POLITECNICO DI TORINO

Corso di Laurea Magistrale in
Architettura Costruzione Città

POLITECNICO
DI TORINO

Tesi di Laurea Magistrale

Classroom acoustics design: algorithms to optimize typology, extension and position of acoustic materials to improve teaching-learning activities.

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Dicembre 2019

CLASSROOM ACOUSTICS DESIGN: ALGORITHMS TO OPTIMIZE TYPOLOGY, EXTENSION AND POSITION OF ACOUSTIC MATERIALS TO IMPROVE TEACHING-LEARNING ACTIVITIES.

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Master thesis

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Polytechnic University of Turin
Master Degree in "Architecture Construction City"
Academic year: 2018/2019

ABSTRACT

The acoustic conditions of classrooms received a lot of attention in the last decades because of their essential role to guarantee effective teaching and learning, especially at the baseline levels of the educational path. Most classrooms in Italy, of every grade and type, do not meet the minimum acoustic requirements for make them fit for their function since until now the laws were obsolete, not in line with the most updated international standards, and so often not observed.

The purpose of this study is to improve the acoustic quality of classrooms for a better teaching-learning process by the development of an algorithm which transposes the indications of the new Italian UNI11532 standard in order to aids, in addition to checking compliance with the acoustic targets, in the optimization of typology, extension and position of acoustic materials. It is a tool addressed to architects, building designers and professionals alike that are involved in the planning, construction and renovation of rooms.

One classroom in Turin has been selected for this study and a basic geometric model has been built in Grasshopper, that serves as the environment for parametric investigation and improvement of acoustics parameters. Reverberation time and STI, which are considered as the most important descriptors in classroom acoustics have been determined using theoretical calculations (Sabine, Eyring and Barron&Lee theories) and geometrical acoustic (GA) simulations (Pachyderm). The latter allows to take into account the scattering properties of surfaces and different combinations of all the acoustic materials . Finally, Octopus has been used to perform multi-objective optimization runs considering as objectives the acoustic parameters and the acoustic design/renovation costs. The algorithm has been developed in order to allow to choose different optimization sets depending on the material or the type of acoustic treatment to optimize.

So aid model provides, essential information on the acoustic quality of the classroom and recommendations on how to increase it by improving teaching-learning activities; information which would normally be time-consuming. The results show that the GA simulations and theoretical calculations are compatible for the solutions without scattering properties. However, the tool developed needs further development in order to extend its application field and provide a user-friendly interface to allow an easy approach for non-expert practitioners.

PREFACE

This thesis is the final work submitted for completion of the Master’s degree in “Architettura Costruzione Città” at the Politecnico di Torino.
In October 2018 I started working on this thesis, however, the interest in this topic started well before, when, within the research project “Io Ascolto”, a series of acoustic measurements were taken in several school classrooms in Turin. Before I did not know how important the acoustics of the classroom were for the teachers but especially for the pupils.
At the beginning, this work had to include only a parametric model of a classroom, together with the evaluation of acoustic parameters to characterize its acoustical performance and its optimization but it ended up to include much more than that.
During the first months I had to learn new software needed to carry out my research and improved my knowledge about the topic. Learning the possibility of the Grasshopper software, I started to think that my thesis work had to be useful and valid for more than one classroom. Hence the idea to develop an algorithm and so a checking and optimization tool of the classroom acoustics that can guide the choices made by architects and by technicians in general. The originality of the proposed tool consists in its uniqueness and versatility.

My research project brings together the topics of architectural acoustics, programming language, parametric modelling and optimization. However, this was very positive, not only because this thesis now looks better than it did before, but also because it has turned out to be an interesting and amazing challenge as I had the opportunity to acquire new skills and thus to improve my knowledge and finally to work on a real case study concerning a classroom. I never imagined I would be able to do all this.

A lot of time has passed since I typed the first lines of this paper, but on the other hand, I have been doing some other things since then. But this is another story about which I will perhaps still write someday.

Just one more thing: if you decide to go on with the reading of this thesis, please, enjoy it.

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0. INTRODUCTION

In Italian schools there is too much noise, the acoustics is norm-less in 9 classrooms of 10 and the teaching and the health of teachers and pupils are the first to be affected. This reveals a study conducted by Ecophon Saint-Gobain [1], on a representative sample of schools. In many cases the limits allowed by the law are exceeded, indeed the reverberation time, in some schools, has even reached peaks of 3 seconds. The maximum threshold set by Italian law [2] is a reverberation time of 1.2 seconds, but in other European countries the limits are even lower, such as in Norway with 0.5 seconds [3] and in England with 0.6 seconds [4] .

Classroom poor acoustics is a major problem in educational environments because of its negative effects on teaching and learning activities. Italian national standards aim at providing indications on the optimal ranges for those parameters that guarantee appropriate acoustical quality for learning purposes (e.g. reverberation time, clarity, speech transmission index) [2, 5-7], but many school buildings date back to early XX century and therefore would need to be completely renovated in order to comply regulations.
Nowadays, the attention to quality within school environments is increasingly of public interest and this work represents an experience of acoustic renovation of the classroom. The main purpose of the study is to provide a guiding-tool that can supports the choices of both the design and acoustic requalification of the classrooms and investigate the effects of different degrees of acoustic treatments, aiming at guaranteeing high acoustical quality for speaking and learning.

This tool was developed in Grasshopper [8], included with Rhino 6 [9], and follows the indications set out by of the new UNI 11532 standard, currently in public consultation and ready to be published. As far as the working method is concerned, during the algorithm development phase, the parametric model in Grasshopper was essential to check its integrity while a parallel Excel sheet [10] allowed to verify the correctness of statistical acoustics formulas, implemented in Python [11] .

Three models of algorithm have been developed to perform an in-depth analysis of various acoustic configurations for the classroom finding some solutions regarding the placement and use of different acoustic materials.
The first two models use the analytical formulae of acoustics to determine those parameters considered as fundamental to obtaining good acoustics while the latest one uses a ray-tracing based codes, Pachyderm Acoustic [12] for Grasshopper. The reason for these choices will be later clarified.
So, some comparisons and considerations will be made based on various parameters predicted. In addition, various multi-objective optimizations will be made to understand the best configurations to ensure certain acoustical standards in the classroom also in relation to the cost-effectiveness.
The comparison between the measurements made before and after the computer simulated acoustic correction operation relates to a classroom of a primary school in Turin.

0.1. Research objectives

The stated objectives of this research project can be summarised as follows:

- design and develop an algorithm that can be both a checking and optimization tool of the classroom acoustics, therefore a mean of supporting the choices in the subject;
- calibrate and test the tool on a real classroom in Turin analysing the current situation and prepare for the subsequent acoustic simulation;
- advance variants of the algorithm in order to find out which one better predict the acoustical performance of the room;
- explore how different geometrical and material features of the acoustical treatments can contribute in enhancing the acoustic quality for the classroom.
- handle the large amount of data obtained from multi-objective optimizations and to figure out which solutions are optimal to find the best scenario that ensures a good environment for children’s learning, also considering their cost and compare them.

0.2. Structure of the thesis

This thesis work is divided into two parts: the first deals with theoretical aspects of the classroom design and acoustics and the new Italian standard on this matter, while in the second part a case study is considered in order to develop and test an algorithm taking into account some topics highlighted in the previous one, in order to evaluate the acoustic performance of the classroom and optimized it.

This thesis is organized into six chapters. In the first two ones an introduction to the classroom environment, its design and acoustics, its acoustic parameters and an overview of the acoustic materials is given. Therefore, it is difficult to set the limits of this part, and some readers may find no need to read it, as it might not tell them anything new. However, it has been considered a fundamental part in this work, because many final outcomes and considerations could not be understood without the knowledge of the latter.

The third chapter of this work deals with the new UNI11532 standard outlining the directions given and the key points that will be essential to design the algorithm.

In the fourth chapter the themes considered in the previous steps are applied in the development of the algorithm. The calibration method of the parametric model and the case study used to test the tool developed is illustrated. So, it offers an overview of the algorithmic implementation of the parametric model and of the indications in the aforementioned standard. A set of geometrical and material options for acoustical treatments is proposed. Each variation can be studied thanks to the developed algorithm, this will allow to measure how the acoustics changes in the classroom.

The fifth chapter deals with existing modelling methods: empirical, wave-based, and geometrical acoustics methods. Their principles, limitations and accuracy are explained. The previous algorithm has therefore been modified to implement these methods and reassess the acoustic performance of the available configurations of acoustic treatments, in an optimization way too.

The last chapter offers a comparison between the three algorithmic models in optimizing the classroom acoustic parameters and the best acoustical configura-

tions are presented. So, the paper ends with a discussion of the outcomes, their accuracy, never perfect but satisfactory, and the reasons for similarities and/or differences.
Finally, appendices contain supplementary material, too cumbersome material to be included in the body of the paper, including the python code, tables, diagrams, and results which may be helpful in providing a more comprehensive understanding of the research topic.

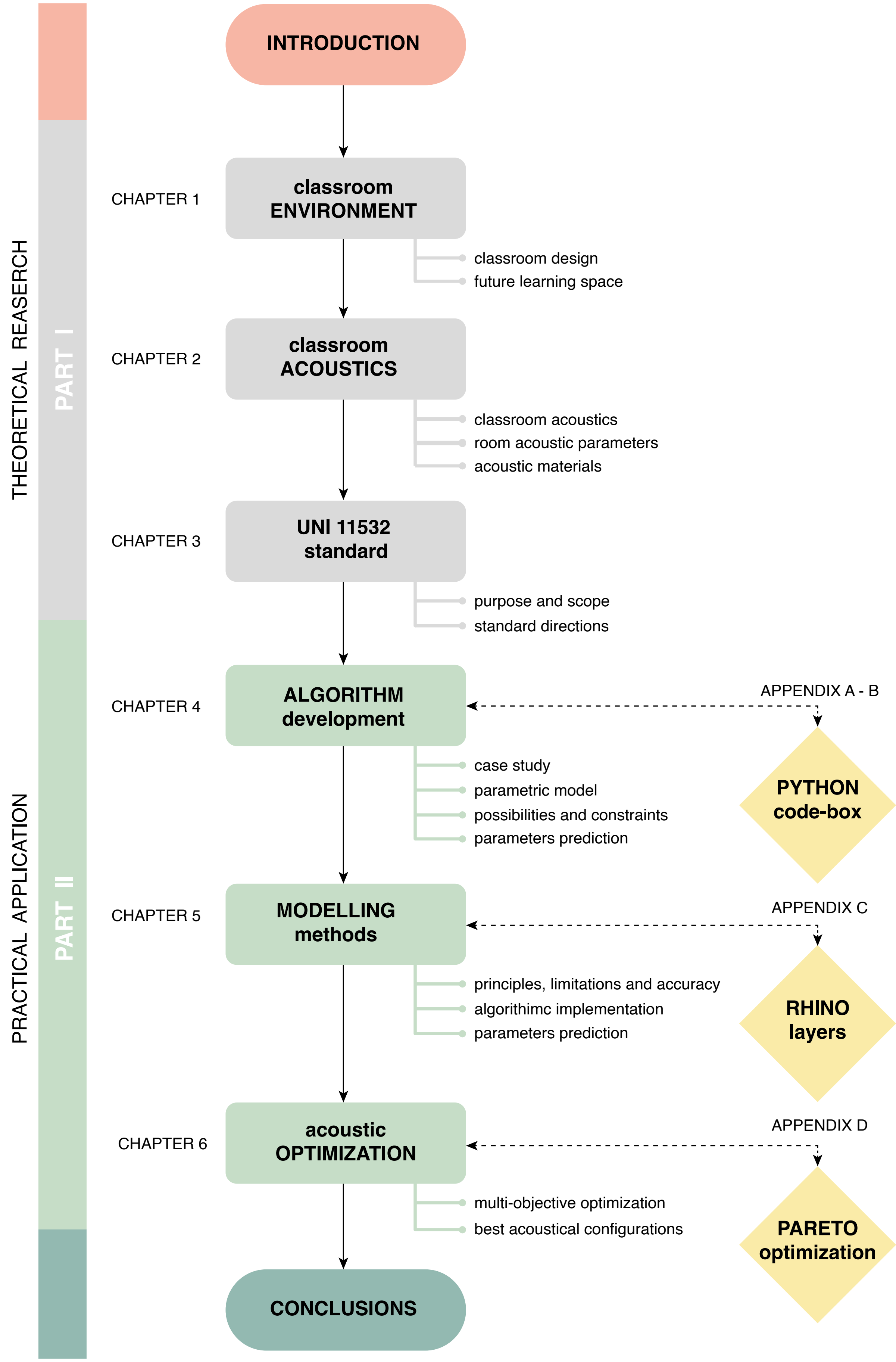

Figure 01. *"Flow chart" of the thesis structure.*

PART I

THEORETICAL RESEARCH

1. CLASSROOM ENVIRONMENT

Classroom environment encompasses a broad range of educational concepts, including the physical setting, the psychological environment created through social contexts, and numerous instructional components related to teacher-students relationship. Research since the mid-1990s [13] has focused on one or more of these aspects and has associated classroom environment variables with numerous positive and negative student effects. More frequently a focus in these studies is about the physical environment that has continued to appear as an influential factor of the behavioural and academic outcomes. Aspects of the architectural classroom design such as class composition and classroom size [14], have been investigated.

1.1. The “hub” of school education

Classrooms are both physical and organizational units where there is a complex relationship between the built structures and their arrangement, teachers, students, and the distribution of the space. The design of classrooms and their shapes can also influence teachers and their decisions on instructional activities differently [15]. In general, smaller classes are associated with students who are less stressed and are more frequently on-task with fewer reported behaviour problems than students in larger classes. Although teachers tend to use similar instructional strategies whether teaching large or small classes, more class time is spent on administrative tasks for larger classes, leaving less time available for instruction.

For a long time, up until a few decades ago, the classroom was only a mechanism for conveying knowledge. Everything was under the control of the teacher who, placing on a platform, had a complete visibility of the classroom.
The classroom was a very uninspiring place and certainly did not encourage the

learning-related activity. A normal room could be used and easily transformed into a classroom, just like any building in a school. In Italy, confronted with a rapid growth of the school population and having to provide for schools even in remote places, thought on the space died in the bud: any rectangular room and few furnishings were sufficient, as mentioned in the Regulation of the Ministry of Public Education of 1860. Basically, no importance was given to the requirements related to well-being, acoustics, lighting, etc.

In 1923 [16] some more precise rules were laid down: the classrooms should have been rectangular, with a height varying from 3.5 to 4.5m; the walls and ceilings had to be painted in light colour and around the hall a 1.80m high plinth, had to be painted in grey; this had to avoid the writing on walls and facilitate cleaning. Today, these dictates might seem obsolete, but how many classrooms, especially in elementary schools, have arrived so far?
As said above, classrooms have always been considered the “hub” of school education, so the remaining spaces have always been seen as ancillary[17]. Each and every school area was designed and structured to serve a specific purpose. It followed that, as the activity for which they were destined was not conducted, they ended up unused [18].

1.2. Classroom shapes and teaching

During the 1920’s, the too rigid system of classroom began to go into crisis, criticisms invested methodologies, but these immediately also ended up involving classroom space and furnishings [18]. As time went by, the evolution of architecture for school buildings has shown that the type-function organization and, consequently, the arrangement of classrooms and furniture have changed in line with the development of new pedagogical concepts (Montessori, Piaget, Malaguzzi, Papert, etc.), and new, improved didactic methods [17].
Many common classrooms are rectangular; this shape is certainly preferable for different reasons:

- low cost and easiness in construction;
- modularity;
- visibility of the teacher;
- compatibility with acoustic, lighting requirements, etc.

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According to Steiner [19], spaces that have rectangular shape activate human thought and can keep it to rigid and linear, where they represent “being efficient” and “narrow minded”.On the other hand, circular spaces represent a more spiritual and heightened sense of feeling.
Therefore, Steiner proposes that these two shapes together reflect “thinking” and “feeling” through architectural design as well [19]. Accordingly, the classroom for the youngest grades should be designed more rounded, whereas the classrooms for older children should be more rectangular as the child’s thought development keep evolving [20, 21]. However, in the acoustic field, circular or elliptic plants should be avoided due to the risk of sound concentration in some positions[22].
Starting from 1970s it finds the L-shape classrooms; introduced to vary from rectangular format classrooms they were designed to catch up with innovative approaches occurred in teaching and learning activities.
An innovative aspect occurred in Montessori schools is the design and use of L-shaped classroom environments [23, 24].

Overall, the literature [25–27] suggests that L-shaped variations of classrooms: can afford flexibility; they provide permanent zones for small groups to work; provides opportunities to create additional, although temporary, activity settings as integrated, flexible and variable systems although the furnishings and furniture in the classroom can be reorganized for individual, one-to-one, small group, and large group activities.

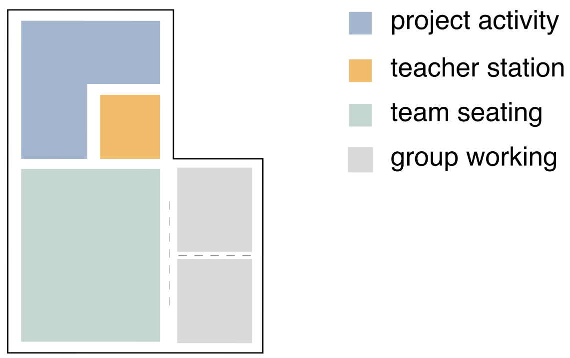

Figure 02. *Conceptual "L" shaped classroom.*

1.3. The classroom of the future: a learning space

Schools are increasingly acknowledging that the traditional classroom with teachers at the front and students facing in one direction for the whole lesson does not enable innovative pedagogical approaches [28].

Up until the 1960's, the main teaching style was didactic with children seated in rows of desks while they listened to their teacher who taught from the front[29]. During the progressive educational reform in the 1960's, however, there was a major shift in teaching style to a more "child-centred" approach which focused on experiential learning and group [29, 30]. This change in teaching style also saw the emergence of open plan classrooms to better facilitate these teaching methods [29].

Policy makers, teachers and researchers have recognised that the opportunity to work in groups, to undertake projects and to collaborate with others beyond the classroom, challenges traditional ways of teaching and learning [28].

Diana Oblinger[31] stated that, “spaces themselves are agents for change. Changed spaces will change practice”. She recognized that spaces designed several decades ago will not reflect the needs of students today while Kuuskorpi and González [32] acknowledged that “the basic structure of teaching spaces does not seem to have evolved much over the past century”.

The teachers of the semi-open plan classrooms in the study by Greenland [33] have confirmed that open plan classrooms enabled a wider range of activities for the children than enclosed classrooms, and that children were more independent and responsible, and benefited socially from the more open plan space. However, at the same time, children in open plan classrooms were more easily distracted visually and by noise compared to children in enclosed classrooms.

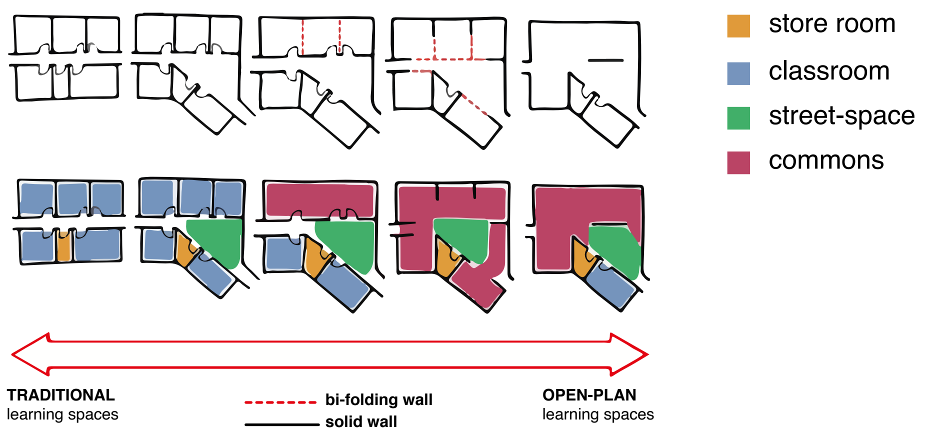

Figure 03. *Evolution of learning-spaces.*

In January 2012, European Schoolnet [34] launched a "Future Classroom Lab" (FCL), an open model of learning zones that provide a way to visualise how different, innovative pedagogical approaches that incorporate ICT (Innovative Technologies for Engaging Classrooms), can be implemented in classrooms and across a whole school. The zones reflect what good teaching should be about: being connected, being involved, and being challenged [28].

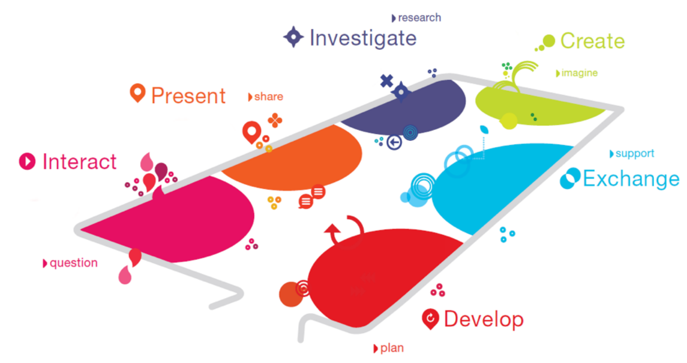

Figure 04. *Six learning zones in the FCL [28].*

1.4. An integrated approach for the classroom design

Even quite small changes to existing classrooms and other spaces within a school can have an important impact on teaching and learning [28].

The Clever Classrooms Report [36] highlighted that differences in air quality, colour and light together can increase the learning progress of primary school pupils by as much as 16% in a single year. However, the report states that the size of the school are not considered to be as important as the design of individual classrooms. The Clever Classrooms report [36] argues that teachers can make small changes "costing very little or nothing", that can make a real difference. For example, there are suggestions for teachers to change the "layout of the classroom", the "choice of display" and the "colour of the walls".

But more needs to be done. Architect should apply an integrated design approach to the design of schools and classroom. The reason for an integrated approach is to consider how changes to one design aspect may impact others; the flexibility of a space, acoustics, ventilation, daylight and energy use are interrelated and a change to one factor often impacts other factors. For example, an effective but noisy ventilation system will introduce fresh air but also increase ambient noise levels [37].

As in any building design, there needs to be a balance between perceiving the whole and breaking the whole down into parts that are easily understood and negotiated [38].

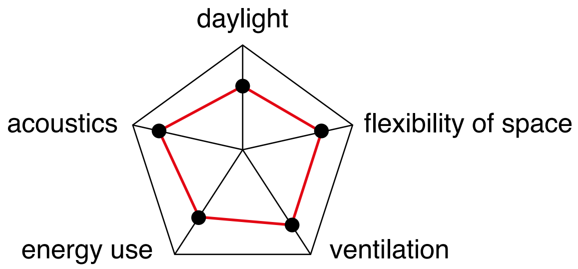

Figure 05. *Conceptual diagram of the integrated design approach.*

Teacher and pupils are at the centre of teaching-learning process, so their needs should be at the heart of a design process. Thus, the importance of communication in a classroom is a foundation requirement for teaching and learning. SCRI Research Report [38]had examined the available evidence of how building design can help schools to create and improve learning environments that are appropriate for current and future educational needs. It explored the impact of learning environments on pupils' achievement, engagement, attendance and well-being. The findings provide a rich source of ideas on improving the quality of the learning environment, so ensuring that pupils and teachers enjoy comfortable communication and a more efficient learning space.

2. CLASSROOM ACOUSTICS

The classroom acoustic conditions are still neglected. Many studies have already shown that poor acoustics in classrooms can affect students and teachers in the teaching-learning process, [39] e.g. inhibit reading and spelling ability, behaviour, attention, concentration, and academic performance [40, 41].
On the other hand, an environment with good acoustics could generate positive effects which includes: reduced vocal strain and voice disorders for teachers; improved concentration; reduced tiredness, fatigue and stress levels; easier to hear and be heard with improved speech clarity; optimized environment for multi-communicational activities such as group work; improved student behaviour and reduced burden on school and classroom management [42].
Theoretical aspects of acoustics such as the parameters for the acoustic characterization of classrooms; and others, more practical, such as surface treatments have been explored.

2.1. The importance of the school classroom acoustic design

When classroom acoustics are poor, it causes problems with how students understand speech, behave, pay attention, and concentrate. Each of these factors can be critical to a student's performance within their education. If a student can not understand what the teacher is saying, they will be overwhelmed by the material and be less likely to ask for clarification questions on the concepts. If these students start acting out, this will further distract other students from their education, and the class will be less effective as a result. This reflects poorly on the students, teachers, and administration.

