and accuracy in design process (Kalay, 2004).

Building Information Model (BIM) tools, as Revit and ArchiCAD, are the most advanced parametric modeling environments. BIM software allow to create accurate digital representations of the building artifacts, from the construction site to its demolition, to analyze and manage every phase of its life cycle. These tools are object-oriented, and combine parametric geometries with several other information about the building and its component parts. Rendering and simplified performance simulations can be directly run within the environment, that in addition offers data-exchange standards and interoperability with other software.

Today-available modeling software can therefore be classified as traditional CAD tools (2nd generation) or BIM tools (3rd generation); geometries can be generated and manipulated either through direct modeling or parametric modeling. According to Frazer, CAAD tools can be differentiated into passive and active systems: the first enable the computer to be used as a mere tool, to assist architectural design, adding little to design process itself; active tools, on the contrary, offer greater potentialities, as are able to generate form (Frazer, 1999).

PERFORMANCE SIMULATION TOOLS

Along with modeling tools, analysis and simulation software have emerged and developed since the 1960s, to help designer to combine their creativity with the assessment of quantifiable performances. Since their introduction in architectural practice, they have significantly influenced the way building are designed, analyzed and constructed. One of the first digital performance analysis tool to emerge was PACE, developed in 1970, that meant to evaluate a comprehensive set of parameters (Kolarevic, 2004; Malkawi, 2005).

Evaluation tools are systems that are able to predict the performance of a project before its construction, revealing to what extent it achieves its goals, and which side effects and aftereffects it may produce (Kalay, 2004). Analysis results are therefore of great importance in every design process, to verify the fulfillment of design requirements and to adjust the proposal during the design process to ensure a required performance.

Kalay, in his book published in 2004, divides evaluation tools in two categories according to the quantifiable or non quantifiable nature of the performance they mean to predict. As regard quantifiable performances, the author accounts tools able to analyze structural, energetic and acoustical performances; while, referring to non quantifiable features, he reports tools meant to predict human factors (perception, ergonomics, impact over social system, and interpreted meaning) by simulating average user’s response to the built environment, and aesthetics, based on the rate of fulfillment of given aesthetic standards or generalized geometrical rules (Kalay, 2004).

Evaluation tools are commonly employed “a posteriori”, to analyze the proposal and verify the adherence to performative requirements. In order to do so, evaluative tools need an object to be analyzed, a set of objectives that defines the desired performances to be achieved, and a method to compare predicted and goal performances.

In late phases of the design process, however, changes tend to be hard to implement, expensive, and limited; most of the key features of the design are already fixed, and only detail modifications can be accomplished. Recently, technological advancement allowed the development of simulation tools able to run quick predictions since early design stages, allowing to combine analysis and synthesis. In conceptual design stages, in fact, great design modifications are still achievable, and are reported to have the greatest impact over the performance of the final design. This approach is known as performance-based design and will be examined in depth in the following chapters (Gaspari, Fabbri, Cancellari, Corazzi, & Vodola, 2017; Oxman, 2008; Shi, 2010; Turrin, Von Buelow, & Stouffs, 2011).

LIMITATIONS OF EVALUATIVE TOOLS

In the following, a series of shortcomings of evaluation tools is listed, to suggest the main drawbacks that appear to limit the use of simulation systems in architectural practice and suggest future improvements.

Given the multipurpose nature of architecture, great effort must be made to conciliate a number of different and often conflicting goals, many of which, as cultural and social ones, cannot be effectively quantified and, therefore, predicted by simulation tools.

Although in recent years, some modeling software allow to run simulations directly within the modeling platform, simulation tools are normally not integrated in the modeling environment, forcing the operators to continuatively switch software to either model or analyze the proposal. This aspect represents one of the most critical drawbacks of the use of analysis tools, as it greatly increases the time needed limiting the feasibility of design approaches that greatly rely on further design optimizations based on performance assessment, as performance-based design method.

Simulating building performance and understanding their outcome require specialized expertise. Architectural drawings and models need to be appropriately arranged to be processed by the analysis tool, reducing the information to the only data relevant for the specific performance analyzed; input data need to be accurate to ensure a truthful assessment.

Moreover, the effectiveness of simulation tools relies on the operator's knowledge in the analysis field, in order to adequately interpret data derived from the simulation, that in most cases are visualized with a one or two-dimensional representations. These outcomes may be hard to understand by non-technicians as architects, making the involvement of external consultants often unavoidable with a consequent increase in cost and time (Malkawi, 2005).

Conventionally, as different problems require different algorithms, simulation environments are designed to predict answer to domain-based problems and analyze building's performances in a specific field. Thus, several tools are employed to analyze the proposal performances in different realms and interoperability and data-exchange play an essential role to make this process possible.

As interoperability became a necessity, data-exchange standards have been established to allow to share data between different software. Moreover, the limitation of needing different tools to analyze different performances, is being overcame by the integration of several simulations in a single environment, increasing the efficiency and the prediction accuracy, and by enhancing interoperability among different simulation software. Basic performance simulations are now starting being integrated in some modeling environment, as the case of Revit. At the same time, data-visualization and user interface are being improved, to ease the utilization of simulation systems and the interpretation of their outcome by non-expert operators (Malkawi, 2005).

As acoustics represents the field of application of this research, a brief description of the state of the art of acoustic simulation tools is presented in the following paragraph.

1.2 ACOUSTIC MODELING TOOLS

Although room acoustic scale model tests are still a useful tool today, technological advancements made commercial acoustic simulation software increasingly more popular- These tools become increasingly more economical, and, at the same time, they become faster, more accurate and user-friendly. The first acoustic simulation software was proposed by Schroeder et al. in 1962, but these tools started being employed in practice since late 1960s and early 1970s. By the 1990s, standard personal computers were powerful enough to run acoustic simulations.

Room acoustic algorithms are classified into two categories: wave-based and geometric. Wave-based methods are computationally-expensive procedures that aim to simulate the actual behavior of sound-wave in the design space, by numerically solving wave equations. Acoustic simulation tools are commonly based on a simplified method known as geometrical acoustics (GA), in which sound-waves are approximated to sound rays or particles: with this simplification, however, wave phenomena as diffraction are neglected. Therefore, geometrical acoustics provides reasonably accurate results when applied over the Schroeder frequency, where room modes are statistically overlapping: this occurs when the room dimensions are large in comparison of the wavelength of the sound analyzed, i.e. for frequency roughly above 125 Hz. Methods as boundary element wave acoustics (BEM) have been proposed to model lower frequencies: indeed, to analyze smaller rooms, subject to modal phenomena, combination of GA with wave-based models is required. (Kuttruff, 2000; Vorländer, 2008)

Digital models demand for a certain expertise by the operator as they need to be appropriately arranged in order to run acoustic simulations. Architectural characteristics such as room volume, surface areas, thickness of building elements need to be defines, as well as the acoustic properties of every surface, expressed by absorption and scattering coefficients or impedance. High detailed models must be properly reduced to make acoustic simulation possible and truthful: object or surface corrugation whose dimension is smaller than the wavelength need to be replaced by a flat surface with adequate acoustic properties. According to Vorländer, a resolution of 0.5m is appropriate for most common cases: bigger elements should be modeled as flat, specularly-reflecting polygons, while smaller ones should be approximated to partly scattering elements (Everest & Pohlmann, 2009; Kuttruff, 2000; Vorländer, 2008; Vorländer, Schröder, Pelzer, & Wefers, 2015).

SIMULATION METHODS BASED ON GEOMETRICAL ACOUSTICS

Methods based on geometrical acoustics can be grouped into two categories: stochastic and deterministic. Tools belonging to the first group simulate sound on the based on statistical approximation, while those pertaining to the latter aim to identify the exact reflection path between sources and receivers. In the following ray tracing (stochastic) and image-source method (deterministic) are analyzed.

Ray-tracing was introduced in late 1960s and was broadly employed since the 1980s: the operating principle of this method is the approximation of sound-waves to rays with a given energy, direction and transition time. It simulates the reflection path history (echogram) that take place, to analyze those rays that pass through a small volume at the listening position: data as energy, arrival time (and direction) of these soundwave is described in a time histogram, which represents the short-time averaged energetic impulse response of the room analyzed.

According to the characteristics of the source, the emitted energy is spread in a specific number of directions, by defining a specific number of rays, each conveying a fraction of the overall energy emitted. When the “sound particle” emitted by the source hits a surface, part of the energy is absorbed, while the remaining part is reflected in a specular or diffuse way. The definition of the analysis depends on the number of rays emitted and the exact angle of emission. The surfaces of the model need to be properly characterized to quantify the amount of energy reflected, scattered or absorbed, so their precise characterization is critical for the plausibility of the simulation. Ray-tracing uses random incidence absorption and scattering coefficients: they are able to model higher order reflections in a reasonably accurate way, while they lack accuracy in low order reflections, that are characterized by a specific angle of incidence. As regards reflections, for specular ones the direction of the reflected ray is determined with the law of geometrical reflection, while in case of diffuse reflection, the effective direction of propagation is determined by the computer in a random way. Similarly, absorption can be modeled by reducing the emitted energy by the absorption coefficient or by considering it as an "absorption probability".

In the late 1970s, another approach, called image source method, was introduced; it represents the operating principle of all current deterministic simulation methods of geometric acoustics. Simulation is carried out by creating virtual images of the actual sources, by mirroring the actual source perpendicularly across the room boundaries. Then, the procedure continues by repeating the same mechanism with the image sources, creating a set of further mirror images, by which the sound at the receiver position can be determined. Actually, once all significant image sources have been determined, the original room is not necessary to define the sound signal received, that is the combination of the contributions of all image sources, each with a different delay time and strength. According to the room shapes, not all image sources may provide reflection in the receiver position, and therefore, a validation process is required to identify and discard invalid image sources. As the number of image sources growth exponentially for subsequent reflections, and most higher order image source are invalid, this test is a time-consuming process. In 1980s two methods were proposed to reduce the time required to validate sources. The first is a hybrid method in which ray tracing is used at the beginning to identify all potentially valid reflection paths and their relative strength, enabling to discarding others and save time; the second is based on the same principle but employs cones or pyramidal beams instead of rays.

Image source methods provide a more detailed specular echogram and are less time consuming than ray-tracing; however, they have a critical drawback if compared to ray tracing, as they cannot take into consideration an essential phenomenon as sound scattering. Again, better results are achievable with hybrid methods combining image source with stochastic simulation models (Everest & Pohlmann, 2009; Kuttruff, 2000; Vorländer, 2008; Vorländer et al., 2015).

AURALIZATION AND VIRTUAL REALITY

All techniques meant to generate audible impressions of virtual models are known under the term “auralization”. The first attempt to generate auditive impressions were carried out in the late 1920s, with the objective of processing sound signals from measurement taken in physical scaled models to simulate the acoustics that a listener would perceive in the room. With that method a number of stringent requirements and several expedients were required to produce realistic output. Digital room models greatly simplify auralization: both geometrical and acoustical data can be insert as numerical data and allows to analyze the head transfer function of the listener, resulting in more realistic and accurate results. Most of currently available commercial simulation tools comes with an integrated auralization option that enables to “listen” the acoustics of the model via the sound card of the computer.

The effect of the virtual environment, in which a known sound signal is emitted, is simulated at the receiver position to generate a realistic impression of the sound in the analyzed space: predicted echograms for each octave band are combined to derive the impulse response of the environment. To make it possible, everything in the environment must be defined, as sound sources, room geometry, surfaces materials and receiver’s response. The sample sound signal is a mono sound with no reverberation, and need to be recorded in anechoic chamber. Once this dry sound emitted by the virtual source, it propagates in the digital environment and is modified by it: the resulting sound, recorded at the receiver position, contains both the characteristics of the original signal and the impulse response of the transmitting system, generating a realistic binaural output that can be reproduced by headphones or loudspeakers (Everest & Pohlmann, 2009; Kuttruff, 2000; Vorländer, 2008;

Vorländer et al., 2015).

As the field of virtual reality is currently experiencing a rapid progress, one of the most compelling application of auralization is the realization of real-time acoustic perceptions to be combined with visual images, to generate a realistic interactive environment. Spatial hearing is a fundamental aspect of human sound perception, that enables to acoustically perceive the space by analyzing temporal, spectral and spatial attributes. To generate realistic virtual acoustic perceptions, sound need to be simulated over all the frequencies of perceivable sound (from 20 Hz to 20kHz) and important wave phenomena need to be accounted, to accurately render timbre, coloration and loudness. Real time simulation is therefore a big challenge and is only possible by significantly reducing the complexity of the environment, employing a data management method and frequency-domain filters in accordance with the specific characteristics of human perception of sound (Vorländer et al., 2015).

STATE OF THE ART OF ACOUSTIC SIMULATION SOFTWARE

Most of currently available acoustical room modeling tools uses a complex combination of methods, according to the order of reflection analyzed: for instance, for low order reflection image source method can be uses, while for higher orders, randomized cone tracing may be preferred (Everest & Pohlmann, 2009). However, since both methods are based on geometrical acoustics, wave-phenomena occurring at low frequencies are not accounted, resulting in a noticeable approximation error. As wave-based methods are computationally expensive, in most cases, the geometric acoustics approximation is considered acceptable; however, in some other situations, as small room with low frequencies sound, wave-phenomena need to be considered. In order to overcome the limitations of the two approaches, some researches have explored the development of simulation that employ wave-based models at low frequencies, and geometrical acoustic ones for upper-frequencies, achieving reasonably accurate and fast results throughout the frequency spectra. (Thomas, 2017)

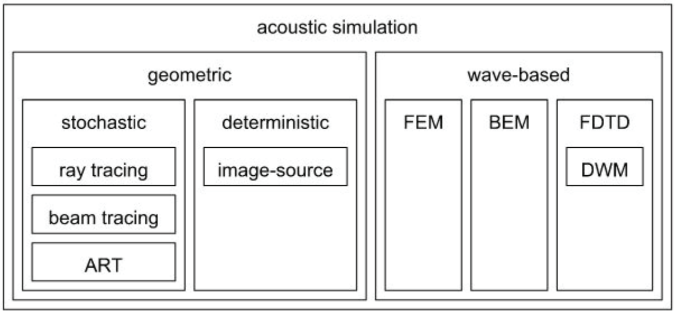


Figure 1: An overview of different acoustic simulation methods, grouped by category.

The following image shows the classification of some of the most widespread acoustic simulation methods.

Some of the most popular currently available simulation software are shown in the table below.

name	*method*	*license*
Odeon	geometric	commercial
CATT-Acoustics	geometric	commercial
Olive Tree Lab	wave-based	commercial
EASE	geometric	commercial
RAVEN	geometric	commercial
RoomWeaver	waveguide	none
E.A.R.	geometric	free
PachydermAcoustics	geometric	free
Parallel FDTD	waveguide	free
i-Simpa	geometric, extensible	free

It is worth noting that: most software comes with a commercial license that limits their audience to paying users, in most cases, professionals; no generally-available software combines wave-based methods with geometrical acoustic ones; only two tools offer wave modeling, one of which is not generally available, and the remaining one needs scripting to be run. Moreover, software developed for research purposes are often not made public. All the cited software were developed for expert users (acousticians), as they all require technical knowledge to run, this way limiting their use for non-expert users as acoustical-unschooled architects (Lu, Yan, Xu, Chen, & Liu, 2016; Thomas, 2017).

Acoustic simulation packages demand for very detailed information about form and materials, and often require format conversions; the model need to be appropriately reduced to make acoustic simulation possible, the manipulation process is complex and need to be repeated for each design modification and the simulations results consist in a large amount of data that is hard to be interpreted (Lu et al., 2016).

An attempt to overcome the mentioned limitations, is Wayverb. This software, developed by Thomas, is a free acoustic simulation tool with user-friendly interface, that, combining wave based and geometrical methods, aim to provide fast and accurate acoustic simulations that can be run by non-expert users; however, at the time of writing, Wayverb is only available for Mac OX (Thomas, 2017).

According to Vorländer, two of the major shortcomings of simulation tools are the unclear guidelines and user interfaces of different software, that may cause uncertain results due to the fact that the operator is not well informed about the data required to run the analysis. Similarly another limitation is the poor level of data-exchange between different software, as different formats are used. However the latter drawback is being overcame by open database projects and, in future, by the integration of acoustic data in BIM software (Kuttruff, 2000; Vorländer, 2008).

Considering the iterative nature of the optimization process in design approaches as performance-based one, the absence or little availability of acoustic software integrated in modeling environments appear to be a critical drawback. Most of the above-cited software are stand-alone, with only two exceptions: E.A.R. and PachydermAcoustics, respectively integrated in Blender and Grasshopper for Rhinoceros. Therefore, in most cases designers are forced to switch back and forth from the modeling software to the simulation one, resulting in a time-consuming and costly process.

1.3 NEW DESIGN METHODS EMPOWERED BY COMPUTERS

Change in the design medium generate change in the design process, that in turn, change the architectural design in process (Achten, 2009). The emergence of experimental design methods demonstrates that computer are not neutral tools, but rather are actively modifying the way architects approaches design (Kotnik, 2010). Computers provided designer of a series of innovative and powerful tools, allowing the exploration of new possibilities, enlarging the frontiers of architectural design. Complex, non-uniform structures are becoming increasingly common in architecture, thanks to the growing utilization of parametric modeling, fabrication and mass customization (Roudavski, 2009).

In the following paragraph a series of classifications of the current design approaches is presented. The proposed taxonomies take into consideration several features of digital design methods, as the rate of improvement provided over traditional tools, the approach to form generation and the evaluation of different design options.

PROPOSALS OF TAXONOMIES OF CURRENT DESIGN METHODS

Various design approaches result from different degrees of understanding and exploration of the possibilities offered by the use of computational tools. Kotnik propose a classification of design approaches to architectural design based on the level of design computability : representational, parametric and algorithmic. In the representational level, computational tools are used as electronic drawing tools: the underlying mathematical description of the form is often unintentional and invisible, as there is no perception of the computational nature that governs the digital environment. The parametric level is characterized by a clear understanding of the computational function, that is used to generate spectra of variation of the final form, as a function of parameter variations, although the algorithmic description of form is not used as design tool. The mathematical relationship between input and form is truly understood and exploited in algorithmic level of computability, in which the geometry is based on algorithmic construction. According to the Kotnik, representational design methods are not-digital, as the involvement with computation is low and computation is not a driving factor of design method; vice versa, parametric and algorithmic level are digital as mark an extension of traditional non digital design approach by exploiting computation (Kotnik, 2010).

Grobman et al. divide design approaches into two categories, according to the generation and evaluation of design alternatives. Linear processes, as traditional design processes and linear parametric design processes; non-linear design processes, enabled by the computer ability to generate new design options. Approaches belonging to the first category, are based on a series of design alternatives generated by the designers: parametric design ease the creation of design alternatives if compared to traditional process but does not provide an efficient way to compare design alternatives. This is considered a limitation, given the multi criteria nature of design problem. Non-linear methods, vice-versa, allow to simultaneously create and evaluate a greater number of design alternatives; moreover they can generate new alternatives derived from other design alternatives taken from different design stages, enhancing design creativity (Grobman, Yezioro, & Capeluto, 2009).

Another attempt to organize current design theories and methodologies is carried out by Oxman. In her classification CAD models, that roughly correspond to representational method (Kotnik, 2010), are ultimately similar to paper-based design methods; formation models mark the threshold to digital design, and are structured geometric processes than provide the designer with high level of control and interaction; generative models set a generative process by means of a computational mechanism. Performance-based design is described by Oxman as subclass of formation or generative models, resulting from a process driven by the assessment of a desired performance (Oxman, 2006).

Considering the sole experimental design approaches, that Kotnik defines as digital methods, it is interesting to identify the current tendencies that are arising. In particular, Achten report the existence of the following trends: (1) user assisted design generation: combining computer's autonomous design generation of part of the design run with traditional design, handled by the architect; (2) performative design (that can be referred to as performance-based design), based on the use of simulation tools in early phase of the design, allowing the design proposal to be optimized to maximize performances; (3) methods that exploit new production techniques, known under the term "fabrication"; (4) the introduction of norms and standards for the digital design model; (5) different decision strategies to define design choices, required by the amount knowledge and information processed by the computer; (6) the possibility to integrate in the digital model information from other sources than designers (Achten, 2009).

Given the finalities of this research, the following paragraphs will be dedicated to performance-based design, analyzing both parametric and generative methods.

1.4 PERFORMANCE-BASED DESIGN

Architecture has a multitude of goals and purposes: it involves various considerations, as psychological, economic, political, environmental, structural and so forth. Since these objectives compete with each other and are often in direct conflict, the designer needs to find the best compromise by weighting each goal according to its relative importance, to finally identify the solution the optimize the overall performance. However, it is worth noting that the point of view of the designer may be greatly different from the ones of other professionals involved in the design process.

Kalay relates the design process to exploratory search: different alternative courses of action are hypothesized, and their effects are predicted to assess at what extent different proposals meet the desired requirements. It is therefore a goal-oriented trial-and-error procedure, in which a series of unsatisfying

software	modeling type	what drives the design	Frazer	Oxman	Oxman	Kotnik	Kotnik	Grobman
Autocad, Rhino...	direct modeling	designer input	passive systems	CAD models	form making	represenational	non digital	linear
Revit, Grasshopper ...	parametric modeling	designer input		formation models	form making/ form finding	parametric	digital	linear
		performance assessment		PBD models				
generative algorithms, shape grammars...	generative modeling	performance assessment	active systems	PBD models	form finding	algorithmic	digital	non linear
		rules + shapes		generative models				

proposals are discarded, and new proposals are generated until a successful solution is encountered. “Design can thus be considered a dialogue between the goals and the solutions within the particular social and cultural context of the project”, during which initial objectives and design alternatives are modified until a solution that fulfill requirements to an acceptable extent emerges. Evaluation is therefore a unavoidable process as it is responsible of the iterative structure of the design process. (Kalay, 2004)

The different performative issues encountered in architectural design can be ascribed into the following categories: 1) structural performance; 2) performance of physical environment; 3) aesthetic and cultural performance (Shi, 2010).

In the architectural discourse, the notion of performance emerged from mid-18th onward under the influence of the scientific development and the biological concept of “environment”. In the late 1970s, the worldwide energy crisis and the growing awareness of the human ecological footprint, made the notion of “performance of physical environment” progressively more recurrent in the architectural discourse. Since then, the assessment of building performance is a remarkable concern among practitioners, and technological advancement made possible to analyze the performance of design proposals in an increasingly quick and accurate manner (Kalay, 2004).

PERFORMANCE AS DRIVING FACTOR OF DESIGN PROCESS: FROM VITRUVIUS TO ADVANCED SIMULATION TOOLS

If traditional approach uses architect’s intuition as design driver, performance-based design uses evidence. The object is generated by simulating its performance: the data extracted from simulation tools are used as feedback for an iterative process of design modifications, until the optimal geometry is achieved. Performance-based design allows to displace traditional know-how and explore new design scenarios that best fulfill the unique requirements of each project. According to Oxman, this method would mark a paradigm shift within architectural practice: from conventional “form-making” to “form-finding" approach (Oxman, 2008; Tang, Anderson, Aksamija, & Hodge, 2012).

Performance-based design approach emphasize the role played by performance in the design, so that the fulfillment of performative requirement is the guiding factor of the design process. Evaluation is the key element of performance-base design: various design options are generated, their performances are evaluated, and new proposals are created by modifying the first options in light of the performance assessments. The design process follows the loop of generation-evaluation-modification, until the optimal configuration is achieved (Kolarevic, 2004; Oxman, 2006, 2008; Shi, 2010). This procedure improves both the design workflow and the final outcome, combining a decrease in cost and time and enhancing design potential and quality (Marble, 2012).

Even if we can find early evidence of this approach in a statement of Vitruvius of more than 2000 years ago, in architectural practice, the method that was employed and persisted until 50 years ago was guided by experience-based know-how, embedded as prescriptions in codes, standards and laws (Becker, 2008).

Towards the end XX century, thanks the growing interest for sustainability, performance-based architecture experienced a new rise and the availability of simulation tools made its application to architectural practice possible.

The prediction of performance since the beginning of the design process provide great advantages, as those design decision made in early design phases have the greatest impact over the performance of the final design (Shi, 2010; Turrin et al., 2011).

One of the more significative advantages offered by computer-oriented design has to do with the generation and the evaluation of different design alternatives during the design process. The ease in elaborating architectural forms boost designer's productivity, allowing them to explore a higher number of design alternatives; furthermore, new compelling opportunities arises by the ability of the computer to directly generate and evaluate design alternatives. Indeed, the huge amount of possible design variations that can be taken into consideration, make evaluation a critical process to allow the identification of the best solution (Grobman et al., 2009).

The current concept of performance-based design was introduced in the 1970s: performance criteria guides the design process through the optimal solution with the support of digital analysis tools. The results of performance simulations run in early design phases, although rough allow to identify beneficial and unfavorable features of the design. Consequently it is possible to investigate different design scenarios and adjust proposal in light of the performance assessment to maximize performance. (Kalay, 2004; Shi & Yang, 2013)

Notwithstanding the mentioned benefits, performance-based design still finds little application in current architectural practice and is mostly restricted to research and high-profile projects.

CURRENT APPROACHES TO PERFORMANCE-BASED DESIGN

In accordance with the taxonomy proposed by Oxman, performance-based method is an approach to design that stretches from parametric approach (that Oxman defines as "formation models") to generative approach, according to the way the optimization process is pursued (Oxman, 2006).

Generative models are based on an automated optimization process: the assessment of performance directly drives the generation of design alternatives. However, at current time, most systems belong to the parametric approach since they are not morphogenetic. These systems are not capable to directly edit the model on the basis of the analysis, this way demanding for the architect's intervention to manually modify the design proposal according to the results of the performance simulation (Oxman, 2006, 2008).

Shi distinguished the generative approach to the parametric one, naming it "performance-driven design" (Shi, 2010). This thesis adopts this terminology when referring to performance-based design assisted by an automatic optimization procedure.

In the following, after a brief introduction focusing on the main features of parametric and generative design, both performance-based and performance-driven design are analyzed and some built case-studies are presented.

1.5 PARAMETRIC DESIGN

One of the earliest example of parametric design was developed by Antoni Gaudí, who constructed a reversed string model of the vaulted ceilings of the Church of Colonia Guell, to analyze different configurations. As regards digital tools, it is noteworthy that parametric equations were already present in the first CAAD tool, Sketchpad, in which drawings were ruled by a series of constraints.

Today several commercial parametric modeling tools are available and are increasingly more used in architectural practice, among which CATIA, Revit, 3DS MAX, Grasshopper, Dynamo and GenerativeComponents ("Computer-aided design/History, Present and Future," n.d.).

In parametric modeling environments, geometries are defined by a set of parameters. As claimed by Kotnik, parametric modeling systems imply the awareness of the computable function, that enables to quickly modify complex geometries and generate different design alternatives. Parametric modeling differs from "traditional" direct modeling, as geometries are based on a series of constraints, dependencies and rules set by the designer. In these models, geometric aspects of structural relationships are defined, while formal quantities are not defined. The creation of a parametric model require greater time in the initial phases, as the operator is asked to define the underlying set of rules; however, in subsequent phases they greatly speed up the generation of design variations, that can be automatically generated by changing the parameters values ("Computer-aided design/History, Present and Future," n.d.; Kotnik, 2010).

Thanks to this "underlying structure", when the values of parameters are altered, the overall geometry changes without compromising its topological characteristics. Form-finding design methods have greatly benefited of parametric tools that ease and quicken the generation of a design variations, and supports the comparison and assessment of different alternatives (Kotnik, 2010; Oxman, 2006, 2008).

PARAMETRIC PERFORMANCE-BASED DESIGN

Oxman, presenting a collection of examples of performance-based design, shows that in most cases performance simulations have been employed in parallel with associative parametric models (Oxman, 2008). The available literature confirms this tendency, as in most cases the design methods combine a commercial performance simulation tool with a parametric modeling environment as Grasshopper plug-in for Rhinoceros, or GenerativeComponents.

Parametric performance-based design is able to combine traditional concerns of architectural design with the building quantifiable and physical performance, and today is increasingly more appealing to architects, thanks to the remarkable improvements experienced by digital tools involved in the design workflow.

With this approach is the designer that manually modify the proposal on the basis of the feedbacks provided by performance simulation. The active role played by the operator make possible not to overlook to performance and balance the rigorous seek for performance-optimized geometry with the architect's intuition and other non-quantifiable features that cannot be considered by computers alone. As Grobman et al. observes, the designer inputs, based on experience and insight, would enhance creativity and the spectra of design alternatives in accordance to designer's sensitivity (Grobman, Yezioro, & Capeluto, 2007).

The operator is required to have a certain level of technical knowledge and expertise: the correct interpretation of data derived from the simulation and the understanding of how the geometry and the performance are related are essential to effectively optimize the proposal. Simulation tools are undergoing rapid advancements, becoming increasingly more accurate and user-friendly, allowing architect to run simplified simulations and correctly interpret their results on their own. In this way, specialized consultants would be asked to accurate analyze only pre-selected design proposals, speeding up the design process (Malkawi, 2005).

Given manual pursue of form modification, the number of iterations, the criteria considered and the features on which performance-based design is applied are limited. However, performance-based design still offers great potentialities especially when applied in early design phases, when design choices have the largest impact on the overall performance of the final design (Shi & Yang, 2013).

CASE STUDY

One of the most notorious architecture developed according to performance-based method is the Swiss RE building (30st Mary Axe) by Foster + Partners in collaboration with Arup, the first ecological tall building in London. Here, formal aspects were pursued in parallel with several environmental performances with the aim of halving the energy consumption if compared to an analogue traditional office building. Different design alternatives were analyzed by generating both 3D models of the steel structures and physical scaled models, with a progressively greater scale as the design workflow proceeded. The aerodynamic shape of the building was defined to minimize wind loads on the building, as the air can smoothly flow around it, allowing the use of a more efficient structural system. Indoor natural ventilation is enhanced by six spiraling wells along the perimeter of the building, that run the entire height of the tower, maximizing daylight penetration in the offices (“30 St Mary Axe (The Gherkin),” n.d.; Beier, 2004; Kolarevic, 2003).

1.6 GENERATIVE DESIGN

Generative methods, that Achten terms “user-assisted design generation”, are based on the ability of computer to autonomously generate shapes on the basis of a series of rules and input. (Achten, 2009) This approach is referred also with the term “digital morphogenesis” (Roudavski, 2009).

In the early 60’s, computers were expected to eventually match or even supersede human intelligence, and several methods and theories to automate design process and achieve “optimal” design were developed. Although today it is acknowledged that “optimal” design is not achievable, computer-based design generation is still one of the most appealing experimental design methods, and has significant advantages over traditional design, especially when applied to limited features, or to enable design exploration during initial stages of design (Grobman et al., 2007, 2009).

In contrast of the traditional method in which the designer manually, with or without the computer aid, defines the geometry, in computer-based form generation, it is the computer that generates the geometry, or part of it, on the basis on raw information. According to the complexity of the design, form generation can occur one or several times, during the design process. Generative systems as grammars and genetic algorithms are well-known in scientific literature, but are still little applied in architectural field (Grobman et al., 2007; Oxman, 2008).

Grobman et al. analyzed different approaches and within this practice, describing their distinctive features and their evolution over time, and classifies them according to the design problem they aim to address and the method employed (Grobman et al., 2007). Evolutionary system as genetic algorithms (GA) appear to be the most popular generative tools. GAs mimic evolutionary process of natural system: a population of design alternatives is generated and evaluated, according to the performance assessment, new alternatives are generated through crossover and mutation from the previous one, in a iterative process that further optimize performances, until the solution that fulfill set requirements is achieved.

Notwithstanding the advantages offered, none of the generative approaches appear to be integrated in architectural software or is commonly used in practice. Grobman et al. endorse the use of custom computer codes to liberate architectural designers from the constraints of pre-set algorithms of currently-available tools. The authors consider the lack of coding skills among architects one of the reason why generative methods are still poorly employed in practice (Grobman et al., 2009). Similarly, they recognize the importance of differentiate process of form generation along the design workflow in accordance to the level of detail demanded. Finally they evidence the critical role played by the designer, whose input is essential to ensure architectural quality (Grobman et al., 2007).

PERFORMANCE-DRIVEN DESIGN

As mentioned before, performance-driven design is based on a generative process, according to which, the assessment of performance is automatically translated into parametric input to generate form modifications. This method relieves the operator of manually change the design proposal according to the results of the performance simulation (Oxman, 2006).

The work of Shea et al. represents an example of generative performance-based design, this time applied to structural issues. She integrates a generative structural design system called “eifForm”, with GenerativeComponents through the use of XML model, and applies this method to generate a series of optimized cantilever trusses to support the roof of a stadium (Shea, Aish, & Gourtovaia, 2005).

To broaden the use of performance-driven design method in architectural practice, Shi and Yang endorse the identification of a design methodology that can be viewed familiar and practical from the perspective of the architects. The authors discuss a proposed design workflow based on the use of Rhinoceros (modeling environment), Grasshopper (script coding component) and Galapagos (optimization module), combined with different simulation tools (Radiance, EnergyPlus and Ecotect) in three different case-studies to optimize either insolation, daylight or energy consumption. The design workflows of three different case-studies are then analyzed from the perspective of the architects, and explored in detail to find critical features and define future improvements directions. Shi and Yang recognize the need of custom codes to integrates different software and therefore endorse the development of a user friendly interface not to require architects to code, as well as the development of multi-objective technique in accordance to the nature of architectural problems (Shi & Yang, 2013).

Although performance-driven approach offers great potentialities to architectural design, it still struggles in finding practical application: in most cases its use is limited to research projects or to minor features of building. Among the reasons of this latency are the low level of control over form generation and the skills required to architects in order to run the procedure.

CASE-STUDY

A built example of the application of performance-driven design is FaBRICKate, by ADAPt, a compression-only structure made of bricks. The project was built using RhinoVAULT, a plug-in for Rhinoceros that, using an evolutionary process, optimize the shape of geometries to make them cope with sole compression forces. Remarkably, this system does not require coding skills to be run, as the plug-in comes with a user-friendly interface and is integrated in Rhinoceros modeling environment. After the form-finding process, the structure was further optimized according to analyses run in external evaluation environments, and was finally tested to real-world conditions using Grasshopper and Karamba (Jones, 2017).

COMPARISON OF GENERATIVE AND PARAMETRIC PERFORMANCE-BASED DESIGN

Performance-based design is significantly limited by the amount of time and manpower required to manually pursue the optimization process. Given these issues, in most cases this method can only be applied in early design stages of the design, becoming unpractical as the design is further developed.

The efficiency of performance-based design strictly depends upon operator's skills and knowledge, as they need to understand the relationship between geometry and performance. Moreover, the manual optimization procedure in most cases is not effective, as the number of iterations is too low: indeed, according to a survey, the average number of iterations is 2.7, definitely not enough to find an optimal geometry (Flager, Welle, Bansal, Soremekun, &

Haymaker, 2009).

Considering the great amount of often conflicting criteria that need to be considered in architectural design process, generative design methods present some advantages, as they are able to deal with the multi-criteria nature of architectural problems. Differently, in performance-based design, the need of operator's involvement usually limits the criteria considered to one or few parameters (Grobman et al., 2009).

Consequently, as regards performance assessment, the overall efficiency of the process is enhanced by the automation of the optimization process of generative design, where design-modifications are based on the analytical and numerical findings of the simulations. Beyond speeding-up the process, generative design enable to deal with several criteria in parallel, and greatly increase the number of iterations (Oxman, 2008; Shi, 2010; Shi & Yang, 2013).

However, it's noteworthy that performance-based design is in some cases preferred, both because it does not require coding skills – that are infrequent among architects - and due to the greater control over form it offers. Indeed, the use of parametric models allows architects to have a higher control over the generation of the model's geometry, ensuring design quality and performance assessment while keeping the good essence of the conventional design method. The adherence to performance requirements and aesthetic concerns are of great importance, and both have to be pursued during the design process, along with other non-architectural criteria, as those belonging to cultural or economic spheres. Therefore, according to Shi and Yang, performance-driven methodology cannot be fully applied to conventional architectural design, since it can only deal with scientifically sound performance analysis (Shi & Yang, 2013).

The following table offers a synthetic comparison of the main features of the two approaches of performance-oriented design:

	PERFROMANCE-ORIENTED DESIGN	
Shi classification	performance-based design	performance-driven design
Oxman classification	formation (parametric) models	generative models
software type (Frazer)	passive	active
design optimization procedure	manual	automated
skills required	good technical knowledge + expertize	less technical knowlege + experise +coding skills
n° of criteria considered	1 or few	multiple
types of criteria considered	quantifiable + non quantifiable	quantifiable
n° of iterations run	low	high
effectiveness of optimization	low	high
level of form control	poor	good
design stages in which it is applied	early design stages	all design stages

Chapter 2

ACOUSTIC PERFORMANCE-BASED DESIGN

2.1 ACOUSTIC PERFORMANCE AS DESIGN DRIVER

In performative spaces, as theatres, auditorium, concert halls, and temporal art spaces, the acoustic quality is an unavoidable issue to be considered to create an architecture suitable to host those artistic representations. The architectural space directly modifies the emitted sound, due to phenomena as sound reflection and absorption occurring over the room surfaces. Therefore, in such spaces performance is two-fold: the artistic performances are deployed in an architectural environment that equally “performs”, as it modifies the sound generated by the artists. Acoustical quality is critical for both audience and performers: it ensures that listeners are able to understand lines delivered by the artists, and at the same time allows the latter to hear each other and perceive their own performance reflected back from the surfaces of the room (Reinhardt, Martens, & Miranda, 2012). However, by no means acoustic design has to be limited to architecture in which sound represents the primary concern.

Acoustic performance-based design (APBD) would be beneficial in a wider variety of cases, as suggested by the growing awareness of the relevance of the role played by acoustical quality even in spaces with other purposes. The acoustic quality is relevant as well in spaces not intended for critical listening and even in urban environments, were acoustical quality do influence the comfort and well-being of the users, and consequently the introduction of acoustical concern in the design of these environment is beneficial.

The design process of these architectures should aim at pursuing both aesthetical and acoustic quality. However, Lu et al. remarks that, especially in performative spaces, neither of the two aspects can be easily achieved due to the intrinsic complexity of these venues, and the difficult and time-consuming process of combining acoustic requirements with architectural ones, given the different design approaches of the two realms (Lu, Yan, Xu, Chen, & Liu, 2016). In current practice the most common approach to design auditorium and concert halls is to rely on well-known typologies (shoe-box, fan, vineyard...) and to integrate acoustic simulation of the design proposal in late phase of design process, where form modification cannot be pursued anymore and improvements can only be obtained by changing materials and other minor features (Peters, 2007, 2011).

Nonetheless, currently available acoustic simulation tools make possible to predict the future acoustic performance of the proposal since the early design phases, this way allowing to identify the dependencies between design geometry and acoustic performance, and to modify the project accordingly (Vorländer et al. 2015). According to Paulson, the design decision taken in the early design phases features the greatest impact over the final outcome and the minimum costs (Paulson Jr., 1976). In that design stage, major changes are still possible since the design is not jet fixed. Later, on the contrary, only minor changes are feasible, and its impact over the final performance is less significant, and the relative cost is greater (Méndez Echenagucia, 2013; Shi, 2010).

This approach let explore novel or otherwise not contemplated architectural solutions, combining architectural, acoustical and even structural engineering expertise. In this way it is possible to displace predetermined forms and enhance the quality of the final design with unique solutions (Reinhardt, Martens, and Miranda 2012).

2.2 RESEARCH OF CASE STUDIES

An array of built and unbuilt projects developed using acoustic performance-based design has been collected. The researches have been conducted on the literature available between March and July 2017, using different searching tools. In the first part of the research scientific literature have been privileged. The main resources used were the catalogs of the academic libraries of Polytechnic University of Turin and online databases as Scopus, ScienceDirect and ResearchGate (retrieved respectively at https://www.scopus.com, http://www.sciencedirect.com/, https://www.researchgate.net/). The search engines found more than 600 matching search results.

To further extend the array of case-studies, also Google web search engine as has been used: this method has proved useful to find information about most recent projects, that at the time of writing could not be found on scientific literature. In all mentioned methods the insertion of significant keywords in the search enquiries is required to filter results. The keywords used to search for references were "performance-based design", "form-finding", "performative design", "performance", "architecture", "design", "generative", "optimization", "simulation", "acoustics", "sound", "concert hall", "music", "auditorium".

The references found using these filters were further refined discarding the results that were not significative for the purposes of this research, or those referring to theoretical studies. Eventually, more than 100 references regarding architectural projects developed using acoustical performance-based design were found.

With the mentioned procedure, the collection gathered both built and unbuilt architectural projects. According to these criteria, more than 80 references were selected and array of 21 case-studies was proposed.

The collection of case studies shows a great degree of variation within, gathering projects with different purposes and dimensions, that range from remarkable high-profile architectures to more ordinary projects. The research focuses on the design workflows to understand when and at what extent acoustic performance-based approach was adopted. It also takes into account the primary purposes of the projects and the software application used to pursue such design method and, if present, the ones used to automate the optimization process. When information regarding the software employed lacked, the author asked for further information via personal communication with the firms involved in the projects.

2.3 CASE STUDIES

2.3.1 UNBUILT CASE STUDIES

MUSIC PAVILLION

Student project

Copenhagen, Denmark

It is a student project of a music pavilion in Copenhagen in which acoustic reflection optimization was adopted to design the arrangement of panels. This case shows the application of performance-based approach in a relatively advanced phase of the project as the acoustic analysis is used to define the composition of acoustic panels to be mounted in the already defined geometry of the pavilion.

The triangulated roof of the installation is made of 358 beams, 129 nodes and 230 panels: one third of them were reflectors, one third absorbents and the remaining were diffusers. A randomized distribution of the panel would create uniform acoustic conditions in the pavilion, while it was required to differentiate the behavior to reduce the sound level in the lounge area and improving the acoustics in the area of the audience. In order to do so, a computer program determined which were the panels that would provide good sound reflections to the audience (direct or almost direct reflections); one third of them were realized as reflectors. Similarly, the same approach was applied to the lounge area: one third of the panels identified by the program as providing good reflectors were in this case treated as absorbents, this way reducing the sound level in the lounge area. The pavilion was then analyzed in

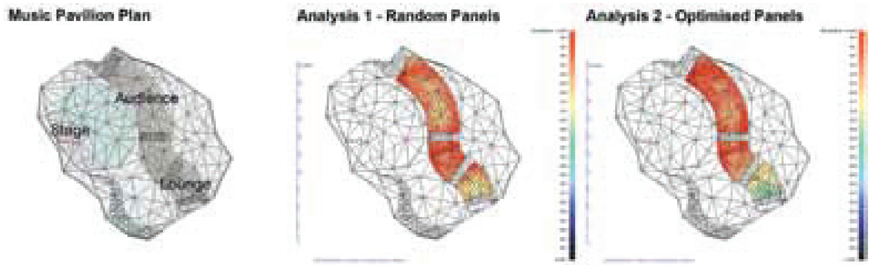


Image 2.1_Music Pavillion, digital images of the structure

ODEON, and the results confirmed a reduction of the sound level of about 3 dB in the lounge area and an improved and more even sound level in the audience zone. (Peters, 2009)

MUSICAL CHAIR

Rosengren-Fowler, Blyth

Sydney, 2012

In occasion of Sydney Festival 2012, the student of Master of Digital Architecture Research (University of Sidney) explored a temporary installation to be located in an existing industrial hall to providing a sense of enclosed space, to define a space for an audience of 400-600 attendants and the stage, where artistic performance could take place.