The acoustic design of school classrooms, both in terms of noise control and room acoustics, is relevant because it affects the quality of oral communication between teachers and students, which is still the most common way of teaching and learn-

ing, and has an effect on the overall performance of pupils, especially those who have not yet developed the skills that allow them to process conversations in the presence of background noise [43, 44].
The efficiency of this communication, and hence, the efficiency of the learning environment, is measured by the acoustic conditions of the classrooms [45]. Excessive noise and late reverberation degrade speech intelligibility [46]. Thus, it is vital to all students because all need to understand the teacher, but it is of particular importance to students who have hearing impairments or learning disorders. The subject of acoustical comfort (ambient noise, sound insulation, reverberation time, speech intelligibility, acoustical materials) in classrooms of primary schools, in secondary schools, as well as in University classrooms has been the focus of several studies around the world [47–51]. Another focus of studies has been the perception of noise by students and teachers, and the influence of noise on those people [52–56].

Besides affecting speech intelligibility, noise and classroom acoustics affect the voice of a speaker. The variation of voice level with noise has been described as the Lombard effect [57]. In situations with only one talker, this talker adjusts the voice power level according to the amplification that a room produces on his voice at his own ears. Moreover, in a scenario with different talkers, the absorption of a room has an influence on the voice power level of each talker, which is known as the café effect [58]. When a teacher speaks in a classroom, besides being heard, he wants to talk comfortably and not to overstrain his voice [43].

2.2. From classroom design to acoustic comfort

There is no perfect classroom design. However, a good acoustics is essential to support learning for all learning environments, from traditional classrooms to future learning spaces [37].
The first aspect to be taken into consideration to guarantee good acoustic quality is the geometry of the space [22]. To correctly dimension the volume for acoustic purposes, the references in Table 01 should be considered, which specify the cubic meters per person depending on the type of activity prevailing in the classroom. Although it does not in itself constitute a guarantee of good acoustics, it can certainly support the subsequent obtaining of suitable conditions.

Table 01. *Volume dimensioning for acoustic purpose [22].*

Intended use	volume index, in m³/occupant
speech	3 to 6
speech and music	5 to 8
music	7 to 12

Once the volume is set, the dimensional relationships and the plant shape are considered. Dimensional relationships must be well proportioned avoiding very long and narrow or excessively low rooms. A rectangular plant is definitely preferable while circular and elliptical plants should be avoided for risk of sound concentrations in some positions. Other shapes, such as trapezoidal plants, can be adopted with the indication to place, if possible, the position speaker on the wider side with the walls converging in the direction towards where the presentation takes place. The other step consists in avoiding repeated and single echoes, and sound concentrations; it is necessary, to manage specifically these reflections through appropriate sound-absorbing or acoustically sound diffusing treatments
So, naturally, in the case of acoustic renovation it can be done by adopting sound-absorbing finish false-ceilings or counter-walls that also corrects the curvature if necessary of the concave surface.

Traditional cellular classroom design typically exhibits good acoustic separation. However, they can restrict opportunities to collaborate, which limits the range of learning activities and concurrent activities that can take place in the learning space. More open and connected learning spaces are more flexible and adaptable and provide greater opportunities for collaboration and a broader range of concurrent activities [37]. They also require management or acoustic separation between different learners and learning activities. An acoustic design that ensures adequate absorption of ambient and activity noise levels is crucial [22]. As far as this possibility is concerned Seep et al. [59] stated that the best way to solve acoustic problems is to avoid them in the design phase.

Movable screens, sliding doors and sliding partitions can be used to divide a larger space into separate areas when required. These can create spatial differentiation in the space; provide nooks and alcoves for small group and individual work. They

also provide acoustic "zoning" in the space, which helps to provide a degree of acoustic separation between activities while maintaining flexibility and adaptability of the space.
Many aspects that appear with the evolution of the modern era serve to deteriorate the acoustic environment of classrooms [60]. In the past, classrooms were silent and pleasant; nowadays, they are relatively more noisy and reverberating [60]. The main reason for the existence of acoustic problems in classrooms is not a lack of resources, but rather, a lack of perception of the problem on the part of the professionals involved and a lack of expertise.
The ability to listen is known to be a duty of the student and not a pedagogic activity or an architectural challenge [44]. Surprisingly, a study conducted in France [61] has revealed that though the range of classroom sizes has remained constant the general acoustic quality of newer schools is often inferior to designs prior to the 1970's.[61]

From the 2000's several countries have introduced standards and guidelines relating to the acoustic design of schools and classrooms. However, they include a number of appendices that are only prescriptive in nature, with specific design suggestions, including choice of materials.

2.3. Existing classrooms

The Italian heritage of school buildings is a large, widespread and largely ancient. More than 60% of the buildings, in fact, were built before 1976 and often require maintenance interventions if not for major requalification [62]. This is enough to understand that classrooms need to be acoustically renewed. A classroom designed without regard to good acoustics will often include a high ceiling of plaster or gypsum board, masonry or gypsum board walls, and tile floor; no coincidence that these are the typical features of historic buildings.

Unfortunately, numerous classrooms fitting this description were built in the days before sensitivity to acoustical needs. In such a classroom, long reverberation times tend to destroy speech intelligibility, especially for younger children. Acoustical problems in existing classrooms can be solved, but the options are often limited. This is because little can be done to change the architectural infrastructure

or HVAC system without great expense. Consequently, the most common and affordable solution is to control reverberation through the addition of sound absorptive materials.
American National Standards Institute [63] set out some criteria to improve the acoustical environment of an existing classroom:

- install a suspended acoustical ceiling in a classroom that does not have one;
- if an acoustical ceiling is already in the room, replace panels with more performing ones;
- add baffles and/or rafts;
- replace window panes, if possible, to isolate the exterior noise;
- install vibration isolators under HVAC equipment, if any, and silencers in the ductwork.

Solutions like these do not significantly increase the construction cost of building a new building. It is when they are included as part of a retrofit that they usually involve high costs.

2.4. Classrooms acoustic parameters

The acoustic performance of a classroom is measured in terms of acoustic parameters, these ones are of particular importance because they are more directly and strongly linked to the intended use of environments. The Reverberation Time (RT) still remains the primary indicator of room acoustic response and it is also known to be the most common descriptor in building standards for room acoustics. But the RT alone can be insufficient to describe the acoustic conditions in non-diffuse environments, especially in rooms where the typical solution is a sound absorbing suspended ceiling; the majority of absorption is on one surface which normally leads to a non-diffuse sound decay

Another parameter, to evaluate the acoustic response better of classrooms is used, the Speech Clarity (C50). The clarity of sound perception is closely related to the duration of the "sound queue" in the room, conventionally evaluated with the measure of reverberation time. In the case of listening to the word, the contribution of the sound reverberation must be such as to create a favourable compromise, which can contribute to direct sound reinforcement, without too long queuing of the tail, masking the signals that take time. Noise from the outside environment

and noises generated in a room cause background noise or residual noise.
Noises can mask the sounds produced by a the speaker and can disturb listening, causing a disagreeable and annoying hearing and hence a general state of dissatisfaction with acoustic conditions [51]. Excessive reverberation and high background noises reduce the intelligibility of the word, understood as a percentage of words or phrases properly perceived by a listener in relation to the totality of the words or phrases spoken by a speaker. Depending on the environmental phenomena mentioned, it depends on the characteristics of the human voice, in particular the intensity of the emission, which varies with the speaker's vocal strain. The most widely used parameter to objectively quantify the speech intelligibility is the Speech Transmission Index (STI).

These three acoustic descriptors are briefly defined e described below so it can give a better understanding of why they all together will give a better evaluation of classroom acoustic quality than just one of them [64].
To avoid confusion, the calculation methods and the parameters target values, as set out by the Italian standard, and used in the algorithm development, will be presented in the next chapter.

2.4.1. Reverberation Time

The Reverberation Time (RT) is defined as the time in seconds required for the level of the sound to drop 60 dB after the sound source is turned off. This sound decay can be measured on a spot in the room after precisely, the switching off of a sound source or by using a room impulse response and reproducing the decay curve that would be produced from a continuously operating source.

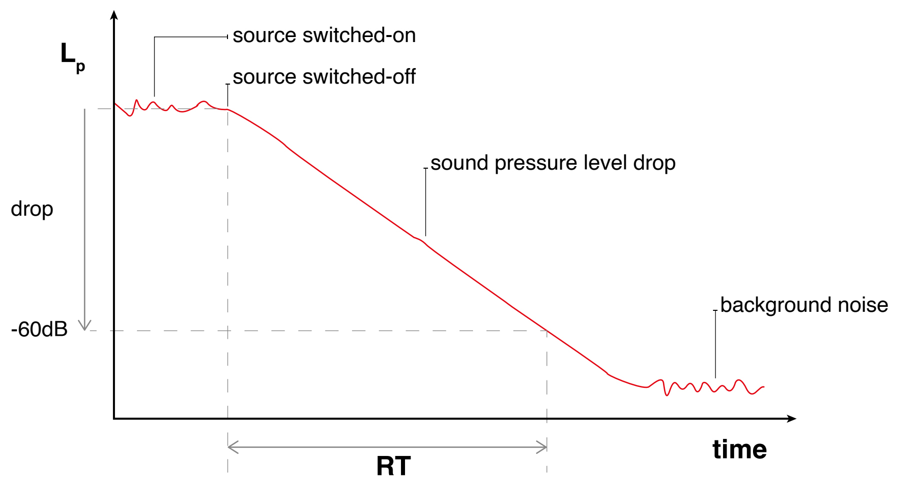

Figure 06. *Graphic representation of the Reverberation Time.*

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It can be calculated using the Sabine formula (1), developed by W.C.Sabine in the late 1890s, and still remains the preferred descriptor to evaluate room acoustics in schools, healthcare facilities and offices, even though most rooms in these buildings cannot be described as a diffused since the acoustic treatment (if any) is normally on one surface only; the ceiling.

$$RT = \frac{0.161 \cdot V}{\sum_{1}^{n} \alpha_n \cdot S_n} \quad [s] \tag{1}$$

where

V is the total room volume, in m³;

α_n is the sound absorption coefficient for partial surface, S_n;

S_n is the surface area of the material, in m².

When measuring RT, it is in practice difficult to reach full 60 dB decay due to e.g. background noise. Instead a decay range of 20 or 30 dB are commonly used. According to ISO 3382 [65] the reverberation times given by the limited decay ranges are denoted T20 and T30, respectively and when determining T20 and T30, the evaluation does not start until the sound level has already fallen by 5dB.
If the reverberation curve is a straight line (solid line in Figure 07) the reverberation times T20 and T30 will be equal. However, if the decay curve is bent (dashed line in Figure 07) these descriptors will differ. The latter occurs typically in rooms with only one absorptive treatment of the ceiling.

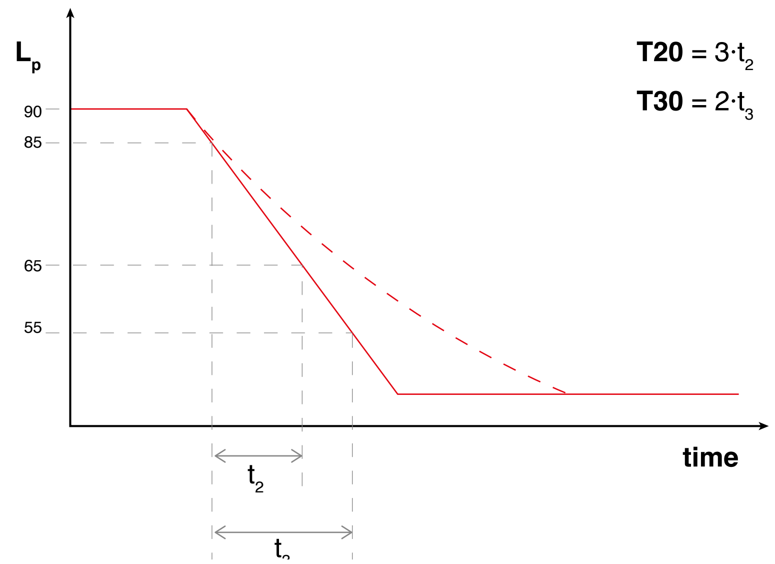


Figure 07. *T20 and T30 can differ if the decay curve is bent.*

Depending on the volume and the use destination, each room has an optimal RT, it can be empirically obtained from the following graph.

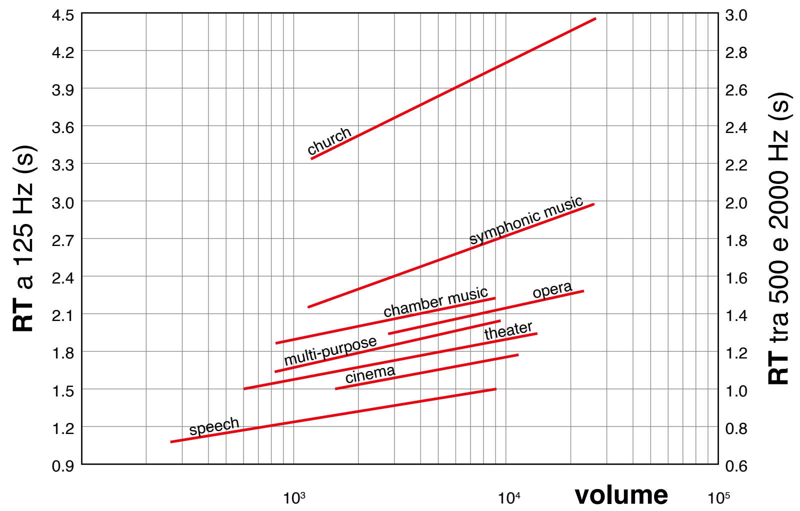


Figure 08. *Optimum reverberation time for intended use.*

2.4.2. Speech Clarity

The Speech Clarity (C50) is expressed in dB and it is an objective measure of the clarity of speech (C80 for music). It is mentioned in the norm ISO 3382 [65] and was defined by Reimer and Muller. The basis for C50 is the fact that late reflections are unfavourable for understanding speech because it causes speech sounds to merge making speech unclear. However, if the delay does not exceed a certain time limit, the reflections will contribute positively to the intelligibility.

The critical time limit separating useful from detrimental reflections is precisely 50ms. For younger people the limit is slightly lower. In fig1. C50 an impulse response is shown where the region for useful and detrimental reflections are indicated.

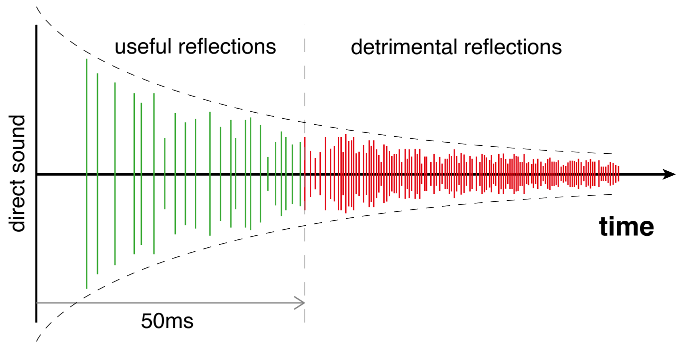


Figure 09. *Relation between useful and detrimental reflections.*

C50 compares the sound energy in the early reflected sound with those that arrives later and represents the ratio between the energy coming to the listener's

ears during the first 50 milliseconds and the energy coming to him from that moment to the end of signal decay.

So, ultimately, C50 measure the ratio of the early sound energy (between 0 and 50ms) and the late sound energy (that arrives later than 50ms), as defined by (2):

$$C50 = 10 \log \frac{\int_{0}^{50ms} p^2 \cdot (t)dt}{\int_{50ms}^{\infty} p^2 \cdot (t)dt} \quad [dB] \qquad (2)$$

C50 is derived from measurement of the impulse response and can assume both positive and negative values: high value is positive for speech clarity.

The impulse response is the pattern showing how reflections from an impulse sound, like a hand-clap or a pistol shot, arrives at different times to the listener. Furthermore, C50 is related to the structure of sound reflections end consequently to reverberation time but also to the distance between speaker and listener.

2.4.3. Speech Transmission Index

The Speech Transmission Index (STI) is an objective measure to predict the intelligibility of speech transmitted from talker to listener by a transmission channel, although it is related to subjective intelligibility scales. As already mentioned above, the intelligibility is understood as a percentage of words or phrases properly perceived by a listener in relation to the totality of the words or phrases spoken by a speaker. STI, basically, measures quality of speech transfer from speaker to listener in an index ranging from 0-1: the higher the STI value, the better speech intelligibility will be.

Below, in Table 02, the relationship between STI values and the quality of speech intelligibility in accordance with the IEC 60268-16 standard, is given.

Table 02. *Speech intelligibility quality based on STI value.*

STI value	quality of the speech intelligibility
$0 < STI \leq 0.3$	bad
$0.3 < STI \leq 0.45$	poor
$0.45 < STI \leq 0.55$	fair
$0.55 < STI \leq 0.75$	good
$0.75 < STI \leq 1$	excellent

It is based on the relation between perceived speech intelligibility and the intensity modulations in the talker's voice, as described by Houtgast, Steeneken and Plomp [66] and reported in the IEC 60268-16 standard [67]: when a sound source in a room is producing noise that is intensity modulated by a low frequency sinusoidal modulation of 100% depth, the modulation at the receiver position will be reduced due to room reflections and background noise. The Modulation Transfer Function (MTF) quantifies the reduction of the modulation index mi of a test signal with spectral characteristics typical of a real speaker and describes to what extent the modulation m is transferred from source to receiver, as a function of the modulation frequency F. Hence, the MTF depends on the system properties and the background noise.

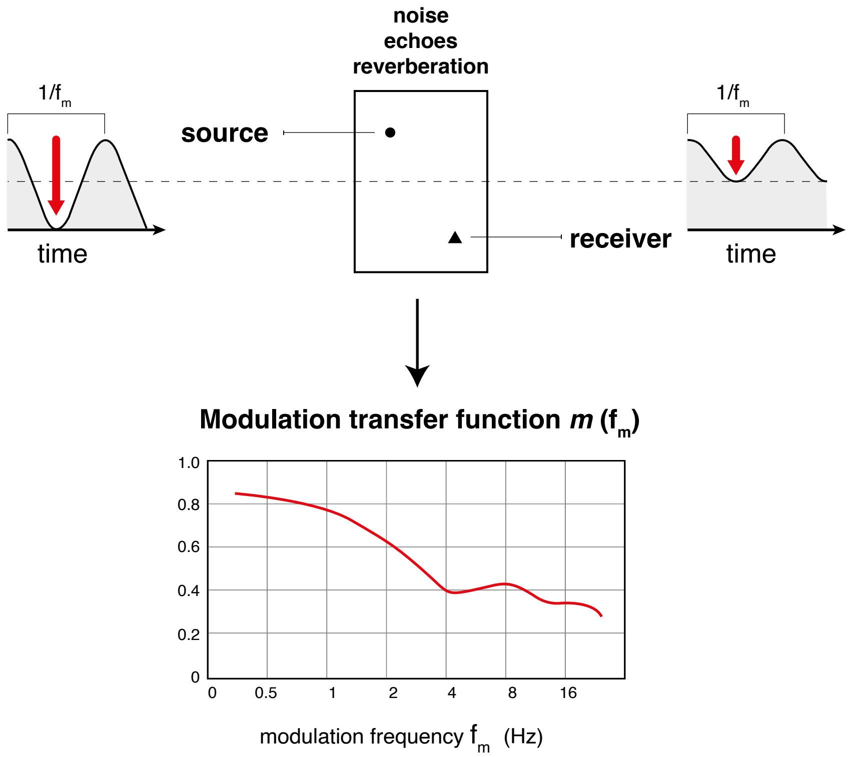


Figure 10. *Reduction of the modulation of a speech signal as a result of background noise, echo and reverberation.*

2.5. Acoustics materials

The acoustic parameters must be controlled through a proper project, whether it concerns new architectural design or, simply, acoustic renovation.

The application of sound absorbing materials in closed environments, for example, results in a reduction in reverberation time by absorbing the energy of late re-

flections and undesirable background noise. In fact, the aim of an acoustic absorption is to achieve an optimal value for reverberation time depending on the type of environment and the activities that take place inside. Each material, in acoustic terms, is characterized by an absorption coefficient representing the relationship between the absorbed energy and the energy that strikes the material itself. When a sound-wave 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). According to the law of conservation of energy (3), the sum of the three coefficients that express the rate of incident sound energy that is absorbed (α') reflected (r) and transmitted (t) is 1.

$$\alpha' + r + t = 1 \tag{3}$$

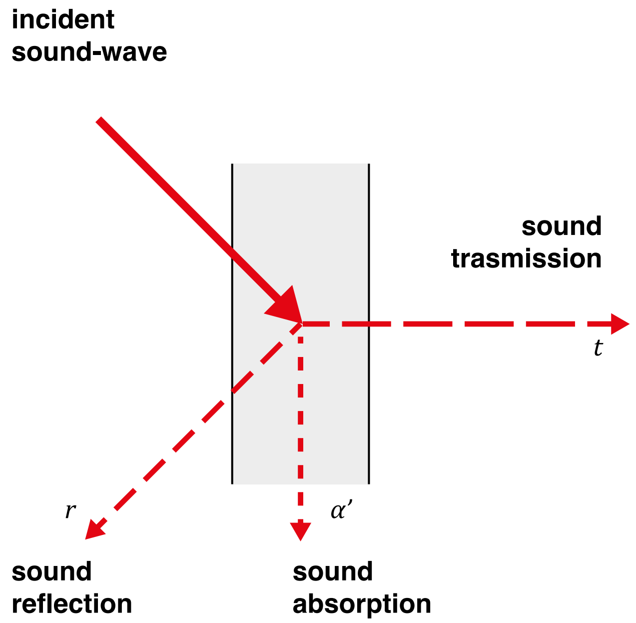


Figure 11. *Sound-wave propagation.*

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 [68]. If, indeed, 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, that complex phenomenon of reflection, known as scattering, takes place [69]; but we will discuss about that later, in the fifth chapter.

Although all materials, when stroked by a sound-wave, absorb, transmit and reflect sound energy, they are commonly classified according to the predominant phenomenon that occurs as absorbing, reflecting or scattering materials.

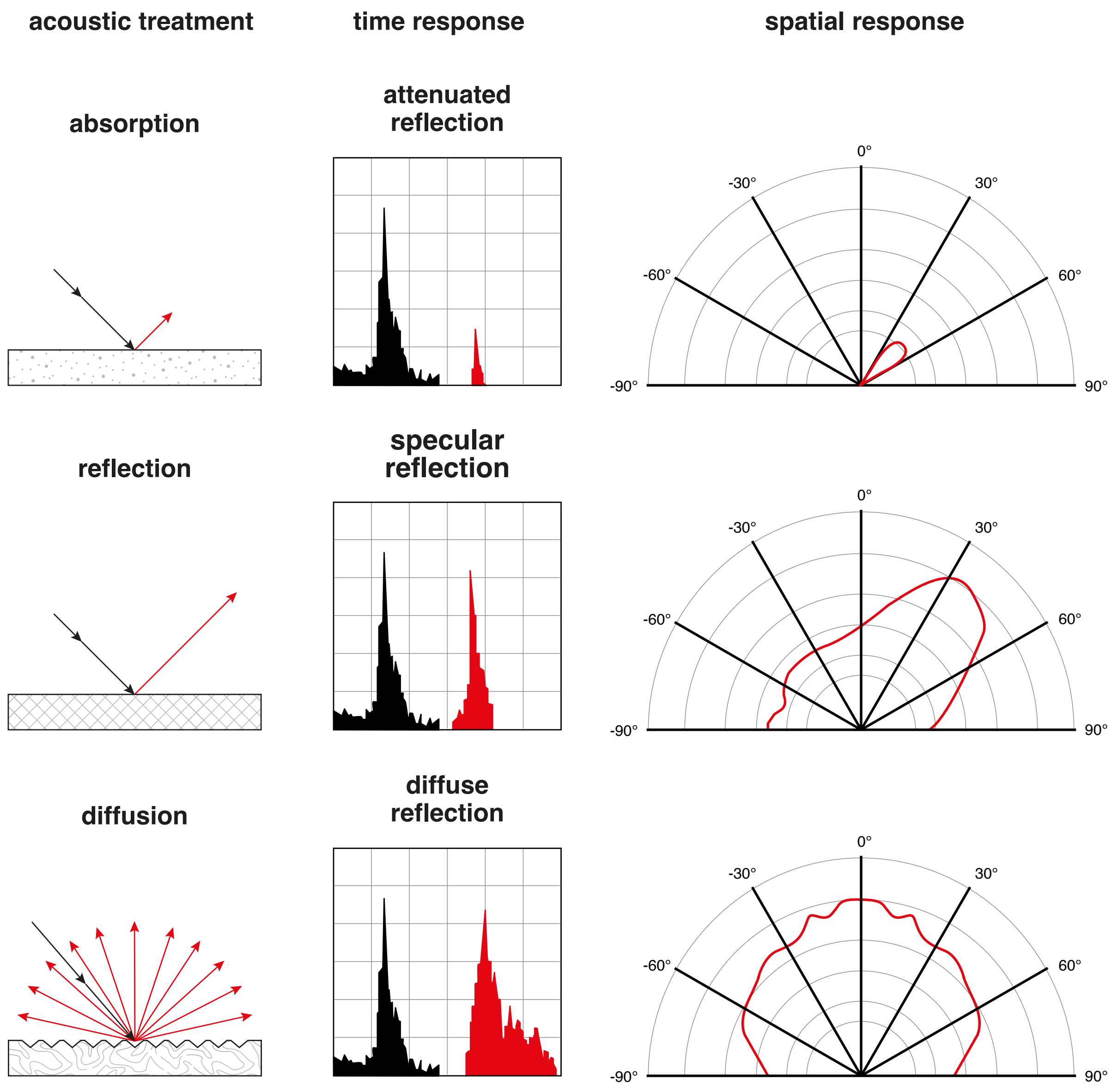


Figure 12. *Correlation between reflection phenomenon and absorbing materials.*

During the last century, 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. 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 sound pressure level (SPL), while diffusers may be applied as well to ensure that early reflections would support the speech without creating distortions [68]. 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.

2.5.1. Absorbing materials

Absorbing materials are the primary technique to control the amount of reflected sound-waves, as they are able to dissipate a part of the sound energy of the incident sound-wave into heat. This phenomenon can take place in several ways and depending on the materials it is effective in for some frequencies. As said above, absorbing material are used to control the reverberation time and SPL, but also to address distortion effects generated by sound 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 [68]. In common practice, the parameter employed to describe the absorbing performance of a material is the sound absorption coefficient α (4). It defines the amount of sound energy that does not return to the space as reflected sound-wave, and thus, is either absorbed by the wall, or transmitted through the material.

$$\alpha' + t = \alpha \tag{4}$$

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 absorbing. It is important to remark that the acoustic coefficient does not provide information about the amount of sound that is transmitted through the material. The sound absorption coefficient of materials is correlated with frequency, and it varies with different frequencies. The sound absorption coefficient frequency characteristic curves can be used to illustrate the sound absorption properties of different frequencies exactly.

The three main categories of sound-absorbing materials that have been used in this work are:

- porous absorbers;
- resonant absorbers;
- membrane absorbers.

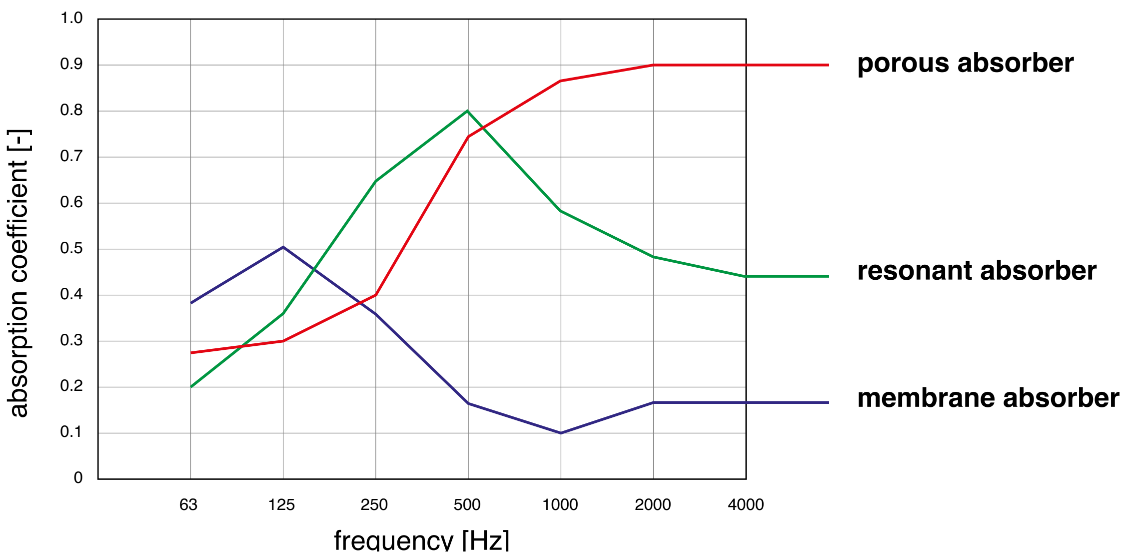


Figure 13. *Absorption curves for absorbent materials.*

These 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 can have good performances also in middle and low frequencies. Differently, resonant and membrane absorbers are more effective with medium-low frequencies, with poor performances in the resting part of the spectrum [70]. To get broadband passive absorption across the frequencies of most interest to design, usually requires a combination of porous, resonant and membrane absorbers.

The following discusses these different sound absorbers explaining calculating formulae, employed in their acoustic design, that will be implement into the algorithm.

2.5.2. Porous absorbers

Porous materials are the most common and broadband types of absorbers: typical porous absorbers are carpets, acoustic tiles, acoustic (open cell) foams, curtains, cushions, cotton and mineral. They are categorized as cellular, fibrous or granular according to their micro-structure where sound propagation occurs in a network of interconnected pores in such a way that viscous and thermal effects cause acoustic energy to be dissipated.

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 sound-waves strikes the material, enters these interstices and is dissipated into heat through viscous effect. Given the fact that 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 do not provide sound absorption [71].

Porous materials are generally most effective at high frequencies: at lower frequencies, the absorptivity increases as the thickness of the material increases: Figure 14 shows the absorption coefficients for mineral wool absorbers illustrating the effect of material thickness; the porous absorber is mounted on a rigid backing.

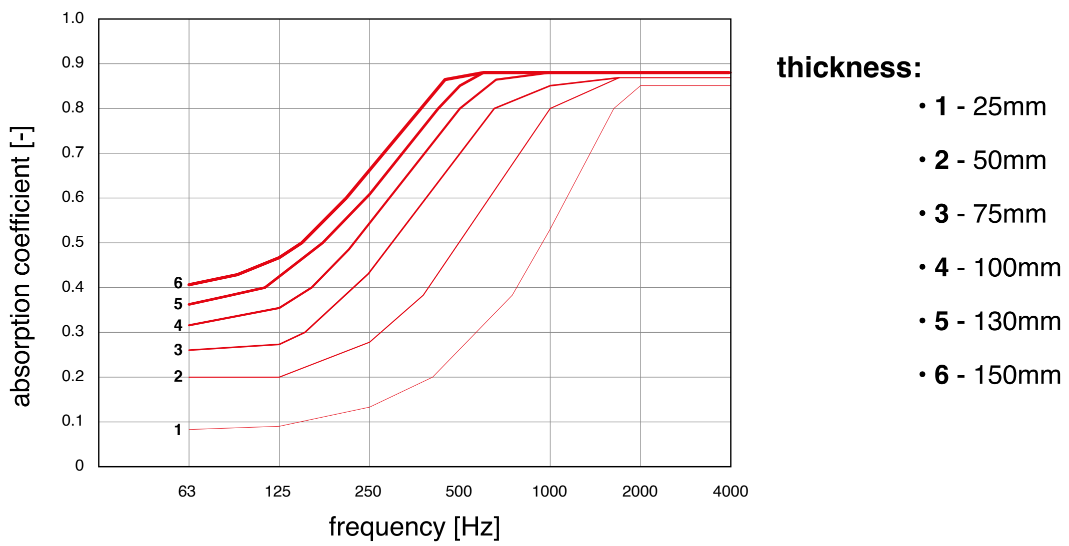
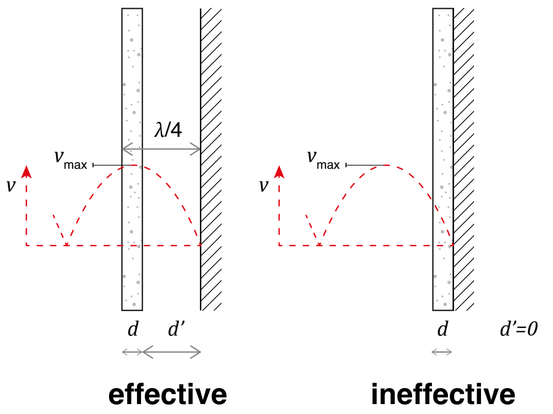


Figure 14. *Incidence of different thickness sound on the mineral wool absorbers' absorption coefficient.*

These curves follow the characteristic shape of porous absorption coefficients, a high pass filter response, although the curves can shift in frequency and move up and down in absorption depending on the characteristics of the material and how it is mounted. For low frequencies, where the wavelength is large, one must go a considerable distance from the wall to reach a point where the particle velocity is significant. This makes porous absorbers inefficient and not particularly useful at low frequency. 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 while at 1/4 wavelength provide maximum absorption [68].

A maximum absorption spectrum can be achieve through design of the minimum frequency the following equations [70]:



$$f_{min} = \frac{c}{\lambda_{max}} \quad [Hz] \tag{5}$$

$$\frac{\lambda_{max}}{4} = d + d' \quad [m] \tag{6}$$

where

c is the speed of sound in air, c = 343 m/s at 20°C;

λ_{max} is the wavelength of maximum absorption, in m;

d is the material thickness, in m;

d' is the distance between the material and the rigid backing, in m.

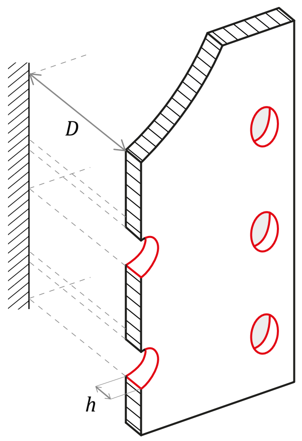
Finally, as porous absorbers are generally prone to damage, they are protected thought the use of acoustical transparent device that also improve their visual appearance. These are facings such as, thin membrane (<2 mm) wrapped around the panel, or perforated panels with a structure opened enough (30%-50%) not to impede the propagation of sound-waves through it [68].

2.5.3. Resonant absorbers

In order to ensure absorption for lower frequencies, resonant absorbers are usually preferred since their dimensions are more compact than porous absorbers. Furthermore, treatments are often placed at room boundaries where porous absorbers are inefficient as the particle velocity is low. By exploiting resonance, it is possible to get absorption at low to mid-frequencies. The absorption characteristics of these resonant devices are a peak of absorption. Unlike porous materials, wide band absorption is difficult to achieve in such devices, resonant absorbers offer a high rate of absorption within a limited range of frequencies [72]. So, one of the frequent challenges in the design of resonant structures is to extend the bandwidth. A typical resonant device is the Helmholtz absorber, which is named after the German physician and physicist Hermann von Helmholtz (1821–94). In

the case of a Helmholtz absorber, the mass is a plug of air in the opening of the perforated sheet. The resonance is produced by the same mechanism which generates a note when you blow across a beer bottle. It is rarely used in the classroom acoustics but absorbing panels that use its physical principle have been constructed by perforating, milling or punching hole-openings in panels: the assumption is that the hole spacing should be large in comparison to hole diameter. 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. Absorbers like these, come in a great variety of materials, finishes and form, and thus, are greatly employed in architectural projects. In fact, they play 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. If wider bandwidth of absorption is required it is possible to apply porous absorption in the cavity of resonant absorbers. 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 following equation [70]:



$$f_0 = \frac{c}{2\pi} \cdot \sqrt{\frac{\rho}{D \cdot h}} \quad [Hz] \tag{7}$$

where

c is the speed of sound in air, c = 343 m/s at 20 °C;

ρ is the drilling percentage;

D is the cavity depth, in m;

h is panel thickness, in m.

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 material in the cavity, close to the neck, or even directly in the openings, where the air velocity is maximum, in order to provide dampening [68, 72]. A method to increase the absorption of perforated panels of oblique-incidence sound-waves at low frequencies, it is to physically subdivide the cavity in single volumes, this way reducing the lateral propagation within the air gap. In case, instead, a layer of porous absorptive is present in the cavity, the physical subdivision is a lower requirement.

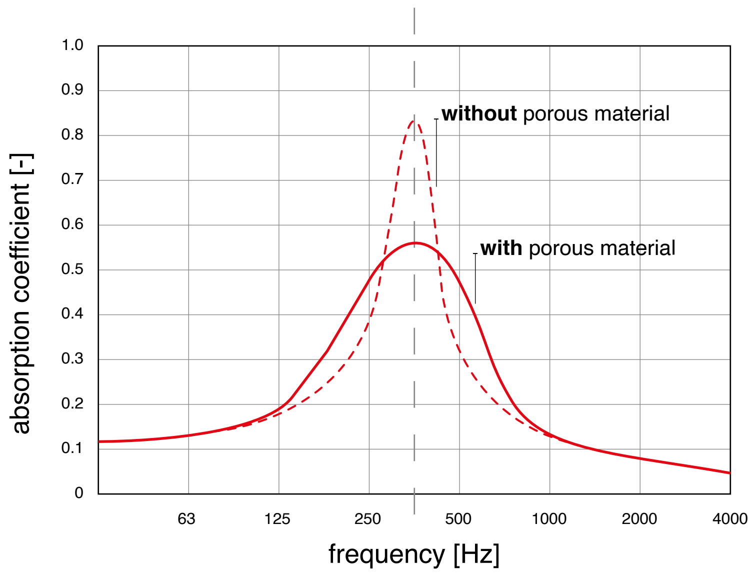


Figure 15. *Absorption curve of an acoustic resonator as a function of frequency, with and without porous material inside the air cavity.*

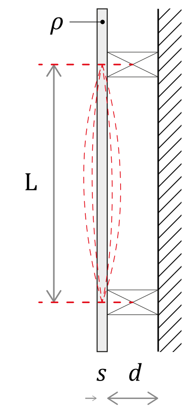
2.5.4. Membrane absorbers

Membrane absorbers are also mass-spring systems, this time however the vibrating mass is a flexible membrane or plate and the spring is air in the cavity between the membrane and the reflective surface. When a sound-wave 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: smaller depth generates higher resistance and moves the absorptive bandwidth to upper frequencies.

Their employment in architectural spaces is due by the great variety of materials

that can be used as panels. However, a small size 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: hence, panels should be at least 0.5 m²; in case of smaller membrane, a resilient fixing should allow the whole plate to vibrate, solving this issue [68, 72]. Similar to Helmholtz resonators, they provide only narrow band absorption, in most cases is below 400Hz, and the peak of absorption is reached at the resonant frequency of the system.

The resonant frequency of this system can be found [70]:



$$f_0 = \frac{60}{\sqrt{M \cdot d}} \quad [Hz] \tag{8}$$

$$M = \rho \cdot s \quad [kg/m^2] \tag{9}$$

where

M is material surface mass, in kg/m²;

d is the air-gap depth, in m;

ρ is the material density, in kg/m³;

s is panel thickness, in m.

This formula provides a useful first approximation but often yield inaccurate results with errors of up to 10 per cent because, unlike Helmholtz absorbers, the prediction of the behaviour of membrane absorbers is difficult as the exact mounting conditions and properties of the membrane are hard to predict and model.

The bandwidth can be increased by increasing the damping, but as with any mass-spring system, this has the effect of decreasing the maximum efficiency of the absorber. 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 [68, 71]. A trade off therefore ensues between bandwidth and maximum absorption.

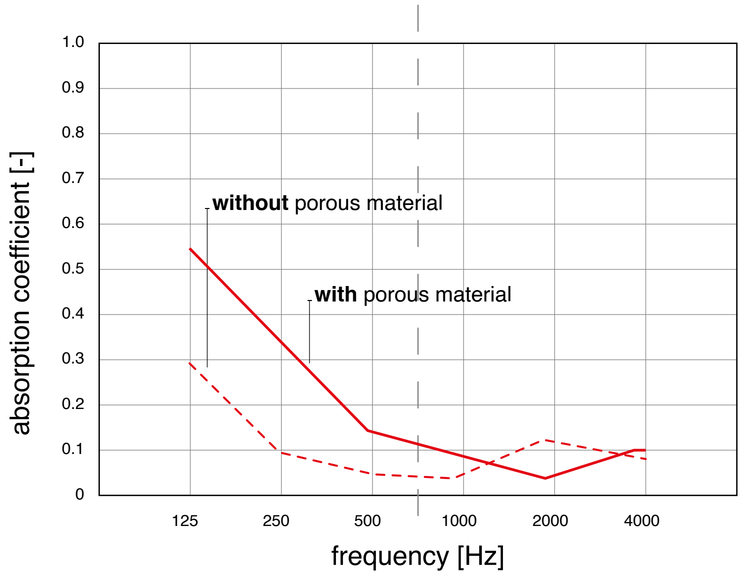


Figure 16. *Absorption curve of a membrane absorber as a function of frequency with and without porous material in the air cavity.*

3. UNI 11532 STANDARD

Poor acoustic quality is common in the Italian educational panorama. Although there are standards stating acoustic requirements that should be met in classrooms or other educational spaces, it is too often not observed.
As in other countries, also in Italy, there is a lack of acoustic expertise in architects, engineers, school principals, teachers and student’s education.
The new Italian UNI11532 standard returns to the North-European legislation, for a long time most up-to-date in this field [22]. It is a review of the UNI11532-2014; at the time of writing, it is composed by two parts: the first is in force since March 2018, the latter currently in public consultation and ready to be published.
The new developments regard the introduction of new aspects relating to acoustic comfort and the noise within the measurement environment, generated by the equipment for example. The standard addresses architects, building designers, building owners, and specialist engineers who are involved in the planning, construction and renovation of rooms covered by this standard. However, the latter still needs to be investigated.

The purpose and fields of application, calculating formulas and the reference values of the acoustic parameters that will be implement in the algorithm described in the fourth chapter, will be presented below. Finally, an overview on the spatial distribution of sound-absorptive and sound-reflecting surfaces in classroom environments will be given. For all the rest, see the full-text of the standard.

3.1. Purpose and scope of the standard

The first part of the standard describes the general common aspects of different application sectors, as well as, defines the descriptors that represent the acoustic quality of an environment in relation to the intended use of the environment itself [73].

Based on the defined descriptors, it recommends evaluating methods and verification techniques. The standard applies to environments with different uses in the following sectors:

- school sector: communicative / collective, small conference;
- health sector;
- catering sector;
- service sector;
- sports sector;
- museum sector: fair, exhibition.

The standard does not cover the acoustic quality of rooms with special requirements, such as theatres, concert halls, cinemas, sacred spaces, or in rooms for the high-quality recording of music and speech (e.g. studios, central control rooms for radio, film, television and sound storage media productions). However, this standard can be applied by analogy to rooms for general musical presentations, multi-purpose rooms.

The UNI11532-2 takes up the room acoustic parameters defined in the first part providing the target values for the school sector and all other uses related to it, both in relation to the intended use of the environment and considering people with hearing impairment, concentration, non-native speakers or with language differences or with different needs.

In the educational environments, the understanding of speech is a primary importance requirement, for which many determinant factors are considered, such as:

- soundproofing to airborne and impact noise between different environments to avoid mutual interaction between spaces;
- sound insulation from outside in order to avoid excessive residual noise;
- the noise level of fixed installations for use by the structure and individual rooms;
- the reverberation of the room;
- the intelligibility of speech.

3.2. Evaluating method

3.2.1. Reverberation Time

The evaluating method recommended for calculating the reverberation time is de-

scribed by UNI EN 12354-6 [74]. It is essentially the Sabine formula as expressed in (1) which take into account the acoustic air absorption.

3.2.2. Speech Clarity

The Speech Clarity C50 can be determined in an approximate way with the formula (10) or in a precise way with the formula (11), in dB, according the Barron & Lee revised theory [75]:

$$C50 = 10log\left[e^{(0.691/T)} - 1\right] \quad [dB] \tag{10}$$

where

T is the reverberation time, in s;

$$C50(r) = 10log\left[\frac{\frac{100}{r^2} + \left(\frac{31200 \cdot T}{V}\right) \cdot \left(1 - e^{(-0.691/T)}\right) \cdot e^{(-0.04 \cdot r/T)}}{e^{(-0.04r/T)} \cdot \left(\frac{31200 \cdot T}{V}\right) \cdot e^{(-0.691/T)}}\right] \quad [dB] \tag{11}$$

where

V is the total room volume, in m³;

T is the reverberation time, in s;

r is the distance of the source from the receiver, in m.

3.2.3. Speech Transmission Index

The measurement method of STI, including the limitations of applying the two parameters, is described in IEC 60268-16 [67].

3.2.4. Overall noise in the environment

Two factors affecting the prediction of STI values are both the noise that occur in the room with not-operating plants, and linked to the environmental context in which the building is located, L_2, and the noise of the room equipment, $L_{ic,int}$. The noise level inside the room L_{amb} is the energetic sum of both contributions, it is expressed as the spatial energy average of the values obtained in the user positions indicated in Figure 17.

The residual noise level in the room, in octave bands from 125 Hz to 4 kHz, is obtained for the different positions shown in Figure 17, starting from the average sound pressure levels in the internal environment due to external noise, L_2, in octave bands from 125 Hz to 4 kHz, in according to the formula:

$$L_2 = L_{1,2m} - D_{2m,nT} + 10log(T/T_0) \ [dB] \quad (12)$$

where

$L_{1,2m}$ is the sound pressure level outside the building, at a distance of 2 m from the facade, in dB;

$D_{2m,nT}$ is the façade sound insulation standardized to the reverberation time, in dB;

T is the reverberation time, in s;

T_0 is the reverberation time reference value, it is equal to 0,5 s for all octave bands in s.

Since $L_{1,2m}$ is considered at a distance of 2m from the façade, if the external sound pressure level refers to the incident noise without considering the building, or ante operam, $L_{1,2m}$ must be increased by 3 dB for all frequency bands considering the reflection on the facade. The noise level of the equipment inside the room is expressed through the $L_{ic,int}$ descriptor, obtained from the spatial energy average of the $L_{pu,c}$ values in the user positions as specified in Figure 17.

$$L_{pu,c} = L_{Aeq} - K1 + K2 \ [dB(A)] \quad (13)$$

where

L_{Aeq} is the equivalent continuous sound level, measured with operating systems, in dB(A);

$K1$ is the noise correction term measured with not-operating systems, in dB;

$K2$ is the standardized term to the reverberation time.

If the difference between the sound pressure level of the noise induced by the systems and the residual noise level L_r is between 4 dB(A) and 10 dB(A) the correction term is calculated using the following relations:

$$K1 = -10log(1 - 10 - \Delta L/10) \quad (14)$$

$$\Delta L = L_{Aeq} - L_r \quad (15)$$

where

L_r is the equivalent continuous sound level, measured with system not in operation in dB(A);

If ΔL is less than or equal to 4 dB(A) the correction term $K1$ is equal to 2,2 dB.

$$K2 = -10log(T/T_0) \quad (16)$$

where

T is the arithmetic average of the reverberation times measured in the octave bands between 125 Hz and 4 kHz, measured in the user positions in the environment, in s;

T_0 is the reverberation time reference value depending on the volume, in s (Table 03).

Table 03. *Reverberation time reference value depending on the volume.*

volume	reverberation time reference
$V \leq 100$ m³	$T_0 = 0.5$ s
$100 < V < 2500$ m³	$T_0 = 0.05 \cdot V \cdot 0.5$ s
$V \geq 2500$ m³	$T_0 = 2.5$ s

3.3. Target values

In order to define the objectives to be pursued, it is fundamental:

- to determine the primary use of the environment according to the categories identified in Table 04.

Table 04. *Rooms categories in relation to the primary use.*

category	room primary use
A1	music
A2	speech/conference
A3	teaching, teacher-pupil interaction
A4	lecture/ communication, special classrooms
A5	sport
A6	no-teaching spaces, library

- to identify the measuring points within the room to determine acoustic parameters, as shown below.

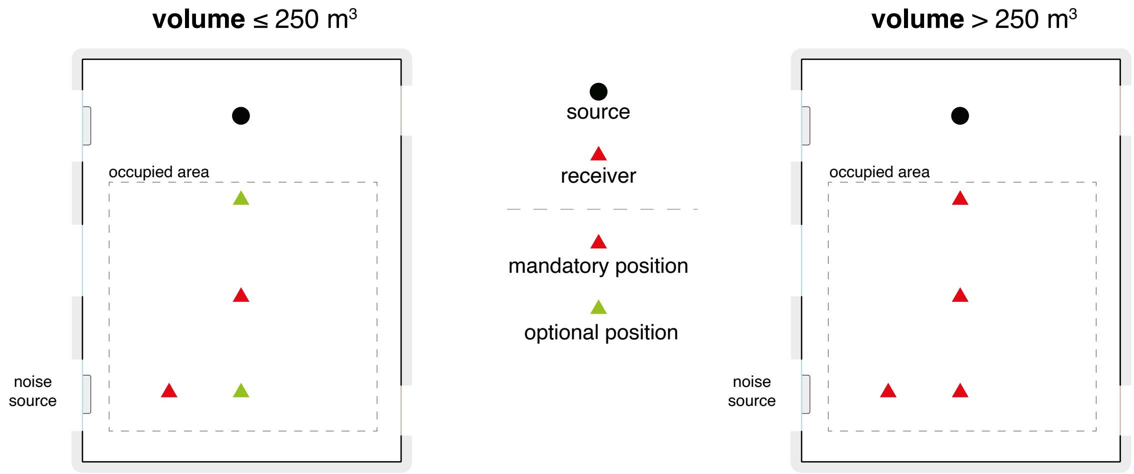


Figure 17. *Identification of measurement user-receiver positions in relation to volume and noise source.*

3.3.1. Reverberation Time

The optimal reverberation time T_{ott} is determined in relation to the specific use destination of the considered environment and its volume, through the calculating formulas reported in Table 05. See the full-text of the standard for the A6 category.