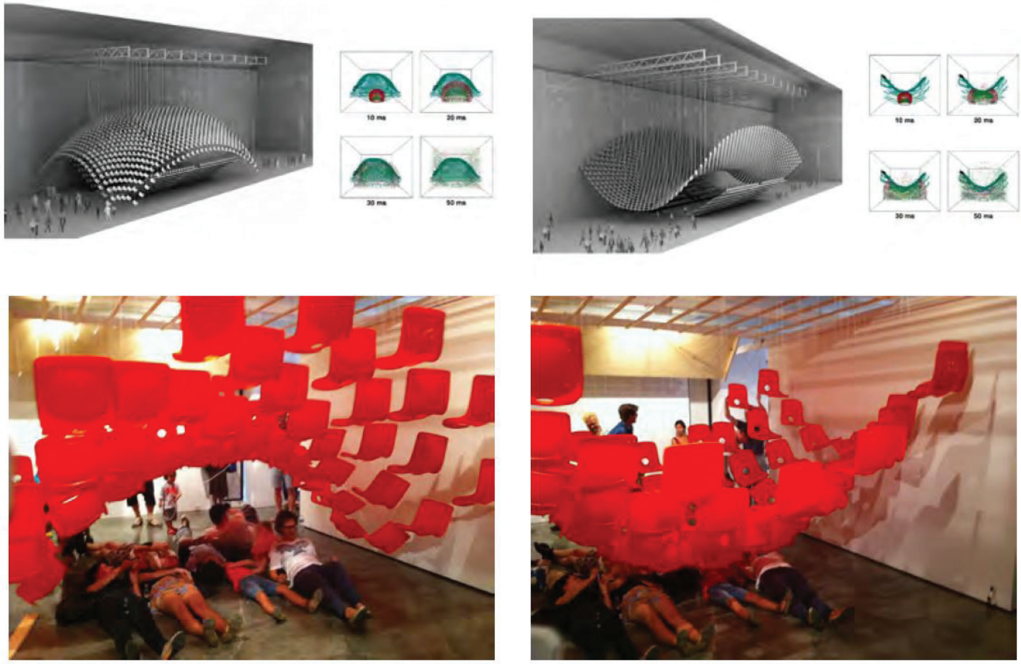


Image 2.2_Musical Chair, digital images and photographs of the 1:10 prototype

The acoustic analysis of the hall showed lack of early reflections to support the direct sound of the performance, due to the presence of hard materials, with a resultant sound quality not suitable for performative arts. To overcome this limit, the project consists in a canopy able to act as sound reflectors,

The project is made of a canopy composed by a series of suspended industrial plastic chairs: the position of each of them can be manipulated to create different overall configurations that correspond to nine different acoustical environments to support the performance. Their synchronized movement generate scenographic effects during the act, enhancing the dramatic

The rules that control the relative positions of the elements are drawn from swarm behavior and inform the 3D model developed in Rhino and scripted in Grasshopper through 9 actuator points.

Two out of the nine configuration, the “dome” and the “saddle” has been analyzed in advance of construction in an acoustical simulation environment through ray-tracing and auralisation. The “Dome” results demonstrate that it provides little benefit since large amount of sound wave escapes from the space between the suspended elements, while in the “Saddle”, since the modules are closer, less sound is dissipated in the hall with a resulting higher quality of acoustic performance. The parameter considered to analyze the speech intelligibility of the two configurations was the Early Energy Fraction (D50), and results show that both configuration provide better performance than the empty hall, and that, between the two, the Saddle configuration is more effective. The results didn’t consider possible improvement made with changes in materials, that would further enhance the performance (Reinhardt et al., 2012).

COMPETITION PROPOSAL FOR A CULTURAL CENTER IN NAGANO

Architect: Reinhardt_jung architects,

Nagano, Japan, 2013

The project was initially developed by reinhardt_jung architects as a competition proposal for a cultural center in Nagano, Japan, and continued as object of research in the Faculty of Architecture, Design and Planning at the University of Sidney. It is an example of performance-based design in which the acoustical performance was considered from early stage of design, to guarantee good acoustic condition in a curved surface indoor environment.

The proposal is a complex curved surface composed by four intersecting

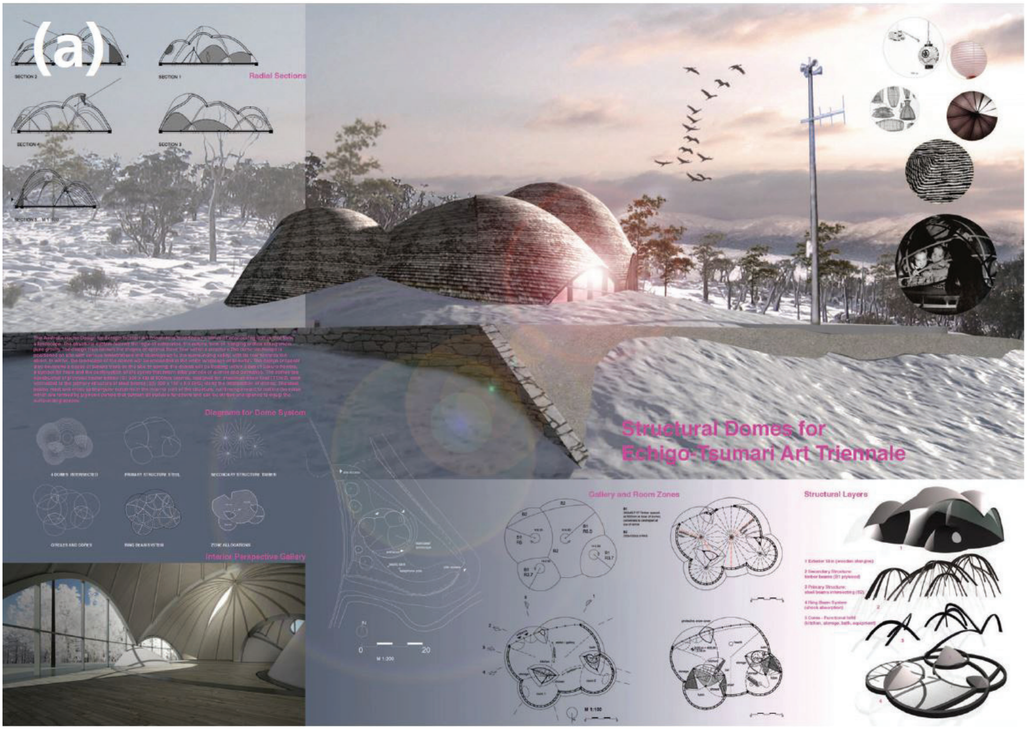


Image 2.3_contest board of Nagano Cultural Center

deflected ellipsoid spheres that forms the enclosure of the performance space; it differs from conventional single ellipsoidal sphere used to host auditoriums, providing varying spatial volumes that can be adapted to temporary requirements.

The design process combines structural and acoustical optimization of the initial shape, given the severe risk of earthquakes in Japan, the high temporary snow loads, and the acoustic requirement of the cultural center. The spheres were initially identified as the ideal formations as earthquake secure buildings, although they are not usually recommended for performative spaces, due to sound concentration caused by reflection of sound waves in curved surfaces. Their geometry was subsequently optimized through an iterative design and analysis process, using structural and acoustical analysis software, with data-exchange among the different environments. The tools employed were Mc Neel Rhinoceros, McNeel plugin Grasshopper, Strand7, ODEON; the acoustic parameter considered were Speech Transmission Index (STI) and Sound Pressure Level (SPL). The structural requirements were solved using a beam system integrating steel and timber framing elements and intersecting rings of steel in base plan. The acoustic requirements were unamplified vocal performances and even distribution of sound level across the audience area. The original sphere model developed in Grasshopper was tested by applying parameter variation (height, diameter, central point of the original ideal sphere...), to understand the relation between changes in geometry and acoustic performance. ODEON analysis was used to identify the form of the cultural center and stage and auditoria locations that best satisfy the requirement: the final shape is made of deflected domes, that show smaller level of sound variation across the audience and an overall increase in speech intelligibility compared to the ideal dome option. The acoustic analysis show that, on a macro scale, by calibrating the deflecting curvature of the intersecting domes, it is possible to reach good acoustic conditions, that can be further implemented by managing the micro topography of the geometry. (Reinhardt, Martens, Reinhardt, Martens, & Miranda, 2013)

BRIDGE DISTRICT REDEVELOPMENT PLAN

Designer: Yasha J. Grobman (professors), student of the graduate workshop of Florida University

Orlando, FL, unknown

Grobman presents this design proposal as an example of digital form finding. The project of Bridge District in Orlando, where acoustic simulation and traffic data were used to locate different function in the area, considering the high level of airborne and structural traffic noise in the selected site. Generative form-finding was used at two level. At the urban scale, traffic was simulated in virtual reality and analyzed by the acoustic simulation software: the results were used to identify the most convenient localization for each function to be inserted in the area. At the architectural scale, different noise reduction

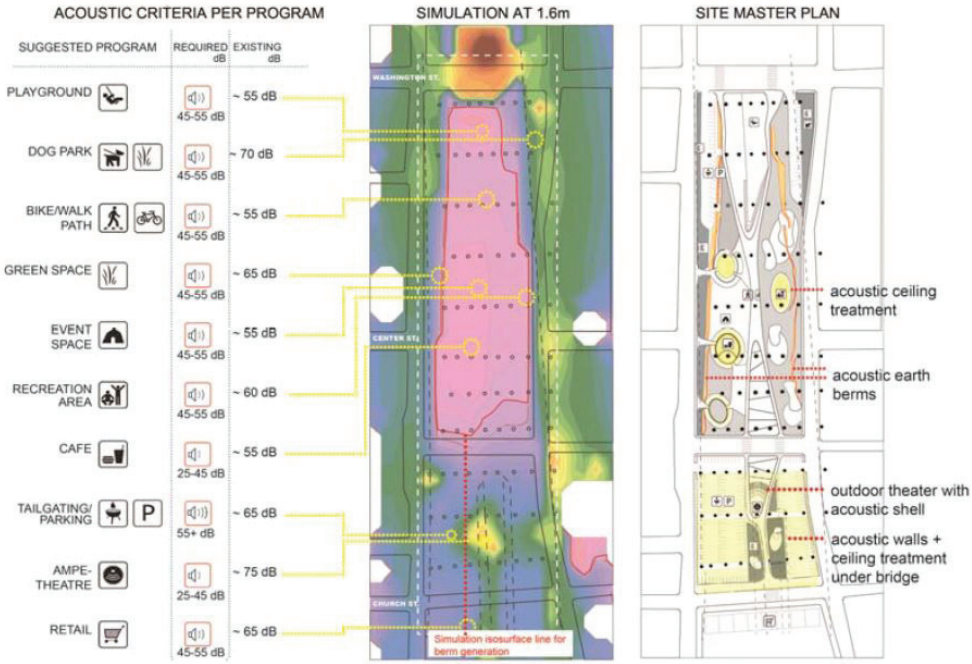


Image 2.4_masterplan of Bridge District proposal

strategies were meant to address the deficits resulting from the masterplan. In the norther part of the area, generative processes guided the design of the profile of an earth berm, that was used to block acoustic line-of-sight in areas that required interpersonal communication: based on the acoustic simulation, pieces of the berm were subtracted in order to improve daylight and accessibility in the site. (Grobman & Ron, 2011)

2.3.2 BUILD CASE STUDIES

THE PHILHARMONIE DE PARIS

Designer: Ateliers Jean Nouvel; Acoustic consultants: Marshall Day Acoustics, Nagata Acoustics, Studio DAP

Paris, France (2015)

An international competition was opened in 2006, along with an acoustic brief setting a series of strict acoustic requirement to be fulfilled by the design of a 2400 seats concert hall. The acoustic brief explicitly called for more than 10 parameters to be achieved in the room, as great clarity and high reverber-

Image 2.5_Philharmonie de Paris, photograph of the interior of the venue

ance, considered by some to be mutually exclusive. The shape of the concert hall had to be a new typology, and several criteria were set, among which to limit the distance between audience and musician by locating the latter at the heart of the room, surrounded by the audience.

The selected project was the one proposed by Jean Nouvel and Marshall Day Acoustics. The solution adopted is made of two nested chambers that balance early and late reflections: the inner provides acoustical clarity and visual intimacy; the outer provides high reverberance. The surfaces defining the inner volume, called “nuage”, works as reflectors, providing the early sound reflections. The design of these reflectors follows an optimization process guided by their relations with the acoustic performance. The concert hall is capable of high versatility: it can be reconfigured to adapt to different genres of music or purposes, as it is equipped with removable seats and canopies and it is possible to change the stage position to increase the capacity of the hall.

The final design is the result of complex iterative design process carried out by the architect and the acoustician. The acoustic design started with analyzing reflections using mirrored surfaces and laser in a 1:50 scale as its complex geometry exceeded the capabilities of common acoustic simulation environment available at that time, and continued with the support of digital simulation tools.

In the early years of design, ray-tracing analysis was carried out directly in Rhinoceros, one ray at a time, to define the best orientation of each part of the reflective surfaces. When Grasshopper became available it was employed to perform ray-tracing analysis in real time, providing a rapid feedback to adjust of the orientation of all the surfaces identified as potential source of early lateral reflections. ODEON simulation was initially used rarely due to the long time required to perform the analysis and the small number of surfaces that could be analyzed; advancement in available digital technology, made ODEON a more useful tool, by allowing a more rapid and accurate analysis to reach the final design (Day, Marshall, Scelo, Valentine, & Exton, 2016; McGar, 2015; “Philharmonie de Paris,” n.d.).

ELBPHILARMONIE CONCERT HALL

Designers: Herzog & de Meuron, Acoustic consultants: Nagata Acoustics

Hamburg, Germany, 2017

The Elbphilharmonie is a new construction by Herzog & de Meuron that stands over a 1960’s warehouse facing the river in Hamburg. The building complex hosts a mixture of different functions: a philharmonic hall, a chamber music hall, restaurants and bars, a panorama terrace, apartments, a hotel and parking facilities. The philharmonic hall lies at the heart of the complex, and its design is based on the vineyard type with a remarkable emphasis on the proximity between artist and audience.

Performance based design was conducted on two levels: the optimization of overall shape, defining the orientation the sound-reflective panels, and with the development of the unique sound diffusing pattern on the surface of each panel. The 10,000 unique acoustic panels that line the ceiling, walls, and balustrades were developed by the architects in collaboration with Nagata Acoustics, and combine acoustic performance and aesthetics through an irregular pattern of cells engraved in the surfaces. Yasuhisa Toyota, of Nagata Acoustics, created an optimal sound map for the auditorium in order to design each panel accordingly.

Each group of seatings of the audience is served by unique sound-reflective wall panels, to create a balanced reverberation across the entire auditorium. The acoustic panels are made of gypsum fiber and feature a pattern of cells that resemble the impression of left by sea shell on the sand; the design of each panel is the result of parametric design in which an algorithm is used to define the best configuration to fulfill the acoustic requirements. The cells are meant to either absorb or scatter the sound, and have a width variation from 4 to 16 cm; the depth of the cell was defined for each portion of wall and ceiling by testing the acoustics of a 1:10 scale physical model ("Architectural Details: Her-

image 2.6_Elbphilharmonie, photograph of the interior of the venue

zog & de Meuron's Spectacular Elbphilharmonie," 2016, "Elbphilharmonie Hamburg Grosser Saal," n.d.; Khan, 2017; Oguchi, 2017; Puiu, 2017; Stinson, 2017)..

WALT DISNEY CONCERT HALL

Designer: Gehry Partners, LLP; Acoustic consultants: Nagata Acoustics Sidney, Australia (1988-2003)

Frank Gehry won in 1988 the competition promoted by Lillian Disney for a new concert hall in Los Angeles, and the project was developed in non-continuous way throughout 12 years from 1989 on. It represents an example of performance-based design, carried out with an extremely basic level of technologies involved: as no robust computer model was available at the early stages of design, the iterative process was done using laser measurement on physical models, subsequently it benefited of the advancements in digital technologies, as CAD drawings and ray-tracing analysis.

image 2.7_Walt Disney Concert Hall, photograph of the interior of the venue

Notwithstanding the lack of suitable digital technologies, acoustical performance drove the design process since the beginning and acousticians were involved since the early phases. Yasuhisa Toyota from Nagata Acoustics developed and tested an array of models with the aim to find the optimal shape for the concert hall, that was meant to have an "in-the-round" configuration. As the hall was going to have a completely natural acoustic, with no adjustable reflective surfaces, the team put a great deal of energy in the effort of finding the optimal shape by creating and acoustically testing physical models, to being able to design the interior surfaces accordingly.

The optimization process was mainly informed by the assessment of early reflections, considered critical in the design of the hall, and, as the side walls are the primary responsible of their generation, great pledge was placed to establish their geometries and locations. Acoustical tests were done in a one-tenth physical model: since everything had to be reduced of the same amount, to reduce the wave length accordingly, they filled the hall with nitrogen to expel the oxygen and water vapor that absorb high-frequency sounds (Kolarevic 2003; "Walt Disney Concert Hall: An Acoustical Wonder" n.d.; Cavanaugh, Tocci, and Wilkes 2010).

CONCERT HALL OF URESHINO CULTURAL CENTER

Designers: AnS Studio, SUEP Architects; Acoustic designer: Nagata Acoustics

Ureshino, Japan (2014)

The form of the concert hall is obtained by combining origami design and acoustic engineering to define the optimal geometry to meet the requirements. The project aims to overcome the conventional design method in which architectural optimization and acoustical optimization are two rather distinct processes. The project is a folding roof, whose shape is the outcome of an interactive design method using three programs: a parametric origami software, an acoustic simulation program and an optimization program. The latter is able to use the data derived from the acoustical analysis tool to effectively find the most performative shape as the final geometry.

The acoustic requirements were an even distribution of sound over the hall and audience, absence of echo and sound focus. The team developed am acoustic simulation program able to analyze sound propagation in a 3d environment over time – as the analysis of the distribution of only direct sound was not considered enough accurate. About 200 possible design options were generated and analyzed; each of the constraints set by the different programs was weighted to allow the optimization process to define the final geometry, finding a compromise that could balance origami rules, acoustic requirements

image 2.8_Ureshino Cultural Center, photograph of the interior of the venue

and design intention. The selected shape is based on the Miura-ori folding pattern, combining visual simplicity with the complexity of the carefully controlled folding depths and angles of the polyhedral surface design ("Ureshino Cultural Center / 2014" n.d.; Takenaka and Okabe 2013).

UNIVERSITY OF IOWA CONCERT HALL

Designers: LMN Architects, Neumann Monson Architects. Acoustics consultants: Jaffe Holden

Iowa City, USA (2016)

The project of the ceiling of the 700-seats concert hall of the Voxman Music Building, combines aesthetical quality with the integration of several systems

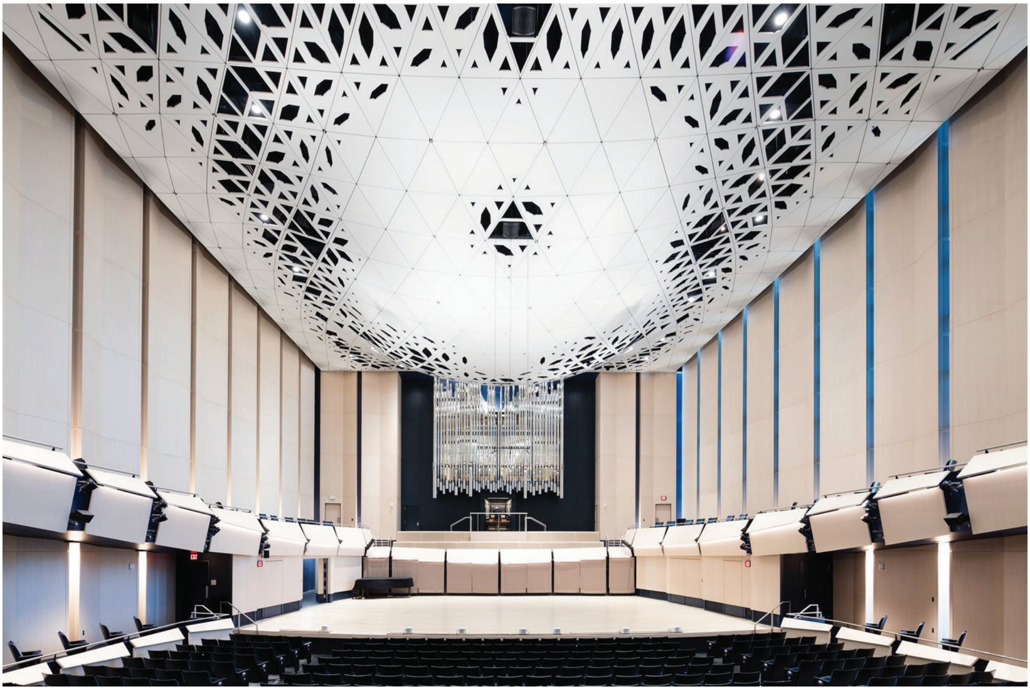


image 2.9_University of Iowa Concert Hall, photograph of the interior of the venue

in one element, composed by 946 unique panels. The ceiling had to be delivered with low-bid procurement process, thus an early collaboration between designers and fabricators was not allowed. Notwithstanding these issues, LMN Architects avoided conservative design with catalogue elements, and developed a custom-made design solution with direct to fabrication data for construction.

The ceiling of main concert hall has been developed using a single parametric digital model, able to integrate and rationalize five technical systems - acoustics, stage lighting, house lighting, audio-visual, and fire protection - in a unique and aesthetically pleasant solution. The digital model has been refined thanks to the collaboration of the consultants of the several disciplines involved, in an iterative process. It had to combine different technical equipment together in a unique system, that was optimized to be built within a low-bid 2D process. As regard acoustics, the form-finding process was done using ray-tracing simulations: starting from a point source, the results were extrapolated to multiple sound sources, to define the optimal geometry to generate the desired performance. It allowed architects in early stage of the design process to understand if a given geometry was viable, without asking the acoustic consultants to analyze every single iteration. Great commitment was placed in optimizing the fabrication of the system, as physical prototypes at different scales of panels and connections were produced to be tested; the parametric collaborative model allows the construction data of each component to be directly generated (Garber, 2017; "Theatroacoustic System for University of Iowa Concert Hall," n.d.)

CONGA ROOM

Designers: Belzberg Architects

Los Angeles, USA (2008)

The Conga Room dance club hosts a series of a multitude of programs (dance hall, stage, restaurant, bars, VIP areas) and occupy a location that was originally planned to host offices, within a mixed used building. The space had to be acoustically isolated from the rest of the building, and at the same time had to adapted to host the new mixed-function, with their corresponding acoustic

image 2.10_Conga Room, photograph of the ceiling

requirements.

Moreover, the forecasting of constantly reaching full capacity, implied that the presence of patrons would have compromise the acoustic performance of walls and floor: as a result, the design of the ceiling system was critical. As the club was located on the second floor of the building, the ceiling had to provide a remarkable aesthetic characterization to the space, able to attract people from the street All these requirements resulted in an undulating ceiling surface, composed by a series of panels combined in diamond patterns, able to provide acoustic isolation from the rest of the building, acoustic amplification, and spatial organization; it also integrates several building infrastructures in one system. The ceiling is made of CNC-milled plywood panels and the final configuration was developed with a parametric model, that underwent a process form-modification based upon feedback of acoustic simulation tools.

The ceiling's panels at the entrance are assembled in a tornado-shape, able to attract visitors, while the ones above the dance-floor, were acoustic concerns are greatest, are combined in a flower-shape pattern. Here different arrangements of petal-panels allow the acoustic performance of the ceiling to be controlled, based on density and porosity, and results in a variety of flower shapes ("Conga Room at LA Live," n.d., "The Conga Room / Belzberg Architects," 2011; Minutillo, 2009).

STAGE BY THE SEA

Designers: Flanagan Lawrence Architects; Acoustic consultants: Arup Acoustics

Littlehampton, Great Britain (2012)

Flanagan Lawrence Architects won an architectural competition promoted by the Littlehampton Town Council in 2012 with a project of two outdoor shells made of concrete, located by the coastline of the city: the smaller shell is used as shelter, the bigger provides a concert stage for outdoor music performances.

Acoustical requirements were the major driver of the design workflow of the outdoor stage, and the final design coordinates them with architectural and structural quality in an efficient and economical method, to create a durable, effective and inexpensive solution. The acoustic design allows music to be perfectly hear in windy conditions at a distance of 50 m from the stage. The design is the result of tight collaboration between architects, acoustical and structural consultants, in which a single digital model was modified by the collaborators of each discipline, following more than 20 design iterations and analysis to optimize the structure, as each partner defined a range of possible solutions to reach the target requirements [35-39]. The double-curved shape of the canopy allows the structure to stand without the support of pillars or framework.

Great pledge was placed in guaranteeing the sustainability of the project: it had to be durable and minimize embodied carbon, and its construction had to

image 2.11_Stage by the Sea, photograph of the concrete acoustic shell

be economical. The innovative construction technique used in the construction is known as shotcrete: concrete is sprayed at high velocity directly onto a reinforced surface, combining cost reduction – as no formwork is required

– with high quality finish (Fang, 2016; Flanagan, 2015; “Flanagan Lawrence – Acoustic Shells,” n.d.; Griffiths, 2014).

RES 3.0

Designers: Pone S, Di Rosario S., Colabella S., Ercolano D., Lancia D., Parenti B., Pignatelli E., and Romano D.

Acireale, Italy (2014)

image 2.12_Res 3.0, photograph of the outdoor acoustic shell

ReS is an acoustic shell meat to host open-air acoustic concert: each year, during a summer school in Italy, a new prototype of the shell is developed, built, and tested. ReS 3.0 is the outcome of the 2014 edition of the summer school Villa Pennisi in Musica (VPM) and capitalize on the performative results obtained in the two previous editions, each year aiming to further enhance its quality. The assessment of the acoustic performance of the previous prototypes serves as a basis from which new improvements are advanced. ReS is an acoustic shell that aims to best match the performance provided by a concert hall, in

image 2.13_Soundforms, photograph of the movable acoustic shell

which all surfaces are designed to provide useful sound reflections.

In the development of ReS 3.0 there were two main objectives: to generate a uniform sound field on the performers, improving the ensemble and avoid any frequency-cancelation event over the entire spectrum of sound; to enhance the sound loudness over the audience, and to enhance spatial perception. Res 3.0 has increased dimensions of the structures compared to the previous prototypes: three rows of small panels were added between the trapezoidal panels, and a QRD diffuser was placed in the backdrop. According to the assessment of the acoustic performance ReS 3.0 provide better results than the previous prototypes (Pignatelli, Colabella, Di Rosario, & Pone, 2015).

SOUNDFORMS

Designers: Flanagan Lawrence Architects; Acoustic consultants: Arup Acoustics

London, United Kingdom (2012)

Soundforms is an outdoor acoustic shell that originally developed as a research project and was then chosen and installed in the Olympic Park of the 2012 London Olympic Games. The structure is an inflatable and moveable shell designed aiming to bring the indoor acoustic quality to the outdoors. The shells is designed to host musical performances in an outdoor context, allowing musicians to hear themselves and to project the music to the audience, producing a louder and clearer hearing performance.

The design is led by acoustic principles and recall the shape of a sea shell. The design is optimized to respond to three different type of music performances -

image 2.14_Aalborg Acoustic Pavilion 2011, photograph of the interior

namely string quartet, small chamber ensemble and a full symphony orchestra - each defined by a set of ratios that determines the positions of the reflective surfaces of the shell. Since it is intended for outdoor use, the structure is designed to withstand a wide range of weathers exposures. Furthermore, as it had to be a movable structure, it is light-weight and it minimize its dimensions when packed for transportation (“Soundforms,” n.d., “The Park’s Bandstand - A built environment story,” n.d.).

AALBORG ACOUSTIC PAVILION 2011

Designers: AREA, Electrotexture Lab

Aalborg, Denmark (2011)

The pavilion is the outcome of a design method that couples acoustic requirements with constructive aspects, using genetic algorithm to drive a morphogenetic process to find the best solution in term of acoustic performance, as well as rationalizing algorithms to optimize components for production, manufacturing and assembly. GA morphogenesis informed both the generation of the overall shape and the reflectors’ configuration. The fitness function that drove the search aimed to obtain the minimum reverberation time as the pavilion was meant to host electronic music, spread via loudspeakers and the aim was to minimize the effect of the pavilion on the already optimized sound emitted by these devices. The structure is composed by reflective panels, that are meant to be an identifiable architectural expression. Their configuration is optimized in order to minimize reverberation time, by maximizing sound reflection between reflectors, avoiding the send the soundwave back to the audience, as well as directing the sound away from the pavilion. The acoustic performance was analyzed using multiple sound sources (loudspeakers) to be placed in each corner of the structure; four models were produced and tested to understand which the most effective parameters were to consider in order to design the reflectors (Foged, Pasold, & Brath, 2012; Furuto, 2011).

AALBORG ACOUSTIC PAVILION 2012

Designers: AREA, Mads Brath Jensen

Aalborg, Denmark (2012)

The pavilion was developed using genetic algorithms paired with acoustic simulation and a parametric model, to have real time feedbacks about the future

image 2.15_Aalborg Acoustic Pavilion 2012, photograph of the interior

performances. A heterogeneous acoustic environment is obtained within the pavilion by introducing computation in early design phases. The parametric model of the pavilion is based on an origami folded structure and is controlled on two different levels: one defining the overall shape - in this case, a simple tunnel - and one is the folding structure, composed by triangular reflective faces, whose position and material composition can be altered. For each level, the control points are properly set to define the geometry within the limitation imposed by architectural constraints. The acoustic parameters considered during the design process were sound pressure level and reverberation time, the latter defined using the Millington-Sette equation. The aim is to obtain two acoustically-different areas within the structure, at the two ends of the tunnel, either with long or short reverberation time, to provide good performances to host speeches and classical music. The material used are plywood and foam and are combined in sandwich elements in which the foam is encapsulated by two layers of plywood. Evolutionary algorithms are used to progressively search for design improvements following the mechanism of selection, crossover and mutation until an optimal solution was reached(Foged, Pasold, & Jensen, 2014).

RESONANT CHAMBER

Designers: RVTR; Acoustic consultants: Arup Acoustics

Ann Arbor, USA, 2012


image 2.16_Resonant Chamber, photograph of the prototype

The first prototype of the responsive acoustic envelope system is a faceted acoustic system, based on rigid origami, that is able to alter its shape in response to changing acoustic conditions of the space, in response to acoustic changing condition and the occupants. It is made of a combination of reflective, absorbing and electroacoustic panels, arranged around an electronic panel. The system is capable to acoustically tune the space in which it is installed through gross deformation of its shape to alter the aural volume, as well as localized adjustments to hide or expose the panels with different acoustic properties. The optimal geometry and materials' characteristics were defined by acoustic simulations and tests on physical prototypes.

The first prototype of the responsive acoustic envelope system is a faceted acoustic system, based on rigid origami, that is able to change its shape in response to acoustic changing condition, and the occupants' behavior. It is made of a combination of reflective, absorbing and electroacoustic panels, arranged around an electronic panel: this flexible system is able to adjust its properties in response to input as ideal reverberation time, acoustic coefficient or directional data. It enables to alter the sound of a performance space dynamically and therefore, being used as an instrument itself. The system is capable to acoustically tune the space in which it is installed through gross deformation of its shape to alter the aural volume, as well as localized adjustments to hide or expose the panels with different acoustic properties. The optimal geometry and the characteristics of the materials were determined by acoustic simulations and tests on physical prototypes (Anderson, n.d.; Filipetti, n.d.; Grozdanic, n.d.; "Resonant Chamber," n.d.; Thün, Velikov, Ripley, Sauvé, & McGee, 2012)

COURTYARD ENCLOSURE OF SMITHSONIAN INSTITUTION

Designers: Foster + Partners, Specialist Modelling Group

image 2.17_The Smithsonian Institute Courtyard Enclosure, photograph of the underneath space

Washington DC, USA, 2007

Foster + Partners in 2012 won a competition for the design of the new courtyard enclosure for the Smithsonian Institution building in Washington. Since early design phases, the computer programming was used as one of the primary design tools, thanks to the involvement of the Specialist Modeling Group, an internal research group. allowing the exploration of a wide range of possible design options. The project is the result of the close collaborations between architects, technical consultants and fabricators. The shape has been generated by a project-specific computer tool that mutually relates different design objectives: the computer scripts developed were continuatively updated throughout the design process to adapt to the arising requirements.

The enclosure consists in a flowing glass canopy that covers the central courtyard creating a flexible space, able to host various type of events. The new structure had to perform at the same time a solar shade, an acoustic absorber and a weather protection device. Since the space underneath was meant to be flexible and host various types of events as receptions, dinners and performances, the design solution integrates acoustic treatment in the bearing structure, that works as a giant absorber. The SMG analyzed the effectiveness of various configuration as regard the structure and the solar shading. The acoustic treatment is integrated in the beams, whose shape was determined to address both structural and acoustic requirements. The proposal is a lattice undulating roof structure that is supported by eight columns arranged in three domes: it allows both to have a glazed enclosure to let the sunlight in, as well as to improve sound absorption (Peters, 2007b, 2011a; "Smithsonian Institution," n.d.)..

FABPOD

Designers: Nicholas Williams, Jane Burry, Daniel Davis, Brady Peters, Alexander Pena de Leon, Mark Burry

Melbourne, Australia (2013)

The project is an acoustic enclosure for meetings to be placed in a large working environment of an university building. The meeting space is able to comfortably seat 8 people and is designed to attenuate sound transmission into and out the meeting area, and provide an internal acoustics that was conductive to small meetings.

The proposal combines partial acoustic absorption and sound scattering in an enclosure made of a system of hyperboloid cells. The sound-diffusing property of these cells is investigated in the project, whose geometry, alike the overall shape, was developed iteratively, by modifying the parametric model of the structure in accordance to the results of the acoustical simulations. The project also aims at enhancing the acoustic quality of the space within which it is installed: both absorption and scattering materials are applied to the exterior surfaces of the structure, with the intent of improving the auditory experience of the surrounding workspace. The project was developed focusing on fabrication aspects, with the aim of endorsing the creation of similar structures to be installed in other spaces (Nicholas Williams et al., 2015; Nick Williams et al., 2013).

image 2.18_FabPod, photograph of the meeting space

MANUFACTURING PARAMETRIC ACOUSTIC SURFACES PROJECT

Designers: Brady Peters, Mette Ramsgaard Thomsen, Katja Viltoft

Smart Geometry Workshop and Conference, Barcelona, 2010

The project was installed at the Smart Geometry 2010 Workshop and Conference: it is basically a wall dividing a space and creating multiple acoustic environments. It attempts to explore new forms and material compositions by using acoustic performance as a design driver and digital fabrication techniques: the project was iteratively tested and adjust to satisfy both requirements.

The installation features a complex understanding of the acoustic performance, and its design is oriented to multiple acoustic objectives. The goal was creating a single curved architectural surface whose geometry and materials were designed to create different acoustic subspaces in the surroundings: from a quiet, enclosed area, the "dull zone", characterized by high level of sound ab-

image 2.19_MPAS project, photograph of the prototype

sorption, to an amplified sound area, with a gradient of acoustic performance between the two conditions obtained by the modulation of the materials. Both the overall shapes and the components were defined in accordance to acoustic parameters.

Acoustic performance drove the design of the overall shape of the installation and the design of the acoustic panels to be mounted ("Manufacturing Parametric Acoustic Surfaces," n.d.; Peters, n.d., 2011a; Wong, 2010)

DISTORTION I

Designers: Martin Tamke, Brady Peters, Niels Jacubiak Andersen (CITA), Ali Tabatabai, Reese Campbell, and Demetrios Comodromos.

Copenhagen, 2010

The project was developed in collaborations with university students for the Copenhagen Distortion Music Festival: it consists in a moveable pavilion to be moved and installed in various location during the festival, both indoor and outdoor. The temporary installation is designed with the aim to create varied sound and light experiences.

image 2.20_Distortion I, photograph of the installation

It is a digitally fabricated, reconfigurable, acoustic pavilion made of sound cones that amplify and distort sound, while a coppery reflective finish turns the pavilion into a kind of kaleidoscope. Different tessellation patterns allow different spatial effects, structural conditions and acoustic effects. This project used parametric design tools to analyze the relationships between material, geometry, and acoustic performance in a digital model. In particular, visual and aural feedbacks were generated using acoustic simulations tools, and the project was adjusted accordingly. The project explores the potentialities combining architectural project with sound design (Campbell-Dollaghan, 2012; “Project Distortion (2010),” n.d., “Project Distortion I,” n.d.).

DISTORTION II

Designers: Brady Peters, Martin Tamke, and Stig Nielsen (CITA), Niels Jacubiak Andersen (Krydsrum), and Magnus and Patric Gustafson (Akustikmiljo))

Copenhagen, 2011

Distortion II is a research project designed, built and tested to create visual and acoustic effects within an open-plan space. The project was designed to extend the work carried out for Distortion I. It is a structure able to define sound and space at the same time.

The installation questions the design of acoustically homogeneous spaces, exploring the potentialities of generating multiple acoustical subspaces. It also aima at defining the acoustical parameters more appropriate to account for these different acoustical quality of the subspaces generated. It is a bending acoustic surface made of a series of trihedral corners with different dimensions create a sound-amplified with a hard and reflective finish and a sound-dampened zone, with a soft and absorbent finish. Following the acoustical simulations, an iterative process was set in which the parametric model was optimized by orienting its elements to meet acoustic requirements. The iterative process was addressed in two approaches: by using an external acoustic simulation environment, and by creating a custom ray-tracing tool working within the modeling environment (Peters, Tamke, Nielsen, Andersen, & Haase, 2011;

image 2.21_Distortion II, photograph of the installation
"Project Distortion II," n.d.).

2.4 ANALYSIS OF THE CASES STUDIES

The following analysis take into consideration only the case studies that were built, focusing on design workflows to understand when and at what extent performance-based approach was adopted. It also takes into account the primary purpose of the projects and the software and tools employed during the design process, as modeling environments, simulation tools, when present, the ones used in the optimization process.

In the following, an analysis of the built case studies is presented, focusing on the design outcomes and the design processes described in the case studies.

ARCHITECTURAL OVERVIEW

The internal variety of the proposed array of cases demonstrates the ability of performance-based approach to be adopted in architecture with different purposes, dimensions and profiles; all cases benefitted of the approach in term of architectural quality and performances - exploring new forms and design potentialities, and in the time and costs required in the design process.

In the selected cases, performance-based approach has been adopted to design either the overall shape of the architecture, or to minor features as the disposition of acoustic panels or their own geometry. When this approach is applied to the major design features, it can lead to the exploration of new shapes that challenge the conventional and well-established ones, achieving "ad-hoc" forms that precisely meets the unique requirements and properties of the single project. It is worth remarking that the challenge to predetermined forms can only be pursued by integrating performance-based design since the early phases of design, to guide an iterative form-optimization process to achieve the ultimate design; otherwise, it can only be applied to minor features, as panel design, or their position and orientation in the hall.

It is noteworthy that free-form has mainly being adopted in smaller projects, as in temporary installations and in the outdoor acoustic shells, while in concert halls and other major projects the design tend to relies on conventional typologies, and performance-based design mostly informs the design of elements such as reflective panels, balconies, or the unique pattern of acoustical panels that lines the venue.

			PROFILE	TYPOLOGY	TYPE OF INTERVENTION	FIELD OF APPLICATION	FUNCTION HOSTED	INTRODUCTION OF PBD FOR ACOUSTICS (A)	SOFTWARE/TOOLS EMPLOYED
PERFORMATIVE SPACES	concert halls + auditoria	PHILHARMONIE DE PARIS	high profile	permanent	new intervention	nuages, fronts and walls of balconies	music performance	A	laser measurements on physical models, Odeon, Grasshopper
		ELBPHILHARMONIE	high profile	permanent	new intervention	panels design	music performance	A	acoustic simulation tool, tests on physical models, Rhinoceros, parametric modeling software, optimization software
		WALT DISNEY CONCERT HALL	high profile	permanent	new intervention	overall shape	music performance	A	ray-tracing program, laser measurements
		URESHINO CULTURAL CENTER	average level	permanent	new intervention	overall shape	music performance	A	parametric origami generator, in house acoustic analysis program, optimization program
		UNIVERSITY OF IOWA CONCERT HALL	average level	permanent	new intervention	ceiling system	music performance	A	SketchUp, Grasshopper, Revit ray-tracing
	dance club	CONGA ROOM CEILING SYSTEM	average level	permanent	retrofit of pre-existing architecture	overall shape	music performance	A	CATIA, Rhinoceros, Ecotect[1]
	outdoor acoustic shells	STAGE BY THE SEA	high profile	permanent	new intervention	overall shape	outdoor music performance	A	Rhinoceros, Grasshopper, ray-tracing (Dynamo for Revit)[2]
		ReS 3.0	research project	temporary	new intervention	overall shape, all subsystems	outdoor music performance	A	Grasshopper, SONIC4GH, Octopus
		SOUNDFORMS	high profile	temporary, movable	new intervention	overall shape	outdoor music performance	A	Rhinoceros, Grasshopper, ray-tracing (Dynamo for Revit)[2]
	pavilions	AALBORG ACOUSTIC PAVILION 2011	research project	temporary	new intervention	overall shape, components	music performance	A	Rhinoceros, Grasshopper, Galapagos
		AALBORG ACOUSTIC PAVILION 2012	research project	temporary	new intervention	overall shape, components	music performance	A	Rhinoceros, Grasshopper, Galapagos
	indoor inst.	RESONANT CHAMBER	research project	permanent, kinetic	prototype	overall shape, panel configurations	various performance	A	Rhinoceros, Grasshopper, Kangaroo
NON-PERFORMATIVE SPACES	glazed roof	SMITHSONIAN COURTYARD ENCLOSURE	high profile	permanent	retrofit of pre-existing architecture	overall shape	music, meetings	A	in-house/custom software
	indoor installation	FABPOD	research project	permanent	prototype	overall shape, components	meetings	A	in-house/custom software, Rhinoceros, Grasshopper, PachydermAcoustics, Odeon
		MANUFACTURING PARAMETRIC ACOUSTIC SURFACES PROJECT	research project	temporary	new intervention	overall shape, components	other	A	parametric modeling software, Odeon
		DISTORTION I	research project	temporary	new intervention	overall shape, components	other	A	parametric modeling software, acoustic simulation software
	outdoor inst.	DISTORTION II	research project	temporary	new intervention	overall shape, components	other	A	in-house/custom software, Odeon

[1] E. Badino, personal comunication, October 4, 2017
[2] E. Badino, personal comunication, April 27, 2017

image 2.23_The table offers a quick overview of the array of projects. The main features of both design processes and final outcomes are reported on the basis of the information drawn from the references. The table focuses on the following aspects of the case studies: project profile (see also Figure 2); temporary or fixed nature; the type of intervention; the features to which APBD was applied (see also Figure 3); the main purpose of the projects (see also Figure 4); the design stage in which acoustic simulation was introduced as design tool; the tools used to pursue the APBD approach. In particular, the tools and software programs reported in the table are the ones that were expressively cited in the references and therefore do not necessarily represent all the software employed during the design processes.

The graphs show information about the different primary purpose (Figure 2) and profiles (Figure 3) of the architecture in which the method was followed, and the features to which it was applied (Figure 4); while Table 1 show a summary of different features of the array of case studies.

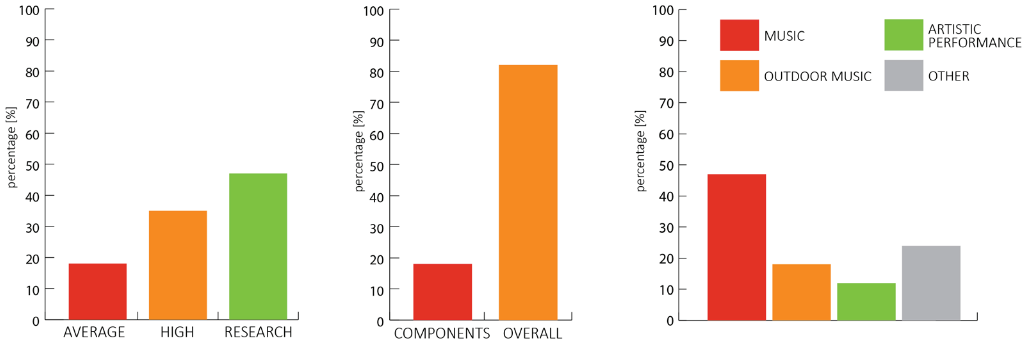


image 2.22_graphs showing: 1) the profiles of the case-studies; 2) the design features to which APBD was applied; 3) the primary pursposes of the case-studies

SOFTWARE APPLICATIONS USED IN THE DESIGN PROCESSES

Performance-based approach requires the integration of simulation programs in the design processes, to predict the performances of the design options advanced and steer further design modifications.

The process of design optimization is allowed by the combined use of simulation tools and parametric design environments with associative geometry; form modifications can be applied manually by the designers, or in an automated manner, with methods as generative design processes. The parametric modelling environment that appear to be most broadly used in the considered array of projects is Grasshopper for Rhino (“Rhinoceros,” n.d.; Rutten, Grasshopper), while Odeon is largely employed to run acoustic analysis (“Odeon,” n.d.); in some cases, also custom tools and in-house software have been utilized.

Grasshopper is a graphical algorithm editor integrated in Rhinoceros, which enable to generate parametric models of complex geometries on the basis of mathematical functions set by the designer, enhancing the user control over form. Grasshopper does not require any programming or scripting knowledge, and therefore can be easily employed by designers. One of the main advantages of parametric modeling if compared to traditional direct modeling tools is the ability to quickly generate a wide number of design options.

Odeon is one of the most popular commercial acoustic simulation software and it is based on geometrical acoustics. With this tool it is possible to predict the acoustic performance of a given environment on the basis of its geometries and the acoustic properties of the materials applied to the surfaces.