The requirements for reverberation time refer to the furnished and occupied state at 80% of the capacity indicated in the project.

Table 05. *Calculating formulae of* T_{ott}

category	T_{ott}	volume
A1	$T_{ott,A1}$ = (0.45·logV + 0.07)	30 ≤ V < 1000 m³
A2	$T_{ott,A2}$ = (0.37·logV - 0.14)	50 ≤ V < 5000 m³
A3	$T_{ott,A3}$ = (0.32·logV - 0.17)	30 ≤ V < 5000 m³
A4	$T_{ott,A4}$ = (0.26·logV - 0.14)	30 ≤ V < 500 m³
A5	$T_{ott,A5}$ = (0.75·logV - 1.00)	200 ≤ V < 10000 m³
	$T_{ott,A5}$ = 2.0	V ≥ 1000 m³

For people with hearing problems or disorders related to concentration or attention, the reverberation time shall comply with categories A3 or A4.

To determine the reverberation time curve in frequency, relating to the optimal time, refer to the figure below.

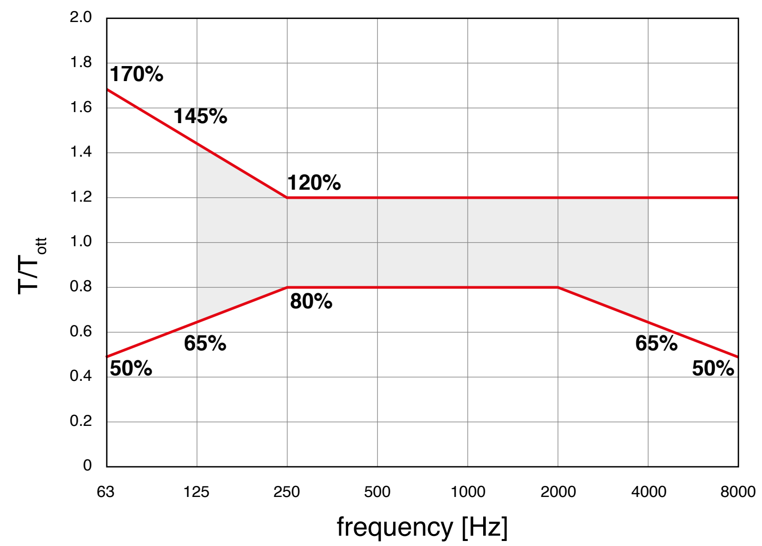


Figure 18. *Frequency dependent tolerance range of reverberation time referred to* T_{ott}.

As far as the A5 category is concerned, the standard suggests considering only the octave bands between 250 Hz and 2 KHz.

Finally, it is provided a conversion equation (12) between the values in the occupied state and the values in the unoccupied but furnished, useful in calculating STI:

$$T_{inocc} = \frac{T_{occ}}{\left[1 - T_{occ} \cdot \frac{\Delta A_{pers}}{0.16 \cdot V}\right]} \qquad (17)$$

T_{occ} is the reverberation time for the occupied room at 80%, in s;

V is the total room volume, in m³;

ΔA_{pers} Additional surface area equivalent to sound absorption of people, in m².

3.3.2. Speech Clarity

The C50 descriptor can be applied to the A1, A2, A3 and A4 categories as an alternative to the STI exclusively for rooms smaller than 250 m³. For rooms with volume ≥ 250 m³ only the STI is applied.

The reference value for a room without the amplification system is: C50 ≥ 2 dB. They apply to furnished but unoccupied rooms with the presence of up to two people. The limit value refers to the arithmetic mean of the values measured in the "Measurement positions" shown in Figure 17. The values measured in each measurement position are obtained as the arithmetic mean of the values in the octave bands 500-1000-2000 Hz.

3.3.3. Speech Transmission Index (STI)

As said above, for rooms smaller than 250 m³ as an alternative to the STI the C50 descriptor can be used.
The reference values for STI are shown in Table 06. They apply to furnished but unoccupied rooms with the presence of up to two people. The measuring points are shown in Figure 17.

Table 06. *Reference values of the STI descriptor.*

	STI	volume
without the amplification system	≥ 0.55	$V < 250$ m³
	≥ 0.55	$V \geq 250$ m³

3.3.4. Room equipment noise

This standard, as alternative to the $L_{ic,int}$ descriptor, to verify the noise due to continuous-operating systems, requires the verification with of the NC curves.
The limit values of $L_{ic,int}$ and for the NC curves are shown in Table 07.

Table 07. *Reference values for $L_{ic,int}$ and NC.*

intended use	$L_{ic,int}$	NC
classrooms and libraries < 250 m³	≤ 34 dB(A)	≤ 25
classrooms and libraries ≥ 250 m³	≤ 38 dB(A)	≤ 30
single offices	≤ 35 dB(A)	≤ 25
exhibition spaces, study spaces	≤ 45 dB(A)	≤ 35
gymnasium, reception, canteens	≤ 45 dB(A)	≤ 35

3.3.5. Overall noise in the environment

The noise levels in the environment, L_{amb}, must comply with what is indicated in Table 08.

Table 08. *Reference values for L_{amb}.*

intended use	L_{amb}
classrooms and libraries < 250 m³	≤ 38 dB(A)
classrooms and libraries ≥ 250 m³	≤ 41 dB(A)
single offices	≤ 35 dB(A)
exhibition spaces, study spaces	≤ 45 dB(A)
gymnasium, reception, canteens	≤ 45 dB(A)

3.4. Spatial distribution of the acoustic material

As a rule, the absorptive surfaces should be distributed evenly throughout the room. Different configurations are shown in arrangements shown in Figure 19.

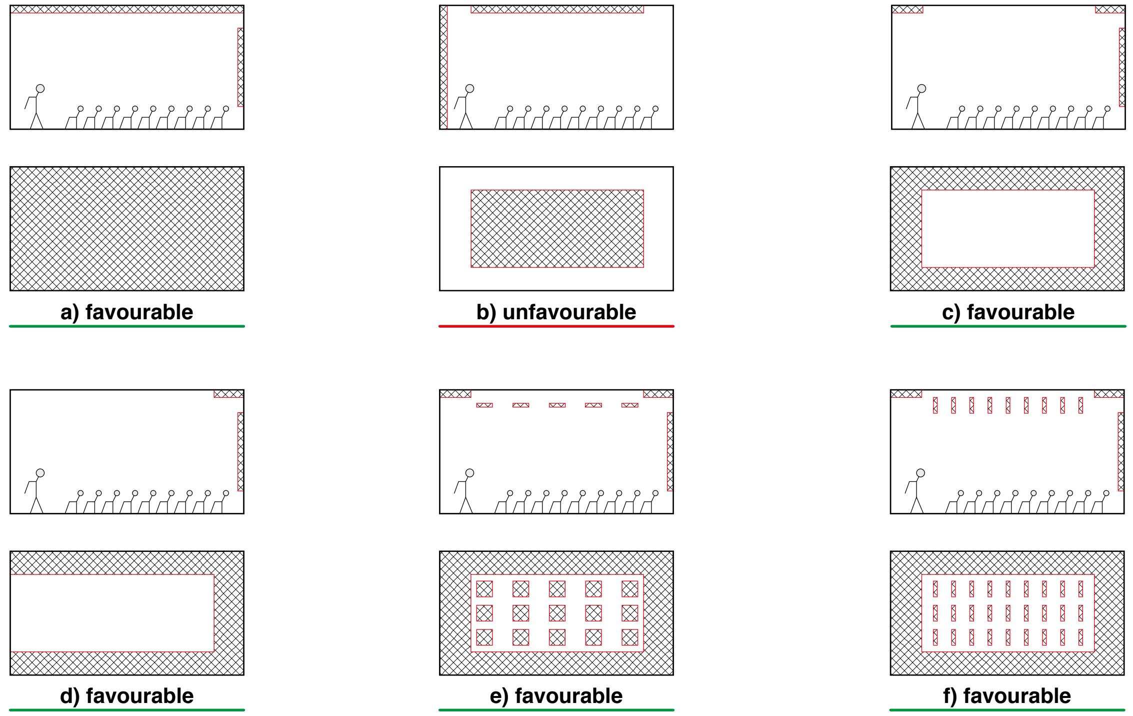


Figure 19. *Distribution of sound absorption surfaces for small and medium-sized rooms.*

Sound absorbers which are primarily effective in the low frequency range are particularly effective near the sound source, and in room corners or angles. If the room has a rectangular ground plan and the walls are plane and not interrupted by furniture, shelving, window recesses or objects such as large notice boards and pin boards, there is a risk that flutter echoes may occur where there is a completely sound absorptive covered ceiling. This can be avoided if a central area of the ceiling is sound reflecting as shown in figures 19c and 19d. However, the walls are to be partially sound absorptive, as compensation. Since there is no risk of over-attenuation in rooms with a volume up to about 250 m³, a ceiling with a fully sound absorptive surface can be used in combination with a similarly sound absorptive rear wall [76].

Wall surfaces that are parallel to each other and untreated are just as unfavourable as concave curved or angled surfaces, which in areas occupied by people (or, possibly, microphone positions) can lead to flutter echoes or focusing of the sound. In this case, sound absorbing or sound scattering materials should be used on at least one wall as shown in Figure 20.

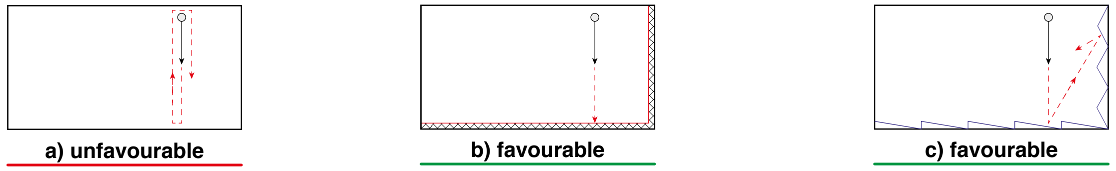


Figure 20. *Distribution of the acoustic material on parallel surfaces.*

In rooms with a length of more than about 9m, time-delayed sound components can be deflected from the rear wall into the front area of the room, either directly or via angle reflections. This leads to a reduction in the level of speech intelligibility (figure 21a). In this case the sound reflecting surfaces shall either be covered with a sound absorptive material, or inclined so that the impinging sound is reflected as a beneficial amplification towards the listeners who are most distant from the sound source (figures 21b and 21c).

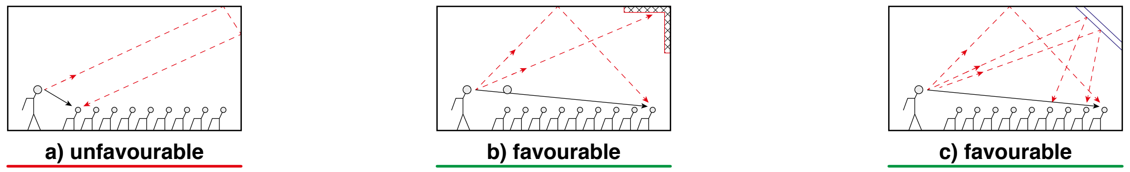


Figure 21. *Rear wall reflections.*

PART II

PRACTICAL APPLICATION

4. ALGORITHM DEVELOPMENT

The scope of this research is to develop an algorithm, parametric model based, to predict the acoustic parameters characterizing a classroom, in compliance with the new UNI standard and investigate the acoustic effects generated by the variation of materials and their geometrical features inside the room. The present work aims to explore the possible solutions able to ensure and optimize acoustic comfort conditions, promoting the awareness of the acoustic consequences of various design and renovation choices since the early phases.
This aims to be as general as possible so that it can fit to a great number of classroom environments. However, calibrating the parametric model on a specific type of school class and applying it to a real case has been the best way to control the algorithm development through ad hoc sheets in Excel.
In this chapter, the experimental phase of the algorithm design and development will be introduced: in particular, the case study, the parametric model, its calibration, its possibilities and constraints will be present the first part; in the following, algorithm acoustics implementations will be given and finally the prediction of acoustic parameters will be discussed.

4.1. A quick overview of the algorithm

The algorithm has been designed and developed in Grasshopper [8] for Rhino [9]. That is because it has been the medium that provided me facilities to deal with algorithm with geometric and data operations. There are two key players, one is the "algorithm" with its implementations and another one is the "geometry and data". Like a recipe, algorithm manages and processes data, gathers input and provides desired output.

Geometry and data are the ingredients where algorithms apply the recipe to them and create the output product.

It consists of over 3500 components grouped into six main categories, shown in Figure 22, relating to the aim, to which each component contributes.

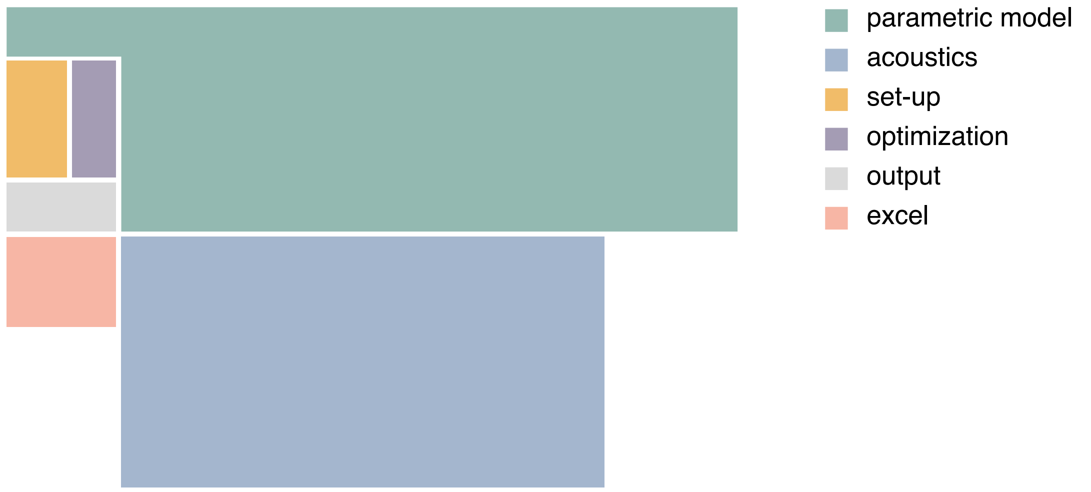


***Figure 22.** Six main categories of the algorithm's components on the GH canvas.*

The "parametric model" category, as the name suggests, group all the components needed to build the virtual model of the room, and hence all the possible acoustic treatments to be applied as well.

In the "acoustics" category, we find many Python components incorporating the acoustics analytical formulas relating both to the acoustic parameters and to the usable acoustic materials, both introduced in the chapter before.

The components in "set-up" allow us to set the parametric model preparing it for the acoustic simulation.

In "optimization", it can be choose the items to be involved in the optimization process described in chapter 6, and start it.

The "output" category shows and compares the results of the acoustic simulation before and after the acoustics project.

Finally, the components in "Excel" write the data to an Excel file [10]; they are related to the settings of the parametric model and the acoustic materials used in each simulation, allowing a subsequent analysis of the simulated configurations.

4.2. Case study

The case study used to test the developed algorithm concerns a classroom of an elementary school of Turin, in a neighborhood called Vanchiglia (Figure 23): the

ALGORITHM DEVELOPMENT

Primary School Ludovico Antonio Muratori located in Via Bettino Ricasoli, 19. The school building has an “E” shape and facing two main streets: Corso Tortona and Corso Belgio where the traffic is moderate, at times intense due to the passage of trams.

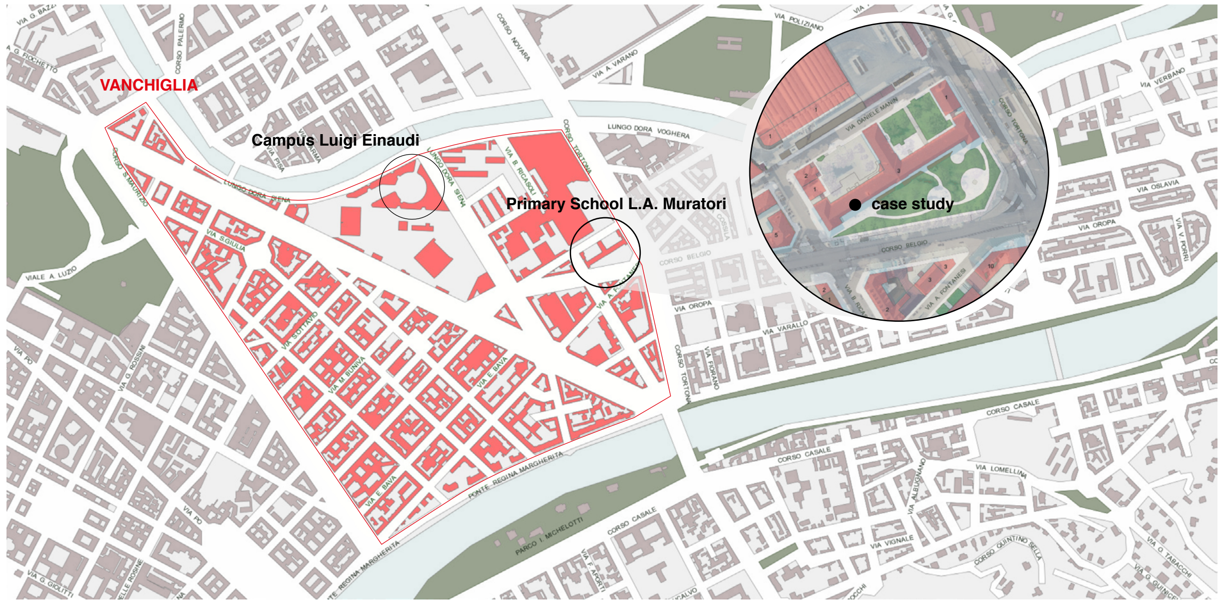


***Figure 23.** Location of the case study and Vanchiglia neighbourhood.*

The building was built in the early of the nineteenth century (1913), and classrooms present high ceilings (height of about 4.5 m and volume of about 250 m^3). The building style and finishing is typically old, with earthenware tiles on the floors and wide windows.

Our case study is located in the part of the school which facing Corso Belgio. Through the analysis of the acoustic performance of this real classroom, the Master thesis project aims at identifying a series of features that are able to guarantee the best performances expressed by the acoustic parameters that characterize a classroom according to the new Italian standard.

Now on will be the only classroom we will discuss.

The classroom has typical plan dimensions for a classroom but in section, a side wall present 3 high windows and the ceiling reaches 4.48m. The volume of the room is about 248m^3.

***Figure 24.** Pictures of the room taken during a measurement campaign.*

All walls are covered by plaster which has very low absorption coefficients and the floor is furnished with ceramic tiles. These are the reasons why the acoustic is very bad inside the classroom comparable to the one of small churches. The configuration of twenty-four pupils inside the classroom is divided in four rows and arranged three by desk.

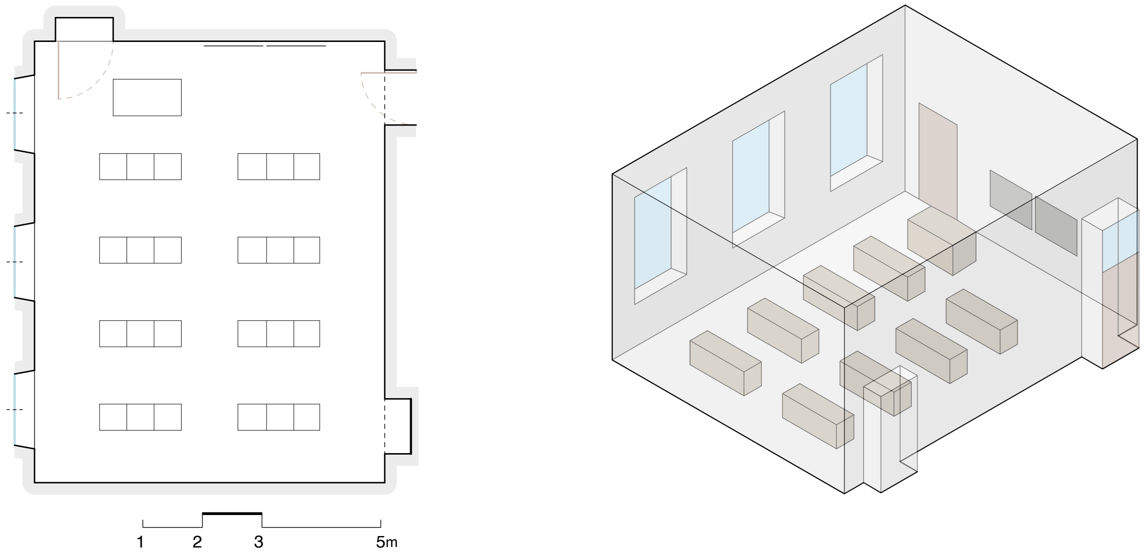


Figure 25. *Plant and 3D view of the classroom.*

In May 2018, this school was involved in the research projects "Io Ascolto" [77], a series of acoustic measurements were taken; the measured reverberation time is reported in the graphic below for each frequency. The value, averaged over the 500 Hz and 2 kHz octave bands,in occupied classroom was 2.01 s with a standard deviation of 0.03 s.

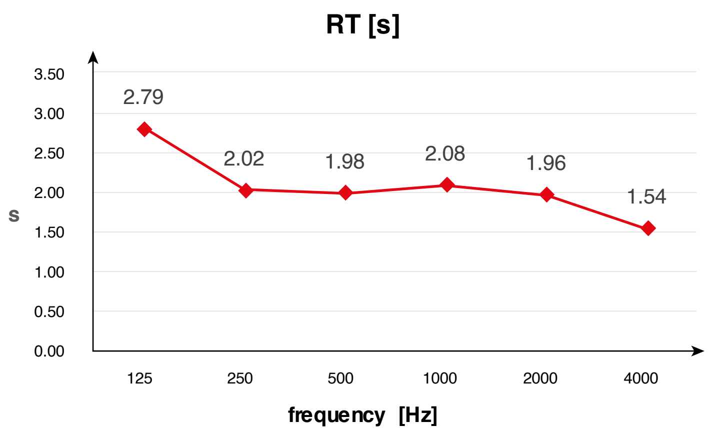


Figure 26. *Measured reverberation time.*

Last July, the present case study was affected by an important acoustic renovation

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by the Swedish Ecophon Saint-Gobain [1].

Figure 27. *Pictures of the room taken after the acoustic renovation phase.*

The acoustic project combined an integral sound-absorbing treatment of the ceiling and a partial sound-absorbing treatment on the side walls. A brick-proof false-ceiling, made with high density plasterboards (100 kg/m³), has been installed on ceiling and covered with porous panels of glass fibres. As for the treatment of the walls, the back wall and a side wall have been covered with fibreglass panels starting from 1.5m in height.

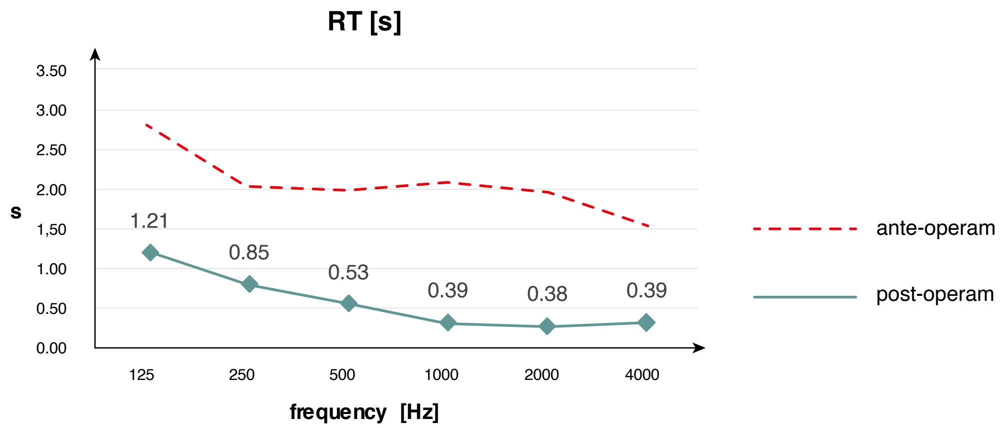


Figure 28. *Measured reverberation time after the acoustical renovation.*

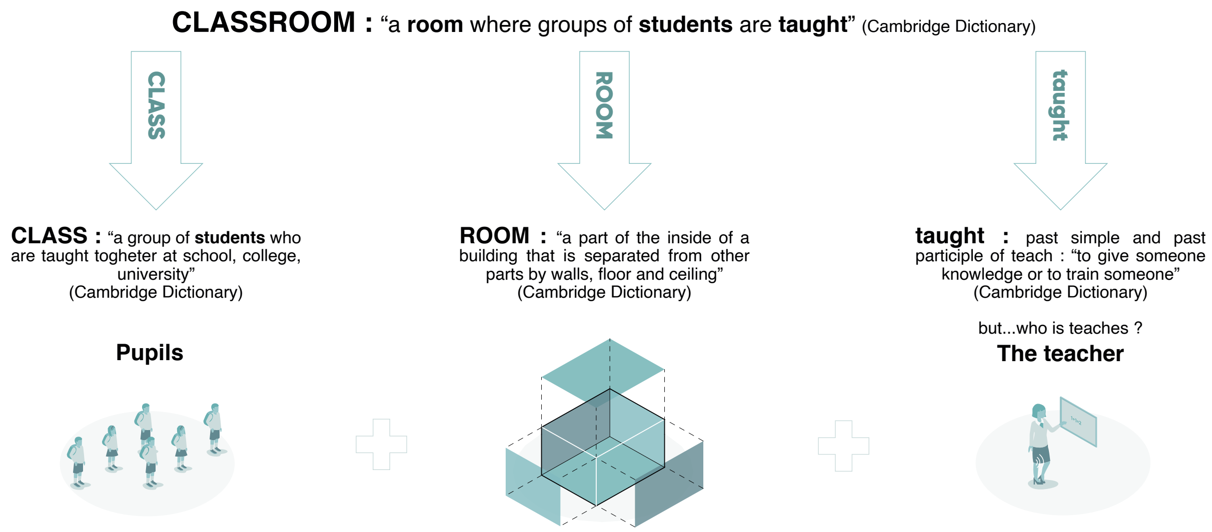
The choice of this classroom was not at all random, but rather was carefully considered; in fact:

- this hosted the first-graders; we have seen how acoustics are important especially at the first levels of the educational path;
- it had a bad acoustic quality as emerged following the acoustic measurements carried out within the research project "Io Ascolto";
- not long after, it would have been acoustically renewed; this would have allowed to really test the algorithm in both phases, ante and post acoustic renovation.

4.3. General approach

Any assessment tool is useful but becomes effective if applicable to multiple objects of study. So, in order to apply the algorithm to a great number of classroom environments, it was necessary to identify a primitive classroom and its features, a kind of archetype with variables and constraints. Moreover, only after defining the parameters' range it could have been done to create the parametric model and develop the algorithm. Employing a decomposition method, the classroom environment has been described as the sum of three elements: a class, a room, a teacher.

Figure 29. *Classrooms' primary elements.*



The variables concerning these 3 primary elements are shown n the next page. These are essentially numeric and dimensional variables, in the sense that the numeric parameter of the model changes because the dimensions or the number of each variables inside the classroom environment change (e.g. windows could change in number and dimensions from one classroom to another). In this phase it is been important to define the ranges of parameter variability, in order to generalize the parametric model as much as possible. This was done through an archive search at the offices of the municipality of Turin. The available collection data was related to about 326 school buildings, of which only primary schools were selected for an actual sample of 109 schools. These in turn was ordered by year of construction, and grouped for decades from 1887 to 1987, the most recent year of construction: for each decade, a number of school buildings were selected at random according to this simple criterion:

- n=3 if $n\_s < 10$;
- n=4 if $10 \leq n\_s < 20$;
- n=5 if $n\_s > 20$;

where n is the number of school buildings to be select and n_s is the number of school buildings built in the decade considered.

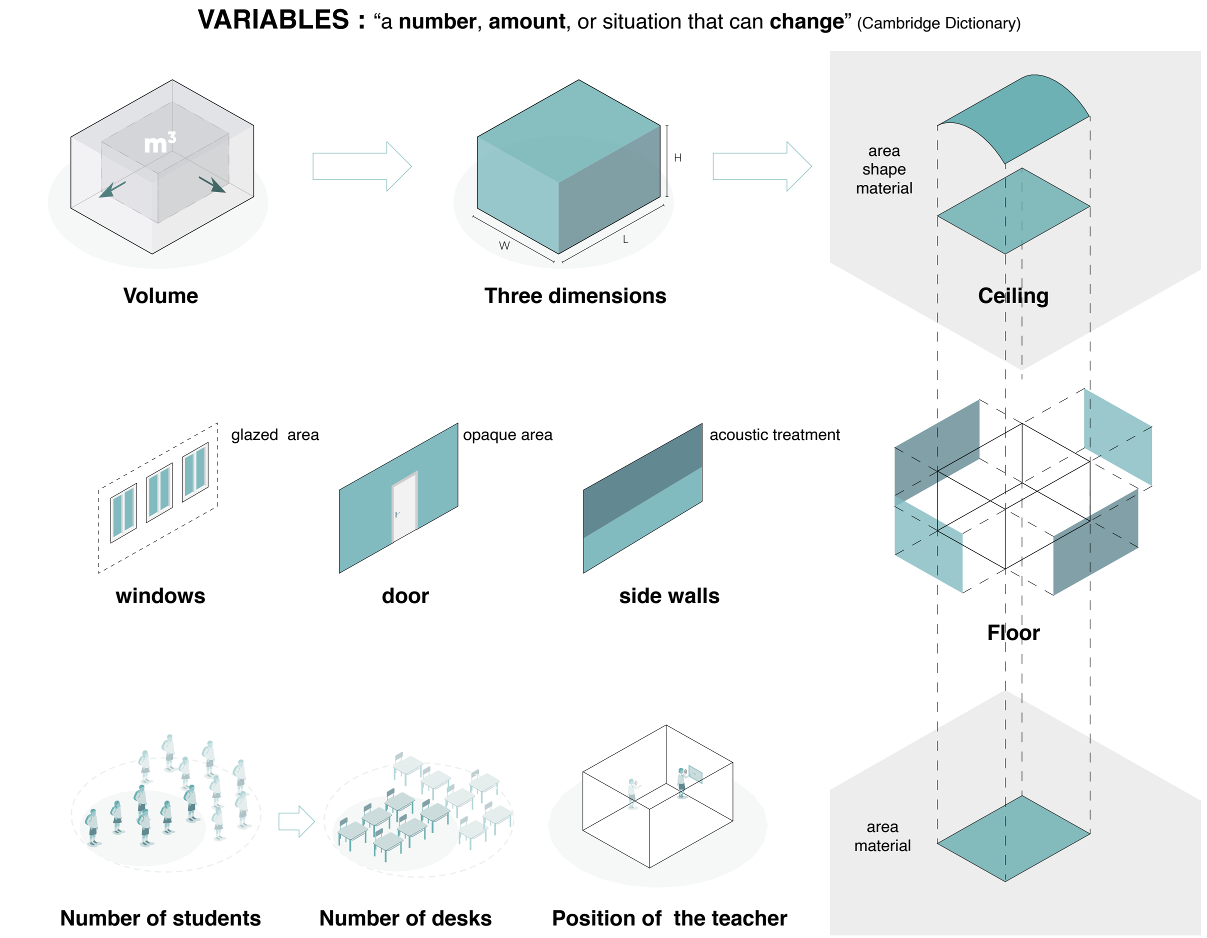


Figure 30. *Main variables of a classroom.*

35 elementary schools have been identified, for a total of 108 classrooms of which have been wrote down:

- dimensions of the architectural envelope: length, width and height;
- number and size of doors and windows.

Clearly these were the only variables that could be recovered from the available old paper documents.

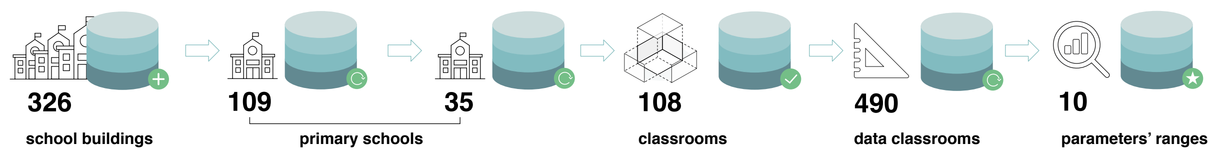


Figure 31. *Schools-classrooms database to define the parameters' ranges.*

Finally, data processing with Chauvenet's criterion[78, 79] , and Dixon's Q test[80, 81] , has detected the possible outliers.

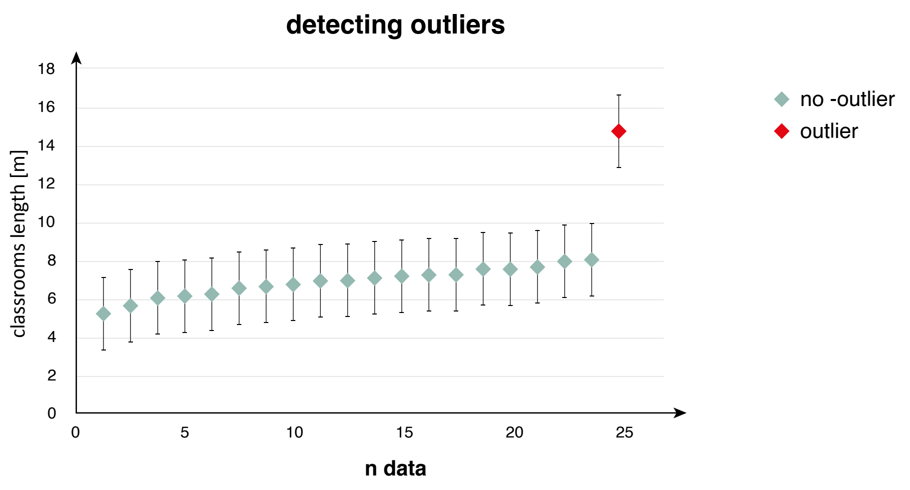


Figure 32. *Detecting outliers on the classroom length parameter.*

The Table 09 below summarizes the parameters' variation intervals identified in this phase.

Table 09. *Rooms categories in relation to the primary use.*

parameter	range	
	min	max
room - length	5.2	9.4
room - width	4.4	8
room - height	3.2	6.1
door - width	0.85	1.3
door - height	2.1	2.4
door - number*	0	2
window - width	0.8	3
window - height	1.3	3
window - number*	0	6
window sill - height	0.6	1.6

(*): for each individual side-wall.

This very general approach was also achieved thanks to the definition of constraints on the parametric model. Some of these are imposed by the current legislation and mainly concern the comfort conditions of the people who live these spaces, while others simplify the model and, as we will see, are absolutely plausible.

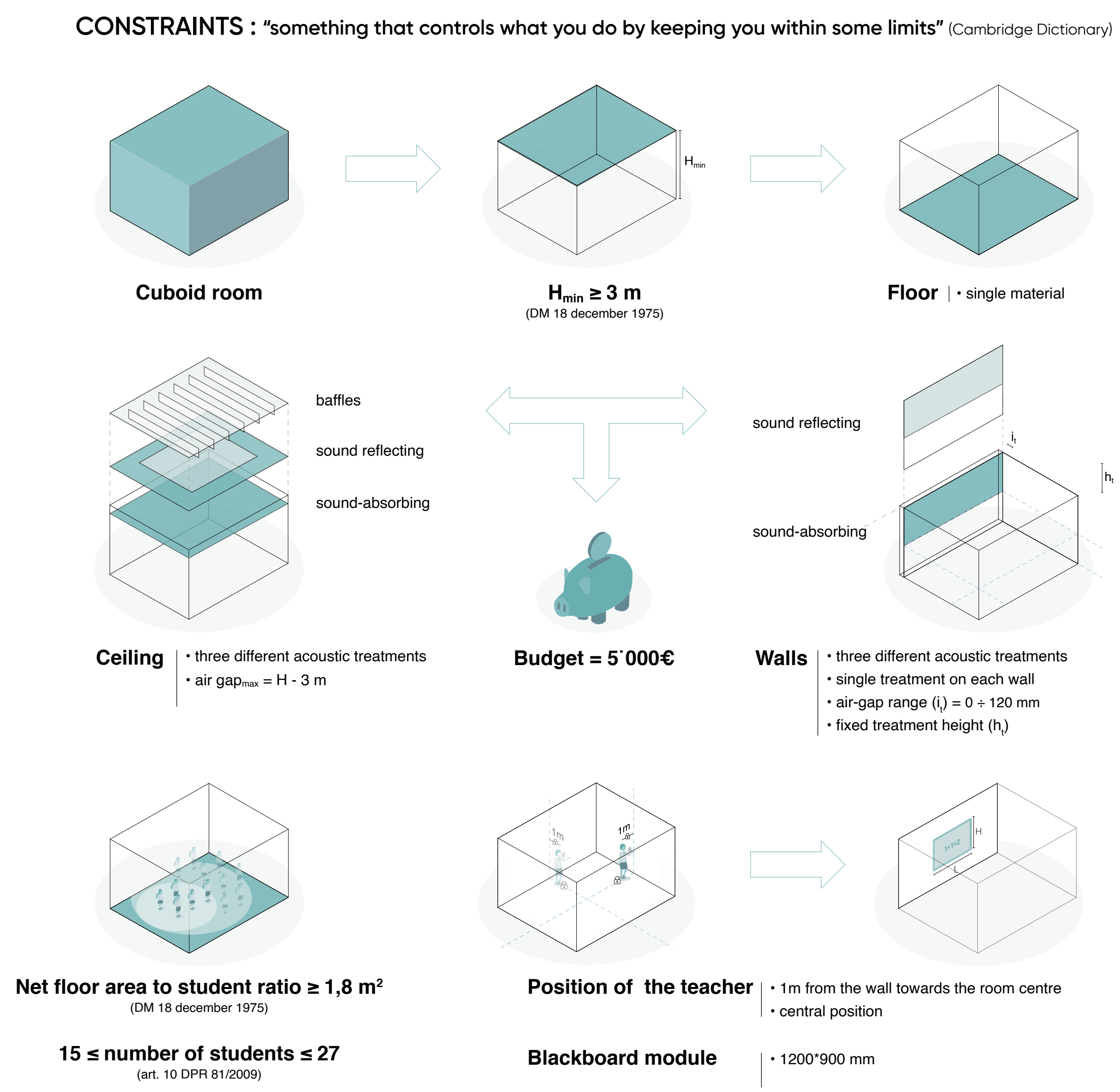


Figure 33. *Main constraints adopted in the parametric model.*

Among the main constraints, we find:

- cuboid room: this means simplifying the model where it presents window recesses or vaulted ceiling;
- single material for no-treated walls, floor, windows, doors and blackboard;
- single acoustic treatment for each side wall;
- fixed acoustic treatment height on the side walls;
- maximum air gap on the side walls;
- three different types of ceiling acoustic treatment;
- minimum height of the room, required by the Ministerial Decree 18 Decem ber 1975 [82];
- the same decree establishes the net floor area to student ratio;

- minimum and maximum number of students in a classroom, in accordance with art. 10 of the DPR. 81/2009;
- position of the teacher;
- blackboard module;
- budget.

All this made it possible to calibrate the parametric model to the primary classroom typology in this preliminary phase, but crucial for the subsequent work.

4.4. Parametric model

The data acquired so far allow us, by using Grasshopper [8] components called sliders, to replicate the existing classroom within a virtual parametric model in a rather simple way, taking into account the variables and constraints previously shown. In fact, through the sliders it is possible to set the dimensions of the classroom, add doors, windows and blackboard and adjust their dimensions.

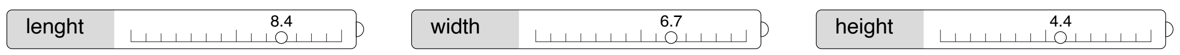


Figure 34. *Representation of the GH sliders, used to define the classroom geometry.*

The model setting phase works on every single wall that takes the name of a number between 0 and 3 and has been calibrated on dynamic ranges so as not to generate errors.

Moreover, when there are more elements to be placed along a wall, as in the case of windows, the alternative to manual layout is the automatic one which follows a default arrangement that "justifies" the elements as happens for words in a text line.

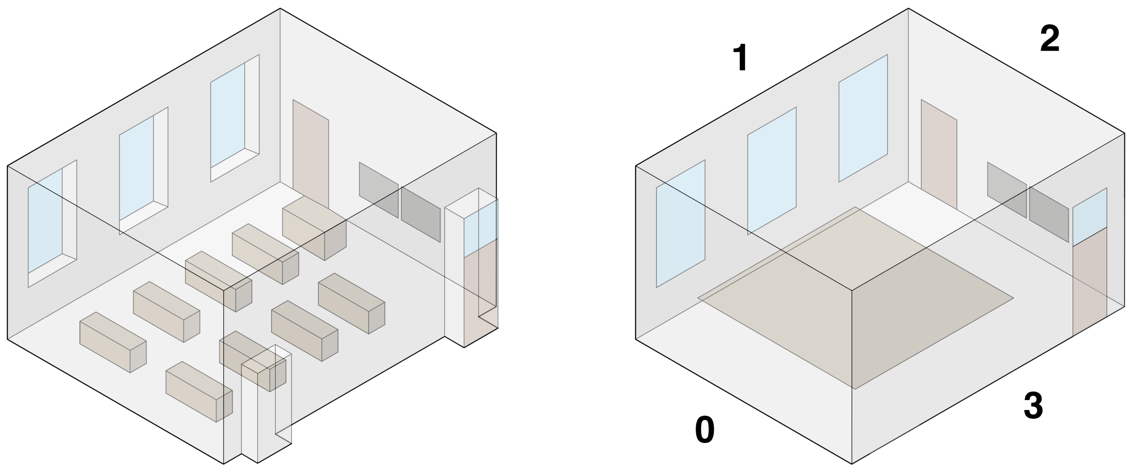


Figure 35. *Comparison between the ad-hoc 3D model and the algorithmic one.*

The virtual model of the existing classroom, at this point, is completed and the algorithm automatically associates to each surface the absorption coefficients set by default and which will be discussed later. The algorithm "stores" the model of the existing classroom and is ready for the acoustic design phase.

It is possible to choose between different acoustic treatments to be applied to the walls and/or to the ceiling in order to improve the acoustical performance of the room, in terms of acoustic absorption, in fact, the sound insulation of the classroom building elements is not addressed.

4.4.1. Wall acoustic treatment

The three types of acoustic materials presented in chapter 2 can be used to cover the side walls of the classroom. Through a selector, available in Grasshopper thanks to MetaHopper plug-in [83], you can choose which walls to treat; it is only necessary to have established the height to split the wall surface, from which to start with the treatment. For the algorithm the surfaces thus identified will be like a membrane absorber; to switch to porous or resonant panels, it is necessary to cover these surfaces with panels of predefined sizes of 600 * 600mm. This has been considered the best choice because it is closer to the real practical field concerning the panels installation and allows to eliminate the waste and therefore not overestimate the square meters of sound-absorbing material. In fact, the algorithm is able to:

- adjusts the height of the splitted surface, previously set, so that it is modular of the panel size (figure 36a);
- arrange panels symmetrically starting from the centre of the surface (figure 36b);
- remove the panels that interfere with the openings (e.g. windows, doors and blackboard) (figure 36c).

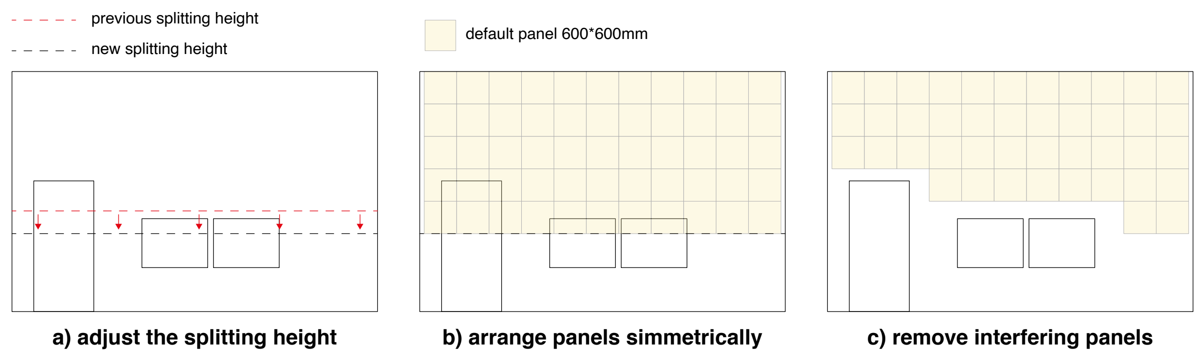


Figure 36. *Algorithmic operations on the wall treatment.*

Finally, you can select whether to add or remove a row of panels to those already provided in the model.

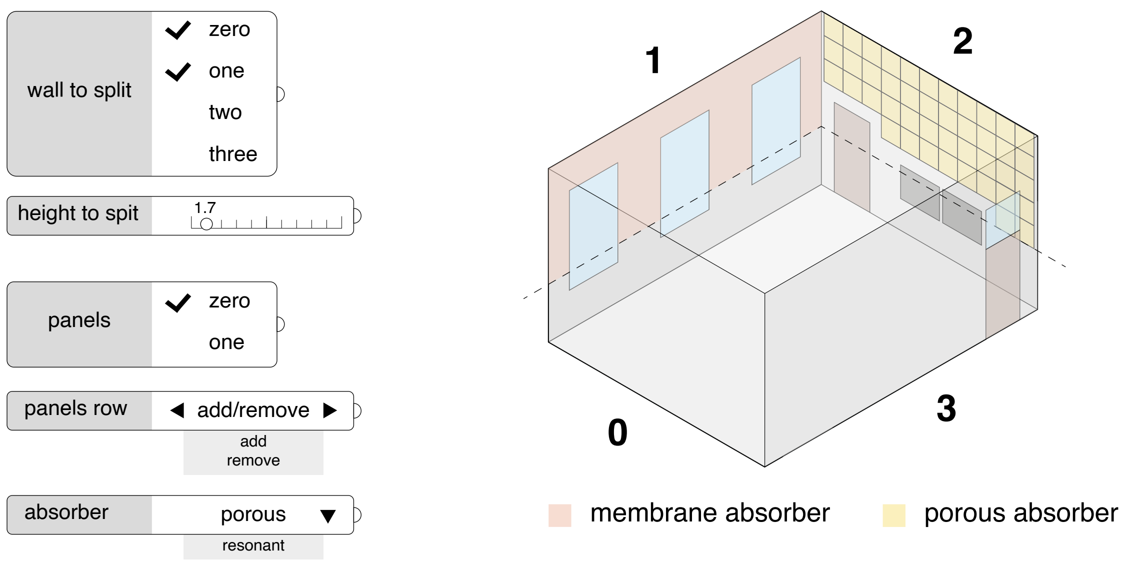


Figure 37. *Available GH components for wall treatment.*

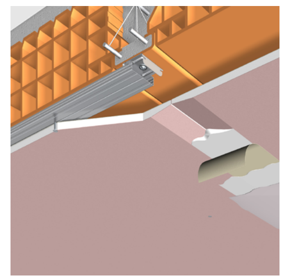
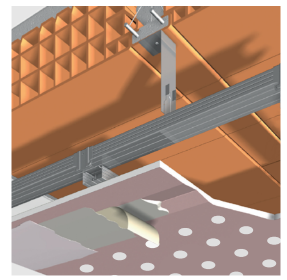
4.4.2. Ceiling acoustic treatment

As far as the acoustic treatment of the ceiling is concerned, the algorithm was developed not only to select different types of linings but also to combine them. It offers four macro-possibilities, namely:

- acoustic treatment of the existing ceiling;
- installation and acoustic treatment of a false-ceiling;
- installation of a sound baffle system;
- installation of an brick-proof false-ceiling.

This last possibility was deemed to be necessary given the difficult condition of many existing classrooms and reading the frequent news reports; moreover, the detachment of brick elements from the ceiling intrados is one of the characteristic degradation phenomena in ancient school buildings. In particular, the brick-proof false-ceiling provides for two alternatives: the first is the in adherence solution (D111), the last is the lowered one (D112). Their main features are shown in the table below.

Table 10. *Brick-proof false-ceiling solutions.*

brick-proof false-ceiling	D111	D112
solution	in adherence	lowered
air-gap	30mm	65÷200mm
boards	gypsum board	perforated gypsum board
perforated area	/	15.5%
thickness	12.5mm	12.5mm
density	1000kg/m³	1000kg/m³
3D view		

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Any choice in setting the model is clearly made using the GH components similar to those shown in the previous paragraph. The acoustic treatments concerning the first two macro-possibilities include an integral sound-absorbing solution (AC100) and a combination of sound-absorbing and sound-reflective lining (AR-C configuration). These have been taken from the Italian reference standard for this work and the German one, DIN 18041 [76]: the first involves the use of porous or resonant panels on the entire ceiling/false-ceiling surface, the last combines one of these two acoustic materials with the membrane absorber according to two different configurations:

- AR-CF: the reflective surface is above the teacher's position;
- AR-CC: an acoustic mirror is in the center of the ceiling.