Customized software applications are designed to adhere to the specific requirements of a project: in the presented case studies, the use of in-house or custom tools is expressively declared in three cases. However, it must be highlighted that some of the most common software applications employed, as Rhinoceros and Grasshopper, support user-customization, and therefor the number of project developed with custom tools is likely to be greater. The potentialities of scripting allowing designers to generate ad-hoc tools and components, widening the possibilities of regular pre-set functionalities offered by programs. However the use of these tools is greatly restricted, as they require coding skills to be set, that are rarely encountede among architects.

Optimization systems are introduced in less than half on the projects analyzed, not considering the case-studies in which the use of custom tools is reported. The use of automated optimization procedures appears to be generally restricted to temporary installations or to minor features of already defined geometries. In these case-studies, the optimization modules cited are Galapagos (Rutten, Galapagos) and Octopus (Vierlinger, Octopus), both working in combination with Grasshopper. Both systems are based on genetic algorithms and are able to create various generations of design options. Each generation is defined by keeping the features that were linked to better performances in the previous ones, and therefore the process is oriented to maximize the adherence to a fitness function, that in this case is the predicted performance.

In the suggested examples, acoustic performance does not necessarily represent the major focus of the design, and can be pursued along with other performances, as structural ones, in an interdisciplinary approach. In this case the design process is oriented by the outcomes of the simulations of the performances to achieve the solution that best fulfill the requirements in the considered performative fields. Consequently, a thigh collaboration between designers and technical consultants is essential for the quality of the final design. Likewise, it is critical that the tools involved in the design process allow data-exchange, to enable and ease interoperability among technicians of different fields.

At current time the absence of a proper platform to couple architectural and acoustical design and the lack of a user-friendly interface in the software involved in the design, implies that the application of performance-based design in acoustic field is mostly limited to notable architectures and research projects.

Digital models need to be approximated in an appropriate way to run acoustic simulations, and consequently the model editing requires some expertise. Moreover, architects do not necessarily have enough knowledge in the acoustic field to autonomously and efficiently employ simulation environments, interpret the detailed and technical outcomes of the analysis, and understand their relations with the geometry. Consequently, the acoustical consultants are often required to run simulations even in early phase of design workflow and provide primary feedbacks on the performances of design proposal, with a resulting rise of time and cost of the process.

Other limitations are the lack of an integrate platforms able to combine simulations in different domains in a single environment and the poor level of interoperability and data-exchange difficulties among different software, the little use of automatization in the form-optimization process, that still mostly relies on designer intervention to apply form modifications.

2.5 FINAL CONSIDERATIONS

Notwithstanding the mentioned benefits of the performance-based approach, it is still rarely pursued in practice, and several methods have been proposed to ease its application in acoustical field. The suggested procedures seem to be very flexible since they follow different approaches: optimization of form and materials using acoustic performance as driving factor, simplification of simulation and geometry reduction to run rapid acoustic tests, or methods to automatically generate performance space geometry by computer.

Automated generative processes appear to be rarely introduced in acoustic performance-based design, and, in most cases, inform the generation of minor design features. The research of Sato et al. investigates the application of genetic algorithms in the design process of the overall shape of a theatre, resulting in an extremely complex and uneven form (Sato et al. 2004). After almost 15 years from that research, generative processes still find limited application in architectural practice, due to the lack of coding skills among architects and the loose control over form generation.

An attempt to overcome the limitations and promote a broader adoption of the method is advanced by the researches of Tsinghua University, who developed a method to design auditoria, integrating acoustic simulation and parametric modeling. The proposed method aims to overcome the limits of both practices by simplifying them to ease their application to architects. Parametric models of auditoriums are generated by using a component-based method by setting specifications of fixed components of venues, providing a quick and efficient way to create parametric model, otherwise extremely difficult to generate, given the complexity and interrelation of elements of auditoriums. Similarly, acoustic simulations are simplified as regard input and output data and process, to be more suitable to architects and to cut the time to run the simulation. Hence, it is possible to quickly analyze a design proposal to provide a primary acoustic feedback and proceed with the design accordingly. The role of acoustician would be the one of testing pre-selected designs to make more elaborated evaluations, analyzing the parameters that were not taken into account in the architects' simulations, and hence, provide the design team with specific suggestions for further modifications (Lu et al., 2016).

Generative optimization processes appear to be mainly limited to research projects and temporary installations, or to optimize minor features of concert halls. Overall, about half of the projects employed generative processes in their design. The lack of coding skills among architects and the loose control over form generation are some of the main drawbacks of generative processes, that seems to limit their practical application. The research of Sato et al., analyze the use of generative algorithms for the optimization of a concert hall geometry, to enhance acoustic performances (Sato et al., 2004). As suggested by their research, generative design lead on the basis of acoustic performance would lead to uneven, and extremely complex shapes, that can hardly be pursued in practice. Consequently, a greater control over form generation is demanded, especially in major projects, as concert halls, explaining why manual adjustments does not appear to be easily replaced by automation.

The achievement of more intuitive analysis systems, the enhancement of interoperability, the introduction of user-friendly generative form-optimization modules and the development of interdisciplinary platforms, able to combine simulation, evaluation and optimization, let foreseen that in future performance-oriented design would be more practical and appealing to architects. Indeed, as it would require less time and less expertise to be pursued, it would be more broadly employed, as its application could be extended from high-profile and research project to more common architectures.

Chapter 3

SOUND ABSORPTION AND SCATTERING: THEORY AND OVERVIEW OF ACOUSTICAL DEVICES

When a soundwave encounters a surface, three phenomena take place onto the interface between air and the surface: a part of energy is absorbed by the material (α'), a part is reflected back in the air (r), the remaining part is transmitted through the material to the other side of the surface (t). Sound reflections can occur either in a specular or diffuse way. In the first case the soundwave is reflected according to the law of geometrical reflection, in the second case the sound is scattered in a diffuse way, with various directions and over a longer time interval. The extent to which these three phenomena occur depends on the acoustic properties of the surface (Cavanaugh, 1999).

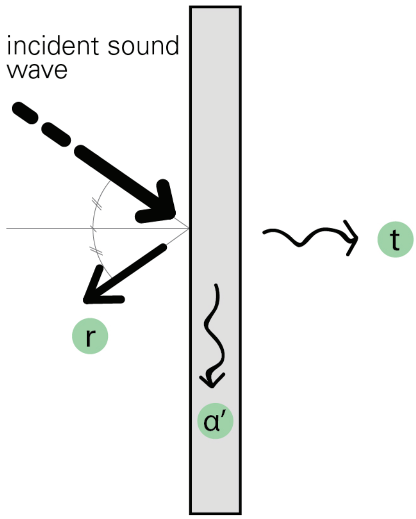


image 3.1_phenomena occurring at the interface between air and a surface

According to the law of conservation of energy, the sum of the three coefficients that express the rate of incident sound energy that is reflected (r), transmitted (t) and absorbed (a') is 1.

$$\alpha' + r + t = 1$$

The factors that influence this phenomenon are the surface's material properties, its texture, and the relationship between the dimension of the surface patterning and the wavelength of the sound.

Although all materials, when stroked by a soundwave, absorb, transmit and reflect sound energy, they are commonly classified according to the predominant phenomenon that occurs as absorbing, reflecting, scattering or transmitting materials. The form of the surface also affects the phenomena occurring at the interface: a surface with a complex surface reflect soundwaves more evenly than monolithic surface – that reflect specularly; a concave parabolic surface generates sound focus, while a convex shape scatters the sound in many directions. The interaction of the soundwave with a given object is also dependent on the similarity or dissimilarity of dimensions between the obstacle and the wavelength. If the object is much smaller than the wavelength, it is unable to interfere with the sound, that will propagate as if is it were not there; vice-versa when the obstacle is much bigger, the sound will reflect back in a specular manner; finally, if the wavelengths' dimensions are comparable with the ones of the obstacle or surface's roughness, a complex phenomenon of reflection takes place, known as scattering (Long, 2006).

The parameters that are commonly employed to describe the effect of a given surface over an incident soundwave are: admittance, impedance, reflection factor and absorption coefficient. The reflection factor, for all angle of incidence and frequencies, express the amplitude and phase change that occurs, by the ratio of the incident and reflected pressure; the surface impedance (z), describes the characteristic resistance of the system against pressure excitation, and depends on the medium density and on the speed of sound in it; the admittance is the reciprocal of the impedance (Cox & D'Antonio, 2004).

Soundwave reflections can highly influence the acoustic quality of a space, and can generate either in beneficial or disrupting effects. When these reflections occur, the sound level increase as the reflected sound support the direct sound emitted by the source.

Reverberation is a key feature in room acoustics: it represents the decay of sound after a sound source has stopped, and is strictly related to the rate of sound reflections that occur in a given space. Higher or lower reverberation time results in different earing perceptions, and can greatly affect the acoustic quality of a space. If the reverberation time is too high, it leads to sound distortion as echoes, while in case it is too short, it may cause the space to be perceived as dead. Reverberation time (T60) measures the time needed by the sound pressure level to decay by 60 dB when a source stops. For indoor spaces with a diffuse field, it can be predicted using the Sabine formula, that, for sound propagating in the air (c=343 m/s), is:

$T_{60} = \frac{0.161xV}{A}$ while the generic equation is: $T_{60} = \frac{55.3V}{cA}$

where A is the equivalent acoustic absorption area, and V is the room volume, c is the sound velocity in the media (m/s).

In case of large amount of absorbers, the Sabine formula is not able to correctly predict the reverberation time. Other formulas where developed in recent years to overcome these limitations, as the Eyring-Norris equation, the most broadly employed one, and the Millington equation. However, the technological advancements of the recent years made geometric model and ray tracing easy and broadly employed tools to run acoustic simulations, able to provide accurate prediction of acoustic indicators as reverberation time (Cox & D'Antonio, 2004).

In outdoor spaces the reverberation time is often considered equal to zero, as it is assumed that rate of sound reflection that occur is negligible, although this assumption is not always applicable to some specific environments as forests or urban areas.

ACOUSTIC MATERIALS: AN OVERVIEW

During the last 100 years, there has been great effort in exploring and studying sound absorptive materials, and in recent years several innovative absorptive solutions have been developed. On the contrary, the study of scattering and diffusers belongs to a more recent period, over the past 20-30 years.

Nevertheless, both absorption and diffusion play significant roles in the acoustic design of spaces to reduce sound distortion. For instance, in indoor spaces, the absorbers are able to reduce the sound energy, controlling reverberation time and decreasing SPL, while diffusers are used to address some acoustic problems, as echoes and coloration, without reducing the sound energy in the space. This property makes diffusers the best choice whenever sound energy has to be preserved; while absorbers are to be used wherever reverberation control is demanded (Cox & D'Antonio, 2004).

Although absorptive materials are able to minimize most of room effect over sounds, a high level of absorption can cause the space to be perceived as dead, so a balance use of diffusers and absorbers has to be preferred as it allows to control sound reflections while ensuring sound liveliness. The desired balance of absorption and diffusion may vary according to personal tastes: if interfering reflection are treated with absorption, a listener would perceive the sound sources as point in space, while in case diffusers are applied the apparent size of the sonic image would be broadened.

The sound we perceive in our daily experience is made of the combination of direct sound, the one directly propagating from the source, and reflected sound, the one that is reflected back to our ears by the surfaces hit by the soundwaves. This combination of waves enables the listener to generate different earing perceptions in accordance to the characteristics of the environment in which the listener and the source are located.

Normally, acoustic tests are carried out in apposite chambers that either maximize absorption or diffusion. A reverberant chamber is a test room characterized by a high rate of reflections due to the reflective surfaces installed in the room, that cause the reverberation time is maximized; on the contrary, an anechoic chamber is meant to reproduce as close as possible the condition of the free field, and its surfaces are made of absorbing materials.

Absorbing materials are tested in a reverberant room to determine the random incident absorption coefficient, while random incidence scattering coefficient are normally measured in a reverberant chamber. To achieve accurate measurements, the samples need to be installed in the test room as close as possible to the as-built elements and edge effect need to be avoided.

ABSORBERS VS DIFFUSERS

Diffusers, alike absorbers, are able to eliminate acoustic problems, as sound distortions produced by reflected soundwaves, but, unlike absorbers, they maintain the sound energy in the space. By scattering the incident soundwaves, diffusers can reduce the amount of reflected sound in a given position, thus eliminating echoes or other undesired effects produced by reflected soundwaves.

According to the primary function and properties of the design space, either diffusion or absorption can be preferred to ensure acoustic quality. When sound energy plays a critical role, as concert halls, diffusers work best as they preserve the sound energy produced by the instruments. Differently, whenever speech intelligibility is a concern, absorbers are employed to reduce the reverberation time and SPL, while diffusers may be applied as well to ensure that early reflections would support the speech without creating distortions (Cox & D'Antonio, 2004).

When selecting an acoustic material, there are a number of requirements to consider, besides the specific acoustic performance to be met. Factors as visual appearance, fire-resistance, mechanical strength, sustainability, ease of installation, or cleanability, may cause a certain material to be more suitable than others in a given project. For instance, as regard mechanical strength, diffusers are generally more durable and resistant than absorbers, and therefore can best suit in aggressive situations (Adams, 2016).

3.1 SOUND ABSORPTION

Absorbing materials are the primary technique to control the amount of reflected soundwaves, as they are able to dissipate a part of the sound energy of the incident soundwave into heat.

Absorbing material are used to control the reverberation time and sound pressure level, but also to address distortion effects generated by sound

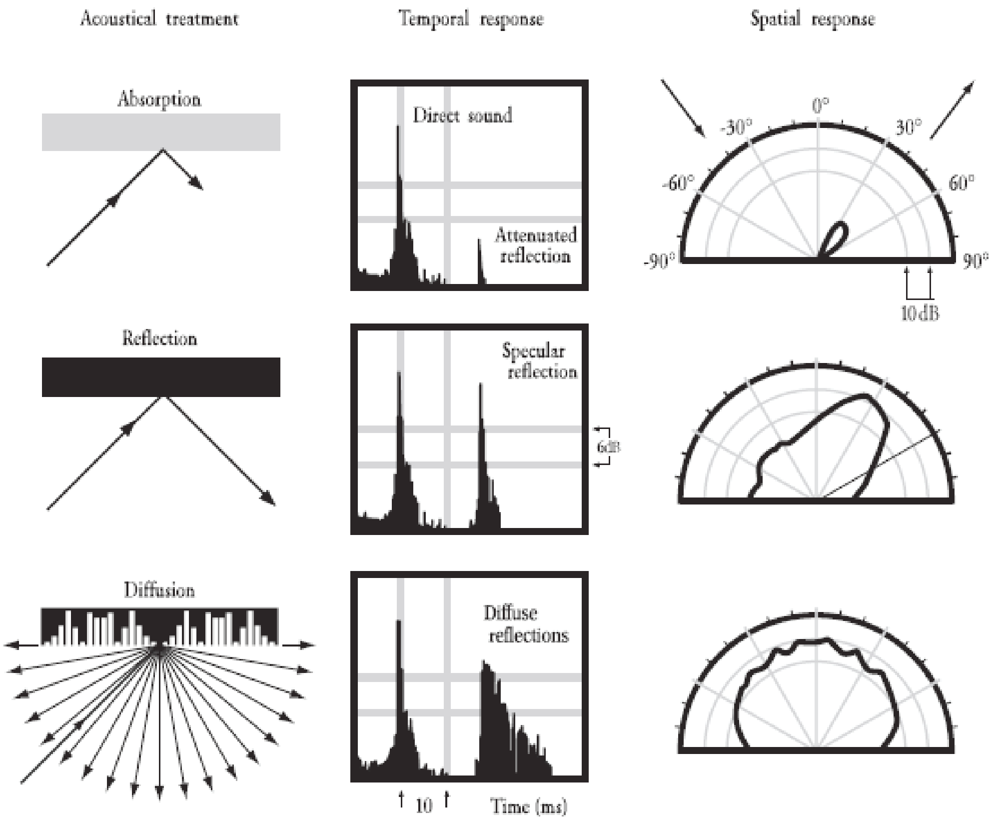


image 3.2_temporal and spatial characteristics of absorbing, specularly reflecting and diffsusing surfaces. [source: Cox & D'Antontio, 2004]

reflections - as echoes, flutter echoes and focusing effects - and to increase speech intelligibility. Nonetheless, an excessive amount of absorbing materials may lead to other undesirable effects, as a dry or dead perception of the space, so a balanced solution must be achieved (Cox & D'Antonio, 2004).

3.1.1 ABSORBING MATERIALS

In common practice, the parameter employed to describe the absorbing performance of a material is the apparent sound absorption coefficient , that is the value that is obtained in acoustical tests. It defines the amount of sound energy that doesn't return to the space as reflected soundwave, and thus, is either absorbed by the wall, or transmitted through the material.

$\alpha' + t = \alpha$

The values may vary from 0 to 1; usually a material is considered sound-reflecting if $\alpha < 0.2$, while if $\alpha > 0.5$, it is considered sound absorbent.

It is important to remark that the acoustic coefficient does not provide information about the amount of sound that is transmitted through the material. In case sound transmission to adjacent rooms is a concern, combining absorbers with other materials, as a massive vinyl barrier, able to block the propagation of sound can reduce sound transmission. (Adams, 2016)

Materials have varying absorption coefficient across the spectrum range, and their efficiency may change according to the frequency of the incident sound. In general, porous materials are most efficient in higher frequencies but have good performances also in middle and low frequencies. Differently, resonant absorbers are more effective with low frequencies, with poor performances in the resting part of the spectrum (Adams, 2016; Cox & D'Antonio, 2004; Ermann, 2015).

DETERMINATION OF ABSORPTION COEFFICIENT

The tests to determine acoustical absorptivity are conducted either in a large resonant chamber or in an impedance tube. In a resonant chamber the sound strikes the surfaces from different directions providing the random incidence absorption coefficient; measures taken in impedance tube are mostly used for prototyping purposes and allow to measure the normal incident absorption coefficient, from which it is possible to calculate random incidence absorption coefficient.

Usually, tests are carried out in 18 different 1/3 octave bands, between 100 and 5000 Hz, to understand the frequency-dependent performance of the material.

The sound absorption power of a material can be expressed by various means, capable or not to plot the frequency dependence of this feature. Single number metrics can be employed to generalize the measured results, but have critical drawbacks as they do not plot the effective absorbing capacity at different frequencies of the material object of analysis.

There are several indicators of absorption that are employed to describe materials. Probably the most common indicator in product specification are the Practical Sound Absorption Coefficient and Noise Reduction Coefficient. The Practical Sound Absorption Coefficient (αp), is a frequency dependent index expressed in 1/1 octave bands from 125 Hz to 4kHz, that is the defined by ISO 11654; the Noise Reduction Coefficient (NRC) is a single figure of merit defined by ASTM C423 and is the average of the absorption coefficients at the frequencies of 250, 500, 1000, 2000 Hz.

Beyond the previously mentioned NRC and αp, there are others indicator as Sound Absorption Average (SAA), Weighted Sound Absorption coefficient (αw), Absorption Classes (from A to E) and the Sabin units. It must be noted that to provide a meaningful indication of the acoustic absorption of a material, the absorbing data have to include the mounting method adopted to test the material sample, as it may have a significant impact over the test results (Adams, 2016; Cavanaugh, 1999; Cox & D'Antonio, 2004, Everest & Pohlmann, 2009).

TYPES OF SOUND ABSORBERS

Absorbing material are classified into two categories: according to their primary operating mechanism: friction and resonance.

Friction occurs in porous and fibrous materials, thanks to their pores and

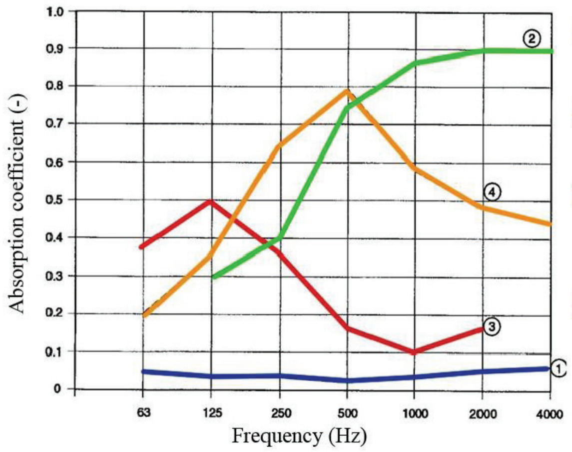


image 3.3_graph showing the variaion of the absorption coefficients over the frequency spectrum for **(1)** drywall board, **(2)** porous material, **(3)** panel absorber, **(4)** perforated panel.

interstices where the compression – rarefaction cycle of air molecules is restrained, and sound energy is transformed into heat. The phenomenon of resonance is enabled by the presence of a system that is set into motion by the incident soundwave: if its natural frequency matches to the one of the sound, the energy is dissipated.

3.1.2 POROUS MATERIALS

Porous materials are the most common and broadband types of absorbers: although are most effective in mid to high frequencies, where the ear is most

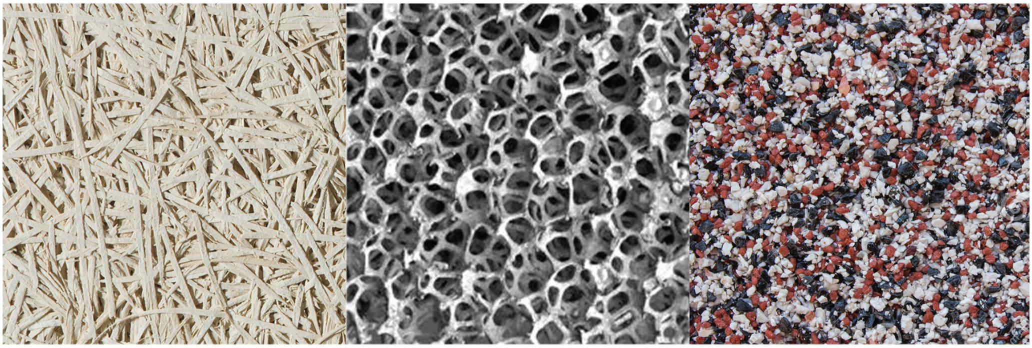


image 3.4_microstructure of porous materials; from the right, fibrous, cellular, granular

sensitive, they provide good performances also in middle-low frequencies.

Porous materials are categorized as cellular, fibrous or granular according to their micro-structure.

The operating mechanism of sound absorption rely on the porous texture of the material, due to viscous effect primarily, and secondarily on thermal conduction. To enable these mechanisms, pores have to be inter-connected through the material, and have openings on the material exposed surface, to enable the air flow to enter the material and dissipate its energy. When the incident soundwaves strikes the material, enters these interstices and is dissipated into heat through viscous effect.

In fibrous materials, the diameter of the fibers highly influences its flow resistivity: natural fibers tend to have larger diameters and to create more irregular interstices than the synthetic ones. In general, the thicker the fibers are, the higher the flow resistance. Some fibrous materials, as mineral wool, are anisotropic, and therefore their effectiveness varies according to the angle of the incident soundwaves.

The sound absorptivity of granular materials is in general uneven across the frequency spectrum, and they usually provide poorer performances than fibrous materials. Nonetheless, granular absorbers are experiencing a rise in the framework of environmental sustainability, due the possibility to employ recycled material in the production process (Adams, 2016).

The absorptive power of porous materials is primarily determined by its porosity and flow resistivity. The porosity is the fraction of the total pore volume to the overall volume of the material; in general, the higher the porosity, the better the absorptivity. It must be noted that in the determination of porosity, closed pores should not be considered as they don’t provide sound absorption.

The flow resistivity (□) measures the resistance experienced by the air flow that enters the absorbers and passes through the pores of the material. The higher the resistance, the greater the amount of sound energy dissipated through viscous effect. Although this parameter plays a critical role in absorption, in case its value is too high, the impedance mismatch would cause the panel to reflect soundwaves, instead of absorbing them. Flow resistivity can be either measured in laboratory following several methods or estimated through formulations.

Other factors that influence the absorptivity of a material are the shape, length and tortuosity of pores. The shape of pores affects the sound propagation, as it influences viscous and thermal effects. If the air propagation path within the material is complex, greater amount of energy is dissipated, since the airflows encounters more resistance. Tortuosity is a parameter that express the orientation of pores in respect of the incident soundwaves, and therefore partially express the complexity of propagation paths (Cox & D’Antonio, 2004).

From these material properties it is possible to retrieve the absorption coefficient and the surface impedance of the absorbers.

Porous materials are generally most effective at high frequencies: at lower frequencies, the absorptivity increases as the thickness of the material increases.

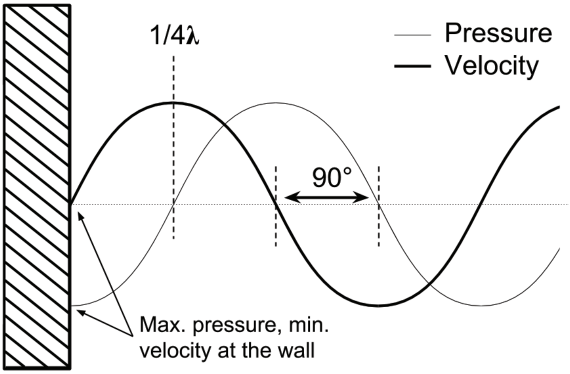


image 3.5_variation of pressure and velocity of a soundwave close to the interface with a boundary surface

The effectiveness of porous absorbers is maximum when velocity of the air particles is the highest. The particles velocity is zero close to the boundary surfaces and grows as the distance from the surface increases, reaching its maximum value at the quarter wavelength position. The image below show the oscillation of particle velocity and pressure approaching the wall.

Therefore, when porous absorptive materials are installed directly on the boundary surfaces, they need to be thick enough to achieve good performances at low frequencies, where the wavelengths are larger. In these cases, the sound energy is absorbed by the part of material that is the most distant from the backing, while the part close to it provide little absorption. Hence, a method to exploit this phenomenon without increasing the thickness of the material is to install the absorptive panel at a proper distance from the boundary surfaces, where air particles move at higher velocity (at least 1/10 of wavelength to provide significant absorption, L' wavelength provide maximum absorption) (Cox & D'Antonio, 2004).

Notwithstanding these solutions, porous materials are poorly used to absorb low frequencies as they either need to be extremely thick or to be greatly spaced from the boundaries. A significant amount of room space would be lost to acoustic treatment, making them unpractical. Hence, in order to ensure absorption for lower frequencies, resonant absorbers are usually preferred since their dimensions are more desirable.

FACINGS

Facings are acoustical transparent devices used to protect or hide porous materials, improving their visual appearance and durability. Their use would ensure dirt or dust particles not being retained by the pores, this way allowing the installation of resistive materials wherever cleanability is required. As porous absorbers are generally prone to damage, facings may be installed to protect them or prevent fibers from material being loss. Protective coverings can be thin membrane wrapped around the panel, or perforated panels. Membranes made of pliable material doesn't alter the performance of porous absorbers, as long as air can easily pass through them. Impervious material, as vinyl of plastic, are transparent at low frequencies, but reduce absorption at high frequencies by preventing part of the acoustic energy from entering the material. This performance reduction is minimized for thin membranes (<2 mm), not rigidly adhered to the porous panel.

The application of paint should be avoided or exclusively restricted to non-bridging paints, and regular paints may lock the pores openings causing a drop in performance.

Perforated panels are able to provide protection without reducing high frequency absorption, provided that their structure is open enough not to impede the propagation of soundwaves through it. The percentage of open area required to ensure acoustic transparency varies according to the thickness

GUIDELINES

- Flow resistivity and porosity are the key parameters that define the absorption power of porous material. In general, the absorption increases for high values of these parameters.
- The effectiveness of porous absorber at low frequency ranges can be increased either by increasing their thickness, in case they are directly applied on boundary surfaces, or by space them from these surfaces. However resonant absorbers are generally preferred to deal with low frequencies.

- In order to maximize the absorption by a wall-mounted porous absorber for a certain frequency, the panel thickness should be λ/4. Otherwise, it is possible to install a thinner panel spaced of λ/4 from the room boundaries. Nonetheless, it is reported that significant absorption is achieved with a thickness/distance of λ/10 (Cox & D'Antonio, 2004).
- To protect porous material from damage or prevent fiber loss, it is possible to use facings, as long that their effect on absorptivity is considered negligible for the design purpose.
- The application of regular paint should be avoided as it may reduce the performance of the absorber by sealing its pores and preventing the air flow from entering its interstices.

of the material: for thin materials, as metal sheets, it is recommended to have at least 20% of open area; for thicker ones, openings should cover from 30 to 50% of the overall area. For smaller percentages, the panel would start behaving as Helmholtz absorbers (Adams, 2016; Cox & D'Antonio, 2004).

3.1.3 RESONANT ABSORBERS

Absorption at low frequencies is better addressed through resonant absorbers. These devices have limited thickness and are available in a great variety of visual appearances, making they more desirable whenever low frequency sound absorption in required. Resonant absorbers are divided into membrane absorbers and Helmholtz resonators. Both devices offer a high rate of absorption within a limited range of frequencies and are used to provide absorption at low to mid-frequencies, where porous absorbers would require a significant thickness or spacing from the walls, to be effective (Adams, 2016).

The operating principle of resonant absorbers is based on sound pressure: consequently, these devices are the most effective when applied directly on room boundaries, where sound pressure is maximum (as seen in the image above for porous materials) (Foley, 2014).

They play therefore a crucial role in controlling SPL, reverberation time and addressing issues occurring at low frequencies, as room modes.

Resonant absorbers function as a mass vibrating against a spring, and provide maximum absorption around their resonant frequency: therefore, by changing the mass and the stiffness of the spring it is possible to tune these devices to make them effective at a frequency of interest. Greater mass and stiffer spring lower the resonant frequency of the system.

Resonant absorbers often come with a layer of porous absorber installed in the cavity, that broaden the frequency range of effective absorption; however, their application is often limited to specialized applications, when the frequencies of sounds can be predicted beforehand, given the narrow range of frequencies in which they are effective (Adams, 2016; Cox & D'Antonio, 2004).

If wider bandwidth of absorption is required it is possible to apply porous absorption in the cavity of resonant absorbers, it is possible to install different types of resonant absorbers, each tuned to different frequency range (Cox & D'Antonio, 2004).

HELMHOLTZ RESONATORS

Helmholtz resonators are named after Hermann von Helmholtz, who discovered their operating mechanism in the 19th century.

An Helmholtz resonator is made of an enclosed volume of air, with a short open neck. The operating principle of Helmholtz resonator is a mass vibrating against a spring; the air comprised in the neck represents the mass, while the air contained in the cavity works as a spring. When an incident soundwave reaches the opening of the resonator, the volume of air internal to the neck is set into motion. This movement alternately compress and expand the air comprised in the cavity: as a result, the friction cause part of the acoustic energy to be

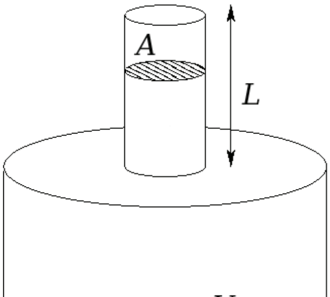


image 3.6_Helmholtz resonator

absorbed and converted into heat.

This mechanism is most effective when the frequency of the sound hitting the absorbers is equal to the natural frequency of the resonator; the absorbing power rapidly decreases at lower and higher frequencies.

Helmholtz resonator can be designed to address specific acoustic problems: in facts, the resonant frequency of resonators, and thus the frequencies in which they are effective, can be controlled by varying the dimensions of the cavity or the neck, altering their volumes. The natural frequency (f0) of the Helmholtz resonator can be predicted with a reasonable accuracy, with this formulation:

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{s}{Vl}}$$

Where c is the speed of sound (343 m/s); s is the cross-sectional area of the neck [m2]; l is the length of the neck [m]; V is the volume of the cavity [m3]

Absorbing panels that use the principle of Helmholtz resonators can be constructed by perforating, milling or punching hole-openings in panels: the hole spacing should be large in comparison to hole diameter. Alternatively, it would be possible to create panels by creating slot openings – easier to be produced - or by leaving a spit space between single elements as battens. The resulting panel works as a multiple Helmholtz resonator, in which the small openings are the necks, and the air gap behind the panel is the cavity. Helmholtz resonators come in a great variety of materials, finishes and form, and thus, are greatly employed in architectural projects.

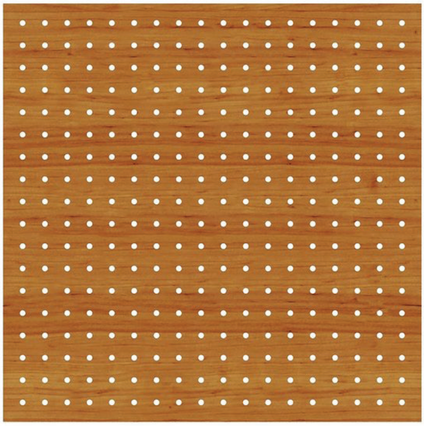


image 3.7_perforated panel

Under the assumption that the panel thickness and the hole radius are much smaller than the acoustic wavelength, the resonant frequency of the overall panel can be determined with the previously-mentioned formulation, considering l as the panel thickness (for a more accurate prediction, it would consider the end corrections), and v as the volume of each unit cell.

By reducing the number of openings, the peak absorption of the panel will decrease in frequency and the bandwidth over which it is effective will be shortened. However, decreasing the resonant frequency, may reduce the peak absorption coefficient, lowering the efficiency of the device. Under the constraints of maintaining the same overall thickness of panel and cavity, the resonant frequency would decrease for growing thickness of the panel.

To improve the absorption of the system it is possible to place a layer of porous absorbers in the cavity, close to the neck, or even directly in the openings, where the air velocity is maximum, in order to provide dampening. Although it broadens the frequency-range of efficiency, the peak value of absorption is often reduced.

A method to increase the absorption of perforated panels of oblique-incidence soundwaves at low frequencies, it to physically subdividing the cavity in single volumes, this way reducing the lateral propagation within the air gap. In case a layer of porous absorbent is present in the cavity, the physical subdivision is less stringent.

Randeberg developed an alternative method to creating perforated panels with lateral elongated necks, and remove the need of resistive material by exploiting viscous effect. They made of two layers of perforated panels distanced about 0.2 mm: in this narrow space, losses occur due to viscous effect, providing similar performances to microperforated panels, discussed below (Adams, 2016; Cox & D’Antonio, 2004).

GUIDELINES

- Helmholtz resonators can be tuned to be effective for a given frequency by altering the dimensions of the neck and the cavity volume. Increasing the cavity volume or the neck length cause the peak absorption to decrease in frequency; greater openings would cause the resonant frequency to increase.
- The resonant frequency of the panel can be lowered by reducing the number of openings or by increasing the relative thickness of the panel.
- Combining different types of Helmholtz resonators, each tuned on a different frequency would increase the bandwidth of absorption; however, it would require a large amount of wall area to be covered with acoustic treatment.
- Absorption performances of Helmholtz resonators can be improved by placing a layer of porous absorption within the air cavity, close to the neck: although it broadens the operative bandwidth, it is often associated to a reduction of the absorption peak.
- In small enclosed spaces, the best devices to treat acoustic modes, occurring at low frequencies, is to use resonant absorbers. They are most effective if installed at the room corners where the sound pressure reaches its maximum for all room modes.
- If the visual aspects of the holes of Helmholtz resonators is undesirable, there are several methods to conceal the system without compromising its effectiveness.

MICROPERFORATED PANELS

If the diameter of the perforations of a Helmholtz resonator are sub-millimetric, sound absorption would occur due to viscous effect in the openings over a wider bandwidth of low to mid frequencies, displacing the need for a porous layer.

This feature allowed the development of micro-perforated panels (MPP), one of the most recent absorption technologies to emerge. One of the advantages of these devices is that their performances can be accurately predicted, as their physical mechanism is simple. Clear absorbers are basically transparent Helmholtz devices composed by two layers of transparent material (acrylic or glass), one of which is micro-perforated. Typically, the panel thickness is comparable to holes diameter and openings are spaced 5 mm from each other; the panel's material does not influence the operating mechanism, and therefore an extremely wide range of material can be employed, making them appropriate even in environments where cleanability is a concern.

Microperforated panel can be designed to absorb over a specific range of frequencies by adjusting material thickness, perforation size and density, distance from the rear reflective wall. As for the other resonant absorbers, performances can be enhanced using porous absorbent in the cavity. Broader frequency range of absorption can be achieved by using multiple layer microperforated panels, spaced from one to another, although it would cause the cost and overall depth of the panel to increase.

Due to the layers' little thickness, these devices are prone to damages due to their lack of mechanical resistance, and may not be the most appropriate solution in hazardous environment, although their resistance can be enhanced by using solution as a honeycomb backing.

GUIDELINES

- Microperforated panels can be obtained from a wide variety of materials, without significative alteration of performances: this feature allows to obtain transparent, washable devices that can fulfill specific requirement
- They can be designed to absorb over a selected bandwidth by altering holes dimensions and density, spacing from the rear wall, material thickness.
- Their performances can be predicted with great accuracy, as the physical principles that generate absorption is simple
- Wider bandwidth of absorption can be obtained by use multiple layers of microperforated panels, each installed at different distances from the reflective wall.

PANEL ABSORBERS

The employment of panel absorbers in architectural spaces is eased by the great variety of material that can be used as panels.

They are composed by a thin rigid panel mounted in front of a rigid wall, parallel to it. When a soundwave strikes the membrane, it is set into motion: the vibration alternately compress the air comprises in the cavity and part of the sound energy is dissipated into heat. The operating principle, as for Helmholtz resonator, is based on a mass vibrating against a spring: in this case the mass is the material sheet and the spring is the air in the airtight cavity behind it. The air contained in the gap between the panel and the reflective surface of the wall works as a spring when the panel is set into motion, opposing its movement: smaller depth generates higher resistance and moves the absorptive bandwidth to upper frequencies.

A simplified design equation that defines the resonant frequency from the characteristics on a membrane panel, without the application of porous absorption in the cavity is:

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

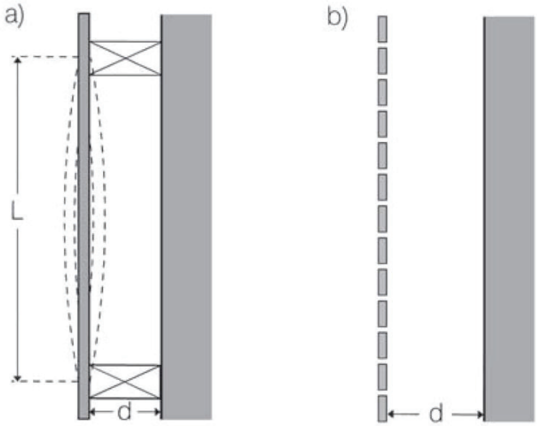


image 3.8_panel absorber [source: Kuttruff, 2007]

Where m is the areic mass of the panel [kg/m^2], d is the cavity depth [m].

However, membrane panels are not simple systems as perforated panel, and their design equations are often inexact; hence, their design method is mainly iterative as their performances are difficult to predict (Cox & D'Antonio, 2004).

Small dimension of the panel can compromise the ability of the panel to vibrate freely since it must be fixed at the edges, reducing the effective mass vibrating: therefore, panels should be at least 0.5 m^2; in case of smaller membrane, a resilient fixing would allow the whole panel to vibrate, address this issue (Adams, 2016; Cox & D'Antonio, 2004).

Similar to Helmholtz resonators, they provide only narrow band absorption, in most cases is below 400 Hz, and the peak of absorption is reached at the resonant frequency of the system. Again, the installation of porous absorbers within the air cavity would increase the performances of the device by extending the frequency range of operation, exploiting the velocity of the air particles within the cavity that are set into motion by the membrane. In this case the layer of porous absorbers should be placed behind the membrane, ensuring that they are not in contact (Cox & D'Antonio, 2004; Foley, 2014).

It is also possible to create a hybrid Helmholtz-membrane absorber by creating openings in the membrane of the panel: these would increase the rate of absorption provided by the porous layer in the overall system, as the holes would ease the access to the porous absorber (Cox & D'Antonio, 2004).

GUIDELINES

- Panels absorbers can be tuned to absorb at a given frequency by altering the thickness of the panel (mass) and the volume of the rear airspace (spring).
- As all resonant absorbers, they work better if placed where sound pressure is high: this occurs on room boundaries, and even more in room corners, where sound pressure is maximum for all modes.
- Membrane absorbers can be tuned by altering their dimensions and the panel material. The resonant frequency of the device increases as mass per area of the panel or the cavity depth decrease.
- Using different types of membrane absorbers, each tuned to a different frequency, would widen the overall bandwidth of absorption provided.
- An application of porous material within the cavity increase the absorption of the device. It is recommended to avoid applying porous absorbers directly on the panel not to increase its mass (it would move the effective bandwidth of absorption to lower frequencies)
- The effect of fixing may compromise the vibration in small panels, that therefore should be at least 0,5 m^2.

3.1.4 VARIABLE ABSORBERS

As space may be used for various purposes, each demanding different acoustic requirements, it is often preferred to have an acoustical environment that can be adjusted over time according to what the space hosts. Variable absorbers allow to control the rate of absorption provided, using a simple mechanism that regulate the exposed area of sound absorbers, allowing the acoustic performance of the room to adapt to different necessities.

Draperies are one of the most common variable acoustical device: they are porous absorbers that mainly provide absorption from mid to high frequencies, while lower frequency absorption can be enhanced by distancing their installation from side walls. It is reported that the absorption provided by drapes increases for deeper folds, and the frequencies of absorption varies according to the density of the material (Cox & D'Antonio, 2004; Everest & Pohlmann, 2009).

Everest also suggest the utilization of other adjustable devices, as portable or freestanding absorbers, that give a certain amount of control over the rate of sound absorption; hinged panels or rotating elements, absorbent on one side and reflective on the opposite; louvered panels backed by porous absorbers, whose surface can create slit openings and work as a perforated panel when needed, closed to reflect sound, or completely open to revel porous absorber; hinged perforated panels, whose position can be varied to modify the resulting resonant frequency (Everest & Pohlmann, 2009).

OPTIMAL SOLUTIONS FOR ABSORPTION

- An ideal sound absorber would provide absorption over the entire frequency spectrum. In practice, this cannot be achieved with a single absorber, but need different absorbers to be employed: porous absorbers provide broadband absorption at mid to high frequencies, with poor performances at lower frequencies. Resonant absorbers, being Helmholtz resonators or membrane panels, are frequency-selective absorbers, that are effective at low to mid frequencies, and can address room modes and other phenomena occurring at low frequencies. Therefore, a combination of different devices can be the most effective solution to provide broadband absorption, and is convenient both. in terms of economical cost (reduced amount of material), and space constraints.
- However, different methods have been proposed to increase the bandwidth of absorption of both resonant and porous absorbers, that are effective to some extent.
- Variable absorbers are devices that can adjust the area of exposed absorbers, this way altering the rate of absorption provided in a space, allowing to adjust its acoustic to different requirements over time.
- A little rate of absorption may generate excessive reverberation, that must be avoided as it creates sound distortion and lower speech intelligibility. At the same time, it is important to prevent excessive level of absorption in a given environment as it may cause undesired effects as a dry or dead acoustical impression of the space.
- In selecting the most appropriate absorbers, it is important to take into consideration the specific requirement of the design space and the risk it will likely be exposed to. Since porous materials are prone to damages, that can reduce their effectiveness and durability, transparent facings can be used to provide protection.

3.2 SOUND SCATTERING

Although scattering elements were used for centuries in rooms, only in the last three decades appeared a concrete effort to understand and measures this phenomenon, along with the exploration of their potentiality to address some acoustic problems.

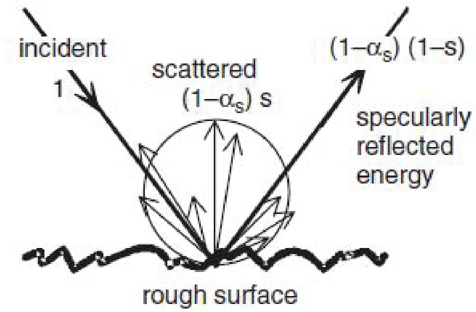


image 3.9_types of sound reflections

The phenomenon of sound scattering take places when the incident sound-wave's wavelength is comparable to the dimensions of the element hit or to the roughness of the stroked surface: in these cases, the soundwave is reflected back in a diffuse way, both spatially and temporally. Differently, in case the wavelength is much bigger than the surface roughness, a specular reflection occurs, as they do not interfere with the phenomenon; while in case the irregularities are greater than the wavelength, each of them can be considered a curved or plane surface over which the sound is reflected specularly. According to Vorlander, scattering occurs when wavelength is equal to the double od the irregularity width, as shown in the image below (Vorländer, 2008).