The AR-C configurations have also been designed to adapt to the two teaching methods presented in the first chapter, namely:

- AR-CF configuration, for the traditional teaching method with the fixed teacher position;
- AR-CC configuration, for the future teaching method where the teacher is keen to make changes to learning spaces, so she is free to move inside the classroom.

These configurations are obtained by real-time constructions by using the image-source technique to find all the specular reflection paths in the room geometry. When a ray is reflected, it spawns a secondary source "behind" the boundary surface. This source is located on a line perpendicular to the wall, at the same distance from it as the original source, as if the original source has been "mirrored" in the surface. This new "image" source now represents a perfect reflection path, in that the distance along the straight line between the receiver and the image source has the same length as the path from the real source to the receiver, reflected in the boundary (Figure 38).

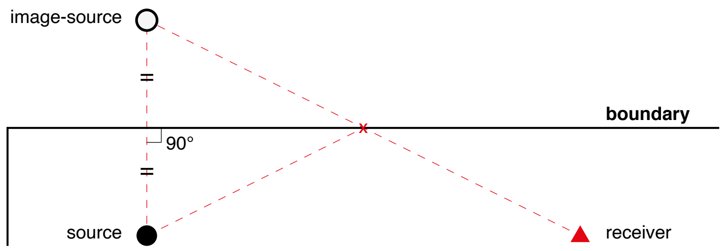


Figure 38. *Image-source technique.*

It should be remembered that the maximum air gap of the false ceiling must be such that the minimum height of the room is not less than 3m and does not interfere with the openings, if at a higher altitude; even then the algorithm dynamically manages the height range of the false ceiling.
The Figure 39 illustrates the image-source technique as embedded in the algorithm.

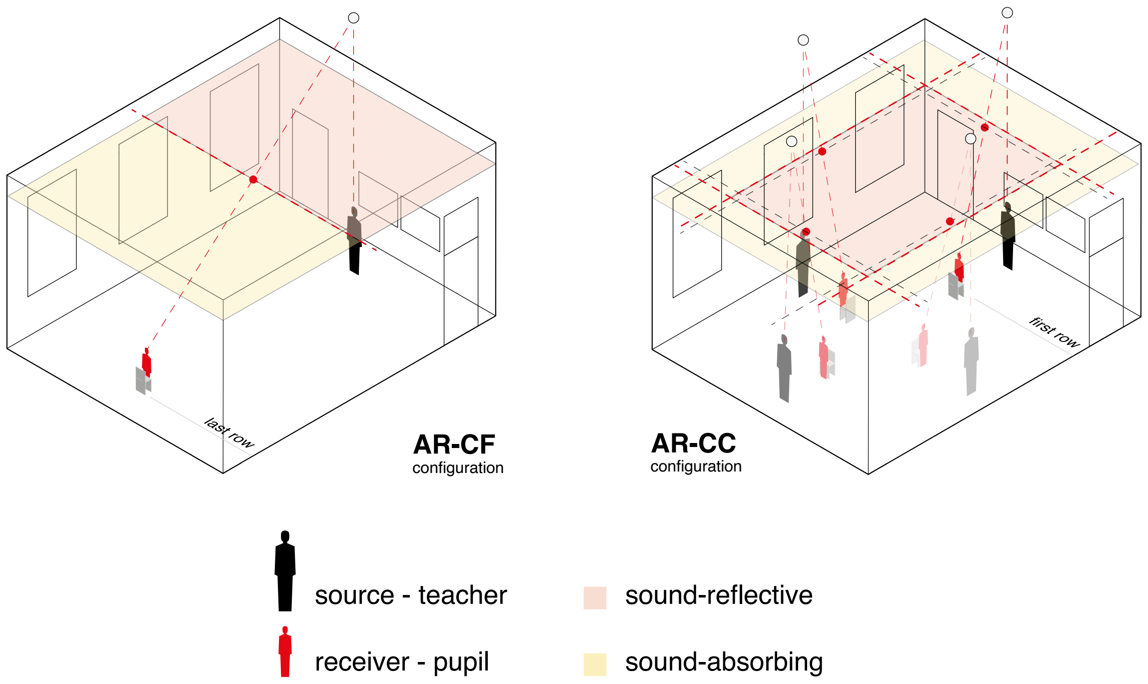


Figure 39. *Image-source technique embedded the AR-C configurations in the algorithm.*

Finally, ceiling sound baffles are an effective acoustic treatment that suspends from the ceiling to increase speech intelligibility and sound clarity [84]. The acous-

tic baffles are suitable in buildings where the volume should be maintained, have limited wall space or need materials out of reach. Since the baffle element installs vertically, both sides have exposure to sound (Figure 40). With an increase in surface area, there is an increase in its ability to reduce reverberation [85, 86].

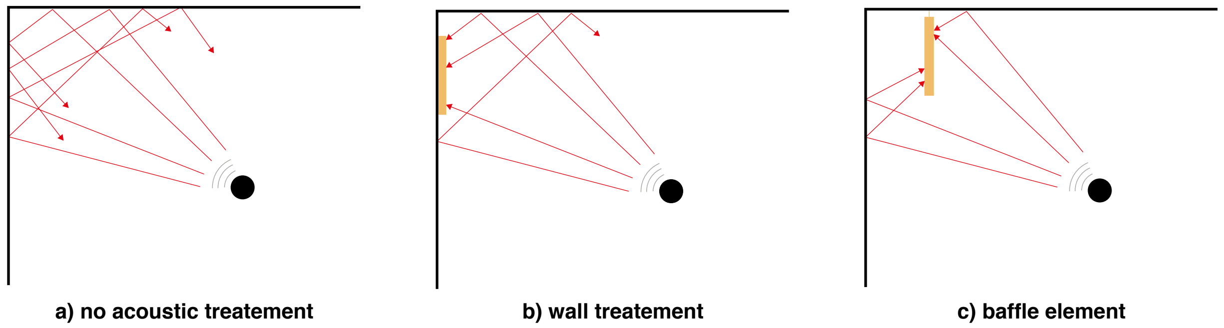


Figure 40. *Baffle double sound absorption.*

In the parametric model, the baffle system is simulated as composed of baffles rows, of which the algorithm is able to calculate the dimensions starting from the size of the single deflector. The possibility of adding a baffle system to cover the entire ceiling surface is always available within the algorithm which is able to automatically identify the surface on which to hang the baffle elements, moreover, if the A-RCC configuration has been selected, the algorithm also gives the possibility to attach the baffles only to the acoustic mirror that characterized this configuration. This system can take different spatial configurations depending on:

- surface to cover*;
- baffle size*;
- baffle direction;
- spacing between baffle rows;
- suspension distance*.

Table 11. *Baffle parameter and values.*

baffle parameter	parameter's values
surface to cover	entire ceiling - acoustic mirror
size	1200*300 - 1200*600mm
orientation	length oriented - width oriented
spacing between baffle rows	300 - 600 - 900 - 1200mm
suspension distance	0 ÷ 300mm

(*): parameters' values differ depending on the model configuration, in order to, as already underlined previously, avoid errors and interference between surfaces. The figure below tries to sum up the ceiling acoustic treatments available one can choose from and their combinations.

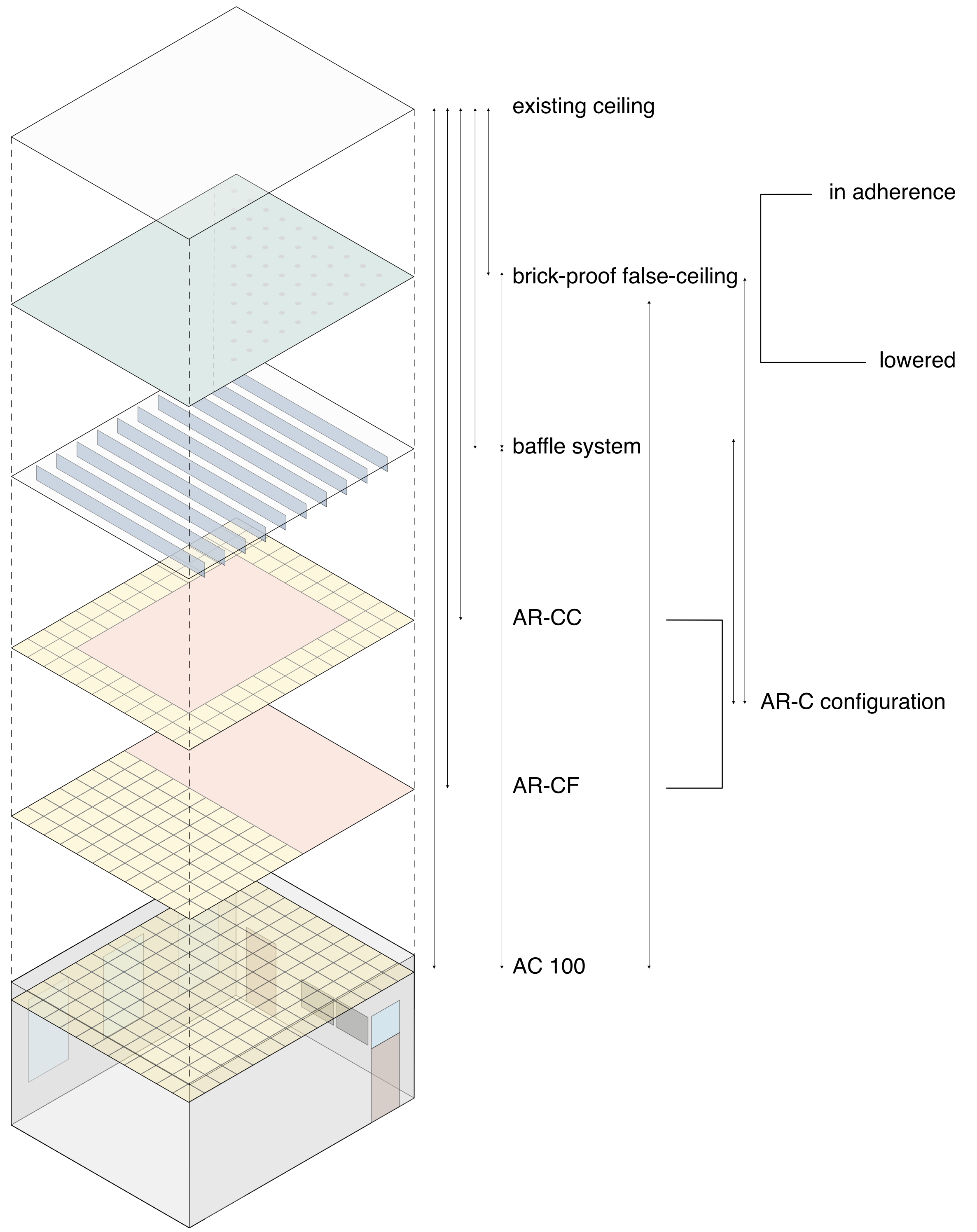


Figure 41. *Ceiling acoustic treatments.*

4.4.3. Room equipment

It has been already seen that the new Italian standard considers the noise generated in the measurement environment, for example the one of room equipment. In order to include this as well, although our case study presents traditional iron radiators, the algorithm incorporates the possibility of adding a fan-coil system inside the virtual model, as in view of their substitution, these could influence the acoustic performance of the room. These are the two most common types of fan-coil system, namely:
- wall mounted;
- ceiling mounted.

The number of fan-coil units is a function of volume (Table 12) and they are arranged according to a simplified layout that distributes them on the mounting wall, such that these elements have a directivity factor Q equal to 2. Finally ,in the algorithm for each of the two types a typical mid-range sound power level has been assigned, derived from the technical data sheets.

Table 12. *Comparison between fan-coil systems.*

fan-coil system	wall mounted	ceiling mounted
mounting surface	wall: 0 - 1 - 2 - 3	ceiling - false-ceiling
if volume < $250m^3$	2 fan-coil units	2 fan-coil units
if volume ≥ $250m^3$	3 fan-coil units	3 fan-coil units
mid-range Lw	45 dB(A)	48 dB(A)

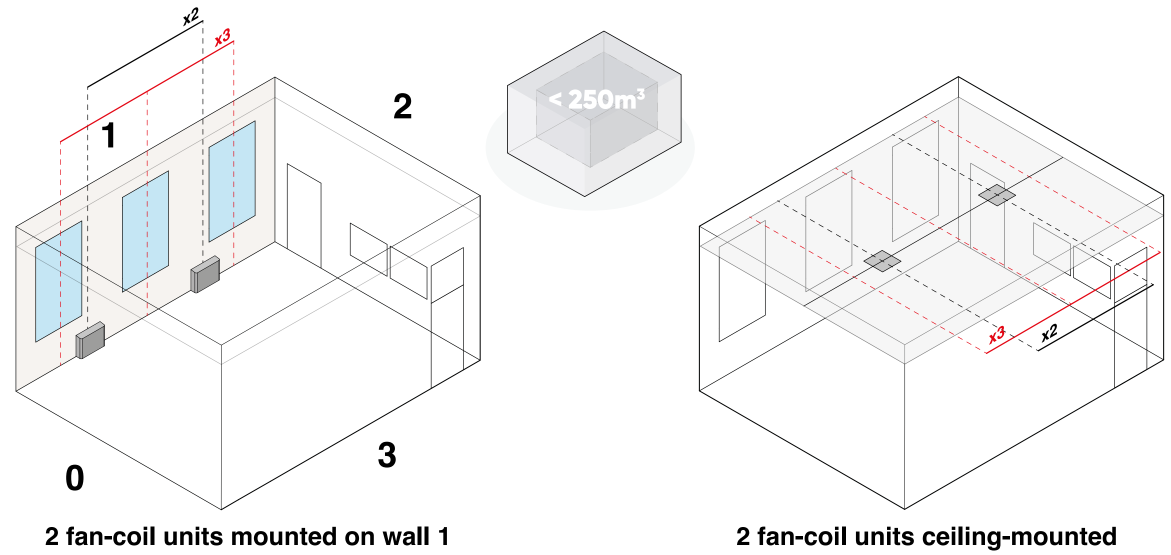


Figure 42. *Fan-coil units arrangement.*

4.5. Algorithm's acoustic materials

In this paragraph, the acoustic materials will be presented as incorporated in the algorithm. In chapter 2, it has already been discussed in general while in the paragraph related to the acoustic treatments, it has been seen how the algorithm is able to automatically associate a type of acoustic lining to a surface or how, through the GH components, choose between one type of absorber or another, for example porous or resonant absorbers. But now it is a question of associating absorption curves to the surfaces that make up the entire parametric model. This operation is managed automatically by the algorithm as well; it has been possible thanks to the constraints defined in the preliminary phase and thanks to the implementation in Python programming language [11] of the formulas for the calculation of acoustic materials and baffle system.

Materials, indeed, have been divided into two categories:

- "fixed" materials;
- "parametric" materials.

The former includes materials that we can typically find in any classroom (e.g. plaster for side walls and untreated ceiling, marble or ceramic tiles for floor, wood for doors etc.) and the absorption coefficients have been extracted from the UNI11532-2 standard (tables 13-14).

Table 13. *Sound absorption coefficients of "fixed" materials used in the algorithm.*

description	frequency (Hz)					
	125	250	500	1000	2000	4000
marble, tiles, clinker	0.01	0.01	0.02	0.02	0.03	0.03
smooth plaster	0.02	0.02	0.03	0.03	0.04	0.05
wooden door	0.10	0.08	0.06	0.05	0.05	0.05
windows	0.28	0.20	0.11	0.06	0.03	0.02
blackboard	0.30	0.24	0.19	0.14	0.08	0.05

Table 14. *Equivalent absorption area for people and furniture expressed in m^2.*

description	frequency (Hz)					
	125	250	500	1000	2000	4000
pupils sitting at the table	0.05	0.10	0.20	0.35	0.40	0.45
desks and chairs	0.07	0.06	0.07	0.07	0.04	0.03

The sound absorption of the pupils is simulated as a plate at 1.10m of height from the floor; the equivalent absorption area is $1m^2$ for each pupil as under the law UNI EN 12354-6:2006 [74].

The algorithm estimates the maximum number pupils by fixing the square meters to pupil ratio = $1,8m^2$ according the D.M. 18 December 1975 [82] and calculates the size of the plate by dividing the estimated area by the distance between the front row and the last one, which by default are 1.5m from the teacher's position and 1.5m from the back wall toward the centre of the classroom wall respectively.

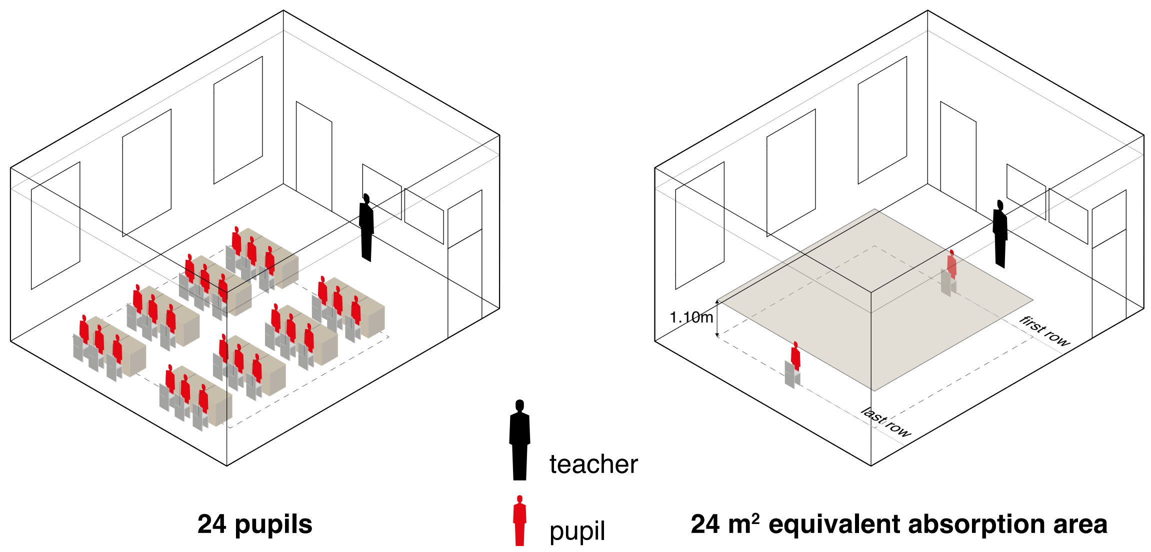


Figure 43. *Pupils' equivalent absorption area.*

Parametric materials include all the ones used in the acoustic design phase (e.g. porous, resonant and membrane absorber, baffle system, brick-proof false-ceiling). The absorption coefficients have been calculated by using:

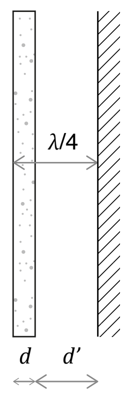
- the formulas presented in chapter 2 for porous, resonant and membrane absorbers;
- the method by Wolfgang Probst [85] for baffle system;
- the data shown in technical specifications of the solutions proposed for the brick-proof false-ceiling.

The code written in Python is presented in Appendix A and the results correctness has been checked through parallel Excel sheets. The input data in formulas sourced from the acoustic treatments setting in the parametric model and the absorption coefficients have been calculated with reference to a typical absorption curve for each type of absorber. The setting phase as always is managed through specific GH sliders for the acoustic treatment of walls and ceiling.

In the tables below some sound absorption curves and the input data variation intervals are shown.

Table 15. *Input data range and sound absorption curve for porous absorbers.*

parameter	treatment position	range
thickness - d	wall	25 ÷ 50mm
	ceiling	
air-gap - d'	wall	0 ÷ 100mm
	ceiling	0 ÷ $h_{air\text{-}gap}$



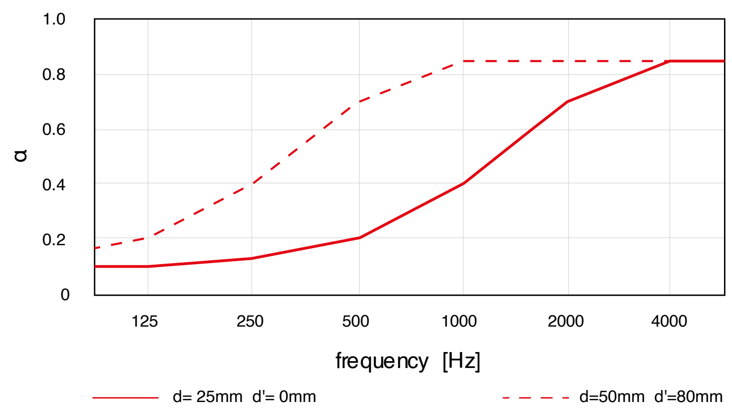
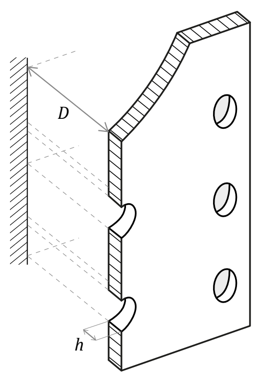


Table 16. *Input data range and sound absorption curve for resonant absorbers, h=12.5mm.*

parameter	treatment position	range
air-gap - D	wall	40 ÷ 120mm
	ceiling	0 ÷ $h_{air\text{-}gap}$
perforated area - p	wall	9% - 15% - 19%
	ceiling	



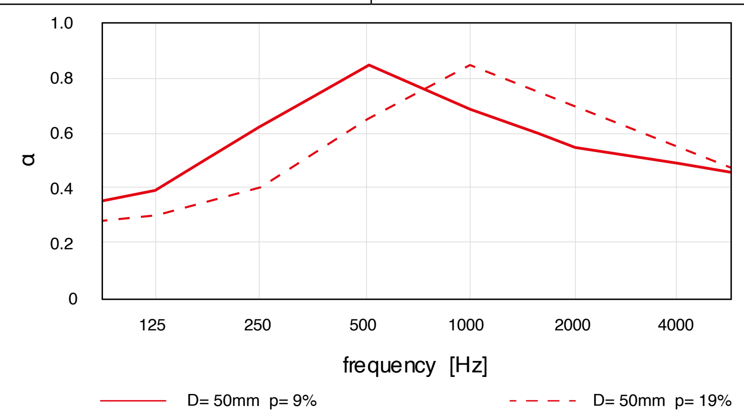
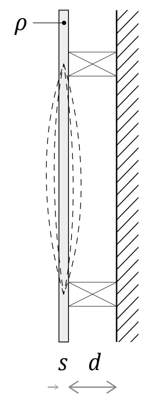


Table 17. *Input data range and sound absorption curve for membrane absorbers.*

parameter	treatment position	range
density - ρ	wall	700 kg/m³
	ceiling	
thickness - s	wall	9 ÷ 25mm
	ceiling	
air-gap - d	wall	40 ÷ 120mm
	ceiling	0 ÷ $h_{air\text{-}gap}$



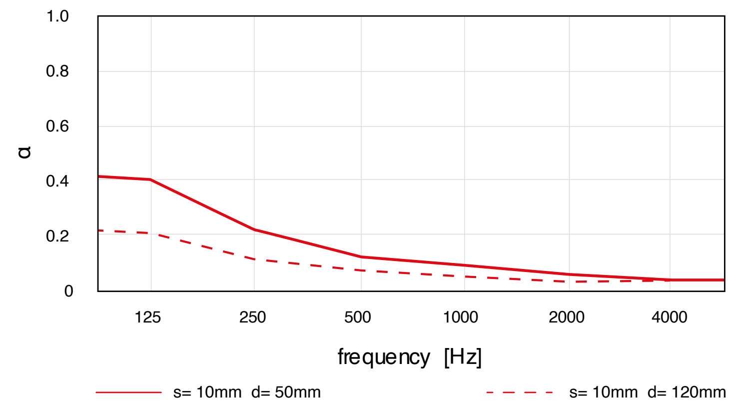
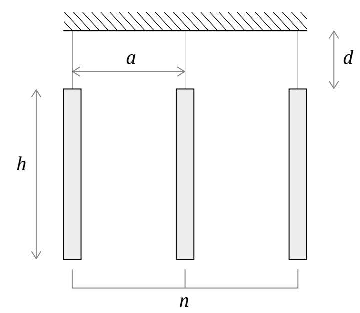
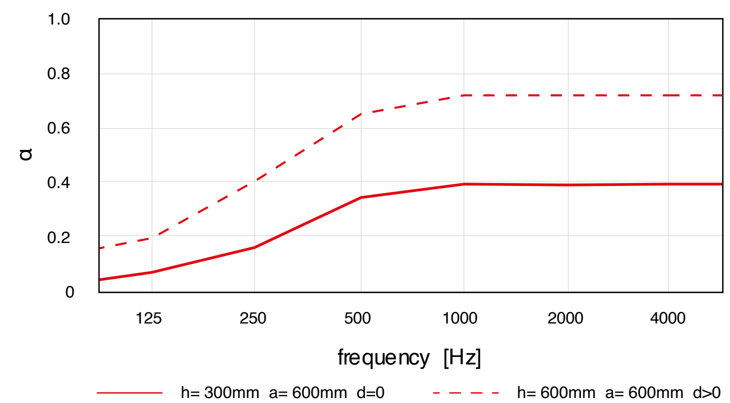


Table 18. *Input data range and sound absorption curve for baffle system.*

parameter	range
height - h	300 - 600mm
spacing between rows - a	300 - 600 - 900 - 1200mm
baffles number - n	6 - 9 - 14 - 26
suspension distance - d	0 ÷ 300mm





As far as the brick-proof false-ceiling are concerned, the main features of the available acoustic solutions have been indicated in Table 11, in the following figure, the respective sound-absorption curves are shown.