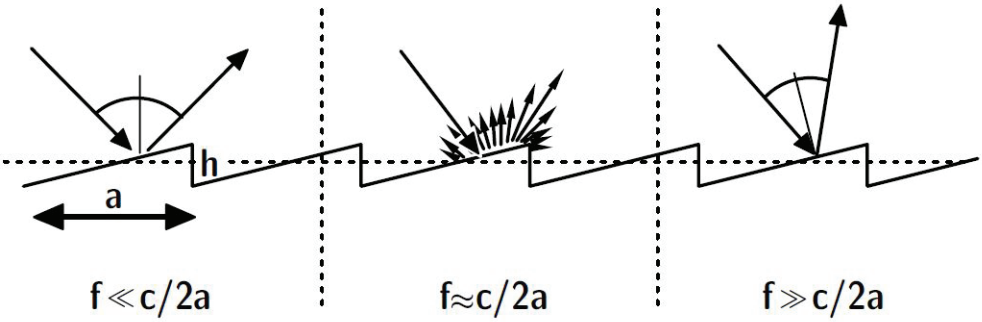


image 3.10_influence of dimensions of the irregularity on the direction of the reflected soundwaves [source: Vorlander, 2008]

When an irregular surface is stroke by an incident soundwave, a significant part of the incident soundwave is scattered in all directions. In general, the reflected sound energy can be divided in two components: a part is reflected in a specular way, the remaining part is reflected in a diffuse way. For a totally diffusive surface the spatial distribution of the scattered soundwave does not depend on the angle of the incident sound: although it is not achieved in room acoustics, it is still a good approximation of real walls, especially in reverberation chamber where many successive reflections occur.

Total diffuse reflection is described by Lambert's cosine law, that defines the intensity of reflected sound in a given point, independently from the angle of incidence. Provided that there is no absorption, the intensity of sound scattered in a given direction is determined as a function of the scattering angle ϑ and the distance r from the wall element dS, following this equation:

$$I_r = \frac{B_0 dS}{\pi r^2} cos\vartheta$$

Where B is the incident energy per unit area of wall per second (Kuttruff, 2000).

Lambert's law is used to describe diffusion provided by geometrical devices, achieving accurate prediction for high-frequencies for incoherent reflections. Although it does not approximate reflection from all devices, as for example Schroeder diffusers, it is commonly employed by computer models in ray-tracing analysis, to calculate diffusion provided by surfaces (Cox & D'Antonio, 2004).

3.2.1 SCATTERING MATERIALS

The following image compares the wave-fronts generated by a planar reflective surface and simplified Schroeder diffuser, when hit by a perpendicular soundwave. A planar surface (on the left) reflects incident soundwaves in a specular way: the points of the surface where the sound is reflected back represent secondary sound sources that irradiate sound creating concentric waves which in turn, by interfering with the adjacent ones, generate linear wave-fronts, parallel to the surface that propagate perpendicularly from it.

Differently, the phenomenon of scattering occurs when an incident soundwave is reflected back by a surface in many different directions and with a time delay, this way contributing to a uniform distribution of sound energy in the space. The image on the right represents the operating principle of a simplified Schroeder diffuser, showing that by changing the phase of the reflected wave-front, both spatial and temporal diffusion in achieved.

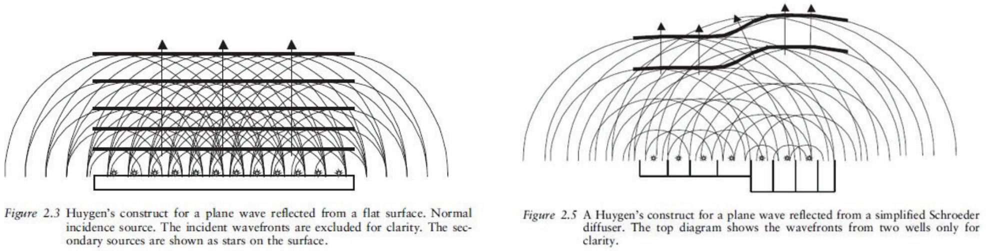


image 3.11_operating principle of a Schroeder diffuser (on the right) in comparison to a planar surface (on the left)

The image 3.12 shows the difference between a soundwave reflected by a flat surface (specular reflection) and a diffuser, as regard temporal distribution of direct and reflected/scattered sound and frequency response of the reflected/scattered sound.

In performative spaces, diffusers break up or diffuse the incident soundwaves around the auditoria: they provide both spatial and temporal dispersion, as the sound is scattered in many directions during a longer time interval. This feature plays an important role in reducing issues resulting from the interference of direct and reflected soundwaves (as comb filtering), that can lead to undesired effects. Indeed, when direct sound is combined with a diffuse reflection (total field), the resulting spectral content allow the direct sound to be more accurately perceived than in case of the combination of direct and specularly-reflected sound (Cox & D'Antonio, 2004).

The effect of sound diffusion varies according to the listener position: if it is placed in the near field, close to the diffusing surface, the beneficial effect of sound diffusion combined with direct sound may not be perceivable. The listener indeed should be placed in the far field, where the polar response is independent to the angle of incidence, the angle of observation and the frequency.

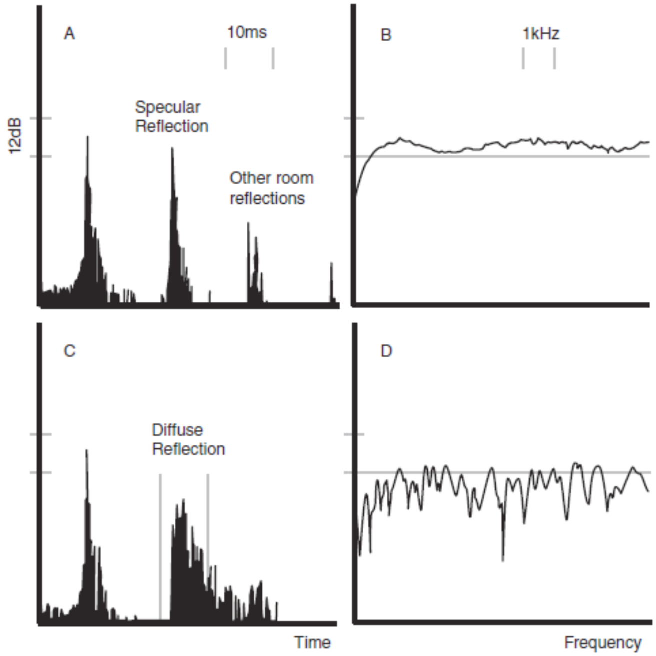


Figure 2.7 Measured temporal and frequency responses for a flat surface (top) and a diffuser (bottom). The frequency responses are for the reflected sound only (after D'Antonio and Cox [1]).

image 3.12_temporal distribution and frequency response of a soundwaves being reflected in a specular or diffuse manner.

MEASUREMENT OF SOUND DIFFUSION

The most common parameters employed to characterize a scattering surface are polar response, diffusion coefficient and scattering coefficient, each plotting different aspects of the scattering phenomenon.

The polar response is a highly detailed way to define the scattering properties of a surface: it describes the spatial distribution of the scattered sound-waves, and is usually provided in one-third octaves for a given angle of incidence. An ideal diffuser would produce a uniform polar response, not influenced by angle of incidence, angle of observation and frequency.

The various techniques to measure the polar response are based on the use of a source to irradiate the candidate surface and a series of microphones placed in radial positions in front on the surface, to measure the resulting pressure impulse response. The output recorded by microphone have then to be filtered in order to remove the sound energy provided by the direct sound from the loudspeaker to the microphones (time gating). According to the type of diffuser under analysis, these measurements are carried out either on a single plane using a 2D goniometer on a semicircle, or over a hemisphere, using a 3D goniometer. It is possible to run the 2D analysis in an anechoic chamber or using a boundary layer technique in a large, non-anechoic room, often on scaled model; with some precautions, this method is quick and easy to carry out. Differently, the hemispheric analysis is more time-consuming and complex, as it requires a greater number of measurements and an anechoic chamber to be run. Consequently, prediction models may be used to facilitate this measurement, or the number of measurements may be reduced exploiting geometrical properties of the surface (symmetry...).

The large amount of data expressed by the polar response often make this measurement unpractical to be used by acoustic professionals. Consequently, the need to express and synthesize this information in a single number arose in the practice. From the 1970s, new coefficients were developed, able to assess the quality of innovative diffusers that were produced since then.

Diffusion and scattering coefficients are used to ease the comparison among diffusing surfaces and be employed in geometric room acoustic models, although they are not able to accurately render the complexity of the phenomenon. To achieve the accuracy of measurements to compare performances of different scattering systems, these parameters are measured using a standard method defined by ISO 17497 : 2004 for diffusion

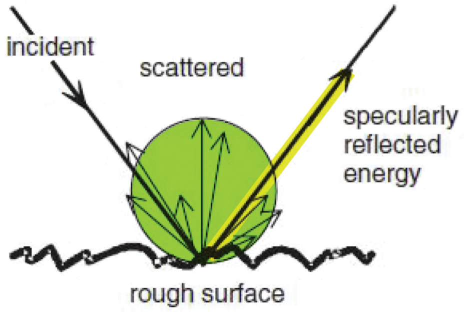


image 3.13_drawing illustrating diffuse vs specular reflection

coefficient and by ISO 17497 : 2012 for scattering coefficient.

Scattering coefficients (s) are commonly employed to characterize surfaces to perform acoustic simulation in geometrical models. It measures the rate of sound energy that is scattered away from a given direction or distribution by dividing reflected sound energy into specular and scattered components. In particular, s can be determined using the following equation:

$$s = 1 - \frac{E_{r,spec}}{E_{r,tot}} = \frac{E_{r,scatt}}{E_{r,tot}}$$

Where $E_{r,spec}$ is the specular reflection (colored in yellow in the image), and $E_{r,scatt}$ is the scattered component (colored in green).

A given surface is to be considered a diffuser in case s≥0,5. Although the parameter does not take into account the spatial distribution of the scattered energy, it is considered accurate enough to be used to predict acoustic performances as it is assumed that in most applications a mixture of different reflections is achieved. This approximation in considered reasonable in reverberant field, while it can lead to inaccuracies in case of early sound fields.

The measurement of the scattering coefficient is made in a reverberant chamber, using a circular test sample on a turntable; in most cases the measurements are done on a scaled sample. The reverberation time need to be measured four times, in which the sample is either present or absent, either rotating or fixed, to eliminate the effects that mat be caused by turntable's flaws. The impulse response is repeatedly measured while the turntable is rotating: from the recorded measurements it is possible to attain the random incidence absorption coefficient, the apparent specular absorption coefficient and the total reflected energy, from which it is possible to achieve the scattering coefficient.

It is also possible to predict the scattering coefficients: Mommertz suggested a method to define the scattering coefficient from polar responses, correlating the scattered polar responses with a reference flat surface; similarly, for Schrodinger diffusers, it is possible to estimate the free field scattering coefficient using the Fourier model, achieving reasonably accurate results

(Vorländer & Mommertz, 2000).

As mentioned, the scattering coefficient does not plot the spatial uniformity of the diffused soundwaves and thus its quality, but it is merely a measurement of the amount of sound energy that is scattered away from the specular direction.

The quality of the reflection generated by the surface is expressed by diffusion coefficients (d), that measures the similarity between the polar response of the surface and uniform distribution, this way allowing to compare diffusers according to their performances. The adoption of this coefficient enabled diffuser designers to explore new solutions, not based on rigid geometric constructs, that could better fulfill the aesthetic requirements expressed by architects.

The diffusion coefficient is frequency-dependent value, evaluated in 1/3 octave bands derived from the polar response, which evaluate the ability of a diffuser to scatter the sound uniformly in all directions, taking into account both the diffuse and the specular reflections. The diffusion coefficients are then averaged to provide a single figure of merit. Various statistical operations have been suggested to reduce data of the polar response in one single number, among which the autocorrelation is favored. If the energy is scattered in all directions, d is equal to 1, if the energy is reflected in one direction, d is zero. Diffusion coefficients can be measured for a given angle of incidence, or for random incidence; since random incidence analysis, for hemispherical case, implies an extremely high amount of measurement, it is normally reduced to normal and 55° angle of incidence.

The reduction process needed to obtain diffusion coefficient results in some drawbacks, as part of the data of the polar response is lost in the process. For instance, only uniform and specular reflections are truly defined, while values between 0 and 1; or else, measured and predicted values tend to be smaller for complex surfaces in application-realistic sizes, than in small samples due to the lobing effect. Moreover, it is impossible to evaluate the evenness of the diffusion across the frequency spectrum when only the frequency averaged diffusion coefficient is provided. These example remarks the importance to test samples of application-realistic sizes, as single object test are not representative of the performance of the overall surface (Cox & D'Antonio, 2004).

TYPE OF SOUND DIFFUSERS

Sound diffusion can be provided either by room elements, as traditional room ornaments (columns, plaster decoration, statues...), or by diffusing surfaces which were mostly developed in recent decades. In both cases the dimension of the incident soundwave's wavelength has to be comparable to those of the elements or of the surface corrugations.

From 1970s onward, new types of sound diffuser appeared on the market: most of them were reflection phase grating diffusers also known as Schroeder diffusers, based on mathematical functions.

Sound diffusers are divided into two categories: surface diffusers and volume diffusers. The first are able to scatter sound in a hemisphere as they only receive sound from a 2ϖ space. Differently, volume diffusers can diffuse sound over a full sphere, providing greater diffusion (Cox & D'Antonio, 2004).

3.2.1 SCHROEDER DIFFUSERS

The invention of phase grating diffusers by Schroeder represents the starting point of diffuser's design: they were the first diffusers able to scatter sound in a predictable manner, achieving "optimum" diffusion on the basis of relatively

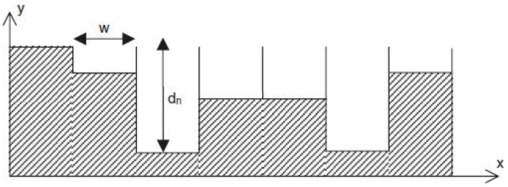


Figure 9.2 A cross section through an $N=7$ quadratic residue diffuser (QRD®).

image 3.14_1D Schroeder diffuser: photograph of a commercial product and drawing showing the section with the significicant dimensions simple design equations.

A Schroeder diffuser consists in a series of wells, with equal width and different depth, separated by thin fins; the depth of the wells is defined according to a mathematical sequence (the most common is the quadratic residue sequence (QRD); others are maximum length sequence, primitive root sequence...); the wells sequences (period) is repeated in the diffuser that, consequently, is periodic. 1D Schroeder diffusers are able to diffuse sound in one plane (hemi-disc), while in the perpendicular one they behave as a plane surface therefore, they are usually analyzed in the plane that contains the maximum dispersion.

OPERATING MECHANISM OF 1D SCHROEDER DIFFUSER

When a plane soundwave hits the diffuser, it propagates within the wells and is eventually reflected from the bottom and re-irradiated in the space. As the wells have different depths, the soundwaves take more or less time to travel along the wells, and therefore is reflected back with a phase change. Outside the diffusers, the interference among these soundwaves cause the sound to be scattered in different directions, achieving both spatial and temporal dispersion. Schroeder showed that if the wells' depth is defined by quadratic square residue sequence (QRD diffusers), the energy scattered into each diffraction lobe direction is the same.

The upper wavelength limit (λ_{min}) to ensure that plane wave propagation dominates within the wells is equal to the double of the well width, as following $\lambda_{min} = 2w$. Above this value, the device scatter sound but diffusion cannot be described with Schroeder theory.

Schroeder diffusers work at integer multiples of the design frequency f0, that is the lower frequency limit that depends on the maximum depth. The relationship between corresponding design wavelength λ_0 and the depth of n-th well of the diffuser (d_n) is governed by the following equation:

$$d_n = \frac{s_n \lambda_0}{2N}$$

where d_n is the n-th well depth; N is the prime number generator (number of wells per period); s_n is the sequence number of the n-th well. In practice, the following formula defines the lowest frequency of diffusion achieved from a given maximum depth (d_{max}) of the diffuser and the largest number of the QR sequence (s_{max}):

$$f_0 = \frac{s_{max}c}{2Nd_{max}}$$

Schroeder diffusers behave as reflective plane surfaces for certain values of frequency, named critical frequencies, that cause the reflected sound to be emitted with the same phase. For QRD diffusers, this phenomenon occurs when all wells' depths are integer multiples of half a wavelength, that is, for mNf_0, where m =1, 2, 3....

Beyond the quadratic residue sequence, other mathematical sequences have been introduced to define the wells' depth. For instance, MLS diffuser are based on the maximum length sequence, although it works only over an octave; Primitive root sequence (PRS) diffusers minimize the specular reflections and generate even energy lobes in the other directions at integer multiple of the design frequency, but present limitations as they only work for discrete frequencies.

Although periodicity is necessary to generate even-energy lobes, they create large minima that cause the scattering energy to be uneven, especially for lower frequencies (the number of lobes increases at higher frequencies): better performances are achieved by increasing the period width, or by creating an aperiodic sequence. Angus proposed methods to combine different Schrodinger diffusers to overcome periodicity limitations: 2 or more phase grating diffusers are arranged in a pseudo random manner to avoid repetitions. A cheaper option, not to employ different diffusers, is to flip some of them, provided that they are asymmetrical. Alternatively, better performances are achieved by employing the Barker binary sequence for diffusers, in which some diffusers are inverted (180° out of phase). Barker sequence provide good performances, provided that the critical frequencies are well above the high frequency limit of plane wave propagation. Otherwise fractal self-similarity property can be combined in phase gratings diffusers to reduce periodicity effect and provide full spectrum sound diffusion: these diffusers are termed fractal diffusers. Each level of the fractal diffuser covers a specific bandwidth, resulting in an extended overall bandwidth coverage.

As mentioned, the lower frequency limit for Schroeder diffusers depends of the well's maximum depth, and in practice is impossible to achieve full bandwidth coverage. Architectural constraints often limit the maximum depth of acoustic panels, and therefore some methods have been proposed to improve the base response without increasing the panel thickness (Jrvinen et al., Mechel; Hunecke).

Generative performance-based design method has been applied in the generation of Schroeder diffusers by Cox, after this solution was envisaged by de Jong and van den Berg in 1980. Technological advancement in recent years indeed allowed computer to run an iterative optimization process to search for the optimal sequence of well depths; optimized diffusers are able to ensure in higher performances than QRD diffusers (Cox & D'Antonio, 2004).

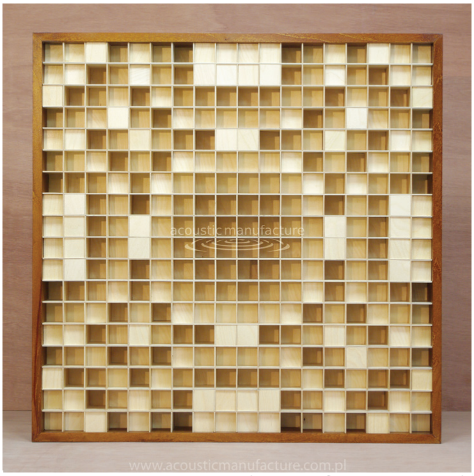


image 3.15_example of a 2D Schroeder diffuser

While 1D diffusers are able to scatter sound over a hemi-disc, and behave as a planar surface in the other directions, multi-dimensional diffusers can scatter sound into a hemisphere. These diffusers are 2D devices able to produce even lobes over a hemisphere. There are two methods to generate 2D diffuser, the first generates sequences, one for each direction, the second is based on the Chinese remainder theorem. The scattered energy in a given position results to be lower in comparison to a 1D Schroeder diffuser, and often have less bass diffusion efficiency than 1D devices

In order to minimize the rate of sound energy absorbed by the devices, it is important to ensure high precision in the construction: cracks in the well bottom may lead to absorption to resonance. Construction materials not to influence the effectiveness of the device, as long as they have rough surfaces. Cloth-coverings must be avoided as they increase absorption (in case it is unavoidable, it must be placed at least L' wavelength far from the device surface). It is also possible to slope the bottom of the wells to reduce absorption (Commins et al.).

One of the drawbacks of Schroeder diffusers, that limit their application in current practice is their visual appearance, that is not always appreciated by architects. Therefore, in recent years new devices were developed, able to combine sound diffusion with different visual aesthetic to meet the demands of architects (Cox & D'Antonio, 2004).

GUIDELINES

- The lowest frequency at which a Schroeder diffuser is effective can be manipulated by altering the maximum well depth. The mathematical formulation to describe the diffusers performance can be applied from the design frequency, to an upper frequency limit determined by the well's width. Above this upper limit, the device still provide diffusion.
- The wells should be narrow to diffuse high frequency sound, but not too narrow to avoid vibrations that cause significant resonant losses (absorption). Moreover, narrow wells increase the production cost of the diffuser. A practical width is at least 2,5 cm and usually around 5 cm (Cox & D'Antonio, 2004)
- The diffusers need to be periodic: at integer multiples of f0, the lobes are generated by the periodicity of the surface.
- The number of periods must be kept under a certain limit, as too narrow diffraction lobes cause uneven scattering due to the large nulls that occur. Five periods are considered by Cox and D'Antonio as a proper amount to ensure periodicity and avoiding too narrow diffraction lobes. (Cox & D'Antonio, 2004)

- The period width must be large to create a high amount of diffraction lobes: as wide well width may lead to specular reflections, it is better to reach a large period width with a large N number, that is usually linked to greater absorption. N number is limited by manufacturing cost, low frequency performances (f0 decrease as N increase) and critical frequencies.
- To achieve better low frequency performance a constant phase shift may be introduced in the quadratic residue sequence.
- To ensure that critical frequencies, the lower critical frequency must be above the maximum frequency of the device.
- The combination of 2 or more different diffusors achieves diffusions for more frequencies, and thus generate better diffusion.
- In order to increase the uniformity of the diffusion at low-mid frequencies, it is possible to use modulation schemes of different diffusers with good aperiodic autocorrelation properties (Angus, Barker). Fractal diffusers can provide and extended bandwidth coverage.
- In order to reduce sound absorption, it is important to ensure a high precision construction and to avoid cloth coverings.

3.2.2 GEOMETRIC DIFFUSERS

Diffusion can be generated by arrangements of geometrical elements, as pyramids or triangles, or by curved surfaces, often preferred as they are better integrated in contemporary architecture.

PLANAR SURFACES

Sound diffusion occurs in finite-sized plane surfaces when the wavelength is comparable to surfaces dimensions due to diffraction caused by edge effect. The correspondent frequency is known as cut-off frequency of the surface: for greater wavelength the soundwave propagates not influenced by the surfaces, for smaller is reflected in a specular manner.

Polar responses of planar surfaces show that in the far field, for increasing distances from the surfaces, the energy is reflected in a specular manner, while in the near field they provide good scattering although the total field that results would be subject to comb filtering.

The polar response of an array of planar surfaces is defined according to the characteristics of a single panel, and the overall arrangements of surfaces. However, scattering generated by an array is quite similar to that of a single plane panel, although it involves more sound energy. In the far field, for middle frequencies, periodic effect dominates, and grating lobes are generated; at lower frequencies, wavelengths are bigger than panel sizes, and the overall polar response is similar to that of a single surface, without periodicity lobes; at higher frequencies, the scattering is governed by specular reflections, with a high number of grating lobes.

However, in common practical applications, the listeners are not located in the far field, but in the near field, where reflection vary across the frequency spectrum, and the uniformity of scattering is progressively lost as the frequency of the incident sound rise.

TRIANGLES AND PYRAMIDS

According to the side steepness, they provide either notch response, good diffusion or specular reflections. For high frequency and normal incidence scattering varies as follows: for angles up to 30°, the surface strongly redirect soundwaves in two directions over relatively wide frequency range; for angles comprised between 30 and 45°, there is a mixture of single and double reflections, resulting in four different lobes; for 45°, the energy is reflected back in a specular manner; between 45 and 54°, double reflections occur that generates two lobes; for greater angles, the number of reflections increase, as well as the number of resulting lobes; finally, with very large angles, above 85° a single broad lobe appears, with a highly directional response.

An array of triangle produces periodicity lobes and large notch for normal direction at certain frequencies, while at other frequencies the attenuation of the specular reflection is less evident, but still perceivable. The performances can be improved by dimensioning the triangle depth as a multiple of half the wavelength, provided that the triangle angle is shallower than 30°; otherwise it is possible to use a wide variety of different triangles with a modulation technique, or increase their depth, although the latter solution may be impractical due to architectural constraints and increased absorption.

CONCAVE SURFACES

Concave surfaces are mainly known for causing sound focus and other undesirable effect, but, if conveniently designed, are able to provide sound dispersion to some extent (their performances are poorer than other surface shapes). Virtually, focusing effect is only a problem at certain receiver distances, close to the focal length of the arc; therefore, provided that the listeners positioning is far from the focus, being it above or below the audience, the sound is diffused.

If the focus occurs in the listening position, it is possible to reduce its effect by placing absorbers in front of the curved surfaces or by installing sound diffusers on the concave surfaces to break up the reflected wave-front.

CONVEX SURFACES

Cylinders generate sound dispersion in one plane, while spheres scatter sound hemispherically. The sound dispersion generated by a single cylinder is fairly omnidirectional, although a single cylinder or semicylinder is often unpractical in real situations. Flatten semicylinders, or smaller portion of cylinders are reported to provide poorer performances. Semicylinders achieve good diffusion both for normal and oblique incidence, but the total field generated by direct and reflected sound is affected by comb filtering, as it lacks temporal dispersion. Therefore, a more suitable solution is to combine semicylinders in arrays, whose performances depends on how the elements are arranged, and the partial contribution of single elements is less significant. Spatial dispersion of sound is reported to be more even if the arrangement is ruled by modulation technique, instead of being periodic. Moreover, the total field of periodic arrangements is still affected comb filtering, although it is reduced in comparison to those of a single element, while random arrangements of many different-sized cylinders is reported to further minimize the filtering effect.

OPTIMIZED CURVED SURFACES

The application of above mentioned diffusers often collides with visual requirements imposed by architects, due to their characteristic visual appearance that is not necessarily considered appropriate. Technological advancements occurred in recent times allowed the creation optimized curved surfaces, a more appealing solution able to scatter sound and being better integrated in contemporary architecture. The design method of these surfaces is performance-based: their curvature is adjusted by the computer to provide optimal scattering as regard the resulting spatial dispersion. Shape parameters are modified by an iterative process run by computer, under a series of constraints, acoustical or non-acoustical, until the best geometry is achieved. However, the optimized does not always meet the aesthetic requirements demanded by designer, and methods have been proposed to control to some extent the final visual appearance while altering diffusion performances.

Once again, when the optimized base shapes are arranged in arrays, it is of critical importance to favor random or pseudo-random arrangements instead of periodic ones, since they provide better performances. Periodicity effect can be reduced by avoiding short repeat distances and using asymmetrical base shapes. The latter are convenient solutions as they can provide different scattering performances by simply being flipped (Cox & D'Antonio, 2004).

GUIDELINES

- Non-planar surfaces have to be preferred as plane panels, single or combined in arrays, do not provide good scattering, due to lack of spatial and temporal dispersion.
- Scattering performances of single triangle or pyramid greatly vary according to their angles. However single elements are often unpractical, and arrays are preferred of small elements are preferred: if compared to a periodic arrangement, modulation of a wide variety of triangles would generate a more even attenuation of specular reflection across the spectrum. Performance improvements are achieved to some extent by increasing the triangle depth.
- Concave surfaces at small distance from the panel provide spatial dispersion as long as the listening position is far from the geometric focus; however, their performances are poorer in comparison to other devices. If the location of the audience is close to the surface focus, either absorbers or diffuser applied on the surface can reduce the focusing effect.
- Convex surfaces, as semi-cylinders, provide good spatial dispersion but lack temporal dispersion, producing comb filtering. Arrays of semi-cylinders are reported to diminish the comb filtering, as the effect of single elements is less evident. Semi random arrangements of different sized semi-cylinders provide greater spatial dispersion and further reduce comb filtering.
- Optimized curved surfaces provide better performances and are better integrated in contemporary architecture than other devices, and therefore generally more accepted by designers. Their use in arrangements is still affected by periodicity effect: it can be reduced by using modulation techniques, by flipping asymmetrical base-shapes and by increase repeat distance.

3.2.3 HYBRID DEVICES PROVIDING ABSORPTION AND DIFFUSION

Hybrid devices, also known as “diffsorbers”, exploit the variation of impedance across their surface to generate a device between a pure absorber and a diffuser, that offers reverberation control and scattering in a single device. They are essentially composed by a combination of absorptive and reflective patches, arranged according to a pseudorandom sequence in a planar or curved surface. They are convenient solution as wherever both diffusion and absorption are required, they are able to make efficient use of limited depths.

Binary amplitude diffsorbers (BAD) are planar devices provide sound absorption at low frequencies and scatter sound above a certain frequency, named cut-off frequency, that is often close to 2kHz. These device s extend the bandwidth of absorption of traditional fabric wrapped absorbers: at lower frequencies they behave as Helmholtz resonators, while for higher frequency they provide scattering. They are composed by a layer of mineral wool faced with a perforated panel, both fabric wrapped: beyond being inexpensive, the cloth hides the perforated sheet, offering a neutral visual appearance that is often preferred by designers. Low to mid frequency absorption is enhanced by increasing the depth of resistive material, by distancing it from the rear wall or by reducing the open are of the perforated panel, although the latter solution would also reduce high frequency absorption. The scattering provided by the panel is still characterized by a coherent specular reflection: if the same operating principle is applied on a curved surface, sound diffusion is enhanced as normal reflection is reduced.

The distribution can be defined by a pseudo-random binary sequence with good autocorrelation properties that minimize periodicity effect and enhance sound diffusion; otherwise it is possible to find the optimal sequence using numerical optimization technique, as genetic algorithms. As for Schroeder diffusers, better performances are achieved for large repeat distance, for modulation of different base-shapes or a single asymmetrical base-shape, or by employing larger number sequences.

It is also possible to create hybrid devices by a combination of different devices: for instance, Cox describes the combination of a Schroeder diffusers with Helmholtz resonators, able to provide scattering and low frequency absorption. These devices can be created by installing the diffusers over a layer of porous absorber, leaving an air cavity behind: this way, Helmholtz resonator can be obtained either by perforating the bottom of Schroeder diffusers, or by spacing the diffusers planks and thus creating a slit opening to the air gap (Cox & D'Antonio, 2004).

GUIDELINES

- Hybrid devices are thin, inexpensive device that provide both sound absorption and scattering in a unique surface, by exploiting impedance variances. The cloth wrap can conceal the visual appearance of the perforated panel.
- Scattering occur for high frequencies, while absorption prevail for lower frequencies: sound absorption at low frequency can be enhanced by increasing the depth of the resistive material, by distancing the panel from the wall, or by reducing the area of the perforations.
- Curved hybrid surfaces lessen the amount of sound energy that is reflected specularly, and therefore provide greater sound diffusion.
- To enhance sound diffusion, the distribution of patches should be determined by a pseudorandom sequence or by numerical optimization; it is also critical to avoid short repetition distance, by using modulation or using large number sequence.

Chapter 4

THE STREET CANYON ACOUSTIC EFFECT

4.1 URBAN SOUNDSCAPES

In the modern cityscapes, noise pollution appears to be a rising problem, that need to be taken into account, especially in the framework of sustainable urban design.

The inhabitants and the ecosystem of contemporary cities are being subjected to high levels of noise, given the great amount of possible noise sources in the urban environment. In recent years, the awareness of disrupting interferences over health and comfort of the city populations has grown, but little has been done.

Indeed, as reported by Sanchez et al., urban soundscapes are generally not taken into account in urbanism, contributing to the criticality of noise problems in our cities. Given the importance of environmental sounds, able to enrich the visual perception of city by its inhabitants, the lack of simultaneous consideration of both visual and acoustic perceptions may produce ineffective interventions in urban areas, often resulting in disuse of public spaces by pedestrians (Echevarria Sanchez, Van Renterghem, Sun, De Coensel, & Botteldooren, 2017; González, 2014; Rehan, 2016).

Noise pollution can be originating from anthropogenic sources, urban transportations, aircrafts, production factories, construction sites and other sources located in the city. In particular, given the continuous growth of urban traffic, the effect of the vehicular noise increasingly became a critical concern.

These sounds, once emitted, are reflected repeatedly over buildings fronts and other city surfaces, enhancing the sound level exposure for pedestrians and over the building facades.

Nonetheless, as mentioned, in most cases urban design does not consider acoustic consequences of city configurations, and noise pollution is mostly addressed a posteriori, with various sound reduction measures whose effectiveness and integration in the urban cityscape is often not optimal (Echevarría Sánchez, Van Renterghem, & Botteldooren, 2015).

4.2 STREET CANYONS

When urban streets are flanked by buildings on both sides, a canyon-like environment is generated, usually termed as “street (or urban) canyons”. The configuration of these places affects various local conditions, as wind, temperature, air quality, signal reception and acoustics (“Street Canyon,” n.d.).

In an ideal condition, the outdoor propagation of sound resemble that of the free-field: the soundwaves do not encounter a significant number of reflective surfaces in their path and propagate in all directions. This principle does not apply however to the urban cityscapes: here, the sounds emitted by sources as vehicles, public transportation, construction sites or social events located in the street are being reflected by the building fronts, generating the “street canyon” effect. From the acoustics point of view, these urban environments are an example of multipath sound propagation.

The described phenomenon is exacerbated for increased building height/street width ratio, causing the soundwaves to be reflected multiple times before escaping the urban canyon, with a consequent increase in the sound pressure level within the street.

This phenomenon is mainly influenced by the rate of sound absorption and geometric and scattered reflections occurring on the building surfaces; on the contrary, usually ground surfaces, that are usually paved with flat hard material, barely contribute to sound diffusion or absorption; finally the sky behaves as a perfectly absorbing surface: when soundwaves are directed toward it, they exit the canyon. (Lyon, 1974; Onaga & Rindel, 2007).

In the last decades, as the study of urban sound has established as a research field in many part of the world, the acoustics of street canyons has been studied and modeled, with increased accuracy (Rehan, 2016).

The first digital simulations of sound propagation in urban canyons were carried out using image source method or ray-tracing, assuming that all building facades were perfectly smooth and provided only specular reflections. Although in some situations this approximation may provide reasonably acceptable results, since in most existing building facades there are certain irregularities, the phenomenon of sound scattering needs to be considered to provide a realistic explanation of sound propagation in street canyons. Consequently, in the following years, various models were developed to take into account sound diffusion of the streets.

As observed by Kang, the sound field in real world street canyons is somewhere in between the diffusing and geometrical reflecting situations: as a soundwave hits a surface, fraction of the incident energy is either absorbed, geometrical reflected or scattered (Kang, 2000). The role of diffusing reflections has been investigated by Kang, who proposed a simplified comparison between two models of street canyon with either diffusing or specularly-reflecting boundaries. More advanced models were developed by Onaga et al. and Can et al., who aimed to model real-world street canyons, where both types of reflections occur (Kang, 2000; Onaga & Rindel, 2007).

Kang compares the simulation of sound fields in street canyons with completely geometrical reflecting and completely diffusing boundaries, using respectively image source method and radiosity methods. Although the analyzed cases are not realistic, since reflection on actual façades occurs both in specular and diffuse way, the comparison provides useful insights. The research focuses on the following aspects: sound attenuation along the length, reverberation, the effect of building height and width, sound distribution in cross sections, distribution of boundary absorption and the presence of multiple sources. The results showed that, in the model with diffusing boundaries outperform the geometrical reflecting one, providing advantages as greater SPL attenuation along the length, and shorter reverberation time (Kang, 2000).

Onaga et al. used the two methods employed by Kang in combination, to account both specular and diffuse reflections. The research focuses mainly on facades' materials, comparing various combinations of scattering coefficients (variation range 0 - 1) and absorption coefficients (variation range 0 - 0.5), plotting the SPL and reverberation time obtained for three different building heights. The results show that scattering affects SPL by provide a noticeable decrease at great distances from the source and a minor increase for short distances. (Onaga & Rindel, 2007).

Finally, Can et al. meant to model the acoustics of real-world street canyons, using a sound particle tracing code, considering the scattering provided by both street surfaces and street fittings, as the latter are normally not considered in simulations, as the ones previously cited. The study confirms the results observed by Onaga on the effect of diffuse reflection over SPL, and goes further considering the ratio H/W of the street in combination with various acoustic properties of ground, façades, and street fittings, to understand their reciprocal relationships and define their relative importance in different scenarios (Can, Fortin, & Picaut, 2015).

Other studies analyze the acoustic consequences of several façade features, as balcony geometries, setbacks from the façade's plane, prominences, windows configurations etc. The research of Sanchez collects and analyze various architectonic solutions, accounting their acoustic consequences in a standard urban canyon. (Echevarría Sánchez et al., 2015)

4.3 MEASURES TO IMPROVE ACOUSTICS OF STREET CANYONS

In most cases, environmental noise issues are not considered during the design process, and are commonly faced when the design is completed, with corrective methods as absorbing pavements or noise barriers. Also the enhancement of façade and window sound insulation may be an option, but Sanchez et al. do not consider reliable solutions as their effect relies on inhabitants behavior, and a simple open window would compromise the effectiveness of these measures (Echevarria Sanchez, Van Renterghem, Thomas, & Botteldooren, 2016).

The reduction of the sound pressure level in urban street canyon can be achieved through the absorption or diffusion of the propagating sound. The first measure would cause part of sound to be lost when the absorbing material is struck, reducing the overall sound energy in the street; the latter would scatter part of the sound toward the sky, causing sound energy to leave the canyon (Echevarria Sanchez et al., 2016). The two measures are equally effective in reducing specular reflections and, since they provide the dominant reflection energy, it results in a decrease in the total sound energy (Onaga & Rindel, 2007).

The role of diffuse reflections in the acoustic field of street canyons has been investigated by Kang, Can et al., Onaga et al.: all researches highlight the benefits provided by scattered reflections over specular ones in these urban environments.

The important role of diffuse reflections over the façades was evidenced by the research of Kang, who concludes his analysis stressing the importance of the presence of scattering elements to ensure some of the benefits observed in purely its diffusive model, compared to the specular one. His research moreover suggests that absorptive devices appear to work better when applied on only one side of the street: in this case, the sound attenuation along the length appear to be greater than when it is applied evenly on all surfaces (Kang, 2000). In particular diffuse reflections, compared to specular ones, cause a great decrease of SPL at great distance from the source, at the expense of a little increment at small distances. (Can et al., 2015; Onaga & Rindel, 2007) Both enhancing and lessening effects of diffusion on SPL appear to be lessen by increased absorption. (Can et al., 2015)

The researches of Can et al. and Onaga et al., evidence that SPL and reverberation time appear to be influenced by building heights and street width (H/W ratio), in relation to various rates of scattering and absorption. Simulations report that the little increment of SPL caused by sound diffusion at small distances appear to be slightly greater in case of higher buildings, while, more noticeably, in case of low rise buildings, the primary effect of diffusion is the reduction of SPL. These phenomena are due the different ease of sound to be reflected towards the sky and therefore, lost: in case of higher H/W ratio, sounds need to reflect more times before leaving the canyon, and there is a greater probability of “sound particles” being reflected towards the ground; lower H/W ratios, instead, ensure that a greater fraction of the overall sound energy propagating is reflected towards the sky, rapidly exiting the canyon. Onaga et al. observed that the sound field in low façade streets is dominated by specular reflections, while for higher facades, scattered ones prevail. Therefore, increase in scattering coefficient have different effects according to H/W ratio. In low façade streets, enhanced diffusion favor both SPL and reverberation time reductions; whereas increased scattering hardly affects the same parameters for high building façades, where the scattered energy would be maintained in the street, and therefore only absorption would work in decreasing SPL. On the contrary, Can et al. observed the little effect of increased absorption in facades of streets with low H/W ratio. (Can et al., 2015; Onaga & Rindel, 2007)

As regards reverberation time, in low façade streets, it may be reduced with both the increase of absorption and scattering coefficients, while, again, only enhanced absorption appears to be effective in high rise streets. On the contrary, reverberation time appear to increase for greater street widths. (Can et al., 2015; Onaga & Rindel, 2007).

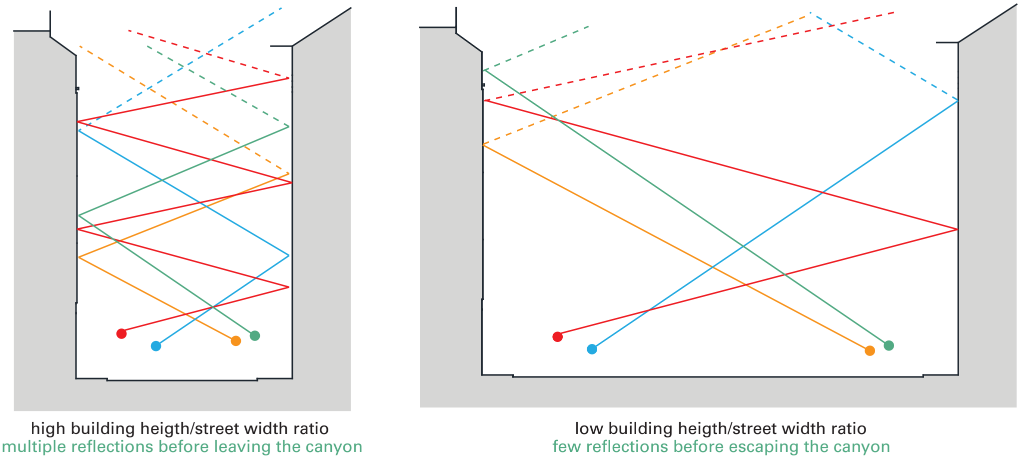


image 4.1_influece of building heigh/street width ratio over the rate od sound reflection occurring within the street canyon

The research conducted by Echevarria Sanchez et al. meant to provide an overview of possible architectonic solutions, by exploring the effect of various street design measures as building shapes, front design, street geometry and street furniture over the noise exposure for pedestrians and on the façades (Echevarria Sanchez et al., 2016). According to the results, solutions involving building geometry mainly provide benefit for façade exposure, while measures applied closers to the source, tend to provide beneficial effect for pedestrian exposure. To reduce noise exposure, it is critical to reduce reverberation and redirect first reflections towards the sky, by placing inclined surfaces near the sound sources. The analyzed measures concerning the geometry of the side buildings' façades are reported in the following.

GUIDELINES

- Both sound absorption and scattering are able to enhance the acoustic comfort within street canyon subjected to noise pollution due to transportation.
- Absorption would cause part of the sound energy to be lost each time the soundwave strikes the material. Scattering surfaces, would spatially disperse soundwaves, directing part of them towards the sky, exiting the canyon. Both measures are equally effective in reducing geometrical reflections.
- Diffuse reflections cause an overall significant reduction of SPL, although at short distances a little increment is reported.
- The acoustic field of street canyon is greatly influenced by the geometrical proportion between the height of the side buildings and the width of the street. Performance simulations identify absorption as the most effective measure to lower SPL level in case of high H/W ratios; on the contrary scattering work best for low H/W ratios, where sound absorption appears to provide limited benefits.

BUILDING GEOMETRY: for the scope of the research, building shapes have been simplified and a single material has been applied, either glass (reflective) or bricks (absorptive). Acoustic simulations were conducted for façade profiles with flat, stepped, convex, concave and inclined configurations. The results showed that the façade shape can have a significant effect over the pedestrian sound exposure and that their effectiveness is more noticeable when using reflective materials. The most effective configurations were flat upward-inclined and concave ones.

SETBACK OF GROUND/FIRST LEVEL: different setbacks from the façade plane are analyzed by varying the depth and the floors involved. Results show the beneficial effect of setbacks for both pedestrians and façade exposures, although their effect for pedestrians is mostly due to the increased distance from the traffic.

BALCONY GEOMETRY: various balcony configurations are analyzed, reporting great benefits for noise exposure along the façades, with little improvements for pedestrians. Sound reductions is mostly caused by the shielding effect of balcony over windows. Different balcony geometries are analyzed, to explore the effect of inclined balcony ledges and ceilings: the most beneficial configuration is the one where both ceilings and ledges are inclined.

TRIANGULAR PROMINENCES OF FAÇADES: the triangular prominences analyzed varied for vertex horizontal and vertical distances from the façade plane. The façade exposure, especially in upper floors, greatly benefits from these measures, while little or even unfavorable effects are observed for pedestrian exposure.

SHIELDED INCLINED WINDOWS: the presence of self-shielded windows, where the glazing is inclined with different angles. The simulation shows that an important beneficial effect is noticed in the façade exposure from the second floor upwards, while it seems to produce a slight increment in pedestrian exposure (Echevarria Sanchez et al., 2016).

- LOW BARRIER SHAPES: a great effect over pedestrian exposure is observed, while little effect is observed on the facades. Barriers appear to be more performing if tilted; with the street dimension of the research, an inclination 30° appear to be the most performing. The addition of a small vertical lamina atop of the barrier further improves the performances. The inclination of the barrier provides beneficial effect along the façade, especially at lower heights. Interruptions between barriers are expected to compromise the SPL reduction observed.
- GREEN ABSORPTION ON VERTICAL LOW BARRIER: the application of frequency-dependent absorption on low barriers, as the one provided by a realistic green wall substrate, enhance SPL reduction. The greater effect occurs with absorption on all faces; the application of source side is more performing than the one on receiver side; the additional application of green absorption on the top of the barrier further enhance the results observed of the source-side application.

All the mentioned studies aim to investigate the acoustic of street canyon subjected to the most common type of noise pollution sources in our cities: traffic and urban transportation. Digital sound sources were indeed modeled to resemble the actual sound generated by vehicles, as regard location, spatial continuity, and frequency spectra of the emitted sounds. The latter aspects, in particular, is critical: given the wave-nature of sounds, each frequency correspond to a specific wavelength, and therefore different sounds behave differently in the same environment, in accordance to the length of their soundwaves. For these reasons, the conclusions drawn by the cited studies may not fit for other sound sources, as the case of people’s chatter. However, the researches still provide useful insights, and will be used as basis for the work presented in the following.

Chapter 5

OVERVIEW OF THE CASE STUDY AND BASIC SETTINGS OF THE MODEL

The scope of this research is to investigate the acoustic effects generated by the variation of materials and geometrical features of an urban façade, when chatting noise is present at the street level.

The present work aims to explore possible design solutions able to address noise in urban areas, promoting the awareness of the acoustic consequences of various design choices since the early design phases. The thesis project is based on a previous Master Thesis, developed by the student Roberto Manca, focusing on the façade of an actual building in Turin, Italy. This thesis project means to further improve the precedent work and explore the impact of new design possibilities over the acoustics of the street canyon considered. In particular, the acoustic influences of the design of the façade of the buildings that face the streets will be investigated: the effect of a series of geometrical variations will be analyzed in the first part, while, in the following, the effect of material variation will be explored.

Finally, a set of guidelines will be defined, in order to support and instruct designers over which are the most effective façade features to better address noise pollution generated by street chatter.

5.1 INTRODUCTION OF THE CASE STUDY: SAN SALVARIO

The case-study of street canyon that will be analyzed and designed in the thesis project is located in the city of Turin, Italy, in a neighborhood called San Salvario (Image 5.1). By the analysis of the acoustic behavior of an actual urban street, this Master Thesis project aims to identify a series of façade features that are able to better cope with chatter noise in an urban setting.

The problem of night-time chatter noise is a relatively new issue in San Salvario: this issue arise from the most recent development of the area.

The neighborhood was mostly built during the second half of the 19th century: the most common type of building is the courtyard residential building, with about 5 floors, originally intended for renting ("Nuovo quartiere di San Salvario," n.d.). Historically, the vocation of the area was almost only residential, with little shops and other facilities for the dwellers. In the recent years, after decades of decline, the neighborhood is recovering thanks to the establishment of new activities in the area.

Image 5.1_Map of Turin, showing the location of the city center, the case study and San Salvario neighborhood (red outline)

New activities appear to compensate the lack of pubs and club this area of the city, exacerbated by the closing of the clubs of the Murazzi riverbank. Thanks to this new bias, the area is recovering and developing a nightlife vocation: the neighborhood now offers a rich variety of restaurants, pubs and clubs, in most cases addressed to the student audience.

The nightlife bent, while increasing the attractiveness and the development of the neighborhood, come along with new issues. The other side of the coin is the nocturnal noise, considered as one of the most critical issues in the area Given the fast and significant proliferation of restaurants, pubs, clubs, that in most cases are active during evenings and late-night times, the acoustics of the neighborhood has changed significantly.

Since the new bias has established many have been the complaints coming from the neighbors, asking to solutions able to reduce the noise pollution produced by the new call. The detrimental impact over the comfort and well-being of the inhabitants is proved by the significant number of newspaper articles issued on the topic (Caracciolo, 2017; “Movida assordante, San Salvario fa causa,” 2017). A local Ordinance was passed, limiting the time slots in which alcoholic drinks to go can be sold by local business (“Ordinanza n 46 - Comune di Torino,” 2017).

Although the Ordinance has proven useful to limit the noise produced by all-nighters, it was not well welcomed by local entrepreneurs who saw their business reduced. Moreover, its application was limited to the summer period of 2017.

Other measures were issued, as no licenses are being released for new activities in the most critical areas of the city (Rossi, 2017).

Beyond these political means, it is important to remark the importance of building façade design in limiting and influencing the acoustic field of urban streets. Noise pollution can be addressed using relatively simple technical measures as replacing windows with more soundproofing devices or applying soundproofing cladding on existing buildings.

However, the design of the building façade can contribute to the reduction of the noise exposure, ensuring the acoustic comfort of the inhabitants. The awareness of the acoustic consequences of certain features of the facades enables designers to promote the well-being of the dwellers since the early design phases. This approach would enhance the design quality and promote a more responsible design, focusing on the wellness of the inhabitants. Such measures would be beneficial, especially in noise-prone areas, and regardless of dwellers technical devices and of the political measures adopted locally.

5.2 OVERVIEW OF THE PRECEDENT WORK

The work of Roberto Manca is divided into various steps. The first phase all the facades of the building of via Saluzzo have been mapped and the building at number 29 was selected as case study. Subsequently, an acoustic survey was carried out measuring SPL and RT on site and an accurate digital model of the chosen building and the street was created, defining all materials applied to its surfaces and with their actual dimensions. Finally, the facades of the context have been created: in this case the façades were not modeled as the actual ones, but a representative façade-configuration was chosen and repeated to create a "generic" context with spatial homogeneity. Once the geometrical model was set, materials were applied to the various surfaces, each time defining the absorbing and scattering coefficients. Finally, an algorithm was set to optimize the both the acoustic coefficients to ensure the soundness of the simulations by comparing the SPL and reverberation time obtained with the outcomes of the actual acoustic survey. A calibration process was carried out by slightly change the acoustic coefficients of each material to minimize the differences between the RT and SPL measured and simulated.

The model developed by Roberto Manca is composed by the building fronts of via Saluzzo, modeling a street length of 80m in the surroundings of the design building (image 5.2).

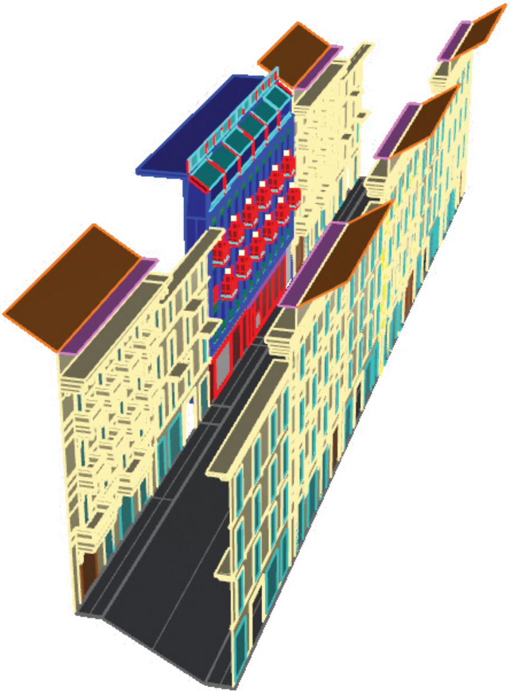


Image 5.2_digital model of via Saluzzo developed by Manca (Manca, 2017)

Once these features were defined, in the following design phase, the material of various features of the façade from the first floor to the roof, were optimized to minimize the noise exposure throughout the façade. PachydermAcoustics for Grasshopper was set in order to calculate SPL in dB and dB(A) and the reverberation time, by recording the acoustical data from 36 receivers placed in the loggias and balconies of the building facade. Each feature of the façade (parapet, balcony ceiling, floor etc.) was assigned a range variation of different possible materials, considering the architectonic constraints imposed. Then, using Galapagos, a generative algorithm was set in order to combine different materials until the solution that minimize the SPL was found.

Subsequently, further simulations were carried out by manually altering the material applied to the street paving and to the façade at the ground floor, to analyze their impact on the results of the simulation.

In the end, also geometrical changes over the façade configuration were attempted: different scenarios were created by changing the balconies and

Image 5.3_Map of San Salvario. The red dot identifies the location of the case study.

loggias to either have balconies-only or loggias-only configurations; the effect of these changes over the acoustic performances were then analyzed (Manca, 2017).

5.3 FIRST STEPS – THE SETTING OF THE MODEL

In the first part of the thesis project, the digital model developed by Roberto Manca was further tested to verify the achievement of simular results. In the end the model was restored and purged from the content relative to his work to obtain a plain version of the model, to be used in the subsequent phases.

VERIFICATION PROCESS

The work started by checking the work comprised in the precedent thesis.

The simulations were repeated with the same settings to verify the adherence between thier results with the ones obtained by Manca. The comparison showed that the results were different from the ones reported in the previous work: the average of the obtained values were about 1 dB less than the of Manca.

This result may be due to the fact that different versions of PachydermAcoustics were used: the precedent thesis project was done using the version 1, while the current work employs a subsequent version.

Finally, a verification process was carried out to check and, in case, correct inaccuracies in the model and in the settings of the acoustics simulation. As regard the simulation, minor adjustments to acoustic coefficients of material were accomplished. The only major modification was that the material applied to the windows at the ground floor was wood, and therefore, it was replaced with glass.

REDUCTION OF THE GEOMETRICAL MODEL

Once the model was checked and set, it was possible to proceed to the next step. Given the forecast of carrying out a number of simulations, it was critical to combine accurate results with time save. The time required to run the simulation is greatly influenced by the complexity of the digital model under analysis. The digital model developed by Manca consisted in an 80 m road section. This model was reduced to the sole portion of the street facing the design façade, and simulations were carried out and compared to the ones of the complete model to investigate if and at what extent the results would vary. The comparison of the results showed that the results of the shortened version were on average -0.4 – 0.5 dB less than the ones obtained by the detailed model, confirming that the reduced model was accurate enough to account for the sound propagation in the design test. At the same time, the time required to run the simulation was halved, allowing to greatly speed up the subsequent phases of the thesis. Most of the simulations reported in available literature over the acoustics of street canyon employ even more complex model than those created in the previous thesis project. According to the available literature, streets need to be modeled for a length of about 120 m to ensure that the simulation would generate a truthful representation of the acoustic behavior of street canyons. However, most available literature on the acoustics of street canyons deals with traffic noise: the sound source is therefore modeled as linear, placed along the length of the street, and emits a sound with a different frequency spectrum. On the contrary the current project aims to reproduce and analyze the sound generated by a chatter: as a consequence, the model employs a point source placed on the platform on the opposite side of the street, emitting a sample sound recorded by Manca.

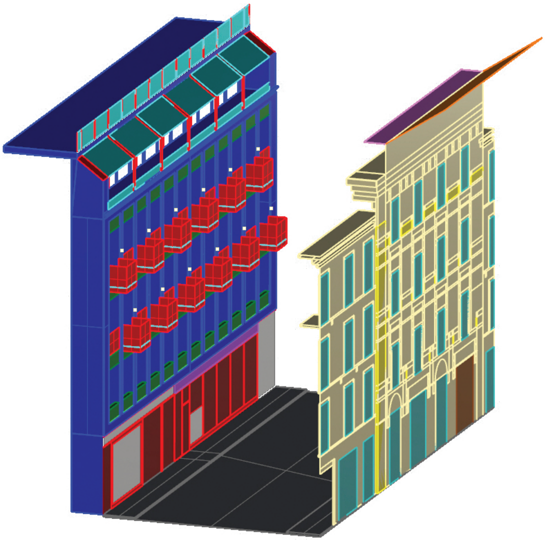


image 5.4_ digital model after geometrical reduction

The results obtained using the lighter model were considered accurate enough for the finalities of this thesis, and therefore the shortened model was employed in the simulations run in the subsequent phases.

FINAL ADJUSTMENTS

Some adjustments were pursued on this model to fix geometrical inaccuracies. In particular: balconies were enlarged to reduce the space between the column and their edges (16 cm in the previous model), as it was not considered adherent to the actual façade, and windows were added at the last level, were they were absent. Moreover, it was considered convenient to simplify the geometries to some extent in order to reduce the little pieces of geometry with specific material that would increase the time of the simulation without significantly increasing its accuracy.

At the end on the process, the model was restored: empty and duplicated layers were deleted, and the file was purged from the unnecessary contents.

Chapter 6

THE ACOUSTIC CONSEQUENCES OF GEOMETRICAL VARIATIONS APPLIED TO THE FAÇADE DESIGN

This research thesis project aims to explore the contribution of façade design in addressing the urban noise pollution and enhancing the acoustic comfort of the inhabitants.

The acoustical quality is considered critical to ensure the comfort of the dwellers and, in general, of the city inhabitants. The awareness of the negative effect caused by acoustical noise over human health and comfort is growing, and the mitigation of urban noise is an unavoidable in the framework of a sustainable urban design.

A building in the city of Turin is taken as case study to explore the effectiveness of a series of geometrical variations informing the façade design in mitigating the adverse acoustic effects of the street canyon. In particular the reference context is characterized by a high level of noise pollution during the night times due the presence of people chatting along the street, that compromise the acoustic comfort of the dwellers.

The building considered is a contemporary construction placed in the neighborhood of San Salvario, that was mainly erected along the 19th century. The urban morphology of via Saluzzo can be considered representative of the Turin cityscape as its geometric relationships can be encountered in many neighborhoods of the city, making the conclusions drawn by this research valid for a wider portion of urban fabric.

The design features that characterize the front of the reference building are considered representative of the most common design options for façade design. The case-study has an alternate balcony pattern from the second to the third floor. Moreover, the presence of the loggias, that run from one building side to the other, from the first to the fourth floor, offers the possibility to investigate the potential contribution of these semi-outdoor spaces in attenuating the street canyon effect.

These features make the reference building a good starting point to explore the effect of geometrical variation over the acoustic quality to better understand to what extent the design choices can be effective in mitigating urban noise pollution. From the assessment of these relationship the current work aims at defining a series of ground rules to orient the design of both ex-novo constructions and retrofit projects in similar urban context.

In the following, a series of geometrical variations are proposed on the basis of the available literature on the topic. The proposed options are referred to the balcony layout, the ceilings of the loggias and the inward inclination of the façade. The acoustic effect provided by each variation has been investigated using an acoustic simulation software, to if and to what extent the proposed geometries could prove beneficial in enhancing the acoustic comfort in the street canyon. By comparing the outcomes of the simulations, it was possible to define which are the most effective solutions to address chatting noise pollution in urban environment.

6.1 METHOD

The design variations identified have been suggested by the available scientific literature regarding the acoustic of street canyon. A series of papers and publications has been considered as reference from which a series of options are suggested and applied to the specific case-study, to identify an array of beneficial measures to dampen noise pollution over the building fronts and at the street level.

The following research aims to isolate the effect provided by the sole geometrical variations of the features of the façade. As mentioned, one of the most critical consequences of urban environment is produced by the high amount of sound reflections occurring over the street fronts.

In the urban cityscapes the sound emitted by sources as vehicles, public transportation, construction sites or other anthropogenic noise is reflected over the building fronts, increasing the reverberation time and sound pressure level. Most common building front are indeed made of reflective materials, as plaster, concrete and glass, causing the soundwaves to be reflected multiple over the facades. The described phenomenon is exacerbated as the height of the side building is great in comparison to the street width, with a consequent increase in the sound pressure level within the street, and a greatest threat to the well-being of the inhabitants.

As described in a previous chapter, the acoustic phenomena associated to street canyons can be addressed by promoting either the scattering or sound absorption. The first would promote the exit of soundwaves from the canyon, with reflecting them toward the sky; the second would cause part of the sound energy to be absorbed by the surfaces.

It was considered of interest to understand how the soundwaves emitted by the source placed in the street interact with the geometrical features of the building. The method aims to investigate the path followed by the soundwaves and determine which are the solutions able to better direct the soundwaves toward the sky or direct them away from the receiver positions.

The geometrical variation proposed were therefore analyzed by applying a reflective material on them and simulating the propagation of the soundwaves using an acoustic simulation software based on the image source method. From the results it has been possible to analyze how each design solutions would interfere with the propagation path of the soundwaves and identify both the most beneficial and less favorable solutions for each group of receivers.

The design area of the project is in Turin in via Saluzzo; the reference is at the number 29 of the street. The geometrical features of the street and façade are described in the following.

STREET DATA

The length of the street that was modeled in around 80 m; the width of the street (from façade to façade) is 11 m; the height of the buildings is between 14 and 18 meters. The street is a one-way vehicular road, that is normally subjected to a low level of traffic. On the contrary, the main noise source is generated by people talking on the street platforms, especially at night times.

BUILDING DATA

The case-study is a contemporary building inserted in more historical context, made of residential buildings built during the 19th century. The building has 5 floors above ground: the ground floor hosts commercial/office activities, while the upper levels are residential. The overall height of the building is 17.8 m while its width is 24.7 m.

The main architectural features of the actual façade are described in the following. The first floor is characterized by four loggias, occupying overall the whole width of the building; the following two levels feature an alternate pattern of balconies; the last floor has interconnected loggias, covered by the inclined roof, upon which there is a terrace.

Nonetheless the present research starts from the conclusion of the previous thesis project and assumes the configuration with all balconies as the base case from which further design options are developed.

As regard the dimensions, the balconies stick out 0.9 m, have a width of 1.56m while the parapets feature a height of 1.30 m; the loggias run over the façade length with a width of 0.95m.

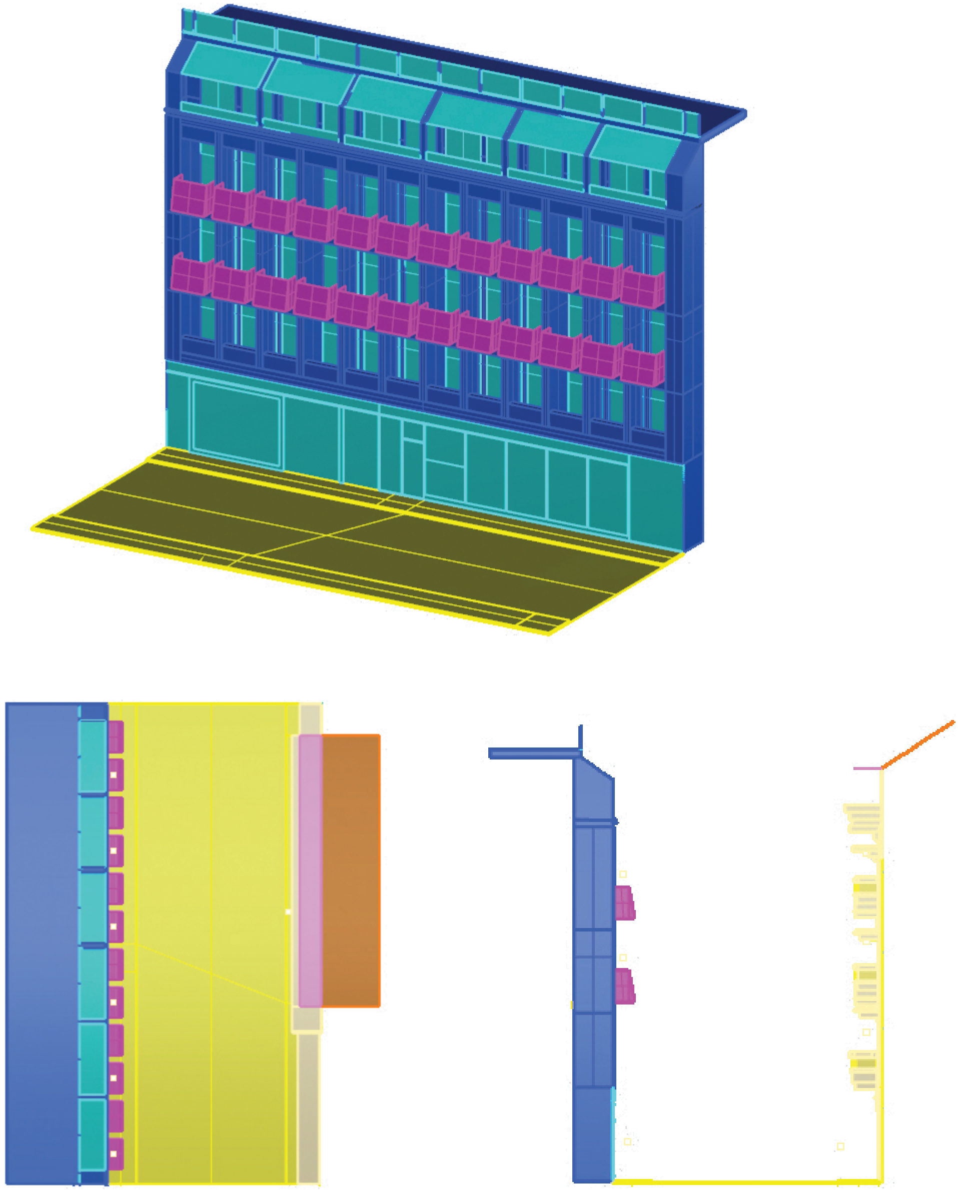


image 6.1_image of the digital model. In order: the first image show the digital model of the facade of the design building (the geomtries of the opposite building front are hidden); the second shows the top view of the entire model; the third illustrates the street section.

6.2 DESIGN VARIATIONS PROPOSED

On the basis to the available literature regarding the effect produced by façade features over the acoustics of street canyons, an array of design options is suggested, and their acoustic effects further explored.

Most published research paper regarding this topic aims at addressing the adverse effects produced by traffic noise. Moreover, the specific case of via Saluzzo differs from most of the urban morphology investigated in previous studies, featuring a high H/W ratio in comparison with other instances.

Given the frequency-dependent behavior of acoustic phenomena, the effectiveness of the measures identified by the precedent works may vary in the specific case of the case study. Nonetheless the publications considered still prove useful in suggesting a number of possible design options and measures able to positively alter the propagation of sound generated at the ground level.

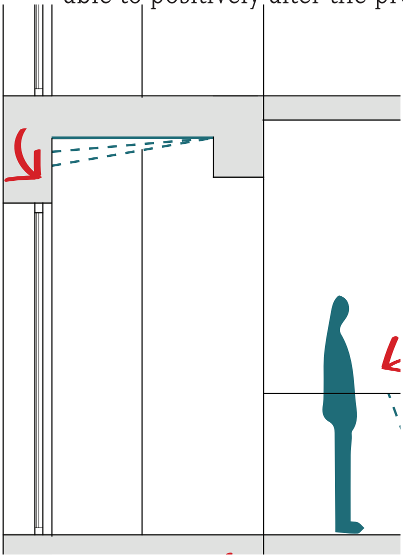


image 5.3_drawing with a simplified explanation of the geometrical changes pursued in respect to the ceilings of the loggias, the parapets, the inferior surfaces of the balconies. The variations informing the balconies were repeated with the 0.9m version of the balconies.

In particular, the research by Echevarria Sanchez et al. collects and explores the acoustical effect of a series of possible façade features by analyzing the variation of SPL over the facades and at the street level (Echevarria Sanchez, Van Renterghem, Thomas, & Botteldooren, 2016). Some of the variations considered by the study are reported in the previous chapter, along with their measured influence over the receivers considered. In the mentioned research, the sound source reproduces the sound generated by urban traffic: it is a line source running along the length of the street. Similarly, the geometrical features of the street section are different from those of the case study in Turin: the height of the floors is 2 level greater and the width of the street is two times that of via Saluzzo, that has an overall greater H/W ratio.

According to the study of Can et al. and Onaga et al. the street canyon effect is influenced by the H/W ratio, and consequently it is expected that the effectiveness of the various measured proposed may vary. Notwithstanding these differences, the work by Echevarria Sanchez et al. provides useful insights over the types of geometrical variations to be explored to enhance the acoustics comfort within the street canyon (Echevarria Sanchez et al., 2016).

A series of geometrical variations are suggested, in accordance to the specific constraints of the case study. These measures aim at enhancing the sound scattering generated by the façade and promote the redirections of the soundwaves away from the receivers and towards the sky.

The geometrical variations selected are applied to some features of the façade of the reference building, in accordance to the specific constraints of the reference building. Various balcony shapes and angles of inclinations of the ceilings of the loggias have been advanced and acoustically analyzed using an acoustical simulation software. Both loggias and balconies are commonly encountered in both contemporary and more older building facades, and it is therefore assumed that the measures and conclusions suggested by this research could provide useful insight for both ex-novo and retrofit projects in critical acoustical environment.

In the end, also the option of inclining the overall façade has been explored to understand the geometrical relationship between the angle of inclination and the corresponding reduction of the area of the facade that reflects soundwaves over the opposite building.

In the following, each design variation proposed is described along with the variation step considered in the simulations. Parametric models of both balconies and ceilings were created in order to control their geometry. A single model was set to generate all the balconies and loggias of the façade, whose geometry could be quickly altered by altering the values of the variables controlling their shape, as the depth or the angle of inclination. Further detail regarding the set of the parametric models can be retrieved in Appendix A.

LOGGIAS

As regard the ceiling of the loggias, an algorithm was set to incline the ceiling of the loggias outwards. The inclination angle of 5° and 10° were analyzed, corresponding to a lowering of the internal edge of the ceiling of either 11 or 22 cm. After applying the same variation to all the loggias of the building, also the effect of a random application of these variation to the ceiling of the loggias was investigate. It was supposed that a random distribution of the variation would enhance the scattering of the soundwaves, enhancing the spatial diffusion of the reflected soundwaves. On the contrary, when all the ceilings of the loggias are oriented with the same angulation, the incident soundwave would be reflected with the same angulation.

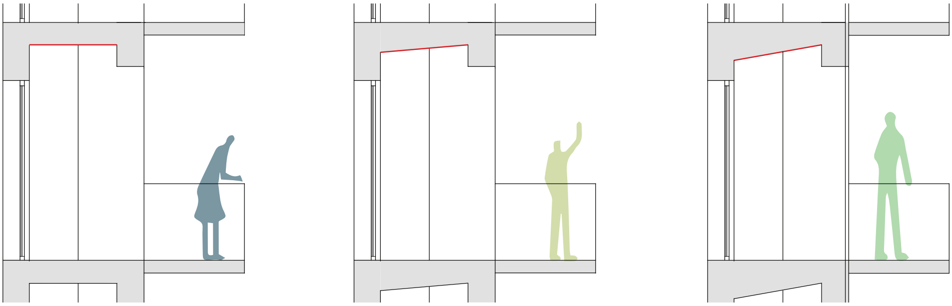


image 5.4_variations informing the ceilings of the loggias. From the right: horizontal configuration, 5° inclination, 10° inclination

BALCONIES

The base configuration of the balconies is the one selected by Manca as the most performing to reduce the SPL recorded by the receivers over the design façade. On the basis of the design variations suggested by Sanchez et al., an array of possible design variation was proposed.

In particular, they were applied to the parapets and the intradoses of the balconies; moreover, the lengthening of the ledge of the balconies was explored. The variations proposed, along with their identification codes are reported in the following.

The inward inclination of the parapets of the balconies increase the angle of the reflected soundwaves: this was expected to move the re-emitted sound upward, increasing the chance for it to exit the canyon without reflecting over the opposite façade. The effect of the inclination of the parapets was investigated by setting two possible variations, corresponding to angles of 10 (P1) and 20 degrees (P2). These variations were either applied to all the balconies, or randomly applied across them.

Similarly, the intradoses of the balconies were inclined, with two possible angulations corresponding to a lowering of the internal edge of either 23 (U1) or 46 cm (U2). Alike for the parapets, it was supposed that the outward inclination of these surfaces would enhance the diffusion of the reflected soundwaves.

Finally, the increment of the length of the balconies was analyzed to explore to what extent its screening function contributed to the acoustic level recorded

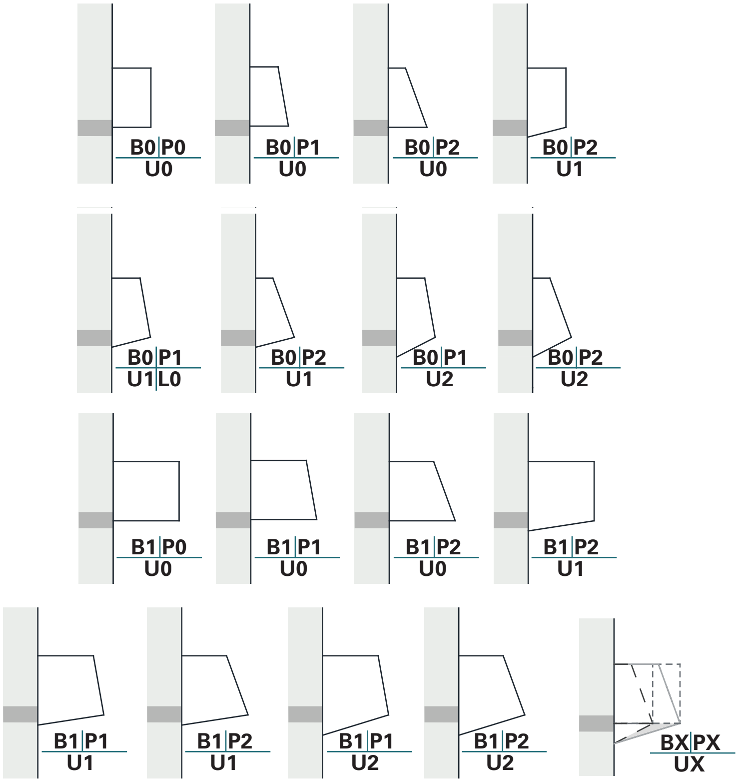


image 5.5_geometrical options for the balconies and identification codes

by the receivers. The cantilever, that was originally 0,9m (B0), was lengthened to 1.5 m (B1).

These possible variations were first applied homogenously to all the balconies of the façade. The first phase consisted of the investigation of the acoustic effect of each variation, that was analyzed singularly. Secondly, the effect of the combined effect provided by the parpet, intradoses and depth variations was investigated. To conclude, a randomized alternative (BX-PX-UX) was generated: here each balcony was randomly informed by the three variations advanced.

The balcony configurations analyzed are collected in the following image, along with their identification codes.

FAÇADE INCLINATION

In the end, the inclination of the overall façade was investigated to understand its acoustical consequences over the receivers located throughout the façade of the opposite building. The tilt of the front was expected to reduce the area of the façade reflecting the soundwaves reaching from the source towards the opposite building, increasing the rate of soundwaves redirected in the sky. The reflecting area would be further minImized for greater inclinations, causing a drop of the SPL measured by the microphones on the opposite façade.

A geometrical scheme has been drawn to understand which part of the façade reflects the soundwaves coming from the source towards the opposite building and how the reflecting area get reduced by the inclination of the façade. The method used to understand this relationship is the image source method, that enable to identify the surfaces that reflect the soundwaves in a given position on the basis of the geometrical law of specular reflections.

Two inclination angles (5° and 10°) were proposed and analyzed, to compare the resulting reflecting portion of the façade with the one of the regular vertical configuration.

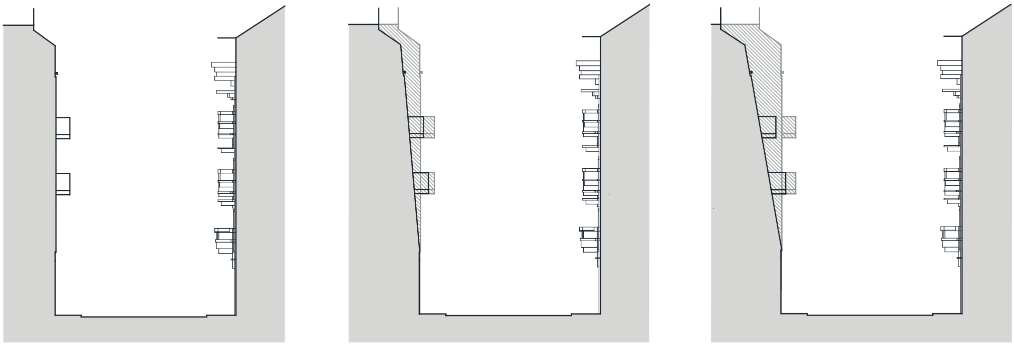


image 5.6_facade inclinations investigated with image source method

INVESTIGATION OF THE ACOUSTIC CONSEQUENCES OF VARIOUS FAÇADE FEATURES

The thesis of Manca determined that the optimal configuration of the façade among the ones considered was the one in which all the loggias at the second and third floor were converted into balconies (Manca, 2017). Starting from this founding, the all-balconies configuration was kept and considered the base-configuration against which compare the results obtained by further geometrical variations. Each design modification was therefore determined, applied to the façade and their acoustical effect analyzed using the acoustic simulation software.

In particular, the geometrical modifications mean to investigate the impact of the inclination of the ceiling of the loggias and the geometry of the balconies. The sound field of the street canyon was described using the SPL measured over the design façade, at the street level and over the façade of the rear building. The SPL is weighted by A curve to account for the relative loudness perceived by the human ear, and therefore expressed in dB(A).

SETTING OF THE AD-HOC MODEL

In order to isolate the acoustic effects of the sole geometrical changes, it is critical to eliminate any sort of effect provided by the specific material applied to the surfaces of the building. Therefore, an ad-hoc model was generated to properly investigate the influence of the geometrical variations of the features of the façade over the sound field. Consequently, reflective materials were applied to the surfaces of the front, to investigate how they interact with the propagation of the soundwaves.

The applied to the design façade were only glass and plaster: the first material was applied to the surfaces of the ground floor and to the glazed elements; plaster was applied to all the opaque surfaces, balconies and loggia ceilings included.

The material applied to the other building on the opposite side of the street and to the street paving were kept in accordance to the ones determined by Manca. In this way, it was possible to investigate the effect provided by each design modification, obtaining results not affected by the acoustical contribute of the specific materials applied to their surface.

		INCLINATION [°]	DEPTH [m]	LOWERING [cm]	INCLINATION [°]
	B0-P0-U0-L0	0	0,9	0	0
CEILING	L1	10	0,9	0	0
	L2	20	0,9	0	0
	L3	random	0,9	0	0
BALCONIES 0,9M	B0-P1-U0	0	0,9	0	10
	B0-P2-U0	0	0,9	0	20
	B0-P0-U1	0	0,9	23	0
	B0-P0-U2	0	0,9	46	0
	B0-P1-U1	0	0,9	23	10
	B0-P2-U1	0	0,9	23	20
	B0-P1-U2	0	0,9	46	10
	B0-P2-U2	0	0,9	46	20
BALCONIES 1,5M	B1-P0-U0	0	1,5	0	0
	B1-P1-U0	0	1,5	0	10
	B1-P2-U0	0	1,5	0	20
	B1-P0-U1	0	1,5	23	0
	B1-P0-U2	0	1,5	46	0
	B1-P1-U1	0	1,5	23	10
	B1-P2-U1	0	1,5	23	20
	B1-P1-U2	0	1,5	46	10
	B1-P2-U2	0	1,5	46	20
	BX-PX-UX	0	random	random	random

image 5.7_description of the geometical options analyzed in the set of simulations

		B0-P0-U0-L0	L1	L2	L3	B0-P1-U0	B0-P2-U0	B0-P0-U1	B0-P0-U2	B0-P1-U1	B0-P2-U1	B0-P1-U2	B0-P2-U2	B1-P0-U0	B1-P1-U0	B1-P2-U0	B1-P0-U1	B1-P0-U2	B1-P1-U1	B1-P2-U1	B1-P1-U2	B1-P2-U2	BX-PX-U)
		all balconies (B0) and regular ceilings (L0)	case zero + ceiling inclination 5°	case zero + ceiling inclination 10°	case zero + randomized ceiling inclination	L0 and 0,9m balconies + ledge inclination 10°	L0 and 0,9m balconies + ledge inclination 20°	L0 and 0,9m balconies + under-balcony edge -23cm	L0 and 0,9m balconies + under-balcony edge -46cm	L0 and 0,9m balconies + parapet 10° +under-balcony - 23cm	L0 and 0,9m balconies + parapet 20° +under-balcony - 23cm	L0 and 0,9m balconies + parapet 10° +under-balcony - 46cm	L0 and 0,9m balconies + parapet 20° +under-balcony - 46cm	L0 and 1,5m balconies	L0 and 1,5m balconies + ledge inclination 10°	L0 and 1,5m balconies + ledge inclination 20°	L0 and 1,5m balconies + under-balcony edge -23cm	L0 and 1,5m balconies + under-balcony edge -46cm	L0 and 1,5m balconies + parapet 10° +under-balcony - 23cm	L0 and 1,5m balconies + parapet 20° +under-balcony - 23cm	L0 and 1,5m balconies + parapet 10° +under-balcony - 46cm	L0 and 1,5m balconies + parapet 20° +under-balcony - 46cm	L0 an randomized balconies (all variables)
third floor	1	40,5	39,8	40,5	39,9	43,3	43,4	40,0	40,1	43,2	43,3	43,1	43,3	38,8	38,6	39,8	38,4	38,5	38,7	39,6	39,0	39,8	41,1
	2	42,0	41,5	42,3	41,5	42,0	42,8	41,2	40,7	41,9	42,6	41,5	42,6	39,8	39,7	40,4	39,6	39,7	39,2	40,6	39,9	40,2	41,3
	3	41,2	40,6	40,6	40,3	44,0	44,2	40,6	40,2	44,0	44,3	43,9	44,1	39,8	39,3	40,1	39,4	39,5	39,3	40,1	39,8	40,5	41,1
	4	44,3	43,7	44,5	44,3	44,5	45,4	43,5	43,9	44,7	45,5	44,7	45,5	39,6	39,6	42,8	39,5	40,4	40,0	43,0	39,9	43,4	44,1
	5	44,5	43,9	44,0	44,2	46,2	46,4	43,9	44,0	46,2	46,4	46,1	46,3	41,7	41,7	42,2	41,4	41,8	41,3	42,1	41,8	42,3	44,9
	6	45,3	44,5	45,4	45,3	45,4	45,5	44,7	44,9	45,1	45,9	44,7	45,6	42,7	42,3	44,4	42,6	42,5	42,2	44,7	42,8	44,9	44,9
	7	44,4	43,6	43,7	43,8	46,3	46,5	43,6	43,3	46,3	46,4	46,0	46,4	40,4	40,4	41,2	40,3	40,1	40,2	41,1	40,4	41,2	46,0
	8	45,1	44,4	44,9	45,0	44,7	45,5	44,1	43,9	44,7	45,4	44,5	45,3	41,1	40,7	43,3	40,6	41,2	41,2	43,6	40,6	43,4	44,5
	9	45,2	44,4	44,7	45,0	46,6	46,9	44,6	44,5	46,7	46,8	46,6	46,9	42,8	42,7	43,0	42,5	42,8	42,7	43,2	42,9	43,2	44,8
	10	44,9	44,2	44,9	44,1	44,6	44,9	44,2	44,1	44,3	44,9	44,2	44,5	40,8	42,5	43,4	40,7	41,4	42,6	43,4	43,0	43,6	44,1
	11	43,8	43,4	43,5	43,4	45,5	45,7	43,2	43,1	45,6	45,8	45,6	45,7	40,7	40,3	41,2	40,5	40,8	40,2	41,2	40,2	41,0	44,9
	12	42,6	42,0	42,5	41,5	41,9	42,9	40,5	40,3	41,6	42,6	41,8	42,5	39,0	38,5	39,9	38,5	38,9	38,0	40,1	38,7	39,8	41,5
second floor	13	44,0	43,5	43,9	43,8	44,0	44,2	45,8	44,1	46,0	46,1	44,2	44,6	43,5	43,7	44,4	45,0	45,3	45,3	45,6	45,9	46,1	45,2
	14	45,6	45,6	45,2	45,5	46,3	46,5	47,2	46,6	47,7	47,7	47,1	47,0	44,1	45,2	45,4	46,2	46,0	46,9	47,1	46,8	46,9	47,4
	15	44,8	44,5	44,5	44,6	45,0	45,5	46,7	45,1	47,0	47,1	45,2	45,7	44,9	45,0	45,5	46,6	46,6	46,9	47,2	46,9	47,1	46,9
	16	47,9	47,6	47,3	47,3	48,5	48,8	49,2	49,1	49,6	49,6	49,6	49,6	46,5	46,4	47,8	47,3	48,2	47,5	48,5	48,3	49,1	49,1
	17	47,3	47,2	47,0	47,0	47,9	48,3	48,8	47,6	49,1	49,4	47,5	47,9	47,9	47,8	48,2	48,7	48,7	48,8	49,2	49,0	49,2	48,7
	18	48,6	48,3	48,1	48,3	49,0	49,5	50,1	49,8	50,4	50,6	50,3	50,3	47,1	47,2	48,3	49,0	49,8	49,0	49,6	49,8	50,3	49,7
	19	48,2	47,7	47,6	47,9	48,0	48,3	49,4	47,4	49,7	49,9	47,7	48,2	47,5	47,7	48,6	48,8	49,2	49,1	49,7	49,7	50,2	48,5
	20	48,7	48,2	48,2	48,6	49,2	49,5	50,2	50,0	50,7	50,7	50,5	50,4	47,2	47,3	48,6	49,2	49,8	49,3	50,0	50,0	50,5	50,0
	21	48,5	48,0	48,2	48,3	48,3	48,7	49,2	47,9	49,6	49,6	48,2	48,5	48,4	48,5	48,9	49,0	49,2	49,4	49,9	49,5	50,0	49,2
	22	47,9	47,6	47,4	47,5	48,4	48,6	49,3	49,1	49,8	49,8	49,5	49,5	46,1	46,1	47,4	48,0	48,7	48,2	49,0	48,9	49,3	49,0
	23	46,1	45,7	45,9	46,2	46,5	46,7	47,8	46,2	48,1	48,3	47,0	47,0	46,0	46,4	47,1	47,4	47,4	47,6	48,2	47,8	48,3	47,3
	24	46,3	46,1	45,9	45,9	46,9	47,0	47,2	47,0	47,6	47,6	47,3	47,3	44,4	44,6	45,7	45,3	46,1	45,4	46,5	46,2	46,9	47,0
first floor	25	46,0	46,0	46,5	45,9	46,3	46,5	46,4	46,6	46,8	46,8	46,9	47,0	46,3	46,3	46,4	46,4	46,8	46,5	46,5	46,8	46,9	46,5
	26	48,2	48,5	48,9	48,4	48,3	48,3	49,0	49,0	49,1	49,0	49,1	49,0	48,9	48,8	48,8	49,2	49,5	49,2	49,2	49,6	49,6	49,0
	27	48,0	48,1	48,6	47,9	48,0	47,9	49,1	48,7	49,0	49,0	48,6	48,6	48,5	48,2	48,3	49,0	49,3	49,1	49,0	49,4	49,5	48,8
	28	50,9	51,0	51,3	50,9	50,8	50,8	51,4	51,4	51,4	51,4	51,4	51,3	51,6	51,6	51,6	51,7	51,7	51,5	51,5	51,5	51,6	51,4
	29	50,6	50,8	51,1	50,7	50,5	50,6	51,4	51,3	51,4	51,5	51,2	51,2	51,1	51,0	51,0	51,5	51,8	51,5	51,4	51,8	51,8	51,6
	30	51,3	51,4	51,7	51,2	51,3	51,2	51,9	51,9	51,9	52,0	51,9	51,8	52,1	51,9	52,0	52,0	52,4	51,9	52,0	52,5	52,4	52,0
	31	51,4	51,6	52,0	51,4	51,5	51,4	52,2	52,1	52,1	52,2	52,2	52,1	52,3	52,2	52,2	52,4	52,7	52,3	52,1	52,6	52,6	52,4
	32	51,4	51,6	51,8	51,4	51,3	51,4	52,1	52,0	52,0	52,0	52,0	52,0	52,2	52,1	52,1	52,2	52,6	52,2	52,1	52,6	52,6	52,1
	33	51,7	51,7	52,0	51,6	51,7	51,6	52,3	52,0	52,3	52,3	52,1	52,0	52,3	52,2	52,3	52,5	52,7	52,3	52,4	52,6	52,6	52,2
	34	50,1	50,2	50,4	50,3	50,1	50,0	50,9	50,7	51,0	51,0	50,8	50,7	50,5	50,5	50,4	50,9	51,3	50,9	50,8	51,3	51,3	50,9
	35	50,2	50,3	50,7	50,4	50,1	50,2	50,7	50,7	50,7	50,7	50,6	50,7	50,9	50,9	50,8	50,9	51,1	50,9	50,9	51,1	51,1	50,7
	36	48,9	49,1	49,6	49,2	49,0	49,0	49,4	49,4	49,5	49,5	49,6	49,6	49,6	49,3	49,3	49,8	49,9	49,6	49,6	49,8	50,0	49,4
street lelvel	37	46,5	46,6	46,5	46,5	46,5	46,5	46,6	47,2	46,6	46,5	47,2	47,2	46,6	46,6	46,6	46,6	46,8	46,5	46,5	47,0	46,9	46,6
	38	48,4	48,4	48,3	48,3	48,4	48,3	48,5	48,8	48,5	48,4	48,8	48,9	48,4	48,5	48,5	48,5	48,9	48,5	48,5	48,9	48,9	48,5
	39	50,8	50,8	50,8	50,8	50,8	50,8	50,9	51,4	50,8	50,8	51,4	51,4	50,9	50,9	50,9	50,9	51,2	50,8	50,9	51,3	51,3	50,9
	40	51,7	51,7	51,6	51,7	51,7	51,7	51,8	52,3	51,8	51,7	52,3	52,3	51,7	51,7	51,8	51,7	52,1	51,8	51,8	52,1	52,1	51,9
	41	51,3	51,3	51,2	51,3	51,2	51,3	51,4	51,6	51,4	51,4	51,6	51,6	51,3	51,3	51,4	51,4	51,8	51,3	51,3	51,8	51,8	51,4
	42	49,0	49,1	49,1	49,1	49,1	49,1	49,1	49,8	49,1	49,1	49,8	49,8	49,1	49,1	49,1	49,2	49,5	49,2	49,2	49,6	49,5	49,2
posite cade	43	45,4	45,4	45,5	45,2	44,5	44,0	45,6	45,4	44,6	44,4	44,6	43,9	45,4	44,3	43,7	45,3	45,2	44,6	43,8	44,3	44,0	44,1
	44	47,3	46,6	47,2	47,2	46,3	45,9	47,1	47,1	46,5	46,0	46,2	45,4	47,5	46,5	46,3	47,1	47,2	46,2	46,1	46,3	46,0	46,1
	45	48,0	48,3	48,2	48,2	48,1	48,0	48,4	48,3	48,0	48,0	48,1	48,2	48,3	48,0	47,9	48,3	48,5	48,1	48,3	48,0	48,1	48,1
	46	47,6	47,5	47,4	47,6	47,4	47,3	48,0	47,7	47,4	47,4	47,3	47,4	47,7	47,4	47,2	47,9	47,8	47,4	47,3	47,6	47,5	47,5

image 5.8_table collecting the SPL for each geometrical option investigated. The average SPL obtained by the three simulation repeated is shown for each of the 48 receivers