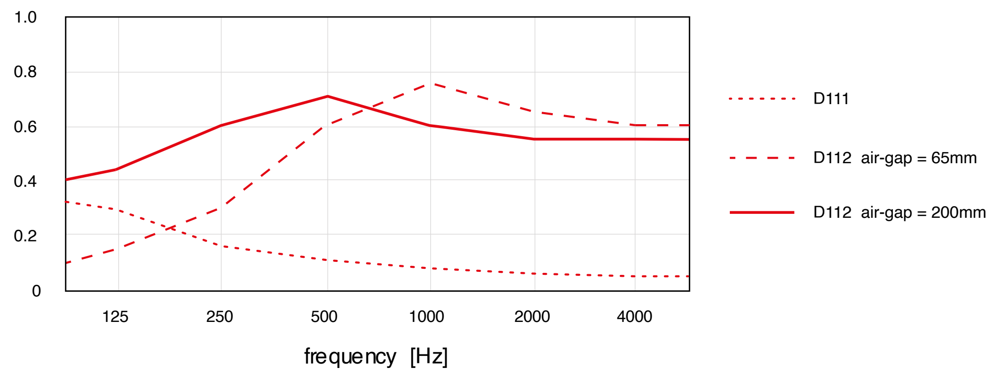


Figure 44. *Sound-absorption curves of the brick-proof false-ceiling solutions.*

4.6. Acoustic parameters and algorithm's output data

The focus has so far been on the possibilities and constraints offered by the developed algorithm both in terms of room geometry and acoustic treatments and on the phase of setting up of the model as well. At this point it is ready for predicting the acoustic descriptors introduced in chapter 2, implemented in Grasshopper, as for acoustic materials, in Python language, using the calculation formulas in the UNI11532 standard. The Python code has been added to Appendix B and the output data correctness has been verified through parallel Excel sheets. The input data sourced from the choices made in the parametric model and the output data are shown in Panel GH component that turns green or red depending on whether the acoustic parameter is respected or not. Moreover, ante-operam and post-operam results are put close making them easier to compare.

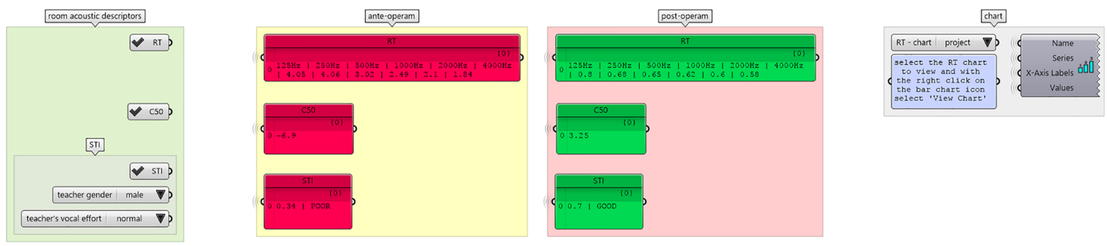


Figure 45. *Output data in Grasshopper canvas.*

As regards Reverberation Time (RT), it is calculated in octave bands from 125 Hz to 4 KHz, both in occupied and unoccupied but furnished condition by associating

the absorption coefficients in Table 14 to the pupil's absorption plan. The output data are also shown on a chart, making easier to compare the ante-operam and post-operam results with the optimal reverberation time curve provided for by the standard. Speech Clarity (C50) and Speech Transmission Index (STI) are evaluated in the measurement positions shown in Figure17, as required by the standard, in particular in the STI calculation, it is possible to choose the gender of the speaker and its vocal effort, summarized in the following table.

Table 19. *Speaker gender and vocal effort.*

speaker gender	vocal effort
male	relaxed
	normal
female	raised
	loud
	very loud

Moreover, two parameters are included in the STI calculation: the room equipment noise, $L_{ic,int}$ and the overall noise in the environment, L_{amb}; both have been introduced in the chapter 3. For the latter, however, we need to define both the sound pressure level outside the building, at a distance of 2m from the façade, $L_{1,2m}$ and the façade sound insulation standardized to the reverberation time, $D_{2m,nT}$: in the algorithm, by default, values have been defined depending on the typology façade of the case study and classification of the road on which the measuring environment faces, according to the BS EN 1793-3:1998 [80] (Table 20).

Table 20. *Facade sound insulation and sound pressure level outside the building.*

$D_{2m,nT}$	road classification	$L_{1,2m}$
45 dB	busy main road	68 dB
	road parallel to a busy main one	58 dB

Looking at the calculation formulas it is clear the close correlation between the acoustic parameters presented in this paper which, in a schematic way have been illustrated in the figure below.

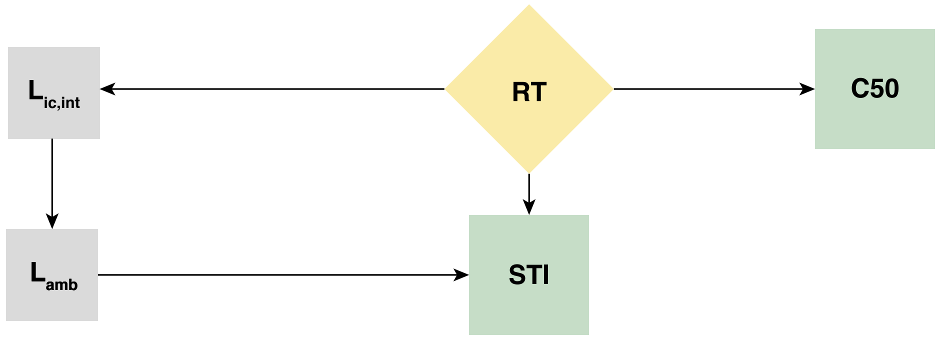


Figure 46. *Correlation between acoustic parameters.*

4.7. Comparison between measured and calculated parameters

This paragraph presents a comparison between measured and calculated acoustic parameters in the case study classroom. This has been an important step to evaluate the accuracy of the predicting model included in the algorithm. Comparison has made both for the untreated room and for the treated room, that is after the acoustic treatment described at the beginning of this chapter.

Table 21. *Dimensional data of the classroom.*

parameter	parameter's value
lenght	8.4 m
width	6.7 m
height	4.4 m
volume	248 m³
total surface	245 m²
occupation	24 pupils

Table 22. *Acoustic treatment of the classroom.*

treatment	absorber	m²
wall	porous, d=50mm d'=0	26
ceiling	membrane, d=200mm*	56
	porous, d=40mm d'=0	56

(*): brick-proof false ceiling.

Figures below shows the 3D model of the actual classroom and the simulated one in the algorithm closer to the real room, and the reverberation curves of untreated

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and treated classroom in occupied condition.

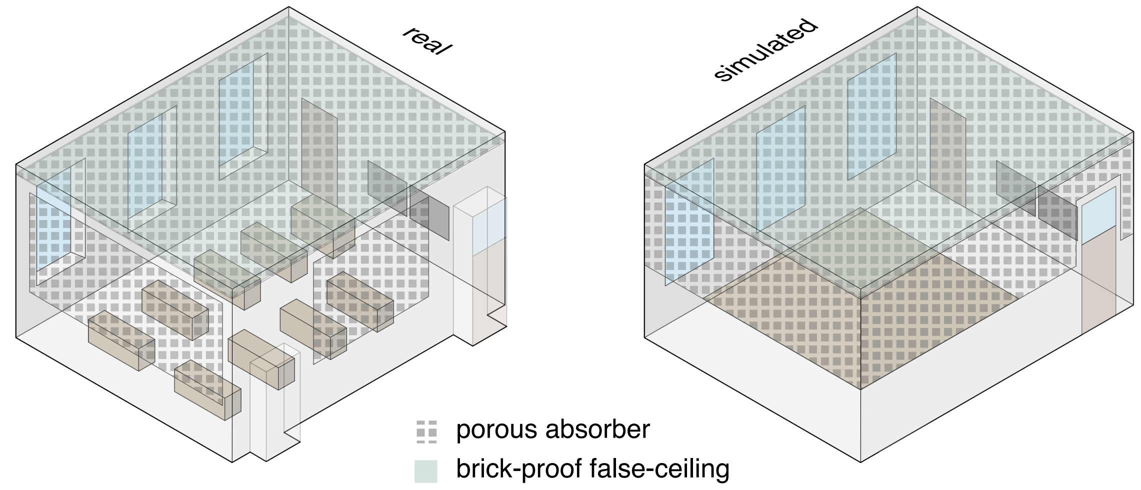


Figure 47. *3D model of the real classroom and the simulated one.*

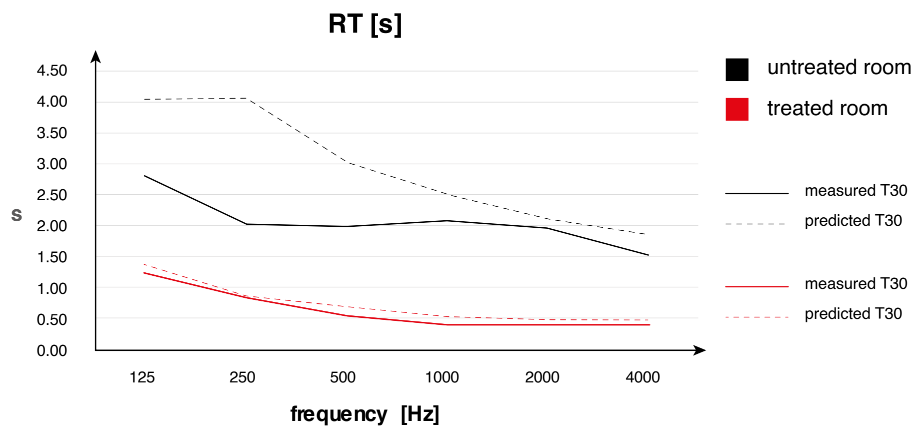


Figure 48. *Comparison between the measured and predicted reverberation time in the untreated and treated classroom.*

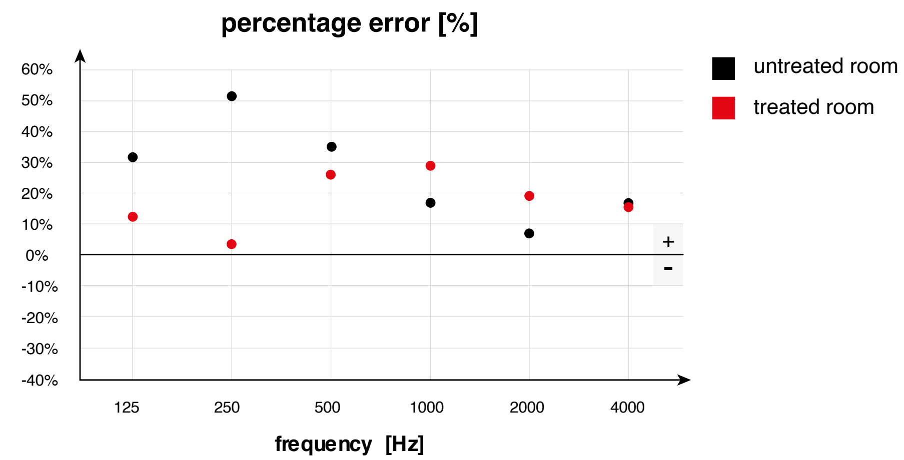


Figure 49. *Percentage relative differences of the predicted reverberation time predicted compared to the measured one.*

A relative difference of 10% is cited by Hodgson [87] and Bistafa and Bradley [88] as an engineering-type accuracy for reverberation time predictions in practical applications, although a just-noticeable difference in reverberation time according to ISO 3382-1 is 5% [89]. In Figure 49, a tendency to overestimate the reverberation times is shown; the Sabine formula predicts this acoustic descriptor with the average relative differences of 10%, across the 500 Hz to 2 kHz octave-bands.

The percentage relative differences of the reverberation time at the low frequencies is in agreement with a study conducted by Astolfi et all. [90], while as regards the medium-high frequencies, this can be explained by the difference in the absorption coefficients of the porous material, used for acoustical treatment, which are higher than those available in the algorithm.

In conclusion, predicted values of C50 and STI are presented in the table below.

Table 23. *Predicted values of C50 and STI acoustic parameters.*

parameter	untreated room	treated room
C50	-6.9 dB	4.1 dB
$STI_{(male; normal)}$	0.34 - POOR	0.75 - GOOD

5. MODELING METHODS

This chapter deals with other two different modeling methods applied in classroom acoustics, which have been implemented in the developed algorithm to assess which one best predict the acoustic parameters and compare them in the following optimization phase. The first method has included the Eyring's formula and the Barron and Lee's revised theory for the calculation of the reverberation time and the reverberant sound pressure level, respectively; the second one is a ray-tracing method using Pachyderm acoustical simulation for Grasshopper. According to a study conducted by Astolfi et al. [90], the first method is suitable for large enclosures with a non-uniform distribution of absorption material in the room.

5.1. Empirical methods

The physical phenomena involved in sound wave propagation inside enclosures are both numerous and complex, making overall analytical computation difficult. Because of the large number of parameters to be taken into account in the description of a real situation, only an approximation of it is possible [91]. There are several approximations, some better than others, but still no one has been proved to efficiently solve both the high and the low frequency problem. From the computational point of view, two different approaches will be discussed: empirical methods and geometrical methods. Sabine model, included in the Italian standard for calculating the reverberation time, is the most popular one and belong to the first group. This method offers a rough estimation in octave bands of parameters as it considers the existence of a diffuse sound field in the space. In that way, only the size of the room and the importance of absorption, but not of the location of each of the surfaces is considered [92]. In many practical cases the assumption of diffuse field conditions for applying Sabine's theory are not in agreement with the existing absorption distribution. This is a very important issue for many rooms, including classrooms, where the sound absorption is typically applied only to the

ceiling area. As far as having sound absorption located mostly on a single surface is concerned, classrooms are very similar to auditoriums because of the high audience absorption on the floor area in this type of room. A fundamental difference, however, is that recommended reverberation times for classrooms are well below 1s [93], whereas in larger rooms, such as opera houses and concert halls, values well above 1s are usually recommended [94].
The sound field will be, in general, sufficiently diffuse if there are not large differences in the basic dimensions of the room, the walls are not parallel, the sound absorbing material is uniformly distributed, and most internal surfaces are divided into parts. In practice, almost all of these requirements are not fulfilled.
The Sabine (1922) and Eyring (1930) equations were derived under different assumptions relating to the sound wave path. The Sabine equation assumes that as a sound wave travels around a room it encounters surfaces “one after another.” The Eyring equation assumes that all the surfaces are simultaneously impacted by the initial sound wave, and that successive simultaneous impacts, each diminished by the average room absorption coefficient, are separated by mean free paths. On the other hand, classic theories of Sabine and Eyring assume that sound pressure variance is zero, as a consequence a perfectly diffuse sound space with a constant sound energy density. Conversely, in a non-diffuse sound field, sound energy density is not constant. Therefore, the fluctuations in the sound pressure levels depend on the considered direction. A non-uniform distribution of absorption in a room is often the main reason for a non-diffuse sound field. Moreover, other phenomena, normally wave-type, such as resonance, interference, and focalization, may produce privileged sound-wave directions avoiding the sound to diffuse across the volume uniformly [95].
According to the classic theory the sound strength should not vary considerably at sufficient distance from the source where the energy of the reflected sound field, equally distributed throughout the space, is dominant. However, Barron and Lee (1988) showed that the reflected sound energy may significantly fall on with increasing source-receiver-distance. Barron and Lee found out that the sound level decay was linear soon after the direct sound in the majority of the halls and the reflected sound level decreased with increasing source-receiver distance. This is due to the fact that receivers closer to the source not only receive a higher level of direct sound, but also higher levels of early reflections because these have travelled shorter distances. Thus, they proposed a model based on the following

assumptions: the direct sound is followed by linear level decay at a rate corresponding to the reverberation time; the instantaneous level of the late decaying sound is uniform throughout the space; the time t_0 corresponds to the time the signal is emitted from the source, therefore the direct sound reaches a point at a distance r from the source after a time $t_D = r/c$ [96].
According to the Barron and Lee’s revised theory of sound decay, the sound energy may be calculated as:

$$G = 10 log(100 / r^2 + 31200 \cdot T / V \cdot e^{(-0.04 \cdot r/T)}) \qquad (18)$$

where

r is the distance of the source from the receiver, in m;
T is the reverberation time, in s;
V is the total room volume, in m³.

The exponential term ($-0.04 \cdot r/T$) marks the difference between the classic and the revised theory. This theory has been implemented only in the Speech Clarity *C50* formula of the UNI11532.
It accounts for the fact that the linearly decaying reflected sound, which is assumed to have a uniform instantaneous level at late time, cannot start before the arrival time of the direct sound $t_0 = r/c$, thus yielding a refined integration limit for the calculation of the total reflected sound level. In particular, there has been significant discussion in the last years about the appropriate starting time t_0 for the integration of the reverberant field [97].

5.2. Geometrical methods

Over the last three decades many room acoustical computer programs have been developed and used for predicting room acoustics quantities. These programs can be classified as wave-based programs and ray-based programs. Sound wave theory, though correct from a physical point of view, is not deemed to be beneficial when it comes to dealing with practical issues in architectural acoustics. Computer simulations are instead typically based on the principles of geometrical acoustics: the concept of a wave is replaced by the concept of a sound ray [91]. Analogous to light rays in optics, a sound ray is seen as a straight line along which a small portion of sound energy travels. Where sound in reality travels through a room from one person to another, rays in a simulation propagate from a defined source point to a receiver, interacting with the geometry of the room model along the way. The task in geometrical acoustics is to find the paths of sound connecting the source and the receiver [99]. Wave phenomena like diffraction and interference are typically neglected. Ultimately geometric acoustics provides an approximation of the acoustical environment in a room. Its application is however justified if the dimensions of the room and its walls are large compared with the wavelength of sound [100].

The real advantage of computer models is to deal with non-diffuse fields where the classical Sabine and Eyring formula may not be appropriate. Since these are to various degrees very common, an approach is required to model these rooms. Thus, methods based on geometrical propagation paths consider the propagation of sound through the air in straight lines, avoid the wave nature of sound, and model in one- or another-way reflections from boundaries. These methods are also called energy-based methods, because in the end, the only thing they consider is the energy which was assigned to every ray or portion of wave and. They are also able to achieve the temporal and spatial distribution of reflections, and so they are suitable for auralization [98]. It has been said that geometrical room acoustics can reflect only a partial aspect of the acoustical phenomena involved in a room, but that, however, is an aspect of great importance 13. In the image-source method, reflected paths from the real source are replaced by direct paths from reflected mirror images of the source. This process is quite simple, and it is already illustrated in Figure 38.

Special interest will be paid to the ray-tracing method whose concept is simple to understand but very complex to compute and is represented in 2D. In 1968, Krokstad et al. [101] carried out the first application of ray-tracing computer modelling.

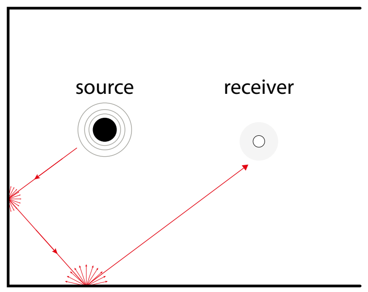


Figure 50. *Principle of ray-tracing.*

The sound power emitted by a sound source is described by a finite number of rays, which will be considered as carriers of power (or of energy or intensity). These rays travel through space at the speed of sound and are reflected after every collision with the room boundaries. During that time, their energy decreases as a consequence of the sound absorption of the air and of the walls involved in the propagation path. When the rays cross the receivers, an energy calculation process is performed, and those data stored. Finally, the impulse response at every receiver is obtained, and with it all desirable acoustic parameters. The attenuation of the energy is calculated according to the absorption of the air and the length of the travelled path, and according to the wall absorption properties. Ray tracing predicts acoustic parameters with very good accuracy, although the accuracy is always low at low frequencies [102-104].

5.3. Sound scattering

The major problem in ray-tracing models lies in the difficulty of knowing the scattering coefficient of materials employed. Scattering coefficient *s* is commonly employed to characterize surfaces to perform acoustic simulation in geometrical models. and it is the most popular method to weight the relation between specular and diffuse reflections in geometrical acoustics.

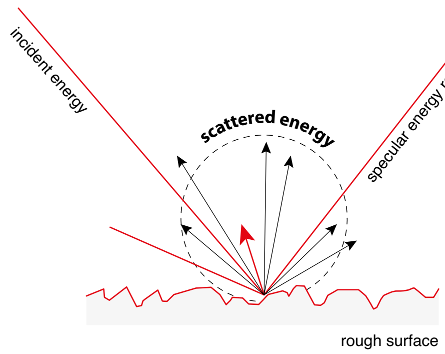


Figure 51. *Scattering phenomenon.*

Sound reflections can occur either in a specular or diffuse way. In the first case the sound-wave 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.

Sound diffusion can be provided either by room elements, as traditional room ornaments (e.g. columns, plaster decoration, statues), or by diffusing surfaces which were mostly developed in recent decades. In both cases the dimension of the incident sound-wave's wavelength has to be comparable to those of the elements or of the surface corrugations. 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 mirror-like reflected. The scattering coefficient *s* is defined as the ratio between reflected sound power in non-specular directions and the total reflected sound power [105, 106].

The selection of scattering coefficient is made according to the geometrical properties of every surface; another aspect of the scattering coefficient *s* is that it not only depends on the frequency, but also on the angle of sound incidence. When a ray encounters a diffusing surface, a random number in the range (0,1) is generated. If the number is smaller than *s* the ray direction is randomized to simulate a diffuse reflection otherwise the reflection is specular [107, 108]. From the 1970s onward, new types of sound diffuser appeared on the market: most of them were reflection phase grating diffusers also known as Schroeder diffusers (Figure 52), based on mathematical functions, consequently, new coefficients were developed, able to assess the quality of innovative diffusers that were produced since then.

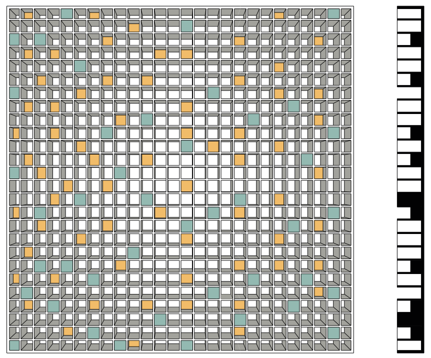


Figure 52. *2D Schroeder diffuser.*

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 make the complexity of the phenomenon. 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. 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 [68].

However, today’s knowledge about which scattering coefficients are realistic and how to determine them is still very limited, and some authors consider it sufficient to characterize each surface by only one scattering coefficient, constant for all frequencies [109, 110].

This assumption can perhaps be accepted if both causes of diffusion are of similar importance. Cox and D'Antonio [68] describe three different coefficients describing scattering of materials: the already mentioned diffusion coefficient, scattering coefficient, and the correlation scattering coefficient as well. According to Arthur van der Harten [12, 111], among these, the one that comes closest to scattering is the correlation scattering coefficient. The others, while standardized, are interesting for comparing products, but not very useful for simulation.

As far as correlation scattering coefficient is concerned, the scattering coefficients used for geometrical acoustics are the percentage of energy that is no mirror-like reflected. The correlation scattering coefficient measures the difference between a reflection from a smooth surface and a rough one. Lastly, it should be pointed out that the scattering phenomenon cannot be considered in empirical models.

5.4. Pachyderm acoustic simulation

Pachyderm is an acoustical simulation plug-in for Rhino by Arthur van der Harten [12]. The program, which has been open-sourced since March 2015, utilizes a hybrid model for the purposes of acoustic prediction and auralization. Thus, itis a collection of acoustics simulation algorithms which can be used to predict noise, visualize sound propagation, and critically listen to designed spaces [111]. Pachyderm has been used in a few form finding studies to perform acoustic analysis. Frequency-dependent absorption and scattering are assigned to geometry per model Rhino layer, via a separate interface. Results can be expressed in several acoustic parameters including reverberation time and noise levels. The parameterization of geometry is supported through an included Grasshopper extension. Like many acoustic software which are based on high frequency modelling techniques, in the scattering simulation Lambert's law is used [111]. Absorption and scattering coefficients cannot be directly altered on the Grasshopper canvas, meaning that parameterization of material properties requires a workaround by cycling through layers with preassigned materials. For the implementation of ray tracing it is important to be aware of its inherent uncertainties and limitations. The level of detail of a geometric model needs to correspond to the frequencies of the simulated sound. Using highly detailed CAD models will lead to unnecessary long computation times, without producing a more accurate acoustic analysis [112, 113]. The amount of rays also needs to be sufficiently large, as does the boundary surfaces to detect the rays.