	L1	L2	L3	B0-P1-U0	B0-P2-U0	B0-P0-U1	B0-P0-U2	B0-P1-U1	B0-P2-U1	B0-P1-U2	B0-P2-U2	B1-P0-U0	B1-P1-U0	B1-P2-U0	B1-P0-U1	B1-P0-U2	B1-P1-U1	B1-P2-U1	B1-P1-U2	B1-P2-U2	BX-PX-UX
AVERAGE DIFFERENCES FLOORS 1, 2, 3	-0,3	0,0	-0,2	0,4	0,7	0,4	0,1	1,1	1,3	0,7	0,9	-1,1	-1,1	-0,4	-0,6	-0,3	-0,5	0,1	-0,2	0,4	0,6
difference floor 3	-0,6	-0,2	-0,4	0,9	1,4	-0,8	-0,9	0,9	1,3	0,8	1,2	-3,0	-3,1	-1,8	-3,3	-3,0	-3,2	-1,8	-2,9	-1,7	0,0
difference floor 2	-0,3	-0,4	-0,3	0,3	0,6	1,4	0,5	1,8	1,9	0,8	1,0	-0,9	-0,7	0,1	0,5	0,9	0,8	1,4	1,2	1,7	1,2
difference floor 1	0,1	0,5	0,1	0,0	0,0	0,7	0,6	0,7	0,7	0,7	0,6	0,6	0,5	0,6	0,8	1,1	0,8	0,7	1,1	1,1	0,7
	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
diff internal microphones fl 3	-0,6	0,1	-0,4	-0,2	0,5	-1,0	-1,0	-0,3	0,5	-0,5	0,3	-3,5	-3,5	-1,6	-3,8	-3,3	-3,5	-1,5	-3,2	-1,5	-0,6
diff internal microphones fl 2	-0,4	-0,3	-0,2	0,1	0,4	1,4	-0,1	1,8	1,9	0,1	0,5	-0,1	0,0	0,6	1,1	1,2	1,4	1,8	1,6	2,0	1,1
diff internal microphones fl 1	0,1	0,5	0,0	0,0	0,1	0,7	0,6	0,8	0,8	0,7	0,6	0,6	0,5	0,5	0,8	1,1	0,8	0,8	1,1	1,1	0,7
AVERAGE DIFF INTERNAL MICROPHONES	-0,3	0,1	-0,2	0,0	0,3	0,4	-0,2	0,7	1,1	0,1	0,5	-1,0	-1,0	-0,2	-0,6	-0,3	-0,4	0,4	-0,2	0,5	0,4
diff external microphones fl 3	-0,6	-0,4	-0,5	2,1	2,3	-0,6	-0,7	2,1	2,2	2,0	2,2	-2,6	-2,8	-2,0	-2,8	-2,7	-2,9	-2,0	-2,6	-1,9	0,5
diff external microphones fl 2	-0,3	-0,5	-0,3	0,5	0,8	1,4	1,1	1,8	1,8	1,5	1,5	-1,6	-1,4	-0,3	0,0	0,6	0,2	0,9	0,8	1,3	1,2
AVERAGE DIFF EXTERNAL MICROPHONES	-0,5	-0,4	-0,4	1,3	1,5	0,4	0,2	1,9	2,0	1,7	1,8	-2,1	-2,1	-1,2	-1,4	-1,0	-1,3	-0,5	-0,9	-0,3	0,9
	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
AVERAGE DIFFERENCES STREET LEVEL	0,0	0,0	0,0	0,0	0,0	0,1	0,6	0,1	0,0	0,5	0,6	0,0	0,1	0,1	0,1	0,4	0,1	0,1	0,5	0,4	0,1
	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
AVERAGE DIFFERENCE OPPOSITE FACADE	-0,1	0,1	0,0	-0,4	-0,6	0,2	0,0	-0,3	-0,4	-0,4	-0,6	0,1	-0,3	-0,5	0,2	0,1	-0,2	-0,3	-0,3	-0,5	-0,4
difference opposite facade, fl 3	-0,4	0,0	-0,2	-1,0	-1,5	0,0	-0,2	-0,8	-1,2	-1,0	-1,7	0,0	-1,0	-1,4	-0,2	-0,2	-1,0	-1,4	-1,1	-1,4	-1,3
difference opposite facade, fl 2	0,1	0,0	0,1	-0,1	-0,2	0,4	0,2	-0,1	-0,1	-0,1	0,0	0,2	-0,1	-0,2	0,2	0,3	-0,1	0,0	-0,1	-0,1	0,0
difference opposite facade, fl 1	0,2	0,3	0,1	0,1	0,0	0,2	-0,1	0,2	0,1	0,0	0,0	0,2	0,2	0,1	0,6	0,1	0,5	0,5	0,1	-0,1	0,1

image 5.9_table collecting the average SPL measured by each group of receivers for the geometrical options investigated.

	B0-P0-U0-L0	L1	L2	L3	B0-P1-U0	B0-P2-U0	B0-P0-U1	B0-P0-U2	B0-P1-U1	B0-P2-U1	B0-P1-U2	B0-P2-U2	B1-P0-U0	B1-P1-U0	B1-P2-U0	B1-P0-U1	B1-P0-U2	B1-P1-U1	B1-P2-U1	B1-P1-U2	B1-P2-U2	BX-PX-UX
AVERAGE SPL FLOORS 1, 2, 3	46,8	46,6	46,8	46,6	47,3	47,5	47,3	46,9	48,0	48,2	47,6	47,8	45,8	45,8	46,5	46,2	46,5	46,3	47,0	46,7	47,2	47,4
average p3	43,6	43,0	43,5	43,2	44,6	45,0	42,9	42,8	44,5	45,0	44,4	44,9	40,6	40,5	41,8	40,3	40,6	40,5	41,9	40,8	41,9	43,6
average p2	47,0	46,7	46,6	46,8	47,3	47,6	48,4	47,5	48,8	48,9	47,8	48,0	46,1	46,3	47,2	47,5	47,9	47,8	48,4	48,2	48,7	48,2
average p1	49,9	50,0	50,4	50,0	49,9	49,9	50,6	50,5	50,6	50,6	50,5	50,5	50,5	50,4	50,4	50,7	51,0	50,7	50,6	51,0	51,0	50,6
average internal microphones fl 3	44,0	43,4	44,1	43,6	43,8	44,5	43,0	43,0	43,7	44,5	43,6	44,3	40,5	40,5	42,4	40,2	40,7	40,5	42,5	40,8	42,5	43,4
average internal microphones fl 2	46,5	46,1	46,2	46,3	46,6	46,9	47,9	46,4	48,3	48,4	46,6	47,0	46,4	46,5	47,1	47,6	47,7	47,9	48,3	48,1	48,5	47,6
average internal microphones fl 1	49,6	49,8	50,1	49,7	49,7	49,7	50,4	50,2	50,4	50,4	50,3	50,3	50,2	50,1	50,2	50,4	50,7	50,4	50,4	50,7	50,8	50,4
AV. INTERNAL MICROPHONES	46,7	46,4	46,8	46,5	46,7	47,0	47,1	46,5	47,5	47,8	46,8	47,2	45,7	45,7	46,6	46,1	46,4	46,3	47,1	46,6	47,3	47,1
average external microphones fl 3	43,3	42,6	42,9	42,8	45,3	45,5	42,7	42,5	45,3	45,5	45,2	45,4	40,7	40,5	41,3	40,4	40,6	40,4	41,2	40,7	41,3	43,8
average external microphones fl 3	47,5	47,2	47,0	47,2	48,0	48,3	48,9	48,6	49,3	49,3	49,0	49,0	45,9	46,2	47,2	47,5	48,1	47,7	48,5	48,3	48,8	48,7
AV. DIFF EXTERNAL MICROPHONES	45,4	44,9	44,9	45,0	46,7	46,9	45,8	45,6	47,3	47,4	47,1	47,2	43,3	43,3	44,2	44,0	44,3	44,1	44,8	44,5	45,1	46,2
AVERAGE STREET LEVEL	49,6	49,6	49,6	49,6	49,6	49,6	49,7	50,2	49,7	49,6	50,2	50,2	49,7	49,7	49,7	49,7	50,1	49,7	49,7	50,1	50,1	49,8
							0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
AVERAGE OPPOSITE FACADE	47,2	47,1	47,2	47,2	46,8	46,6	47,3	47,1	46,9	46,8	46,8	46,6	47,3	46,9	46,7	47,4	47,3	47,0	46,8	46,8	46,6	46,8
average opposite facade, fl 3	46,4	46,0	46,3	46,2	45,4	44,9	46,4	46,2	45,6	45,2	45,4	44,7	46,4	45,4	45,0	46,2	46,2	45,4	45,0	45,3	45,0	45,1
average opposite facade, fl 2	47,8	47,9	47,8	47,9	47,7	47,7	48,2	48,0	47,7	47,7	47,7	47,8	48,0	47,7	47,6	48,1	48,1	47,8	47,8	47,8	47,8	47,8

image 5.10_table collecting the SPL variations generated by the geometrical option investigated for the receivers grouped in accordance to their position.

The effect of each design modification was analyzed using 48 receivers, grouped according to their positions. Receivers were divided into three groups: those placed on the design façade, those in the street and those on the opposite building. The receivers over the balconies and within the loggias are localized according to the instructions provided by the ISO 1996-2:2007 regulating the assessment of environmental noise. The internal microphones are 0.6m away from the front surface, while those external are 2m far. For each receiver, the sound pressure level in dB(A) was measured. The results obtained by each design modification were compared to the case-zero, represented by the balcony-only configuration defined by Manca, to define which were the most and less favorable solutions.

6.3 THE SIMULATION

GENERAL SETTINGS OF THE ALGORITHM

An algorithm was set to retrieve the SPL of each receiver expressed in dB(A) for each design modification. Each simulation was repeated three times to ensure the truthfulness of the results and average out possible incoherent outcomes.

The case-zero, represented by the balcony-only configuration is B0-P0-U0, the regular ceilings of the loggias is L0. 21 possible design variations were investigated and their acoustical results were compared to that of the reference case: 3 variations were applied to the ceiling of the loggias (L1, L2, L3) and 18 to the balconies. Those variations pertaining to the balcony geometry were grouped according to the dimensions of the balconies to explore how various ledge lengths influence the effect of similar intrados and parapet inclinations.

The table 5.7 summarizes all the variations investigated, labeling each variation with the corresponding code and describing the geometrical features of each option.

The receivers were grouped in accordance to their position, to understand how the acoustic of the design façade, of the opposite façade and the street was affected by the single design modification pursued. To further distinguish among results, the recorded values were grouped and averaged in accordance to the pertaining level of the receivers. Similarly, receivers were sorted according to their distance from the façade, separating those analyzing the SPL on the balconies from the ones analyzing the SPL within the loggias.

The results were then compared to the one of the reference case to obtain the relative average decrease or increase of SPL observed for each group of receivers.

6.4 DISCUSSION OF THE RESULTS

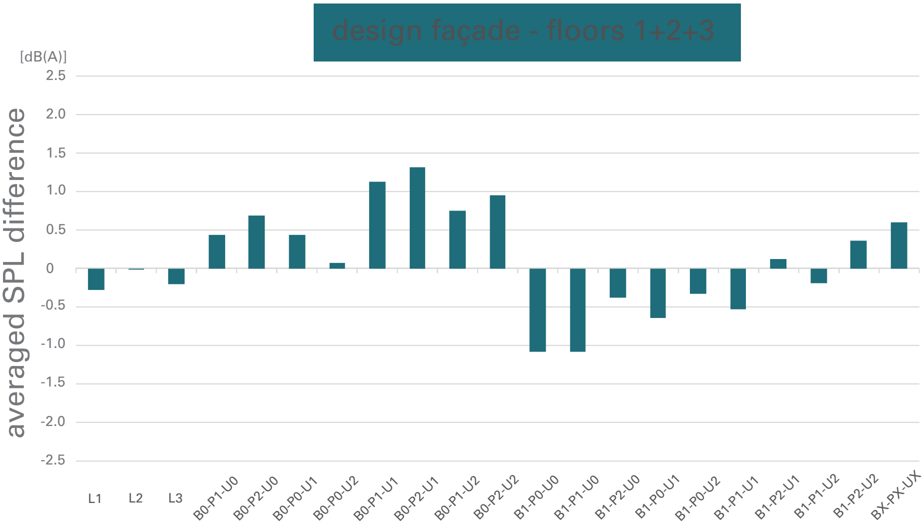
The results of the simulations are shown in the following tables. The table 5.5 gathers the averaged value SPL for all the 48 receivers, for each design modification. Table 5.6 shows the average values for receivers grouped in accordance to their position (design façade, street level, opposite building). As regard those localizes in the facades, they are further divided in accordance to their pertaining level. Those of the design façade are classified in accordance to their distance from the surface of the façade: the internal ones are the ones placed within the loggias, the external are localized on the balconies.

Table 5.7 compares the values considered in the Table 2 with the corresponding ones of the reference case (B0-P0-U0-L0). In particular, negative values represents a decrease in SPL measured for the proposed design variations, while positive values states greater value of SPL compared to the reference configuration.

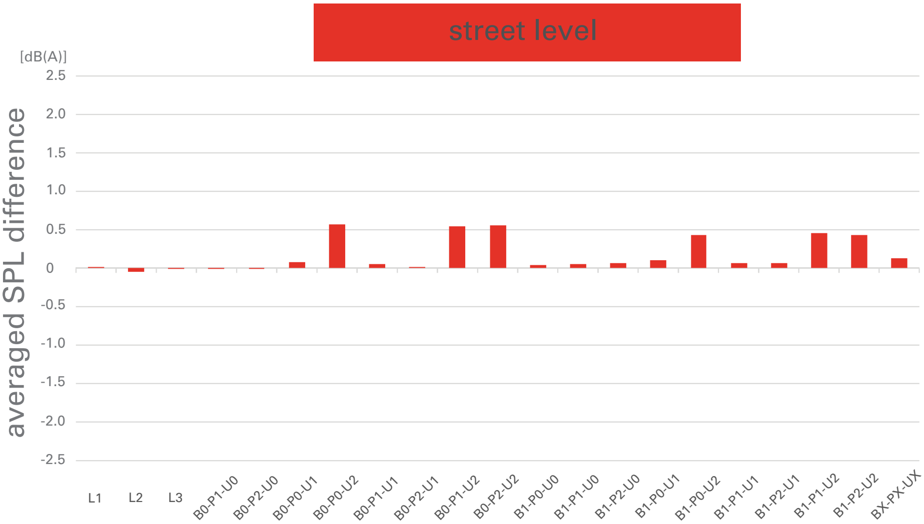
GENERAL RESULTS FOR EACH GROUP OF RECEIVERS

In the following graphs the sound pressure level difference obtained for each design option is plotted. The difference obtained for each design modification: Graph 1 shows the average SPL variation in respect to the receivers of the design façade; Graph 2 in respect to the street level; Graph 3 is referred to the microphones localized on the opposite front.

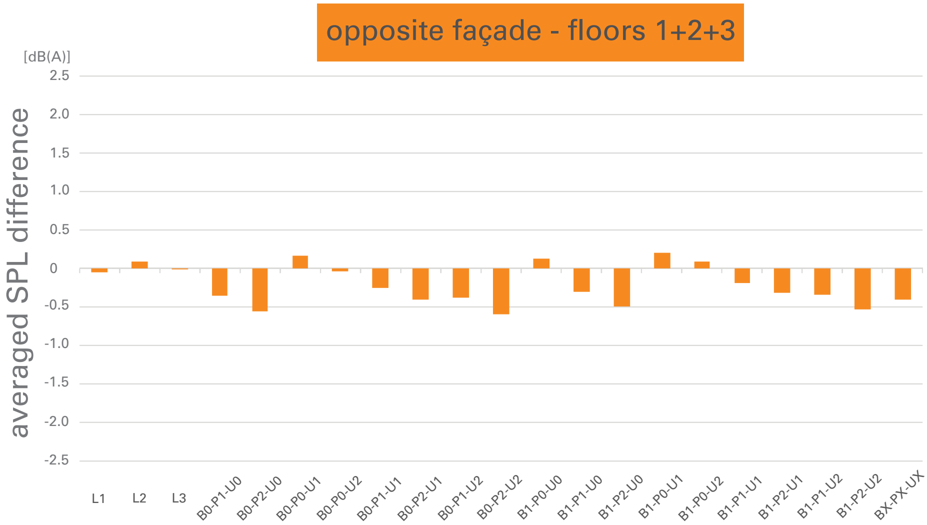
In general SPL variations are considered relevant it their absolute value is



		L1	L2	L3	B0-P1-U0	B0-P2-U0	B0-P0-U1	B0-P0-U2	B0-P1-U1	B0-P2-U1	B0-P1-U2	B0-P2-U2	B1-P0-U0	B1-P1-U0	B1-P2-U0	B1-P0-U1	B1-P0-U2	B1-P1-U1	B1-P2-U1	B1-P1-U2	B1-P2-U2	BX-PX-UX
LOGGIAS	ceilinig inclination	10	20	random	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BALCONIES	total depth	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	random
	inferior edge inclination	0	0	0	0	0	23	46	23	23	46	46	0	0	0	23	46	23	23	46	46	random
	ledge inclination	0	0	0	10	20	0	0	10	20	10	20	0	10	20	0	0	10	20	10	20	random



		L1	L2	L3	B0-P1-U0	B0-P2-U0	B0-P0-U1	B0-P0-U2	B0-P1-U1	B0-P2-U1	B0-P1-U2	B0-P2-U2	B1-P0-U0	B1-P1-U0	B1-P2-U0	B1-P0-U1	B1-P0-U2	B1-P1-U1	B1-P2-U1	B1-P1-U2	B1-P2-U2	BX-PX-UX
LOGGIAS	ceilinig inclination	10	20	random	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BALCONIES	total depth	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	random
	inferior edge inclination	0	0	0	0	0	23	46	23	23	46	46	0	0	0	23	46	23	23	46	46	random
	ledge inclination	0	0	0	10	20	0	0	10	20	10	20	0	10	20	0	0	10	20	10	20	random



		L1	L2	L3	B0-P1-U0	B0-P2-U0	B0-P0-U1	B0-P0-U2	B0-P1-U1	B0-P2-U1	B0-P1-U2	B0-P2-U2	B1-P0-U0	B1-P1-U0	B1-P2-U0	B1-P0-U1	B1-P0-U2	B1-P1-U1	B1-P2-U1	B1-P1-U2	B1-P2-U2	BX-PX-UX
LOGGIAS	ceilinig inclination	10	20	random	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BALCO NIES	total depth	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	random
	inferior edge inclination	0	0	0	0	0	23	46	23	23	46	46	0	0	0	23	46	23	23	46	46	random
	ledge inclination	0	0	0	10	20	0	0	10	20	10	20	0	10	20	0	0	10	20	10	20	random

greater than 1 dB. The values shown in the graph plotting the averaged SPL measurements from all the receivers of the design facade are in most cases smaller than 1. Only four values are significant, namely those of B0-P1-U1, B0-P2-U0, B1-P0-U0, B1-P1-U0: the firsts report an increase in SPL level, while the latter its reduction in respect of the reference case.

All data, although not significant in term of sound perception, can be analyzed to understand the general trends of SPL variations considering the overall number of receivers located in the facade. The inclination of the loggias seems to provide little beneficial effect, and in particular the angle of 5° seems more favorable than that of 10°. As regard the balconies, the SPL variation is greatly influenced by their depth: all the design variations proposed for 0,9m balconies results in an overall increase of SPL across the façade; on the contrary most options with 1,5 m depth result in a decrease. In general, the inclination of the ledge is associated to greater SPL values, due to the reduction of the screening effect of the parapet in respect to the soundwaves coming from the sound source. This trend is more evident in the 0.9m balconies, while it is visible only for the 20° inclination in case of the deeper balconies. In general, the combinations of the various ledge inclinations and under-balcony edge lowering seem to result in an increase in SPL over the façade, as a result of the sum of the contribution of the two measures. Finally, the randomized configuration, combining a random value for all the geometrical variations applied to the balconies, result in an increase in SPL greater than 0,5 dB.

The averaged SPL variations assessed for the various design options in the street are all smaller than 1dB, reporting the little influence of both loggias and balconies geometry over the sound pressure level at the ground. In most cases, a slight increase of SPL is reported, that seems highly correlated to the under-balcony edge lowering of 46 cm.

Finally, slight decreases of SPL are reported for most design options informing the geometries of the balconies on the front of the opposite building. These results let suggest that the balcony shapes do contribute in promoting the redirection of soundwaves toward the sky, but the forecast values, none of which overcome go beyond 1 dB, report the little effectiveness of the sole geometrical variations in enhancing the acoustic comfort on the opposite façade.

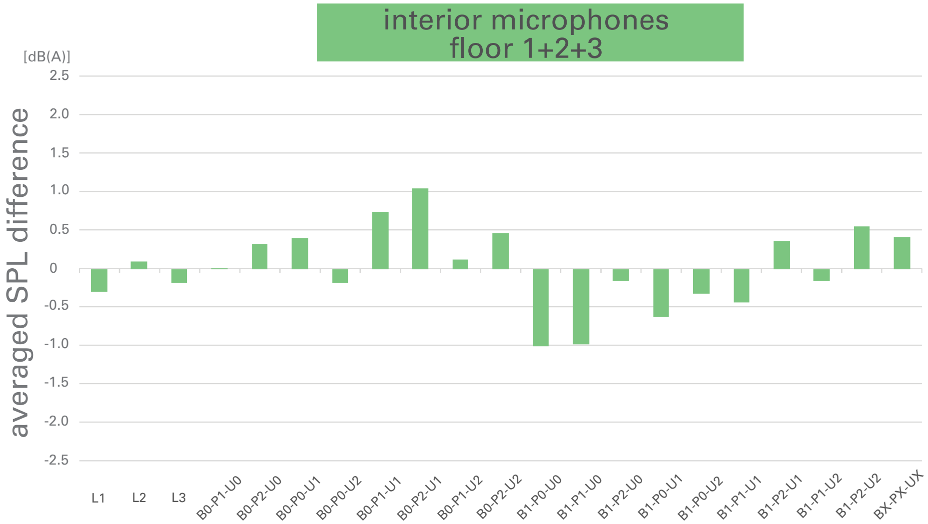
DESIGN FAÇADE RESULTS

In the following, the SPL measured by the sole receivers located in the design façade will be analyzed for each design variation. The microphones are grouped in interior and exterior microphones in accordance t their distance from the façade, the first group plot the SPL within the loggias, the latter that on the balconies. The loggias are present from the first to the third floor of the building, while the balconies are located in the second and third floors only.

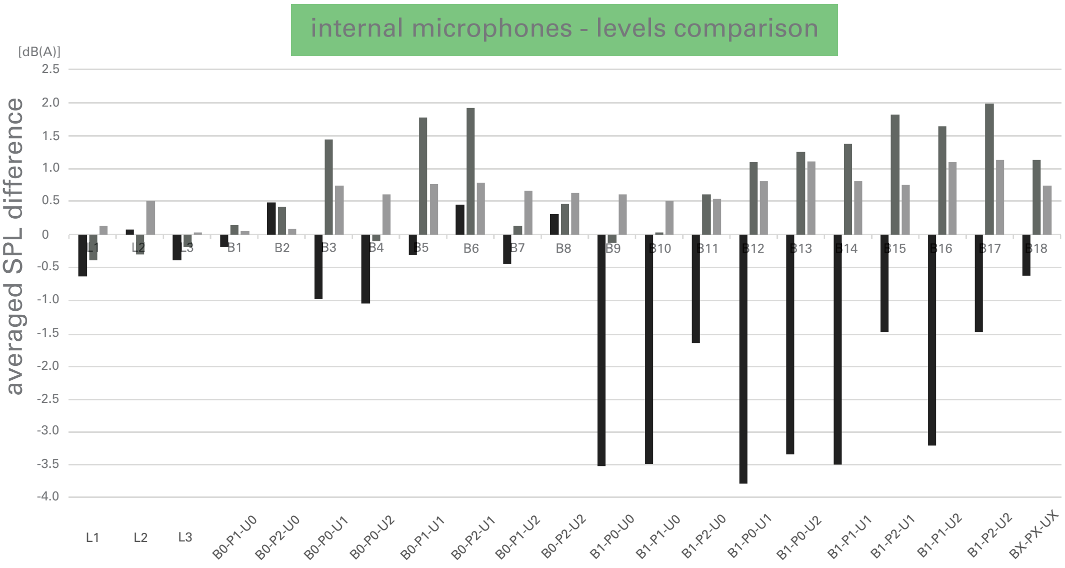
The analysis of the estimated sound pressure level differences over the design façade is divided in two parts, one examining the results for the exterior microphones and one for the interior ones.

INTERIOR MICROPHONES

The average of the interior microphones of the design façade is shown in the graph for each geometrical option proposed. Only three options provide a



		L1	L2	L3	B0-P1-U0	B0-P2-U0	B0-P0-U1	B0-P0-U2	B0-P1-U1	B0-P2-U1	B0-P1-U2	B0-P2-U2	B1-P0-U0	B1-P1-U0	B1-P2-U0	B1-P0-U1	B1-P0-U2	B1-P1-U1	B1-P2-U1	B1-P1-U2	B1-P2-U2	BX-PX-UX
LOGGIAS	ceilinig inclination	10	20	random	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BALCONIES	total depth	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	random
	inferior edge inclination	0	0	0	0	0	23	46	23	23	46	46	0	0	0	23	46	23	23	46	46	random
	ledge inclination	0	0	0	10	20	0	0	10	20	10	20	0	10	20	0	0	10	20	10	20	random



significant variation of SPL, namely B0-P2-U1, B1-P0-U0, B1-P1-U0. B0-P1-U2 correspond to an increase of 1 dB, while the other two variations generate a SPL reduction of 1dB. In case of 0,9m balconies, the combined effect of ledge inclination and lowering of the under-balcony of 23 cm results a peak of SPL. Similarly, also the deeper balconies report a drop in performance due to the combined effect of the two variations.

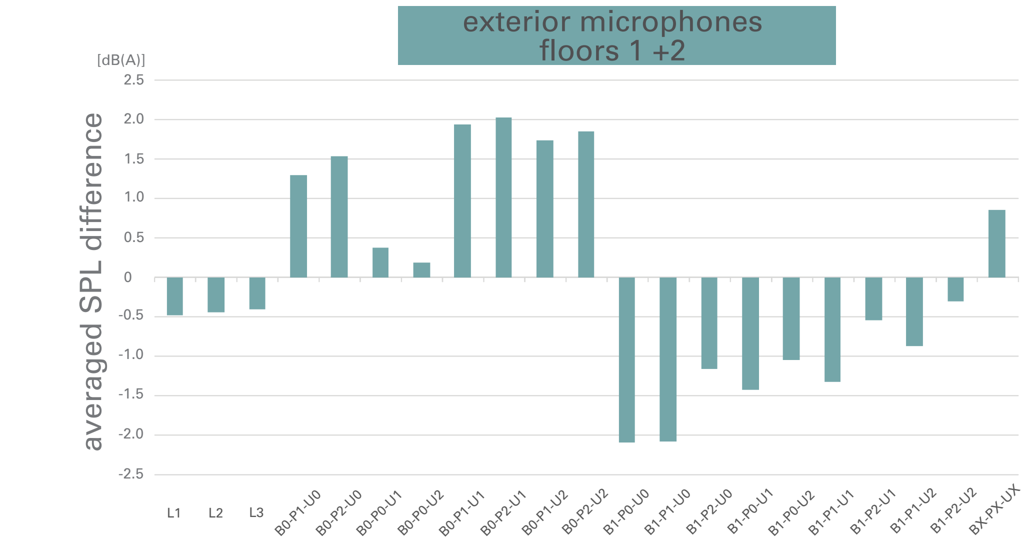
The graph above describes the variation of SPL measured by the interior microphones grouped by floor. The first floor seems to be little influenced by the design variations proposed, reporting little increment of SPL for most solutions. The upper floors, and particularly the third, report the greatest variations. These values seem to be highly influenced by the lowering of the under-balcony surface. The second floor reports a significant increase of SPL especially for 0,9 balconies with -23cm under-balcony lowering and for those 1,5m balconies, featuring both variations steps of the same feature. The third floor on the contrary report remarkable reduction of SPL for all 1,5 m balconies configuration, that is reduced for -23cm under-balcony lowering.

Smaller but still significant reductions are measured for B0-P0-U1 and B0-P0-U2 configurations, featuring the same lowering.

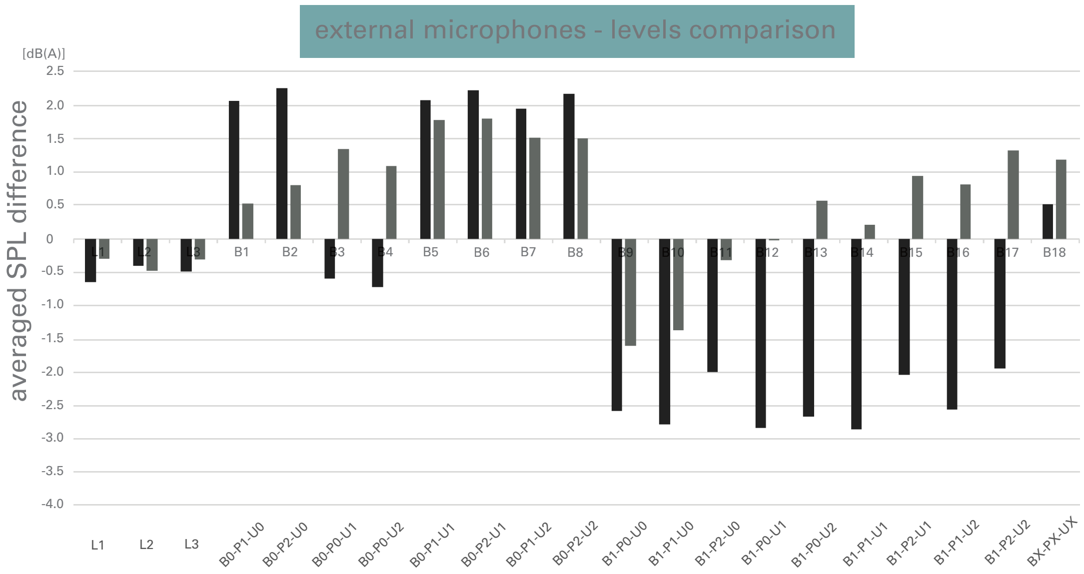
EXTERIOR MICROPHONES

The graph of the exterior microphones plots a number of significant SPL variations. In general, the design options when applied to the 0,9m balconies result in an increase in SPL; while the opposite is true for the 1,5m balconies that report a significant reduction of SPL for most configurations. The reduction of the screening effect of the parapet is clearly visible in the 0,9 balconies, where all significant increases of SPL are reported for the configurations featuring inclined ledges. The 1,5m balconies report a lowering of the performances for the design modifications. The randomized configuration, namely B18, generate an increase in SPL, with a value comprised between the combined configurations of 0,9 and 1,5m depth balconies.

The graph above compares the variation of SPL measured by the external



		L1	L2	L3	B0-P1-U0	B0-P2-U0	B0-P0-U1	B0-P0-U2	B0-P1-U1	B0-P2-U1	B0-P1-U2	B0-P2-U2	B1-P0-U0	B1-P1-U0	B1-P2-U0	B1-P0-U1	B1-P0-U2	B1-P1-U1	B1-P2-U1	B1-P1-U2	B1-P2-U2	BX-PX-UX
LOGGIAS	ceilinig inclination	10	20	random	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BALCO NIES	total depth	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	random
	inferior edge inclination	0	0	0	0	0	23	46	23	23	46	46	0	0	0	23	46	23	23	46	46	random
	ledge inclination	0	0	0	10	20	0	0	10	20	10	20	0	10	20	0	0	10	20	10	20	random

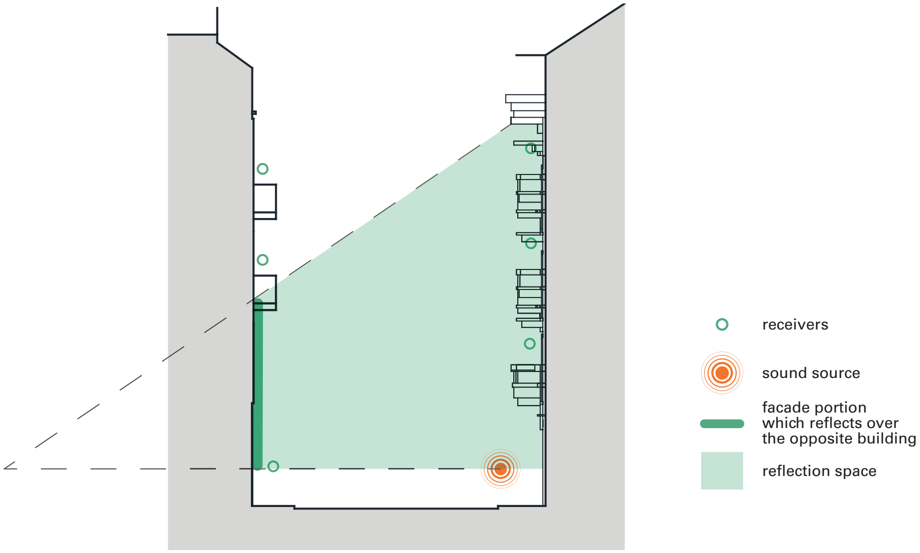


receivers of the second and third floor. Alike to the case of the interior microphones, deeper balconies promote SPL reduction, especially for the third floor. The increase of SPL reported for design variations applied to 0,9m balconies is liked to the inclination of the ledge, and this trend it more remarkable for the receivers placed in the third floor than for those pertaining to the second.

THE EFFECT OF THE INCLINATION OF THE BUILDING FRONT

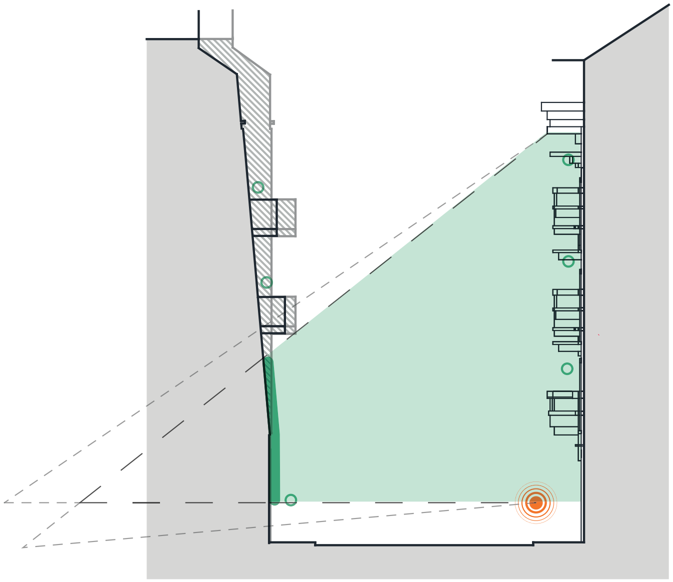
The following images show the schemes developed with the image source method to investigate the effects of different inclination angle over the reflecting area of the design façade. With this method it is possible to conduct a simplified inquiry based on the rules of the specular reflections to identify the surfaces that reflect the soundwaves in a position of interest. In the specific case it is investigated which portion fo the façade reflect sound over the opposite building, and the extent to which this area is reduced for increased inclination angle of the front.

The following image show the section of the street in which the height of the reflecting surface of the façade is highlighted in green. The first image is the regular configuration featuring no inclination; the following two images represent two possible inclination angles, namely 5 and 10° and the correspondent reduction of reflecting area in respect to the basic configuration. It is assumed that smaller reflective area would be beneficial, since would increase the rate of soundwaves exiting the canyon by being reflected toward the sky, with a consequent reduction of the SPL measured on the opposite façade. The inclination of 5° is able to reduce the reflective area of 19,4° while with a tilt of 10° the area is reduced by 37,6%.



facade inclination: 0°

image 5.10_results of the geometrical inquiry of the vertical configuration of the facade, to define the portion of the design facade redirecting soundwaves arriving from the sound source towards the opposite building



facade inclination: 5°
-19,4% reflecting area

image 5.11_results of the geometrical inquiry of the 5° inclined configuration of the facade, to define the portion of the design facade redirecting soundwaves arriving from the sound source towards the opposite building. The percentage describes to what extent this area is reduced by inclining the building front in comparison to the vertical condition.

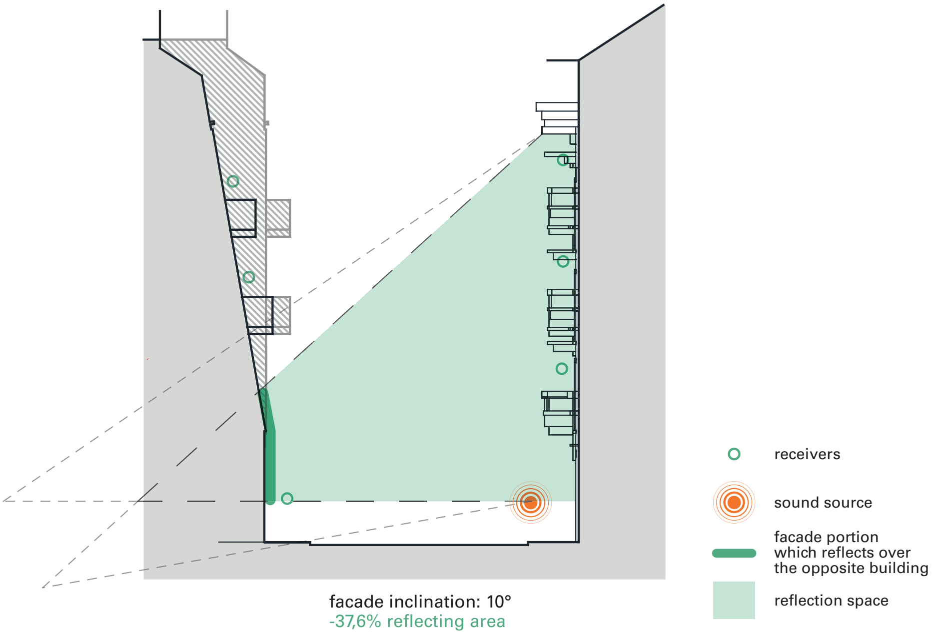


image 5.12_results of the geometrical inquiry of the 10° inclined configuration of the facade, to define the portion of the design facade redirecting soundwaves arriving from the sound source towards the opposite building. The percentage describes to what extent this area is reduced by inclining the building front in comparison to the vertical condition.

Chapter 7

THE ACOUSTIC EFFECT OF DIFFERENT GEOMETRIES AND ACOUSTICAL PROPERTIES OF AN URBAN FACADE

The following phase features the introduction of material variations to the façade. In the previous phase, the acoustic effect of the geometrical variations advanced were analyzed by considering sole effect provided by geometries: reflective materials were therefore applied to them, to avoid results being affected by the effect of acoustical phenomena other than specular reflections.

The objective is to explore the acoustical effect provided the geometrical variations in combination with various materials applied to the surfaces of the facade. The two variations are considered in parallel as it is assumed that the effectiveness of the application of a given material may vary in relation of the geometrical features of the surfaces to which it is applied and vice-versa.

The main objective of this phase is the definition of the acoustical properties and geometrical features that are more beneficial for the acoustic quality of the street canyon. In this case, therefore, the variations explored represents the opposite conditions of both the geometrical features previously considered and acoustic properties of the materials. Consequently, the conclusions drawn from the analysis of the results can be generalized to provide insights over the design of building façades set in critical acoustical scenarios.

The geometrical options considered are those presented by the reference case and those representing the boundary conditions of the variations advanced in the previous phase. It was expected that for the possible geometrical variations comprised between the limits, the resulting acoustic effects would be comprised between those of the two limit conditions. As regard the variations of materials, three surfaces of the facade were selected: the balcony ledges, the inferior side of the balconies and the surfaces of the loggias. These surfaces are affected by the geometrical variations proposed, and therefore it is assumed that the effect of the application of these materials may vary in accordance to the geometrical variation considered.

The main objective of these phase is to investigate to what extent the SPL was affected by the application of either absorptive, reflective and diffusing materials to the geometrical variations. Consequently, for each group of surfaces, four materials with opposite acoustical properties were selected. In particular, the chosen materials were either high frequency absorbers, low frequency absorbers, reflective or scattering surfaces.

Finally, an algorithm was set to iteratively analyze all the possible combinations of materials for each geometrical option. The averaged SPL value are recorded for each combination of geometries and materials for the design façade, that of the building across the street, and the ground level. It was therefore possible to compare the results and understand which the most effective combinations of geometrical and material features are in order to mitigate the adverse effects of urban noise.

7.1 METHOD

The overall number of material and geometrical combinations considered is 1152. The geometrical options considered are 18, resulting for 9 balcony designs and 2 inclinations of the ceilings of the loggias. For each geometrical option, 64 possible material combinations were investigated.

The surfaces considered for the geometrical variations are the three ledges (front and sides) of the balconies, the balcony surface downward oriented, the surfaces surrounding the loggias, ceilings included.

A database of acoustic material suitable for outdoor and semi-outdoor environment was gathered, along with their relative acoustic properties.

From these options, for each group of surfaces, 4 materials were selected, featuring opposite acoustic properties. In the end, 64 material combination are explored for each geometrical variation.

The acoustic assessment of the 1152 possible options is empowered by Grasshopper and Galapagos in combination with Pachyderm. Similar to the case of the previous step of the research, an algorithm is set to explore all the possible combinations of materials for each geometrical variation: for each material combination the average SPL observed over the reference façade, the street level and the façade of the building across the street is recorded. Final conclusions are drawn to define to what extent the various combination proposed are able to enhance the acoustical quality observed in the three locations.

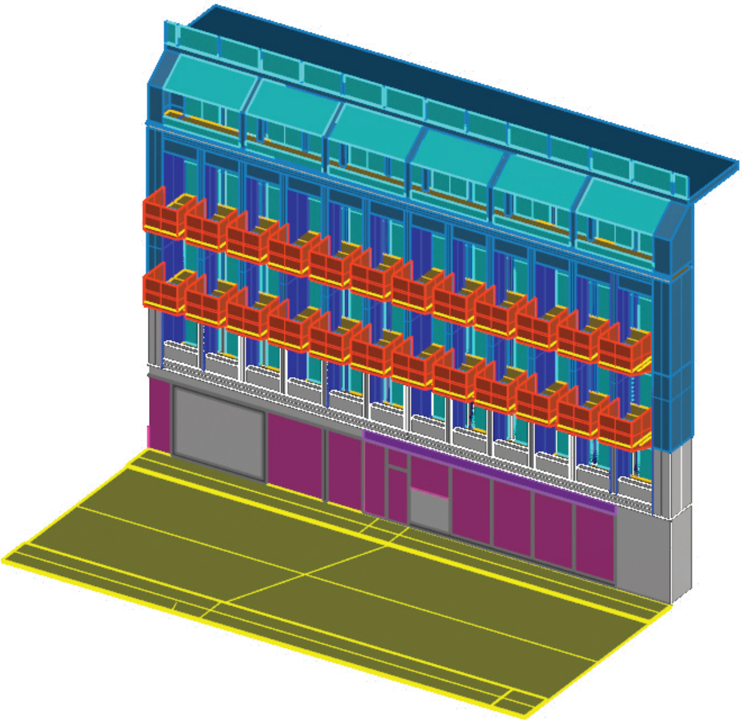


image 7.1_image of the digital model of the building facade (the geomtries of the opposite building front are hidden)

7.2 THE MATERIALS

For each group of surfaces, four materials with opposite acoustical properties were selected. The materials considered for each element are shown in the tables below, along with their acoustic coefficients.

The absorption and scattering coefficients reported in the table were combined as follows. The absorptive properties of sound absorbers were defined on the basis on the data provided by product specifications; differently, the scattering coefficients applied to them were those of a standard low-scattering configuration identified as reference.

As regard sound reflective materials, both specular-reflective and scattering surfaces are made up by combining material with low absorption coefficients (i.e. reflective) and either low scattering coefficients, in case of reflective surfaces, or high scattering coefficients, in case of the diffusing surfaces.

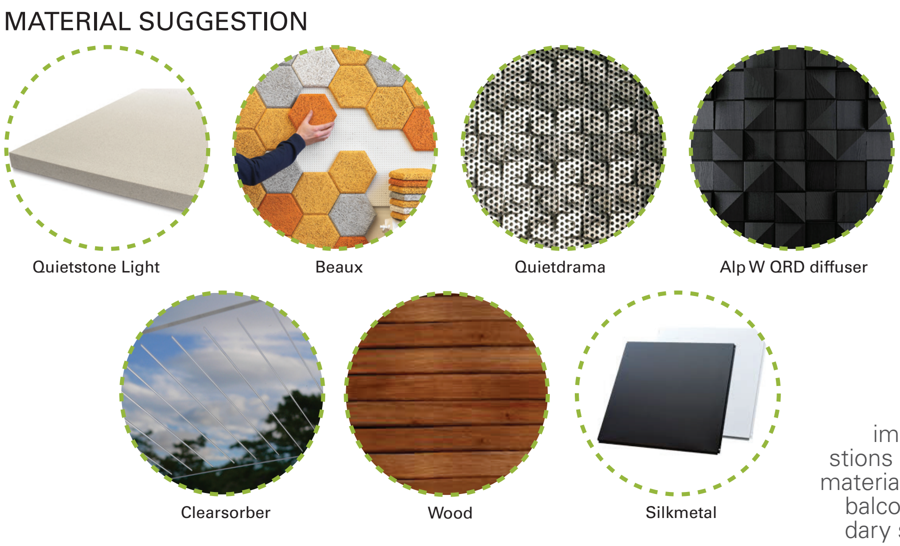


image 7.2_suggestions of some of the material applied to the balconies and boundary surfaces of the loggias.

		NAME	COEFFICIENTS	absorbtion coefficients								
				62,5	125	250	500	1000	2000	4000	8000	AVERAGE
loggia surfaces	ABS, LOW FREQ	**Silkmetal**	**absorption coefficients**	0,92	0,92	0,92	0,89	0,72	0,77	0,77	0,74	**0,83**
			scattering coefficients	0,01	0,01	0,01	0,02	0,03	0,05	0,08	0,12	**0,04**
	ABS, HIGH FREQ	**Beaux**	**absorption coefficients**	0,1	0,1	0,1	0,15	0,25	0,5	0,9	0,6	**0,34**
			scattering coefficients	0,01	0,01	0,01	0,02	0,03	0,05	0,08	0,12	**0,04**
	REFLECTIVE	**wood**	**absorption coefficients**	0,01	0,01	0,01	0,05	0,05	0,04	0,04	0,04	**0,03**
			scattering coefficients	0,01	0,01	0,01	0,02	0,03	0,05	0,08	0,12	**0,04**
	SCATTERING	**plaster**	**absorption coefficients**	0,01	0,01	0,01	0,01	0,02	0,03	0,1	0,12	**0,04**
			scattering coefficients	0,06	0,06	0,06	0,48	0,98	0,98	0,88	0,88	**0,55**

		NAME	COEFFICIENTS	absorbtion coefficients								
				62,5	125	250	500	1000	2000	4000	8000	AVERAGE
under-balcnoies	ABS, LOW FREQ	**Quietsone Light**	**absorption coefficients**	0,55	0,55	0,55	1,05	1,1	0,9	0,8	0,9	**0,80**
			scattering coefficients	0,01	0,01	0,01	0,02	0,03	0,05	0,08	0,12	**0,04**
	ABS, HIGH FREQ	**Quietdrama (Rigidized Metal)**	**absorption coefficients**	0,05	0,05	0,05	0,31	0,73	0,97	1,07	1	**0,53**
			scattering coefficients	0,01	0,01	0,01	0,02	0,03	0,05	0,08	0,12	**0,04**
	REFLECTIVE	**glass**	**absorption coefficients**	0,13	0,13	0,13	0,1	0,09	0,08	0,08	0,08	**0,10**
			scattering coefficients	0,01	0,01	0,01	0,02	0,03	0,05	0,08	0,12	**0,04**
	SCATTERING	**plaster**	**absorption coefficients**	0,01	0,01	0,01	0,01	0,02	0,03	0,1	0,12	**0,04**
			scattering coefficients	0,06	0,06	0,06	0,48	0,98	0,98	0,88	0,88	**0,55**

		NAME	COEFFICIENTS	absorbtion coefficients								
				62,5	125	250	500	1000	2000	4000	8000	AVERAGE
balcony ledges	ABS, LOW FREQ	**Clearsorber (RPG)** t15mm, d0,95, b6	**absorption coefficients**	0,3	0,63	0,44	0,19	0,08	0,02	0	0	**0,21**
			scattering coefficients	0,01	0,01	0,01	0,02	0,03	0,05	0,08	0,12	**0,04**
	ABS, HIGH FREQ	**Quietdrama (Rigidized Metal)** 1RL +1'' acou. Mat	**absorption coefficients**	0,05	0,05	0,31	0,73	0,97	1,07	1	1	**0,65**
			scattering coefficients	0,01	0,01	0,01	0,02	0,03	0,05	0,08	0,12	**0,04**
	REFLECTIVE	**glass**	**absorption coefficients**	0,13	0,13	0,1	0,09	0,08	0,08	0,08	0,08	**0,10**
			scattering coefficients	0,01	0,01	0,01	0,02	0,03	0,05	0,08	0,12	**0,04**
	SCATTERING	**plaster**	**absorption coefficients**	0,01	0,01	0,01	0,02	0,03	0,1	0,12	0,12	**0,05**
			scattering coefficients	0,06	0,06	0,06	0,48	0,98	0,98	0,88	0,88	**0,55**

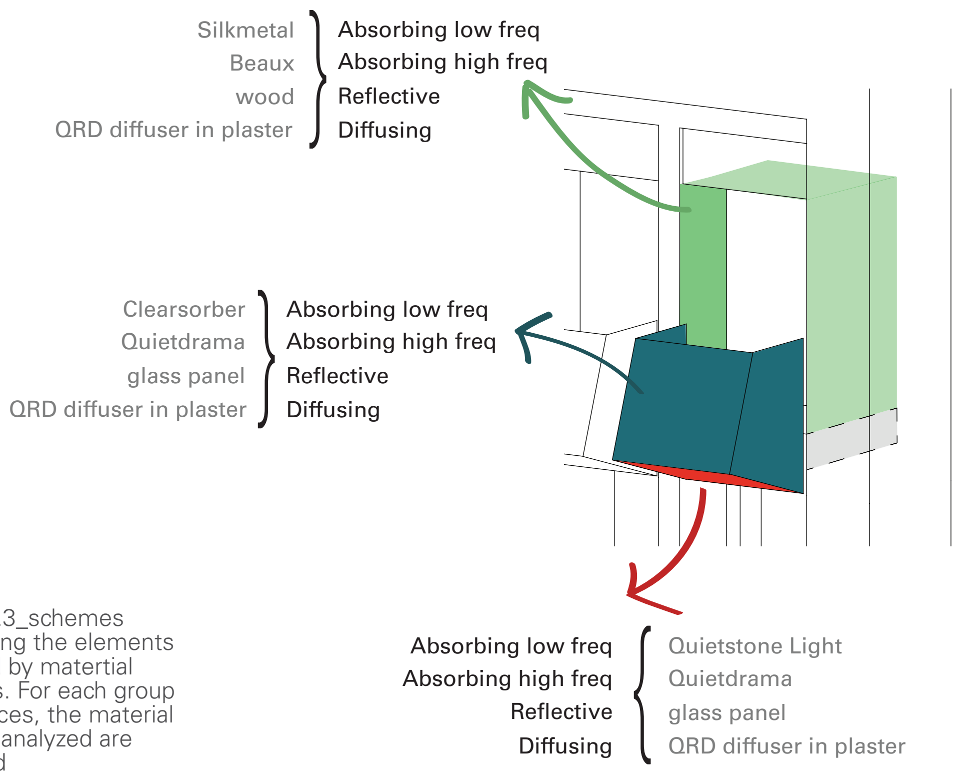
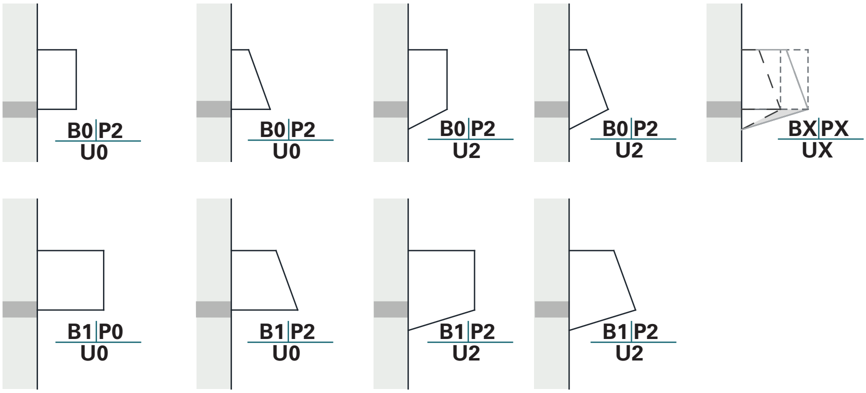


image 7.3_schemes identifying the elements affected by matertial changes. For each group of surfaces, the material options analyzed are reported

7.3 GEOMETRICAL VARIATIONS

The geometrical options proposed are those corresponding to the boundary values assumed by the variations considered in the previous step. This choice is grounded on the assumption that from the analysis of the boundary conditions it is possible to infer the performance for the options in-between. Consequently, it was considered both correct and time saving to cut the number of the geometrical variations previously proposed, as a greater number would have increased the time of the simulations without adding data that could not be deduced at posteriori.

The options considered are the inclination of the parapets (20°), the lowering of the edges of the inferior surface of the balconies (-46cm), the increase in balcony depths (1,5m) and the inclination of the ceilings of the loggias (10°). The following images show the geometrical variations proposed along with their identification codes.



7.4 DISCUSSION OF THE RESULTS

The results of the 64 material variations have been collected and analyzed for each of the 18 geometrical variations. The procedure followed to set the simulation algorithm is described in Appendix B.

The following graphs plot the ranges of SPL variations occurring due to material changes for each geometrical variation analyzed (in green) and the averaged SPL recorded for each option. The results are collected into three graphs, each one focusing on a group of receivers. The results are compared to that of the case-0, representing the all-balcony configuration identified by Manca: the striped green bars represent the difference between results achieved by the most performing solutions and those the reference case.

In general, it appears that the advanced options significantly affect the SPL over the façade, while little variations are observed over the façade of the building across the street and at the street level. This result demonstrates the potentialities of the design of the façade in enhancing the acoustic comfort of the dwellers, remarking the importance of the awareness of the acoustical consequences of the design choices. Although limited, the results plotted by the receivers in the other locations show that a proper design can also contribute to some extent to the sound quality on the opposite building and ground level.

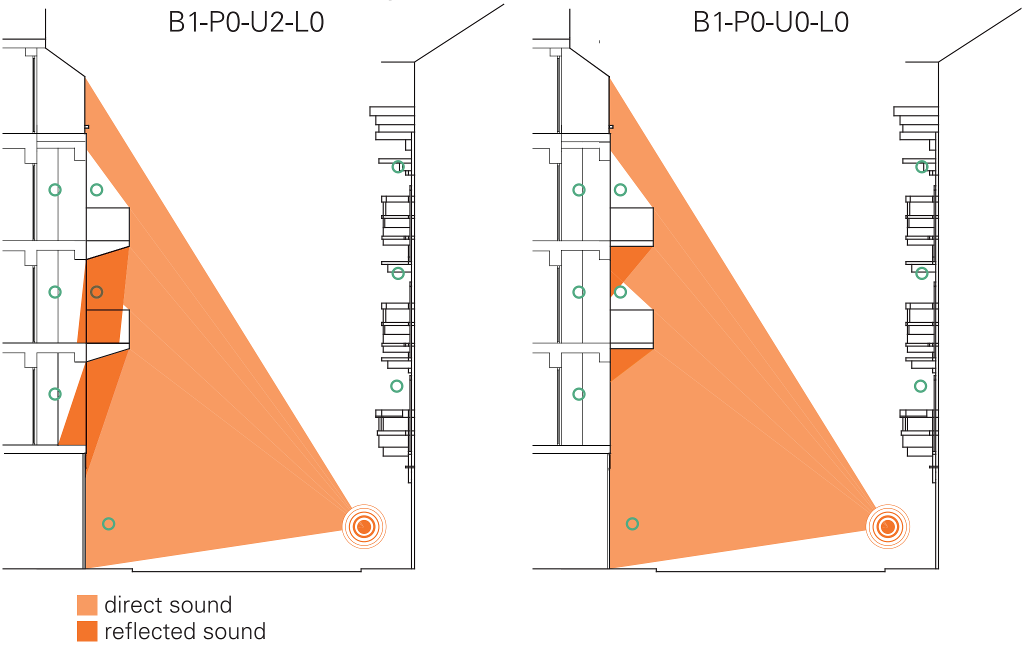
DESIGN FACADE

		AVERAGE SPL [dB(A)]			MATERIAL VARIATIONS			SOUND PRESSURE LEVEL [dB(A)]	
		DESIGN FACADE	STREET	OPPOSITE FACADE	PARAPETS	UNDER BALCONIES	LOGGIA SURFACES		
B0 P0	BEST	43,0	49,3	46,0	P_AH	U_AL	L_AL	AVERAGE	45,0
U0 L0	WORST	46,5	49,7	47,3	P_R	U_S	L_S	SPL VARIATION	3,6
B0 P2	BEST	44,1	49,3	45,8	P_AH	U_AL	L_AL	AVERAGE	46,1
U0 L0	WORST	47,7	49,8	46,9	P_S	U_R	L_S	SPL VARIATION	3,5
B0 P0	BEST	43,8	49,4	45,9	P_AH	U_AL	L_AL	AVERAGE	45,5
U2 L0	WORST	46,9	49,9	47,3	P_R	U_S	L_S	SPL VARIATION	3,2
B0 P2	BEST	44,0	49,4	45,9	P_AH	U_AL	L_AL	AVERAGE	46,1
U2 L0	WORST	47,8	49,9	46,8	P_S	U_S	L_R	SPL VARIATION	3,8
B1 P0	BEST	40,4	49,4	45,9	P_AH	U_AL	L_AL	AVERAGE	43,4
U0 L0	WORST	45,5	49,7	47,1	P_R	U_R	L_S	SPL VARIATION	5,2
B1 P2	BEST	42,1	49,3	45,7	P_AH	U_AL	L_AL	AVERAGE	44,5
U0 L0	WORST	46,5	49,8	46,8	P_S	U_R	L_S	SPL VARIATION	4,4
B1 P0	BEST	40,3	49,4	45,7	P_AH	U_AL	L_AL	AVERAGE	43,6
U2 L0	WORST	46,1	50,1	47,1	P_R	U_R	L_R	SPL VARIATION	5,8
B1 P2	BEST	42,0	49,3	45,7	P_AH	U_AL	L_AL	AVERAGE	44,7
U2 L0	WORST	46,9	50,2	46,9	P_S	U_R	L_S	SPL VARIATION	4,9
Bx Px	BEST	43,2	49,4	45,7	P_AH	U_AL	L_AL	AVERAGE	45,4
Ux L0	WORST	47,3	49,7	46,7	P_S	U_R	L_R	SPL VARIATION	4,0
B0 P0	BEST	43,0	49,3	46,0	P_AH	U_AL	L_AL	AVERAGE	45,2
U0 L1	WORST	46,7	49,8	46,9	P_S	U_S	L_S	SPL VARIATION	3,7
B0 P2	BEST	44,2	49,3	46,0	P_AH	U_AL	L_AL	AVERAGE	46,3
U0 L1	WORST	47,9	49,7	47,0	P_S	U_R	L_R	SPL VARIATION	3,8
B0 P0	BEST	43,7	49,4	46,0	P_AH	U_AL	L_AL	AVERAGE	45,5
U2 L1	WORST	46,9	50,1	47,1	P_R	U_R	L_S	SPL VARIATION	3,2
B0 P2	BEST	44,1	49,4	45,7	P_AH	U_AL	L_AL	AVERAGE	46,3
U2 L1	WORST	48,1	49,9	46,9	P_S	U_S	L_R	SPL VARIATION	4,0
B1 P0	BEST	40,5	49,3	45,9	P_AH	U_AL	L_AL	AVERAGE	43,6
U0 L1	WORST	45,8	49,7	47,0	P_R	U_R	L_S	SPL VARIATION	5,3
B1 P2	BEST	42,1	49,3	45,9	P_AH	U_AL	L_AL	AVERAGE	44,6
U0 L1	WORST	46,6	49,8	46,8	P_S	U_R	L_S	SPL VARIATION	4,5
B1 P0	BEST	40,4	49,4	46,0	P_AH	U_AL	L_AL	AVERAGE	43,8
U2 L1	WORST	46,3	50,1	47,1	P_R	U_R	L_R	SPL VARIATION	5,9
B1 P2	BEST	42,1	49,3	45,6	P_AH	U_AL	L_AL	AVERAGE	44,8
U2 L1	WORST	47,0	50,1	46,8	P_S	U_R	L_R	SPL VARIATION	5,0
Bx Px	BEST	43,3	49,3	45,7	P_AH	U_AL	L_AL	AVERAGE	45,6
Ux L1	WORST	47,4	49,9	46,8	P_S	U_R	L_S	SPL VARIATION	4,1

The inclination of the loggias does not appear to provide significant SPL variations. The most performing solution is the B1-P0-U2-L0, that record the minimum SPL on the design façade, and minimize the overall SPL recorded by all the receivers installed.

This solution features a deeper cantilever, coherently with the results obtained by with the simulations considering only the effect of the geometrical variations. However, B1-P0-U2 did not prove the most beneficial in the previous simulation, according to which the most favorable geometrical option was B1-P0-U0. In this case, therefore, the acoustical properties of the materials applied to it did change the effectiveness of the geometrical options, demonstrating the importance of considering geometrical variations in parallel with material changes.

Considering the SPL recorded on the design façade, the most performing solutions are those featuring a deeper cantilever of the balconies. The



inclination of the parapets increases the sound pressure level recorded by the receivers placed in the design façade, due to the reduced screening effect provided by the parapet in respect to the soundwaves reaching from the source. A slight decrease of SPL is observed the geometrical options featuring the inclined parapet on the façade of the building across the street; however, the SPL reduction is not enough to be considered significant in practical terms. These results are in line with the trends obtained in the previous simulations considering the effects of the sole geometrical variations.

The first graph represents the variations of the SPL in the design façade in comparison to that of reference case. The most performing solution is B1-P0-U2-L0 that achieves 40.3 dB(A), featuring balconies with a 1,5 m depth, vertical parapets and inclined under-balconies. Almost the same results are obtained by the B1-P0-U0-L0 configuration, that differs from the previous by featuring no inclination in the inferior surface of the balconies. Not significant SPL variations are due to inclination of the ceilings of the loggias, that therefore provide a little contribution to the average SPL observed over the façade.

The less beneficial is B0-P2-U2-L2, that records an average 48.1 dB(A): it features a 0,9 m cantilever and the inclination of the parapets, under-balconies and ceilings of the loggias. In general, the worst results correspond to the geometries featuring the inclination of the parapets.

MATERIAL COMBINATIONS

Given the SPL variations due to material changes observed for the various geometrical options by the receivers on the design façade, it is considered of interest to investigate which are the most favorable material combinations. The following table reports, for each geometrical option, the most and least effective material combinations, along with the average SPL and the variation range.

Absorption appear to be the most beneficial measure to treat the acoustic of the specific urban environment. As mentioned in the chapter focusing on the acoustics of street canyons, sound absorption appears to be the most effective solution to enhance the acoustic quality of urban environment featuring a high H/W ratio, as that analyzed. These results are therefore in accordance to the conclusions drawn by Onaga et al. (Onaga & Rindel, 2007).

The most effective solutions of each geometrical option feature the same combination of sound absorbing materials: a high frequency absorber (Quietdrama perforated panel) for the ledges and a low frequency one for the under-balconies (Quietsone Light) and loggia surfaces (Silkmetal). Besides the influence of operative frequencies range, it must be noted that these material features the highest absorption power over the whole frequency spectrum. In general, all the solutions achieving the lower SPL values for each geometrical option, features the application of sound absorptive materials to the surfaces of the loggias. The variation of the acoustical properties of the surfaces defining the balconies proves less effective than that of the surfaces of the loggias. Both reflective and scattering materials are indeed presents in combination with sound absorptive surface of the loggias in the most favorable material combinations for almost all geometrical options.

On the contrary, the worst results are achieved by the application of reflective and scattering materials to all the surfaces considered. The effectiveness of sound scattering in enhancing the acoustical quality of street canyon is affected by the H/W ratio of the street: in this case, the high rise of the building in comparison to the street width compromises the effectiveness of sound diffusion. This result is coherent with the analysis of Onaga et al. which claimed that the effectiveness of sound diffusion is greater when the H/W ratio is smaller, as it increases the rate of soundwaves that exits the canyon by being redirected towards the sky (Onaga & Rindel, 2007).

FINAL CONSIDERATIONS REGARDING THE MOST PERFORMING GEOMETRICAL SOLUTION

As mentioned, the geometrical configuration that in this analysis proves more beneficial, was not linked to the greater SPL decrease in the previous simulation, when only the effect of the variation of the geometry was considered. This result demonstrates the ability of different acoustical properties to alter the performance provided by the geometries to which it is applied, remarking the importance of considering the combined effect of material and geometrical variation in pursuing the most performing solution.

In this analysis, B1-P0-U2-L0 reaches the lowest SPL in the design façade, with slightly better results than B1-P0-U0-L0. This result is in contrast with the results obtained in the simulations considering the effect of the geometrical variations alone. As regard the geometries of the balconies, the B1-P0-U2, which previously resulted in a SPL reduction greatly inferior to that of B1-P0-U0, in this simulation features comparable results to it. A similar variation is observed for B1-P2-U2, that in the previous analysis was the worst solution among the deeper balconies, since it was the only resulting in a SPL increase. In this case, however, the results of B1-P2-U2, although poorer than the ones previously mentioned, are comparable to that of B1-P0-P2.

In order to understand the reason why B1-P0-U2-L0 proves the most performing geometrical configuration when absorptive materials are applied to it surfaces, a geometrical scheme has been advanced.

The scheme has been done using image-source method: it appears that the inclination of the surface under the balconies cause the reflected soundwaves to be directed towards the receivers located on the lower balconies. Differently, when the same surface is horizontal, the reflected soundwaves seems to miss the receivers, passing close to them.

When this surface is reflective, as the case of the first simulation employing only plaster and glass, the flatten configuration proves more beneficial. However, when a sound absorbing material is applied to it, the situation changes: the receivers are less affected by the reduction of reflected soundwaves in case of the horizontal configuration, while the inclined ones proves more beneficial.

Chapter 8

THE INVESTIGATION OF THE EFFECT OF FURTHER MATERIAL CHANGES

A final inquiry is pursued to investigate the effect of a series of material variations applied to the remaining parts of the façade and the street paving. The material changes advanced are in this case manually applied to the configuration B1-P0-U2-L0, that was identified as the most performing in the previous research step.

The intent of these analyses is to understand to what extent the design of the façade is capable of enhancing the acoustic quality within the street canyon. The elements affected by these material changes are: 1) the surfaces of the ground floor of the reference building, 2) the exterior surface of the façade, 3) the street paving.

The modification of the facade, being them referred to the materials or the geometries, are empowered by the designers involved in the project of the building. On the contrary, the street design, and along with it the selection of the materials applied to the street paving, are under the responsibility of the city administration. Consequently, the comparison of the SPL reductions provided by the street paving and that provided by the façade design provides is used to explore to what extent the public administration and the architectural designers have the potentiality to enhance the acoustic comfort in urban canyons.

In particular it investigated the effect provided by the application of sound absorptive materials to the surfaces of the ground and first floors, to the exterior facing of the façade and to the street paving.

To conclude, the effect of sound scattering was investigated. As mentioned in

Chapter 4, both the phenomena of sound absorption and sound scattering can be exploited to enhance the acoustics of urban canyon. According to Onaga et al., the effectiveness of the two measures vary in accordance to the geometrical ratio of the street section (Onaga & Rindel, 2007). In this case, the effect of the application of sound scattering to the exterior surface of the façade and the combined effect of the enhancement of sound scattering and sound absorption in the proximity of the sound source is investigated.

Finally, considering the façade portion reflecting soundwaves toward the opposite building that was identified a previous step, it was attempted to change the material applied to the façade in that portion only to verify if it resulted in a drop of SPL on the building across the street. To conclude, also the combined effect of sound scattering and sound absorption is explored and compared the effect provided by the sound absorption alone to understand to what extent the phenomenon of sound diffusion contribute in lowering the SPL in the street canyon.

The average of the SPL obtained by the B1-P0-U2-L0 configuration with the "optimal" materials, and the above-mentioned material changes were compared with the SPL of the reference case. It is therefore possible to compare the SPL reduction provided by the geometrical/material options of the "optimal" configuration and to assess how the conclusive material changes can further enhance its performances.

8.1 MATERIAL CHANGES TO THE SURFACES OF THE FAÇADE AND TO THE STREET PAVING

The application of sound absorbing materials to the exterior surface of the facades and to the street paving is expected to further enhance the SPL reduction obtained with the B1-P0-U2-L0.

In particular, the material changes proposed inform the exterior facing of the façade of the reference building, the glazed and metal panel defining the ground floor and the street paving. The SPL of the 48 microphones are recorded and analyzed by pertaining floor and relative position (internal and external microphones).

As regard the ground floor, it was explored the effect of the application of a transparent sound absorber to the glazed elements of the façade, that were originally in glass and the application of perforated metal panels in replacement of the original flatten ones.

Microperforated panels are based on the operating principle of Helmholtz resonators, and provide sound absorption exploiting the phenomenon of resonance. In particular, the material applied to the glazing is a microperforated panel made in plastic material, that when applied at a certain distance from the backing glass is able to provide sound absorption. As this material is transparent, it is suitable for shop windows or whenever natural lighting is required in the interior.

The enhancement of the sound absorbing properties of the street paving is expected to reduce the SPL recorded in the street canyon. Given the position of the sound source, it is expected that the enhancement of sound absorption in its proximity would produce a drop in SPL, as is would cause a great rate of emitted soundwaves to be absorbed by the road paving. The comparison of the SPL reduction provided by this material choice is useful to understand the capability of the public administration in addressing acoustical issue in urban areas as the one considered.

The application of a sound absorptive material to the exterior facing of the design façade is expected to further increase the SPL reduction recorded. Considering the geometrical inquiry done to define the portion of the façade that reflects the soundwaves towards the opposite façade, it was considered of interest to verify the conclusions previously obtained. Therefore, a further test was done by applying sound absorbers only on the lower portion of the building front, and then, the exact opposite. The results were then compared to those obtained with the application of sound absorber to the whole surface of the façade.

		NAME	PRODUCT DETAIL	APPLICATION	COEFFICIENTS	acoustic performance								
						62,5	125	250	500	1000	2000	4000	8000	AVERAGE
GROUND FLOOR	GLAZING	**Regular glass**[1]	*generic glass*	*outdoor*	**absorption coefficients**	0,13	0,13	0,1	0,09	0,08	0,08	0,08	0,08	**0,10**
					scattering coefficients	0,01	0,01	0,01	0,01	0,01	0,02	0,05	0,06	**0,02**
		Transparent Absorber (DeAmp)	*plastic panel; 2 layers*	*outdoor*	**absorption coefficients**	0,4	0,83	0,81	0,59	0,52	0,23	0,14	0,14	**0,46**
					scattering coefficients	0,01	0,01	0,01	0,02	0,03	0,05	0,08	0,12	**0,04**
	METAL	**Steel**[2]	*generic glass*	*outdoor*	**absorption coefficients**	0,01	0,01	0,01	0,06	0,07	0,1	0,12	0,12	**0,06**
					scattering coefficients	0,01	0,01	0,01	0,01	0,01	0,02	0,03	0,04	**0,02**
		Quietdrama (Rigidized Metal)	*perforated metal*	*outdoor*	**absorption coefficients**	0,05	0,05	0,31	0,73	0,97	1,07	1	1	**0,65**
					scattering coefficients	0,01	0,01	0,01	0,02	0,03	0,05	0,08	0,12	**0,04**

[1][2] Manca, 2017

	NAME	PRODUCT DETAIL	APPLICATION	COEFFICIENTS	acoustic performance								
					62,5	125	250	500	1000	2000	4000	8000	AVERAGE
FACADE	**Plaster**[1]	*generic*	*outdoor*	**absorption coefficients**	0,01	0,01	0,01	0,02	0,03	0,1	0,12	0,12	**0,05**
				scattering coefficients	0,01	0,01	0,01	0,02	0,03	0,05	0,08	0,12	**0,04**
	Silentstone (JCW)	*aggregate*	*outdoor*	**absorption coefficients**	0,8	0,8	1,05	0,95	0,75	0,8	0,85	0,85	**0,86**
				scattering coefficients	0,01	0,01	0,01	0,02	0,03	0,05	0,08	0,12	**0,04**

[1] Manca, 2017

	NAME	PRODUCT DETAIL	APPLICATION	COEFFICIENTS	acoustic performance								
					62,5	125	250	500	1000	2000	4000	8000	AVERAGE
ASPHALT	**Regular asphalt**[1]	*generic asphalt*	*outdoor*	**absorption coefficients**	0,01	0,01	0,01	0,04	0,1	0,2	0,3	0,3	**0,12**
				scattering coefficients	0,01	0,01	0,01	0,04	0,1	0,2	0,3	0,35	**0,13**
	Asphalt OPA 0/6	*acoustic asphalt*	*outdoor*	**absorption coefficients**	0,58	0,58	0,5	0,6	0,52	0,38	0,45	0,45	**0,51**
				scattering coefficients	0,01	0,01	0,01	0,04	0,1	0,2	0,3	0,35	**0,13**

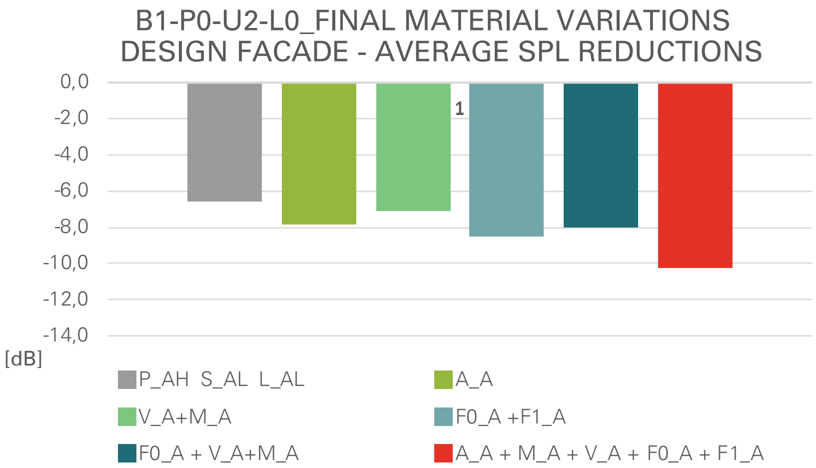
[1] Manca, 2017

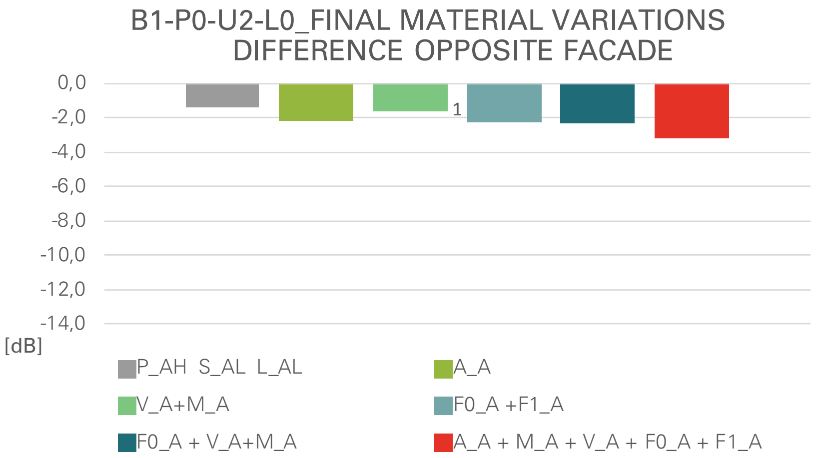
8.2 DISCUSSION OF THE RESULTS

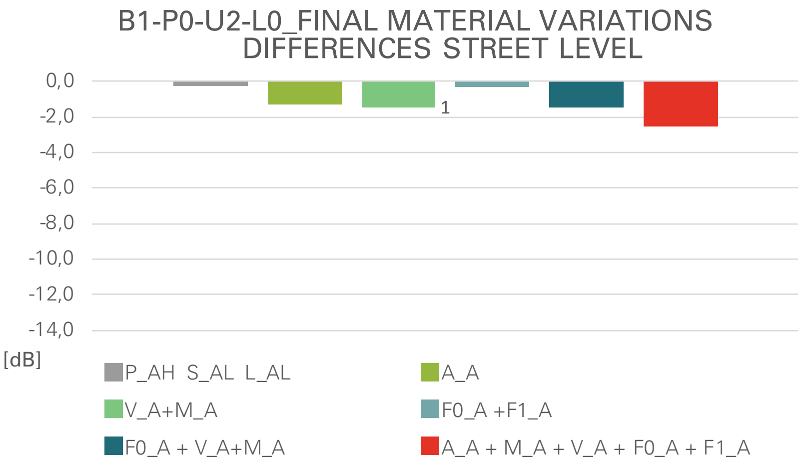
As results collected during exploration of the application of sound absorptive materials to the remaining surfaces of the facade and to the street paving are discussed in the following.

The graphs below plot the SPL reductions in comparison to the case zero (all balcony configuration identified by Manca with the application of only reflective materials (plaster and glass) occurring over the two facades considered and at the street level (Manca, 2017).

The grey bar represent the SPL reduction provided by the most performing







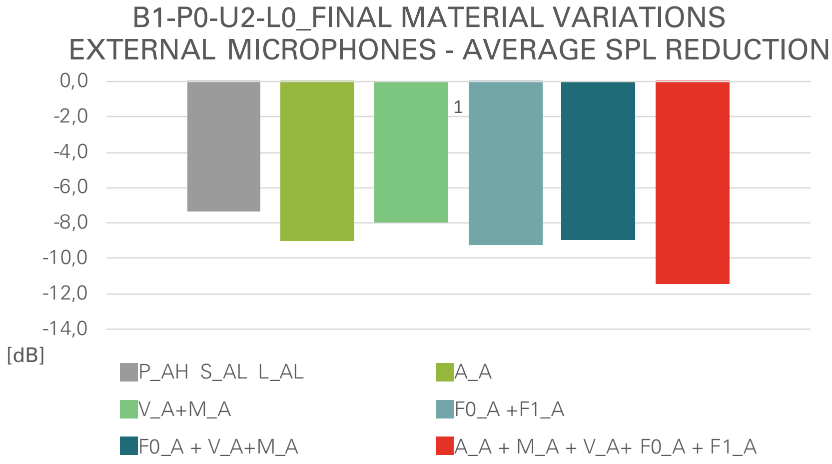
configuration of the balconies (geometry and material) in comparison to the reference case. The following bar plot to what extent the measures advances are able to further enhance the acoustic performances.

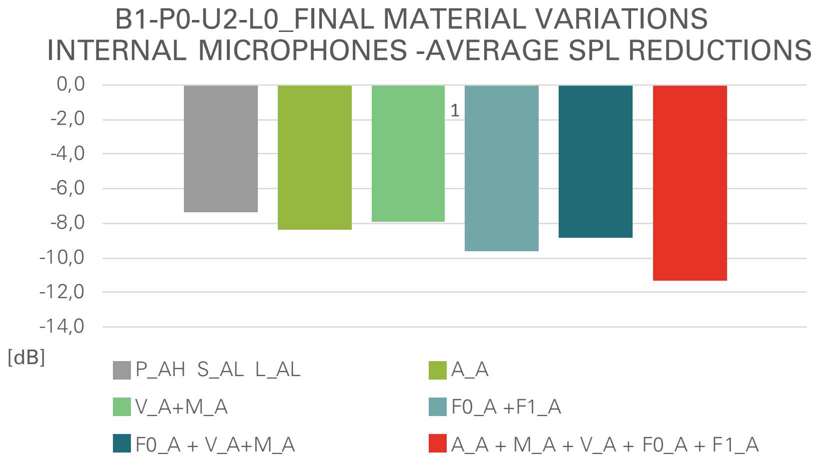
The material changes pursued are: application of acoustic asphalt (A_A); the application of sound absorbing material to the glazed and metallic element of the ground floor (V_A + M_A) and to these elements plus the front surface up to the first floor (F0_A + V_A + M_A); to the entire facade (F0_A + F1_A); and finally to all the mentioned surfaces at once (A_A + M_A + V_A + F0_A + F1_A).

The greater variations are observed in the design facade: the application of sound absorbing material to the street paving result in a further SPL reduction of 1,4dB. As regards the facade, a sound absorptive material applied to the exterior facing greatly enhance the acosutic quality in the facade, with a further SPL reduction of almost 2 dB.

The application of sound absorptive material to the surfaces of the ground floor alone provides some further SPL reductions, but better results are provided in combination with sound absorptive material applied on the facade of the first floor.

The following graphs plot the SPL reduction experienced by the external and internal receivers. These material changes affect the SPL on the balconies and within the loggias of almost the same extent. This results, that goes in contrast to the ones obtained by the simulation involving the sole geometrical effect, is likely to be due to the application of sound absorptive materials to the surfaces of the loggias, that dampen seems to dampen the SPL variation between internal and external microphones.





By combining the effect provided by the enhancement of sound absorption over the facade and on the street paving, the overall SPL reduction obtained is a reduction of 10 dB over the design facade, of 2.5 dB and 3 dB respectively at the street level and over the opposite facade.

The SPL reduction at the street level is greater whenever sound absorption is aplied to the nearby surfaces (lower portion of the facade, street paving). On the opposite facade, SPL reductions are reported for both the application of sound absorptive materials to the facade surfaces and to the street paving. In particular it appear that the surfaces over which the application of sound absorption proves beneficial are the lower ones.

Chapter 9
CONCLUSIONS

Using a parametric model in combination with an acoustic simulation software it has been possible to investigate the effect of geometrical and material changes applied to the façade features of a reference building. In particular, a set of possible balcony geometries and surface inclination was investigated.

The acoustic effect was described for each design modification by the sound pressure level measured on the design façade, at the street level and on the façade of the building across the street.

The geometrical changes were firstly investigated with the application of an acoustically-reflective finish. The variations of sound pressure level observed were therefore only influenced by the geometrical changes, and by the way the proposed configuration reflected the soundwaves arriving from the sound source.

After this step, the effect of material changes in combination with a set of geometrical options was investigated. Three group of façade surfaces were affected by material variations. The material selected for this step featured opposite acoustic properties (i.e. specularly reflective, absorptive at high or low frequencies, diffusing).

Finally, a set of further material changes was pursued manually to investigate how the enhancement of the sound absorptive or scattering properties of the surfaces of the façade could further enhance the results obtained. In the end, these results were compared to the SPL reduction provided by the application of a sound absorptive asphalt to the street paving.

The data collected in the previous steps allow to provide answers to the inquiries defined at the beginning of the research project. In the following, the themes highlighted in the introductions are analyzed in light of the results gathered during the thesis work.

1. Performance-based design is identified as the most suitable design procedure in projects in which acoustic performance is a concern. The major benefits are reported when the assessment of the performance is introduced since the early design phases, when major changes are still possible and require a limited economical cost to be pursued.On the basis of the analysis of the case studies developed using acoustic performance-based design gathered, it was possible to identify which are the drawbacks that seems to limit its application in current architectural practice, and to suggest a series of possible improvements to endorse a wider adoption of the method
2. A series of geometrical and material options is applied to the façade of reference case study building, to evaluate how they influence the acoustics of the street canyon.
   The effect provided by the geometrical options alone are limited: the variations of SPL measured are little in comparison to those obtained considering the effect of geometrical variations in combination with material changes. However, the trend observed in this phase are coherent with those reported in the following set of simulations. The SPL over the façade is greatly affected by the balcony depth and the inclination of the parapets: the first results in a decrease in SPL, while the latter reduces the screening effect of the parapet with respect to the direct sound arriving from the sound source and result in an increase in SPL.
   In general, the SPL reductions are greater for the upper floors in comparison to the lower ones. The greater variations are observed for the receivers measuring the SPL on the balconies, while those placed within the loggias record moderate variations.
   In the following phase, the effect of the application of material with opposite acoustical properties is investigated. The surfaces to which these materials were applied are those involved in the geometrical variations,

as the acoustical properties applied to them may alter the overall acoustic effect provided by the solutions. The results plotted that the effect of geometrical and material changes mainly affect the SPL recorded over the design façade, while little variations were recorded on the street level and opposite building. The material featuring sound absorbing properties are those that correspond to the greatest reductions of SPL observed for all the geometries investigated.
The effect of the inclination of the loggias in in this case almost negligible, as no significant variations are observed by the comparison of the configuration featuring horizontal and inclined ceilings. As regard the geometrical variations of the balconies, the roles played by the cantilever depth and inclinations of the parapets are confirmed: in particular, all most performing solutions feature the deeper balcony configuration. The inclination of the surface under the balconies, that in the previous set of simulations seem to provide an unfavorable effect is in this case reconsidered: when a sound absorber is applied on it, it results in a SPL decrease greater than that provided by the flatten configuration.

3. From the mentioned outcomes, a series of strategies can be inferred to support the design of building front located in acoustically critical environments as that considered in the reference building. As regard the material, sound absorption is related to the most favorable solutions; sound reflective materials are applied to the façade surfaces in the less favorable configurations. It also seems that the surfaces that influence the SPL the most are those lining the loggias: all the best solutions for each geometrical variation features the application of sound absorbing materials of these surface. Moreover, the application of sound absorptive material to these surfaces dampen the SPL variations that was observed between the microphones placed on the balconies and those located within the loggias.
As regard the geometrical options of the balconies, the SPL over the façade is reduced for increased balcony depths. The inclination of the parapet and that of the inferior surface of the balcony have a disrupting ef-

fect over the SPL measured. However, in case sound absorptive materials are applied to the latter surfaces, a significant SPL reduction is observed. These simulations confirm the little effect provided by the inclination of the ceilings of the loggias.
The application of a sound absorptive material to the exterior surface of the façade results in a significant SPL reduction over the façade. The application of a sound absorptive asphalt to the street paving provide a SPL reduction slightly inferior than that provide by the treatment of the exterior façade. The installation of sound absorbers over the surfaces of the ground floor moderately enhances the SPL reduction over the façade; the SPL reduction over the opposite building facade is comparable to that resulting from the treatment of the entire façade with absorptive materials.
Overall the most performing solution identified results in a SPL reduction of almost 7 dB in the design façade in respect to the reference case, represented the façade configuration B0-P0-U0-L0 treated with sound reflective materials. Although moderate, SPL reductions are observed also for the microphones placed in the opposite façade and at the street level.

4. In the end, the SPL reduction provided by the various design options tested on the façade was compared with that obtained by applying a sound absorptive paving to the street. Overall the SPL reduction provided a proper façade is greatly superior to that provided by the street paving alone. In the case study analyzed, the application of acoustic asphalt is able to lower the SPL over the building facades of about 1,5 dB. On the contrary, the design of the façade alone is reported to be able to reduce the SPL up to 9,5 dB.

   This result remarks the importance of the role played by architectural designers in addressing acoustical issues arising in contemporary cities. The features of the fronts of the buildings facing street canyons, when properly designed, can contribute to the enhancement of the acoustic comfort of the dwellers. A design method stressing the importance of acoustical performance is therefore essential if facing the projects of building fronts placed in acoustically-critical environments. The ground rules proposed by this research intend to make designers more aware of the potentialities of façade design in addressing acoustical issues in urban environments.

APPENDIX A

THE DIGITAL MODEL

BASIC SETTINGS AND INSTALLATION OF THE REQUIRED SOFTWARE APPLICATIONS

In order to develop the present work, a series of tools need to be installed. In particular, the software applications required are a parametric modeling environment, an acoustic simulations software, and an optimizer. Rhinoceros, Grasshopper and PachydermAcoustics are considered for the purpose of this thesis the most suitable applications. ("Rhinoceros," n.d.; Rutten, n.d.; Van der Harten, n.d.) Grasshopper and Pachyderm are two open-source plug-ins of Rhinoceros: Grasshopper (GH) is able to generate geometries on the basis of an algorithm set by the user and comes along with an integrated optimizer system Galapagos. This procedure represents a significant advantage over classical direct modeling method since it speeds up the generation of possible design variations. PachydermAcoustics is a free acoustic simulation system and is integrated in Grasshopper and Rhinoceros. Therefore, it is possible to run the acoustic simulation directly in the modeling environment, without the need of an external piece of software. Finally, two other plug-ins were used: the most relevant is GhPython (Piacentini, n.d.) that enable users to generate Grasshopper custom-components using Python scripting language (van Rossum, n.d.). This option is extremely useful whenever it is required to run a specific task that is not provided by the pre-set tools in Grasshopper.

The installation and the basic setting of the mentioned tools is briefly explained in the following.

The evaluation version of the last release of Rhinoceros can be retrieved at the software webpage, choosing the proper OS (link: https://www.rhino3d.com/download). The file downloaded when executed would install Rhinoceros on the device following the guided procedure. After the installation is completed, it is possible to proceed with the installation of Grasshopper and PachydermAcoustics plug-ins. Grasshopper plug-in is can be downloaded at the link https://www.rhino3d.com/download/grasshopper/1.0/wip. To add the plug in to Rhinoceros it sufficient to drag and drop the file .rhi in the drawing window of the modeling environment. Finally, Pachyderm Acoustics can be downloaded at http://www.perspectivesketch.com/pachyderm/ and installed executing the file .exe contained in the zipped folder.

This thesis project was carried out using the latest releases of the mentioned software, namely Rhinoceros 5.0 SR 14, Grasshopper 0.9.0076 and PachydermAcoustics 2.0 RC20.

Further Grasshopper plug-ins are used to set the algorithm: Human (available at: http://www.food4rhino.com/app/human) and GhPython (available at: www.food4rhino.com/app/ghpython). The first is required to allow Grasshopper to recall the layers of the Rhino model while the latter is required to create custom component written in Python programming language.

For further information about the installation and the basic setting of these tools consult the thesis of Roberto Manca, offering a detailed step by step guide. (Manca, 2017)

GENERAL SETTINGS OF THE DIGITAL MODEL

To run the acoustic simulation is necessary to develop the digital model of the street and design façade in accordance to certain criteria. In particular, PachydermAcoustics applies materials by layers and requires the geometries to be sorted by layer in accordance to the material applied to them.

The model used to run the simulation was based on the balcony-only version of the model developed by Roberto Manca in Rhinoceros, considering only the street portion proved relevant for the soundness of the acoustic simulations. The model of the design façade was therefore purged from the unnecessary contents and the geometries were sorted by layer according to the material applied, being it glass or plaster. New layers were created to contain the geometrical variations proposed. The original loggia ceiling and the original balconies were kept of separate layers, to allow to either exclude or include their geometry in the acoustic simulations as necessary.

Using Grasshopper an algorithm was set to create the parametric models of the ceiling of the loggias and the balconies, in order to ease the creation of all the geometrical variations to be analyzed. The procedure is described in the following paragrapshs.

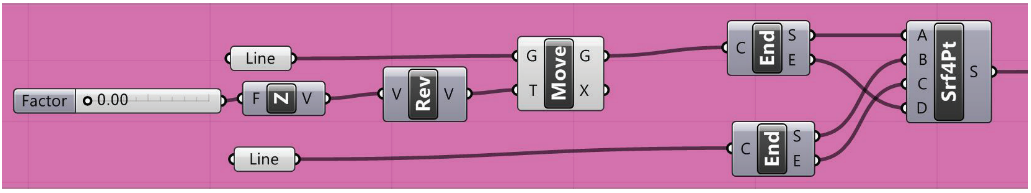
PARAMETRIC MODEL OF THE INCLINED LOGGIA CEILING

The parametric model of the ceiling of the loggias was created in two configurations to differentiate the case in which the same inclination is applied to all the ceilings of the façade to the one in which each ceiling is informed by a different inclination.

The method to create the first model is described in the following step-by step guide.

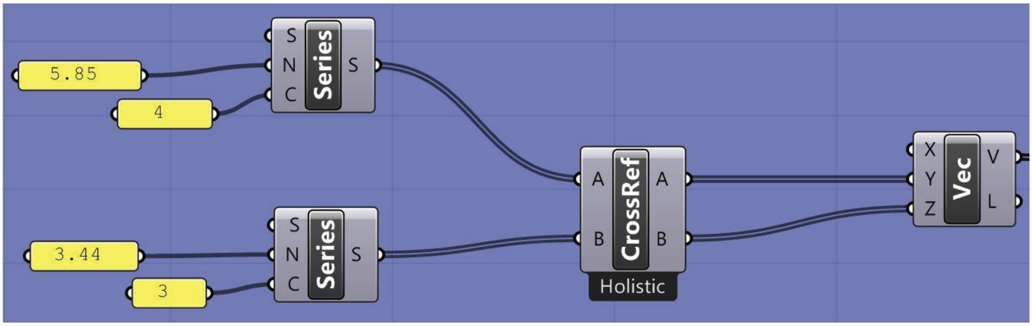
Grasshopper is able to generate parametric model using algorithms set by the user. To lunch Grasshopper just write Grasshopper in the command bar of Rhinoceros. The algorithm is defined by inserting in the “canvas” a series of components and plugging them to generate the algorithm.

1. The internal and external edges of the loggia ceiling are imported from Rhinoceros to Grasshopper as a line using the “line” GH components (from Params > Geometry). For each edge: right click on “line” component in GH; set one line; select the line in Rhino; click enter)
2. The internal line is moved (copied) with the “move” component (from Transform>Euclidean). The Move component has to input plug: G needs to be linked to the geometry to move; T needs to be linked to the translation vector. To set define the possible distances a Number Slider component (from Params>Input) is created and its number range is set from 0 to 22 (right click on it; edit and set variation range, type of number and accuracy as required). The number slider is then linked to a Unit Z vector component (from Vector>vector) to make the edge move vertically; the vector is then connected to the T plug.
3. To crate the ceiling is now necessary to generate a planar surface from the edges imported in the Line components. The required component is



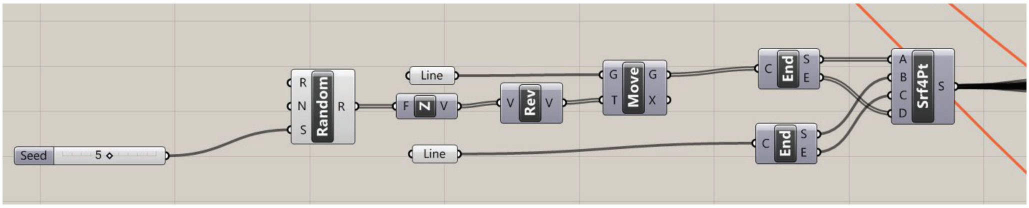
4PointSurface (from Surface> Freeform) and need the vertex of the surface to be linked to the A B C D input plugs. To extract the extremes of the edges, each line needs to be linked to an End Point component (from Curve> Analysis): the outputs need to be plugged in the input plugs of the Srf4Points component in the correct order.

4. Up to this point, a single loggia ceiling has been created. In order to copy the geometry in all the twelve loggias of the façade a further step is required. To define the locations of the loggias, a grid has been generated using to Series component connected to a Cross Reference component. The Serie component generate a series of numeric values in accordance to the starting number (S), step (N) and count (C). The number of each can be set by right clicking on the plug and inserting the number in Set Number or Set Integer according to the cases, or by connecting a Panel (Params>Input) component with the number written in it. The outputs of



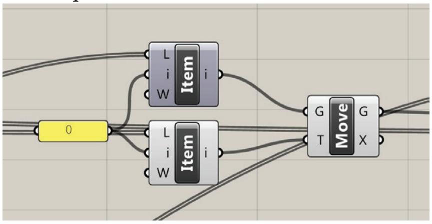
the Series components are linked to the Cross Reference component (Sets> List). Finally, the Cross Reference output is linked to the Y and Z plugs of a Vector XYZ component (from Vector>vector), whose V output is plugged in the Move component acting on the 4PointSurface component to copy the ceilings in the right locations.

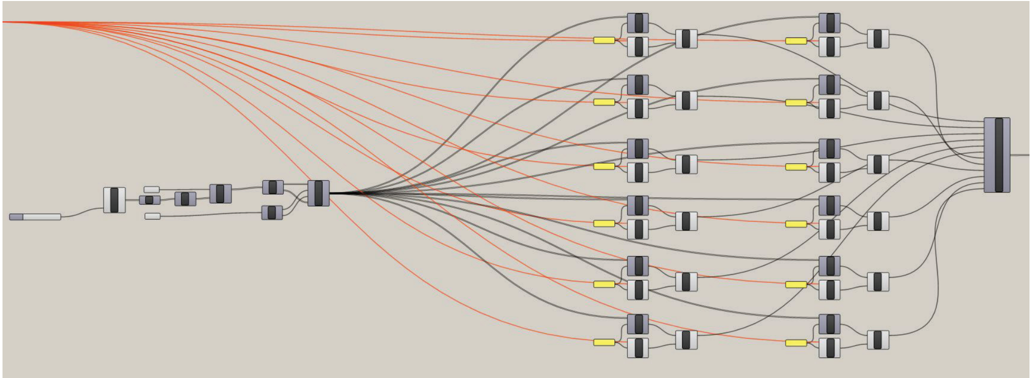
The generation of the randomized version of the ceilings is generated in a similar way. To introduce the random measures of the angles a Random



component is inserted (from Sets>Sequence). The range (0 to 22) and amount of number (12) of the random series need to be set; it is also possible to change the seed number of the random serie by altering the number in S plug. Once set, the Random component is connected to the Unit Z vector. The remaining components are the same used in the generation of the first model: in this case however the number of surfaces being generated is 12.

To make every ceiling loggia incline differently the 12 outputs of 4PointSurface need to be sorted and moved to a different location of the grid. In order to do so each surface need a unique Move component, properly set. In order to sort each grid point and each surface, two List Item components (from Sets> List) are required.



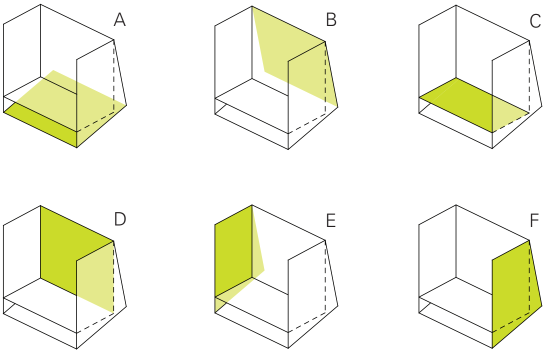


The output of the 4PointSurface and CrossReference components need to be insert in the L plug, while to recall a single element from the lists, a panel is plug to the index (I) plugs.

These 4 components are copied 12 times, varying the number set in the panel from 0 to 11. The output of all the move components are then plugged in a Merge component (from Sets>Trees).

PARAMETRIC MODEL OF THE BALCONIES

The parametric model of the balcony has been developed starting from a two line, representing the internal vertical edges of a balcony, from which surfaces are generated by copying the lines and extracting the vertexes of the lines. The geometry of each balcony consists in 6 planar surfaces (A+B+C+D+E+F), each modeled starting from its vertexes (see image below).



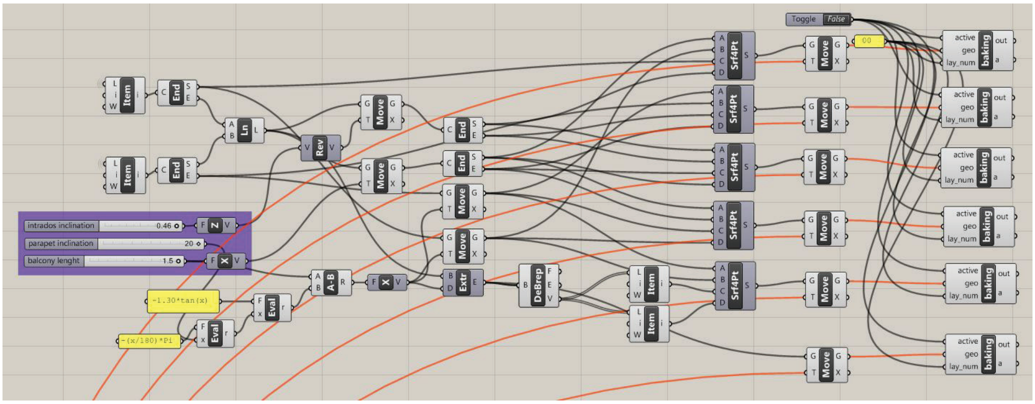
In analogy to the case of the loggias' ceilings, there are two distinct procedures to generate the homogeneous and the random configurations of the balconies. The procedure is described as follows:

1. The lines have been imported in Grasshopper with Line component by right clicking on it and selecting "set Multiple Lines". From the list, each line has been isolated using List Item.
2. The start and end points of each lines are extracting using End Point. A new line, representing the internal edge of the balcony floor, is created with the component "Line" (from Curve>Primitive) from the lowest extremes of the two lines. This new line undergoes two processes: in the first, the line is moved downward using the Move component with a Unit Z and a Number Slider defining the range of distances (from 0 to 46).

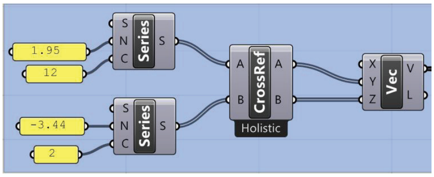
In this case Reverse component (from Vector>vector) has been inserted between the Unit Z and Move components to allow the insertion of positive values in the number slider. The latter line represents the internal edge of the intrados of the balcony; its extremes are extracted by the End Points components. The second process is the creation of its external edge, linked to the parapet, by copying the line along the x axis (with Unit X, Number Slider and Move components). This line the rotation axis of both the parapet and intrados configuration and is required to generate the two corresponding surfaces. Again, the vertexes of this line are defined by an End Points component.

3. The surface of the intrados (A) can now be generated using a 4PointSurface in which the vertex of the two edges of the intrados are plugged.
4. To locate the upper edge of the parapet, the geometrical relationships are exploited, to generate the internal side of the parapet and the floor of the balcony starting from the angle of inward rotation of the parapet. The internal surface of the parapet, and so the external edge of the floor the floor, are located at a distance corresponding to the overall balcony length diminished the tangent of the angle of rotation of the parapet multiplied for the length of height of the parapet. To establish this relationship a Panel component, an Evaluation component (from Maths>Script) and a Substraction component (from Maths>Operators) are used. As the formula in Panel need angles expressed in radiant, a further Evaluation and Panel components are added to convert the degrees in radians.
5. Once this distance is obtained, the upper vertex of the starting lines and the internal edge of the floor are copied along the x axis using the outcome of the formula as motion value. The vertexes of the line are extracted with another End Point component. At this point the external surface of the parapet (B) is created with a 4PointSurface component using the edges of the defined lines. The floor (C) is generated by extruding its internal edge with Extrude component (from Surface>Extrude) using the same vector. Using DeconstructBrep (from Surface>Analysis) the external edges are extracted to be plugged to the 4PointSurface component defining the

internal surface of the parapet (D). Finally, the lateral sides of the balconies (E+F) are obtained with two further 4PointSurface components connecting the upper vertexes to the lowest ones on each side.

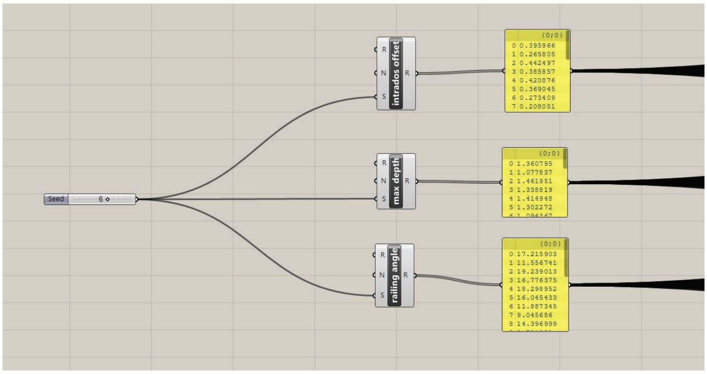


6. The balconies have been copied throughout the grid with a process similar to the one used for the ceiling of the loggias

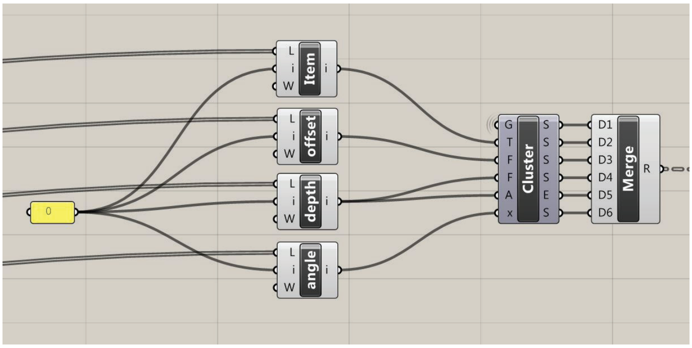


To generate the randomized configuration, 24 groups of components are generated, each informing the generation of a single balcony. For practicality sake all the components generating the balconies are collected in a single cluster (select all components, right click and select Cluster).

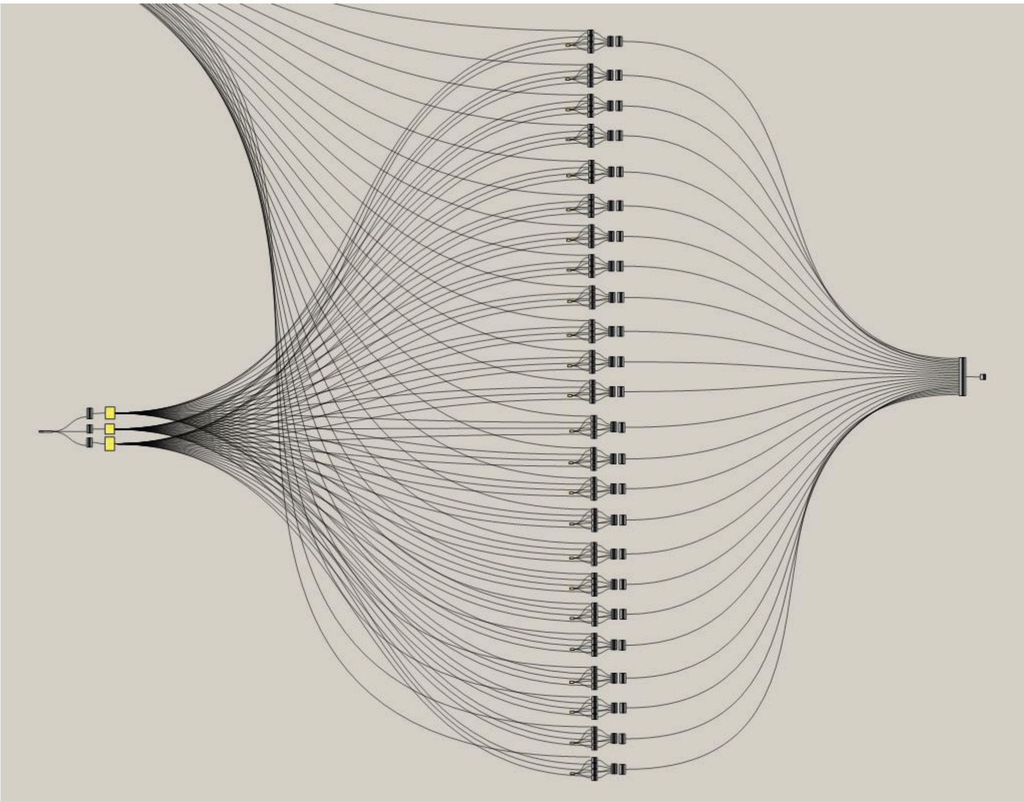
Three random components are used to generate the series of random numbers informing the offset of the intrados, the parapet inclination and the balcony depth.



The output of the rando series are then plugged as input in the List Item components extracting the values informing the variation of each balcony, likewise the procedure used for the random ceilings of the loggias.



Each of the 24 random values is extracted in sequence and plugged into the 24 cluster components creating the balcony geometry.



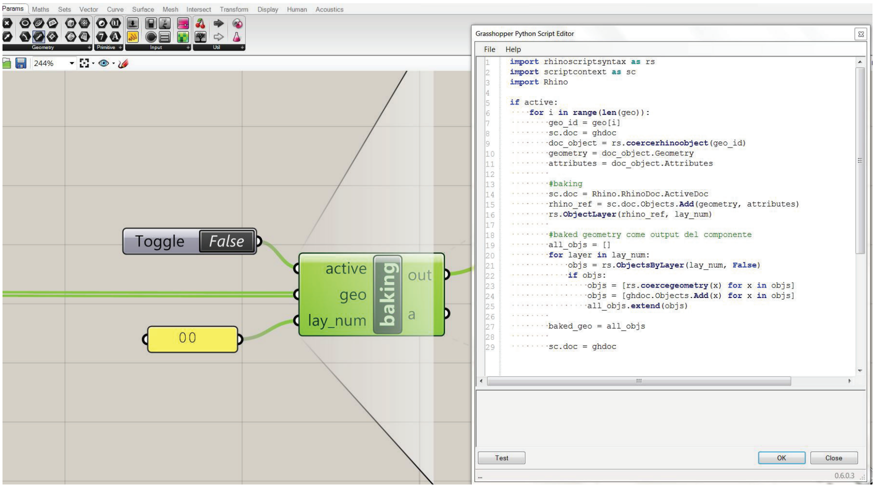
CUSTOM COMPONENT FOR THE BAKING OF THE GEOMETRIES

Once the parametric models defining all the possible design variations are set, it is possible to create a single variation by altering the number in the number slider as required: the preview of the geometry is visible in Rhinoceros as a transparent red geometry. However, in order to allow the simulation to run and explore the effect of each design option, PachydermAcoustics requires the parametric geometry to be “baked” i.e. created and imported into Rhinoceros modeling environment.

A custom component of GH is therefore created to bake the geometry in a specific layer defined by the user. Every design option will be saved on a distinct layer, to allow the geometry to be imported in the simulation tool when required.

Using GhPython plugin it is possible to create a custom component written in Python programming language (from Maths>Script). By double clicking on it, a text editor is opened, and it is possible in which it is possible to write and test the script.

GhPython component can be greatly customized: in the specified case three input plug were created: the first was linked to a Boolean Toggle component to enable or disable the component. The second labeled “geo” import the geometry created by GH; the third allows to specify the pertaining layer of the baked geometry.




```python
import rhinoscriptsyntax as rs
import scriptcontext as sc
import Rhino

if active:
    for i in range(len(geo)):
        geo_id = geo[i]
        sc.doc = ghdoc
        doc_object = rs.coercerhinoobject(geo_id)
        geometry = doc_object.Geometry
        attributes = doc_object.Attributes
        
        #baking
        sc.doc = Rhino.RhinoDoc.ActiveDoc
        rhino_ref = sc.doc.Objects.Add(geometry, attributes)
        rs.ObjectLayer(rhino_ref, lay_num)
        
        #baked geometry as output
        all_objs = []
        for layer in lay_num:
            objs = rs.ObjectsByLayer(lay_num, False)
            if objs:
                objs = [rs.coercegeometry(x) for x in objs]
                objs = [ghdoc.Objects.Add(x) for x in objs]
                all_objs.extend(objs)
        
        baked_geo = all_objs
        
        sc.doc = ghdoc
```

APPENDIX B

THE ACOUSTIC SIMULATION

In the following the procedures followed to set the acoustic simualtions in Pachyderm are described for the two sets of simulations pursued. The basic setting of the simulations software, detailed in the first part, are valid for both the simulations. While the first only focused on geometrical variations, however, in the second analysis, material changes are investigted. Consequently, both the digital model and the algorithm in Grasshopper needed to be propertly updated in light of requirements to analyze material combinations.

However, similar general settings were used for both the simualtions sets. The main difference between the two is the introduction, in the second step, of a semi-automated procedure to pusue simualtions and a custom component to record the data of each of the 1152 combinations analyzed.

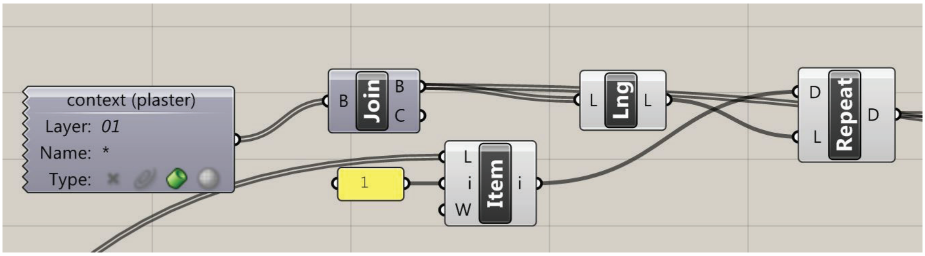
GENERAL SETTINGS OF THE DIGITAL MODEL TO RUN THE ACOUSTIC SIMULATIONS CONSIDERING THE EFFECT OF GEOMETRICAL OPTIONS

The final Rhinoceros document consisted in 31 layers: the first ones were the ones relative the context and were kept unaltered throughout the simulation process, with the same settings used by Manca. The following layers on the contrary contained the geometry variations proposed of the loggias ceilings and the balconies. This proved useful to consider each simulation separately in the Grasshopper environment and quickly recall a design option without the need of generating it again.

In GH canvas order to consider each design option and to run the acoustic simulation, it was enough to alter the layer number in the Geometry Pipeline components, and subsequently run the simulation.

The simulations were run using a number of rays of 100 000 and 1 as reflection order. The SPL measured by the 48 receivers were collected in an Excel spreadsheet; each simulation was repeated three time to ensure the homogeneity of the results; the average of the simulations outcome was considered as the significant results.

ACOUSTIC SIMULATIONS

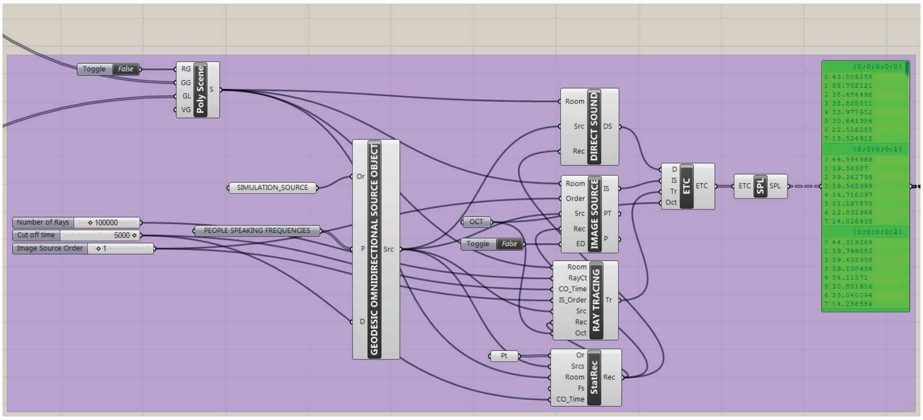


PachydermAcoustics is an open-source program that work within the Grasshopper environment. Once installed, a new ribbon toolbar is visible in the interface, named Acoustics, where all the components required to run the acoustic simulation can be found.

The geometry is imported in Grasshopper from the Rhinoceros environment using the Polygonal Scene component. The geometry of each layer is recalled with the Geometry Pipeline component: the geometries are joined in a list using a Join component (from Surface> Util), and the list length it obtained employing a List Length component (from Sets>Lists). The material applied to the geometry of each layer is defined by selecting a single value from the LayerTable component (available in Human) using a List Item and a Number Slider. A Repeat component (from Sets>Sequence) multiplies the layer number for the number of geometries of each layer. This process is repeated for all the layer whose geometry need to be considered in the acoustic simulation.

Lastly, two lists are created using the Merge component: one collecting the geometries (all the B outputs of the Join components) and one collecting the material (i.e. layer) associated to them (gathering all the outputs of the Repeat components).

These two lists represent the input parameters of the GG and GL plugs of the Polygonal Scene component. The S output of this component is connected to the Image Source, Ray Tracing, Direct Sound components (Room inputs). The sound source is defined by the Geodesic Source component that requires the location of the source (extracted with a Point component) and the Power Spectrum (retrieved using a Number component that represent



the SPL for each octave bands). The receivers are defined by importing the points representing their position using a Point component and plugging it into the Stationary Receiver component (Origin). The Ray Tracing calculation is based on the respective component requires as input, in order: the room

```
#import math
#list(map(int.__sub__, int(x), int(y))
import math

#weight cuve A / octave band
a = []
a.append(dB[0]-26.2)
a.append(dB[1]-16.1)
a.append(dB[2]-8.6)
a.append(dB[3]-3.2)
a.append(dB[4])
a.append(dB[5]+1.2)
a.append(dB[6]+1.0)
a.append(dB[7]-1.1)


dBall = []
for x in a:
    dBall.append(math.pow(10,x/10))
somma = sum(dBall)

dB_a = 10*math.log10(somma)
print dB_a
```

geometry, the number or rays (connected to a number slider components, to allow fast variation of the accuracy of the calculation), the cut-off time (in ms), the image source order, the source, the receivers and the octave bands The Image source calculation is performed by the Image Source component, requiring beside the geometry, the Source and the reflection order inputs. The Direct Sound component collect the Source and the geometry of the room. The output of Direct Sound, Image Source, RayTracing components are plugged in the Energy Time Curve component, along with the Octave band output. Finally, the Sound Pressure Level for each receiver is obtained using the SPL components; the output, collecting the SPL for each receiver sorted by octave bands is visible in the green panel in the image.

To obtain a single value of sound pressure describing the acoustic field for each receiver, the Sound Pressure Level weighted with the A curve was calculated. To ease the algorithm, a custom component was written in Python to do the calculation and return the value. The script of the python component is visible in the image below.

MATERIALS

As mentioned, PachydermAcoustic applies material by layer. Consequently, in the model each layer, beyond containing a specific set geometry, is associated to a specific material.

The procedure to set the material specifications is as follows. From the Rhinoceros interface, type PachyDerm_Acoustic in the command bar: the Pachyderm interface is opened and the materials can be set from the "material" menu, by defining the absorption and scattering coefficients. Pachyderm allows to save the absorption coefficients of material under a name set by the user; this function is extremely useful to assign material to the layer avoiding to manually insert the coefficients. The scattering coefficients, diversely, cannot be saved, and need to be set every time manually for each layer.

SOUND SOURCE AND SOUND RECEIVERS

The overall number of receiver placed was 48. 36 receivers were placed in the loggias and balconies of the design façade. All receivers were set at a height of 1.65m and were set at different distance from the rear façade in order to analyze the SPL within the loggias and on the balconies and compare the values. The position of the receivers was defined in accordance to the ISO 1996-2:2007 normative, titled "Acoustics - Description, measurement and assessment of environmental noise". The norm at point 8.3 identifies the appropriate measurement procedure of noise in outdoor environment, defining the position of the microphones in respect to the reflecting surface, that in this case is that of the building façade. According to the norm, microphones should be placed within 0.6 and 2m from the reflective surface.

Therefore, the microphones on the balconies were set at a distance of 2 meters from the façade, while the ones in the loggias were 0.6 m far from the wall. The sound pressure levels were sorted in accordance to the position of the receivers, to separate the most external ones – plotting the acoustics of the balconies – to those placed more internally, within the loggias.

Beside the microphone over the design facade, it was considered of interest to investigate the effects of the proposed design variations over the SPL measured at the street level and over the façade of the opposite building. Therefore, a new line of receivers, similar to the ones at the upper floors, was added at the street level, at and height of 1.65 m and a distance of 0.6m from the facade: to cut the time of the simulation, the number of receivers was reduced to 6, placed coherently with the grid of the receivers on the upper floors. Moreover, 6 receivers were placed on the balconies of the opposite building, 2 per each floor. These receivers, in accordance to the ones placed in the design façade, were positioned at 0.6m from the façade, and therefore their results can be compared to the ones observed in the design façade.

SETTINGS UPDATES TO ALLOW THE CONSIDERATION OF THE COMBINED EFFECT OF GEOMETRICAL AND MATERIAL OPTIONS

The analysis the combined effect of geometrical and matetrial options over the acoustic of the street canyon, impied the acoustic assessment of 1152 design options.

The performative analysis were pursued with a partially-automated procedure, empowered by Galapagos, a component integrated in Grasshopper. This component is a single-objective solver which employs evolutionary algorithms to problem solving. In order to work, it requires a set of variables (i.e. number slider components to which it is connected) and a numerirc value, that describes the result obtained, and a fitness function, who defines the objective of the optimization procedure. By iteratively change the variables, it is able to identify sets of design options featuring better performances, until the "optimal" one is identified. Galapagos can perform optimization by exploiting Genetic Algorithm or a procedure known as Simulated Annealing.

This component, although developed as an optimizer, has been used in this phases to automate the simulations.

PARTIAL AUTOMATION WITH GALAPAGOS

Galapagos is a solver integrated in Grasshopper. The potentialities offered by this tool have been exploited in the case of the assessment of the 1152 design options, to speed up the simulation process by automating the variations of the number sliders.

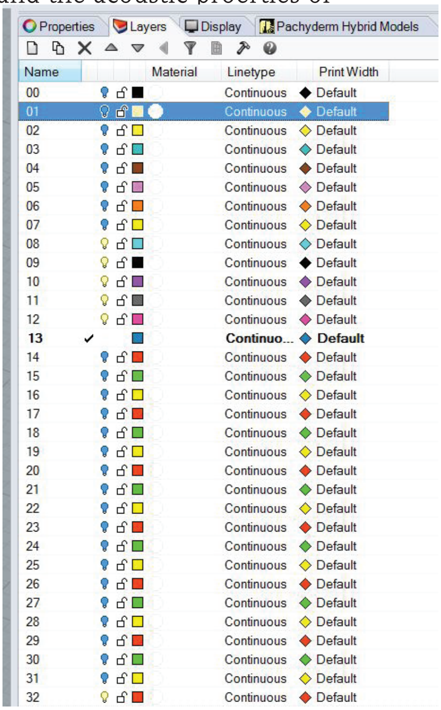
The Rhino model defining the geometries was developed in a way similar to the one used to perform the analysis of the geometrical changes.

All geometrical configurations investigated were saved in separate layers within the same Rhinoceros file. In this case, however, it was required to subdivide the surfaces defining the balconies into three separate layers: one for the parapets, one for the under-balcony and one for the floor. This division was dictated by the need to consider the parapets and the under-balconies separately, as the effect of material changes applied to these surfaces was investigated. The balcony floors, although not affected by the material changes, were placed on a different layers as its geometry changed in relation to the configuration of the balcony.

The geometries defining the parapets, the under-balconies and the boundary surfaces of the loggias were recalled in Grasshopper using the Geometry Pipelines components as it was done in the previous sets of simulations.

The material variations were introduced by connecting Number Slider to the components defining the pertaining layer for each of the geometries imported with the Geometry Pipelines. In this way it was possible to change the material (i.e. layer number) applied to the surfaces for each iteration. As Number Sliders can only variate within a range of continuous values, it was required to set the layers accordingly. Four layers were therefore created in sequence to define the acoustic properties of each of the three group of surfaces considered. The acoustical coefficients describing the acoustic performances of the material were set in Pachyderm following the procedure previously described.

Once the geometry pipelines, the number sliders and the acoustic proerties of the materials were set, Galapagos was connected to the numbers sliders and to the number component describing the average SPL recorded over the design facade. The functionalities of Galapagos were used not to pursue an actual optimization process, but merely to automate the variations of the materials applied to the surfaces: indeed, Galapagos iteratively analyzed the 64 material combinations without the intervention of the operator. In this way it was possible to analyze the performances of 1152 by setting 18 automated procedure in Galapagos, each analyzing a certain geometrical configuration.



The four layers containing the surfaces defining the balconies and the ceilings of the loggias were recalled by typing their identification number

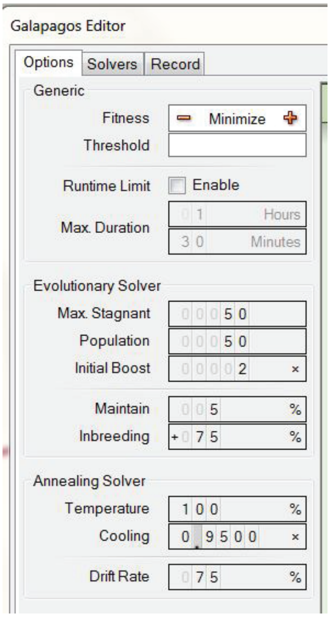


image B.5_setting of the Galapagos simulated annealing solver.

in the Geometry Pipelines components connected to the proper range of layers that defines the material changes.

By double clicking on the Galapagos component, it is possible to open its interface and set the solver. In this case, it was considered more effective to employ the Simulated Annealing solver. The setting used to perform the simulations are reported in the image aside.

The algorithm to perform the acoustic simulation is similar to the one used in the investigation of the effects provided by the geometrical configurations only.

In this case, given the number of simulations to perform, the number of rays used is 50000 instead of 100000.

The average of the SPLs obtained with simulations employing 50000 and 100000 rays were compared to ensure that the accuracy of the results was maintained.

The comparison showed that the differences between the results obtained with the two setting was negligible, namely the SPL differed of about 0.1 dB. The time required to run the simulations with 50000 rays was halved.

One of the drawbacks of Galapagos is that it does stores the input (variables) and output (simulation results) of the performative assessments. In this case, on the contrary, it was required to store for each iteration the averaged SPL recorded in the three locations along with the information regarding both the material combination and the geometrical configuration under analysis. Consequently, a custom component written in C# was created. This “Galapagos Recorder”, for each iteration pursued, collects the data regarding the materials applied to the surfaces (layer number), and geometry configuration (ID code) and the average SPL measured in the street level and in the two facades investigated.

The input required by the compoent are: the identification name of the number sliders whose variation need to be recorded, the path to .txt file defined by the user, the panels in which the results of the SPL in the three locations is printed.

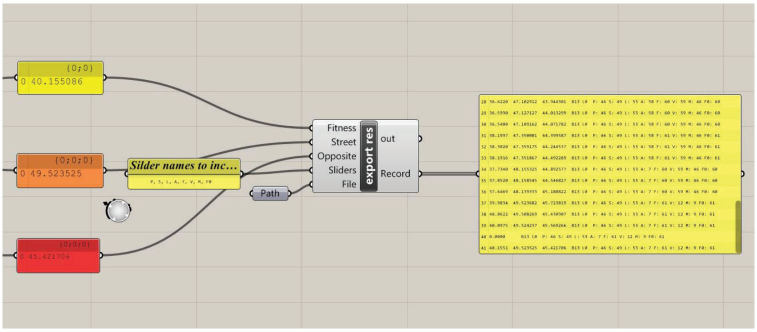
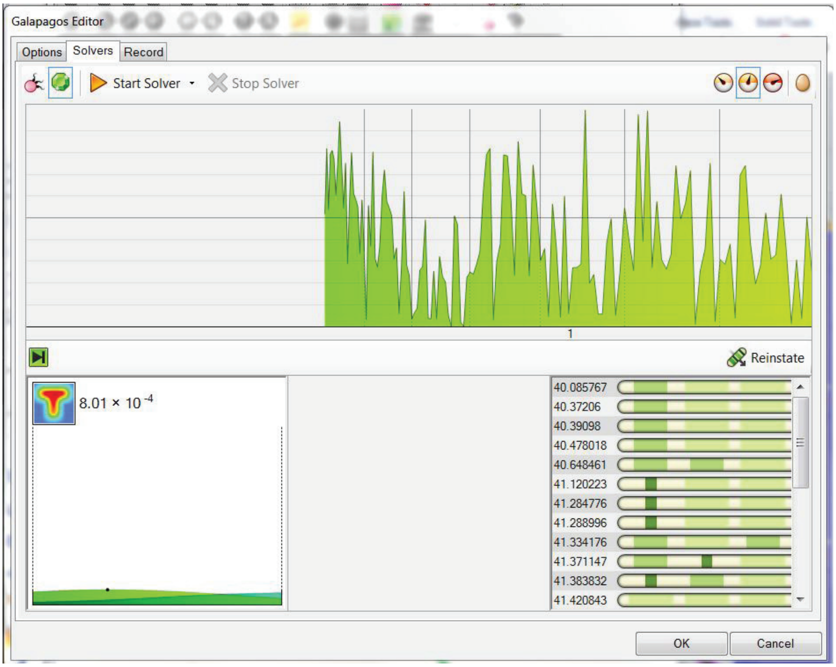


image B.6_custom component written in C#, connected to the panel plotting the averaged SPL measured in the three locations and the panel recalling the number sliders names to be recorded. The panel on the right shows tha context printed by the component in the txt file.

The solver iteratively analyzed all the possible material combinations and ordered the options from the most to the least performative. In the image below the interface of Galapagos at the end of the simulations set is shown.



The data referred to each simulation round was stored in an external .txt file created by the operator. Once the simulations were concluded, the content of the files were copied in an excel spreadsheet, in which they were automatically distributed in the columns and lines of the table.

The C# script allowing this procedure is reported in the image at the end of the Appendix.

FINAL CONSIDERATIONS

Galapagos is not likely to be the best tool to pursue this kind of procedures. It was developed as an optimizer, best works with continuous values and does not support the export of the results nor it record the variables associated to each iteration. In this case it was used merely to automate the simualtions, and a custom component was required to store data. Moreover, after all the possible options have been analyzed, Galapagos repeats the simulations , and no function was found to prevent this to happen. These are some of the main drawbacks of the followed procedure, that could be enhanced by employing more time-saving and simple solutions.

```
<summary>
This class will be instantiated on demand by the Script component.
</summary>
lic class Script_Instance : GH_ScriptInstance

lity functions

bers

**/
rivate void RunScript(double Fitness, object Street, object Opposite, string Sliders, string File, ref object Record)

 // Create the line of text describing the current state.
 var sliders = FindSliders(Sliders);
 var sliderStates = new string[sliders.Length];
 for( int i = 0; i < sliders.Length; i++)
   sliderStates[i] = string.Format("{0}: {1}", sliders[i].NickName, sliders[i].Slider.GripText);
 var currentState = string.Format("{0:0.0000} \t {1:0.0000} \t {2:0.0000} \t {3} \t {4}", Fitness, Street, Opposite, "B13 \tL0", string.Join(" \t", sliderStates));

 // Append the current state to the file. This will create a new file if it already exists.
 System.IO.File.AppendAllLines(File, new string[] { currentState });

 // Output all data from the file.
 Record = System.IO.File.ReadAllLines(File);

**/

rivate Grasshopper.Kernel.Special.GH_NumberSlider[] FindSliders(string nameString)

 string[] names = nameString.Split(",".ToCharArray());
 var array = new Grasshopper.Kernel.Special.GH_NumberSlider[names.Length];

 // Find all sliders by nickname.
 for (int i = 0; i < names.Length; i++)
 {
   string name = names[i].Trim();
   foreach (IGH_DocumentObject obj in GrasshopperDocument.Objects)
   {
     var slider = obj as Grasshopper.Kernel.Special.GH_NumberSlider;
     if (slider == null) continue;
     if (slider.NickName.Equals(name, StringComparison.Ordinal))
     {
       array[i] = slider;
       break;
     }
   }
   if (array[i] == null)
     throw new Exception("Slider with name: " + name + " could not be found.");
 }

 return array;
```

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