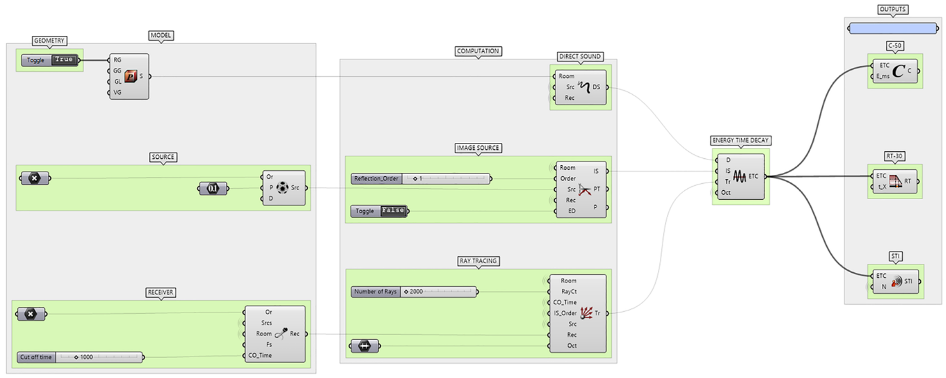


Figure 53. *Pachyderm data flow on Grasshopper canvas.*

5.5. Algorithm implementation

To include methods described above, the developed algorithm has been modified in some parts discussed in the following paragraph. The implementation of the Eyring and Barron & Lee theories has been quite simple, essentially that has been a substitution in GH Python component of the reverberation time formula and the reverberant sound pressure level one respectively. In particular, this last one has been applied both to determine The sound pressure level of the speaker and room equipment. In particular, this latter formula has been applied both to determine The sound pressure level of the source and room equipment.

The Eyring equation, is:

$$RT = \frac{0.161 \cdot V}{-S \cdot ln(1-a)} \quad [s] \tag{19}$$

where

V is the total room volume, in m³;

a is the is the average surface absorption coefficient;

S the total room surface area, in m².

MODELING METHODS

As for Sabine's formula, the sound air absorption has been neglected.

According to the classical theory, the reverberant sound pressure level, $L_{p,r}$, in dB, is uniform throughout the room:

$$L_{p,r} = L_w - 10log(A) + 6 \quad [dB] \tag{20}$$

where

L_w is the sound power level, in dB;

A is the total acoustic absorption, in m².

As already mentioned, according to the revised theory by Barron and Lee the reverberant sound pressure level, $L_{p,r}$, in dB, decreases with the distance from the source:

$$L_{p,r} = L_w - 10log(R) + 6 - 0.174(r/T) \quad [dB] \tag{21}$$

where

L_w is the sound power level, in dB;

R is the room constant, in m²;

r is the distance of the source from the receiver, in m;

T is the reverberation time, in s.

As far as the ray-tracing methods is concerned, its implementation has resulted substantial changes in the algorithm structure in the light of what has been said before; especially relating absorption and scattering coefficients that cannot be directly altered on the GH canvas, meaning that parameterization of material properties has required a definition of a database of materials assigning through Rhino layers. Moreover, this limit does not allow the implementation of the Python code related to the noise level of the room equipment that has been therefore neglected in the ray-tracing model. The database contains 35 materials given in the Appendix C. Most of these have derived from a selection and clustering of materials parameterized in the source-algorithm whose scattering coefficient has been obtained from a research that has compared simulated outcomes with the measured ones; other are scattering materials added in the parametric model and selected from the literature[56]. Based on the assumption that every surface scatters at least 10% of reflected energy and that with tiny bit of surface roughness (as with smooth plaster) scatters between 15% and 25%, at the suggestion of van der

Harten; materials in a typical classroom have been considered as no-scattering materials. The figure below shows the three scattering curves assigned to materials in Pachyderm.

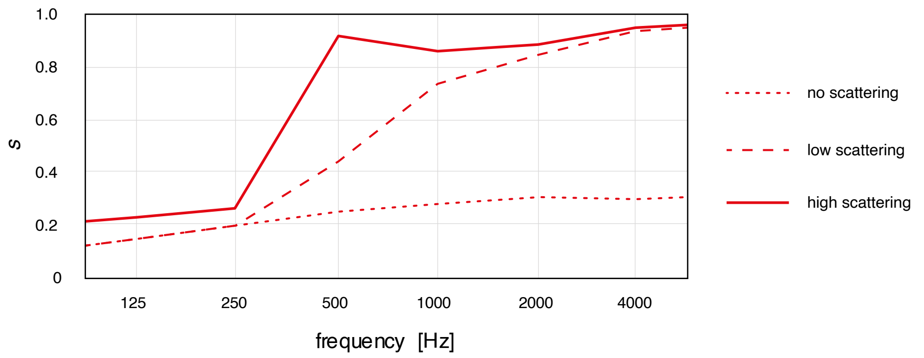


Figure 54. *Comparison between the three scattering curves of materials in Pachyderm.*

5.6. Comparison between measured and calculated parameters

In a similar way to the previous chapter and under the same assumptions, a comparison between measured and predicted acoustic parameters in the case study classroom, is presented.

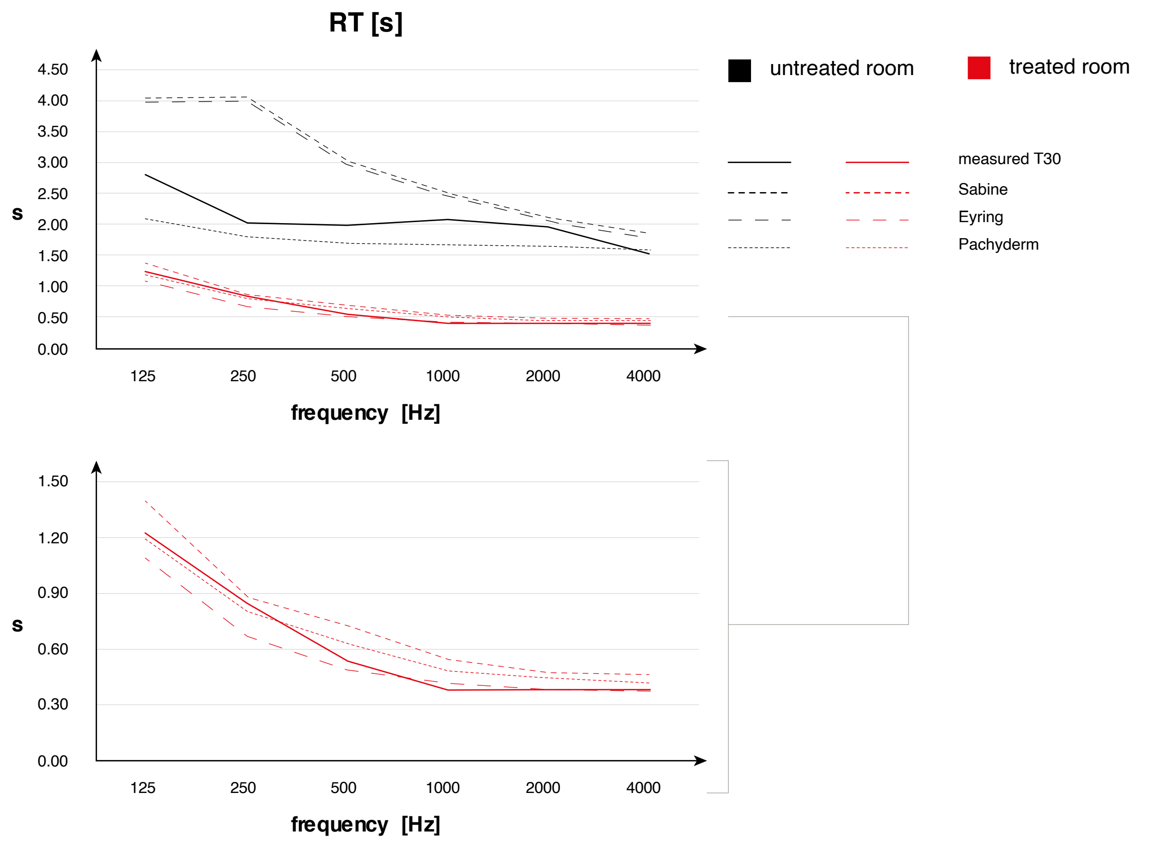


Figure 55. *Reverberation time predictions with various calculation methods.*

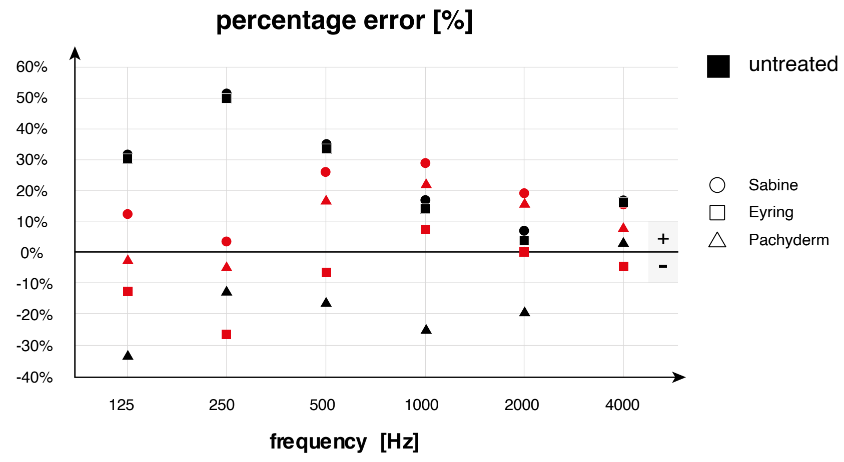


Figure 56. *Percentage relative differences of reverberation time predictions with various calculation methods.*

Figure 55 shows that the prediction methods applied to the algorithm get mixed results especially in the untreated room with lower differences at high frequencies. The focus on the treated room condition and the Figure 56 show that, except for the Eyring formula, prediction methods generally overestimate reverberation time across the mid frequency bands. This tendency, like in similar study conducted by Astolfi et al. [90] seems to suggest that the absorption values of the pupils, employed in the algorithm are too low in comparison with the in-field conditions.
With respect to the accuracy of the methods, it should be remembered that this has been assessed in other studies [88, 90, 104] and it is not the purpose of this work; the algorithm model is only a good approximation of the real model as shown in Figure 47, therefore the same considerations apply as previously. However, it can give useful information on the classroom acoustics quality, tips on how to increase it by improving teaching-learning activities. Finally, predicted values of C50 and STI in the acoustically treated classroom are presented in the table below.

Table 24. *Predicted values of C50 and STI acoustic parameters.*

method	parameter	value
Sabine	C50	4.1 dB
	$STI_{(male;\ normal)}$	0.75 - GOOD
Eyring and Barron&Lee	C50	4.9 dB
	$STI_{(male;\ normal)}$	0.77 - EXCELLENT
Pachyderm (number of rays: 2000 cut-off time: 1000s)	C50	5 dB
	$STI_{(male;\ normal)}$	0.71 - GOOD

6. ACOUSTIC OPTIMIZATION

Until now, optimization techniques have rarely been used for acoustic design purposes compared to structural or form-finding ones. Guidelines on the typology, amount and positions of acoustic materials and optimal configurations both for classrooms and other indoor environments as offices or restaurants are missing. In this chapter the developed tool is proposed, coupling to an optimization plug-in for Grasshopper, in order to aids in the investigating on acoustic and cost-effective solutions ensuring and optimize acoustic comfort conditions. This tool allows professionals to easily define the best solutions for the acoustic set-up of a classroom and similar rooms, promoting the awareness of the consequences of various design and renovation choices since the early phases. Moreover, the transition between geometric parametric model and calculation methods, that is usually a time-consuming affair, has been investigated. The optimization variables for the theoretical models have been: typology and extension of the acoustic materials, i.e. porous, resonant and membrane absorbers, thickness of the air-gap or of the porous layer, thickness, density and air-gap of the membrane absorber, holed percentage, thickness of the massive layer and of the air-gap of the resonant absorber, geometry of the acoustic baffles. In the case of GA simulation, the optimization process included typology, extension and position of a list of acoustic materials, which also comprised sound diffusers.

6.1. Octopus

The optimization process consists of routines that are repeated. Of itself, a loop operation and a multi-objective evaluation cannot be defined using the standard Grasshopper components. In this regard, Octopus [114] seems like a promising alternative, since the components included in the looping process are evaluated under a multi-objective way in a separate context, which in turn allows it to be used as a solver.

Octopus is a plug-in for applying evolutionary principles to parametric design and problem solving. It allows the search for many goals at once, producing a range of optimized trade-off solutions between the extremes of each goal. Octopus introduces multiple fitness values to the optimization. The best trade-offs between those objectives are searched, producing a set of possible optimum solutions that ideally reach from one extreme trade-off to the other. Based on SPEA-2 and HypE from ETH Zürich and David Rutten's Galapagos User Interface [114].

Octopus extends the functionality of Galapagos [8] by introducing multiple fitness values (multi-objective) to the optimization process. Similar to the plug-in Galapagos, Octopus is an evolutionary simulator that can approach optimal solution sets through iterative tests and constant self-adaptation. Unlike Galapagos, however, Octopus possesses the ability to cross-reference multiple parameters simultaneously, whereas Galapagos is limited to a single parametric input. The pink component below is the Octopus plug-in on GH canvas.

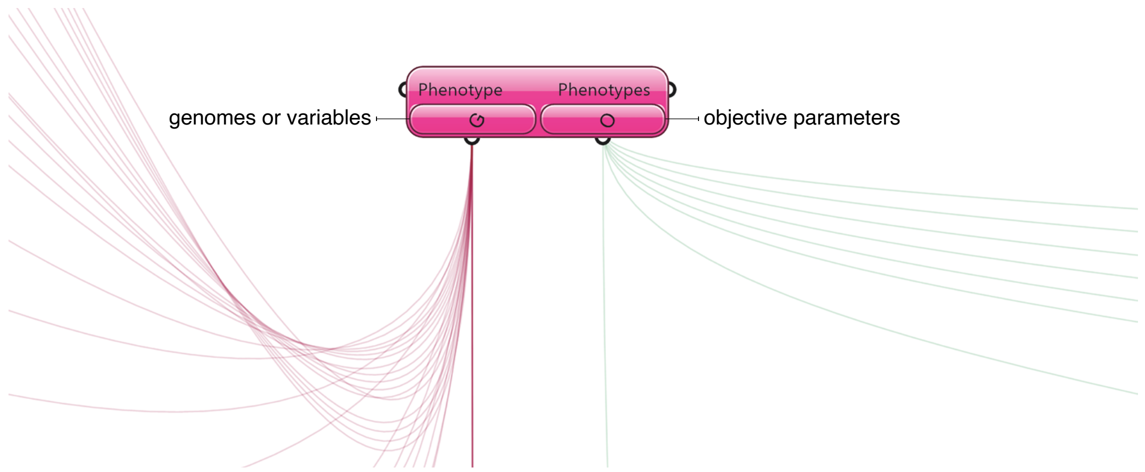


Figure 57. *Octopus plug-in on Grasshopper canvas.*

Similar to the Galapagos plug-in, Octopus requires the same inputs, but as mentioned above, allows the flexibility to input multiple objectives instead of just one. Once Octopus has collected data, it begins to map the information on a coordinate grid that is setup based on the objectives set. Here, one can access the full range of data and separate the solutions that fall in the favourable median from those that do not. After sorting, one can 're-instate' the favourable solutions, or in other words, select their specific data points to appear in Grasshopper. There is a narrow but distinct range of options amongst optimal solutions. Each of these solutions falls within the most desirable range of outcomes, but individually possesses its own advantages and disadvantages that would make it more or less favourable for further design development.

In this case, the final result cannot be considered as a single individual, because the multi-objective optimisation is producing a set of solutions which fit both the initial requirements. This group is generally called Trade-off or Pareto-front.

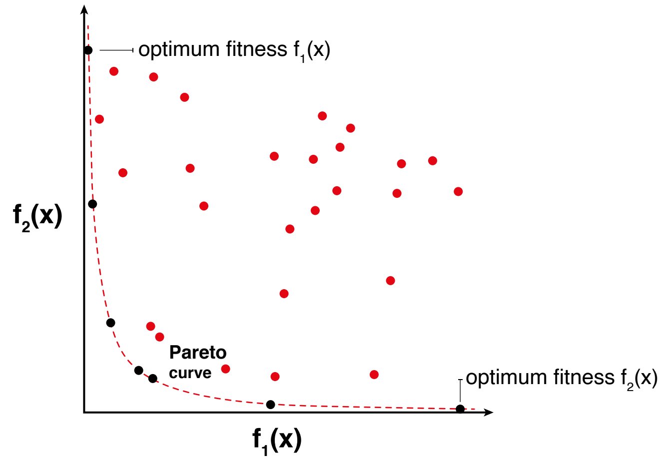


Figure 58. *2D Pareto-front solution set.*

6.2. Approach of evolutionary solving

A series of simple tests have been conducted to evaluate the extents at which Octopus is capable of interpreting and correctly operating on the models described in the previous chapter. Octopus connects to variable 'slider' inputs of a parametric model and compares their values to a defined numeric output to assign a score to that same model. In this fashion the performance of a design configuration is linked to its properties, which enables the possibility to automatically iterate and improve on an overall design. Evolutionary algorithms – upon which platform is based (SPEA-2 and HypE) are stochastic search methods that mimic the metaphor of natural biological evolution and / or the social behaviour of species [115]. These algorithms are generally used to solve optimization problems. The approach of evolutionary solving is characterized by the assessment of a pool or population of design solutions, rather than a single solution. Out of this pool, individual solutions are selected according to their adjustment to a fitness function (a formulaic description quantifying performance goals) and new solutions may be generated through mutations and crossovers of previous elites, which are those configurations displaying the most favourable traits with respect to the fitness criteria. It is not within the scope of this project to assess or develop upon the specifics of any evolutionary algorithm. The applicability of an evolutionary solving mechanism to the issue of acoustic optimization of classroom spaces is merely tested.

6.3. Multi-objective optimization

The process of optimization describes the synthetic search for the best state within a model, usually under a set of restrictions [116]. Negotiating the architectural implications associated with limiting sound propagation in open workspaces, by definition comprises a trade-off between acoustic performance measures and the acoustic design costs. Multi-objective optimization, which is the search for optimal values for two or more of such conflicting objectives, comes into play. The compromise between different performance aspects may be described with Pareto optimization, a state in which one thing can only improve at the expense of another [116]. As a conclusion to the development phase of this study, multi-objective optimization is performed on a parametric model of the case study classroom. The overall process is aimed at finding a set of configurations in which a vast improvement of room acoustic conditions is balanced with a limited low-cost solution .

6.3.1. Variables

The start point for the final model is the classroom space in its current layout and material properties. The position of all the walls, the floor and ceiling, plus pupil's arrangement is fixed. The optimization variables used in the predictive models have been: properties, typology, extension and the position of the acoustic materials which included porous, resonant and membrane absorbers (total: 28), and also sound diffuser in the GA simulation (total: 32). In the table below are summarized the optimization variables used in the theoretical models and in the geometric one.

Table 25. *Optimization variables.*

optimization variables acoustic materials		**theoretical models** Sabine, Eyring with Barron&Lee	**GA simulation** Pachyderm
typology		✔ (parameter)	✔ (parameter)
extension		✔ (parameter)	✔ (parameter)
position		✘	✔ (parameter)
porous	thickness	✔ (parameter)	✘
	air-gap	✔ (parameter)	✔ (rhino layer)
membrane	density	fixed	fixed
	thickness	✔ (parameter)	✔ (rhino layer)
	air-gap	✔ (parameter)	✔ (rhino layer)

optimization variables acoustic materials		**theoretical models** Sabine, Eyring with Barron&Lee revised theory	**GA simulation** Pachyderm
resonant	thickness	fixed	fixed
	air-gap	✔ (parameter)	✔ (rhino layer)
	drilling percentage	✔ (parameter)	✔ (rhino layer)
sound diffuser		✘	✔ (rhino layer)
baffle	spacing	✔ (parameter)	✔ (rhino layer)
	height	✔ (parameter)	✔ (rhino layer)
	number	✔ (parameter)	✔ (rhino layer)

The differences in the number of variables, as already mentioned in the previous chapter, are linked to the limits and possibilities offered by the acoustic simulation in Pachyderm [111]. In fact, Pachyderm allows to take into account the scattering properties of surfaces and different combinations of all the acoustic materials, but the absorption and scattering coefficients cannot be directly altered on the Grasshopper canvas, meaning that parameterization of material properties requires a workaround by cycling through layers with preassigned materials.
For this reason, a database of acoustic materials, compatible with those available in the other models, has been built and from which the algorithm "catches" materials depending on the parametric model set-up. Finally the algorithm has been developed in order to allow to choose different optimization sets depending on the material, the type of acoustic treatment to optimize, design choices or project constraints.

6.3.2. Objective-parameters

All runs are performed utilizing the same experimental setup. A single source and a total of four receivers are placed in the room model at fixed positions as indicated in Figure 17 by the Italian standard, all at a height of h = 1,1m. The results of the acoustic parameters are used to assess the acoustic performance of each instance. The specific goal of these runs is thus to maximize said acoustic performance, in terms of Reverberation Time (RT) and Speech Transmission Index (STI) while, at the same time, satisfying the conflicting criteria of keeping the design costs. The following objective-parameters are defined:

• Reverberation Time (RT) in octave bands from 125 Hz to 4 kHz (total: 6): it has been minimized on the optimal reverberation curve provided by the UNI11532, calculated in real time by the algorithm developed. In the theoretical models, this descriptor has been calculated by Sabine and Eyring formulas respectively. In the GA simulation, the acoustic software Pachyderm, have been used for the RT calculation.

• Speech Transmission Index (STI): it has been minimized on the maximum STI value of 1. In both theoretical models it has been calculated according the IEC 60268-16 standard [55],coupling the revised theory by Barron&Lee [63] in the second one. In GA simulation, the acoustic software Pachyderm, have been used for its calculation.

• Budget: this objective parameter refers to the costs for the acoustic treatments; these have been agreed with the EDILOG area of Politecnico of Turin . These are indicative prices referring to the typology of acoustic materials, partly derived from the price-list of the Piemonte region.

Taking into account the features of the acoustic materials and solution shown in tables 10,15,16,17,18 and Figure 54, prices are summarized in the table below.
Each price(€/m²) includes the following:

- labour;
- supply of the material;
- overhead (13÷17%);
- company's net profit (10%).

Table 26. *Price-list of the acoustic materials.*

typology of acoustic absorber	material	Price [€/m²]
porous	mineral/polyester fibre	47
membrane	gypsum/wood board	51,5
resonant	gypsum/wood perforated panel	62,5
sound diffuser	wood	400
baffles	mineral/polyester fibre	388
membrane brick-proof false-ceiling D111	high density gypsum board	76,8
resonant brick-proof false-ceiling D112	high density perforated plasterboard	92

Results

A large number of Octopus optimizations were performed on a laptop fitted with an i7-4710HQ CPU clocked at 3,0GHz. The settings within Octopus were mostly kept to their defaults, applying HypE reduction and mutation. Population size has been set to 50 instances per generation, which results in a total combined amount of over 10.000 evaluated solutions.

The results show compatible acoustic parameters to those obtained with the theoretical calculations leading to a validation of the optimization method. However, significant differences in the calculation time were found: for the theoretical models 1500 runs in about 2 hours was carried out, while 750 runs in about 20 hours were performed for the GA simulation.

In the table below the statistics of performed optimizations in Octopus are shown.

Table 27. *Statistics of performed optimizations in Octopus.*

	Sabine	Eyring Barron&Lee	Pachyderm
number of variables or genomes	28	28	32
number of objective	8	8	8
total number of evaluated solutions	1500	1500	750
amount of completed generations	30	30	15
total runtime [h]	1.4	1.8	20.8
average evaluation time/solution [s]	3.4	4.3	100.1
Pareto optimal solutions in final gen. [%]	78	89	33

It must be pointed out that the percentage of Pareto optimal solutions in the final generation of Pachyderm, is largely determined by the presence of another acoustic material, the sound diffuser, but also by the itself nature of the ray-tracing model, in fact later at a cycle of 10 run-to-run simulations with unchanged variables the values obtained differed from each other, remaining however within 5%.

Pareto results (Figure 59 on the next page) are quite similar for the two theoretical models, while the GA algorithm shows a dispersion of solutions due to the low number of runs and the inclusion of position of the acoustic materials and of sound diffuser in the optimization process. Moreover, in the Pachyderm model, on the overall pool of solutions, the maximum value of budget due to the price of sound diffusers, was reached. The 2D Pareto-front and the multi-axes views have been added to the Appendix D.

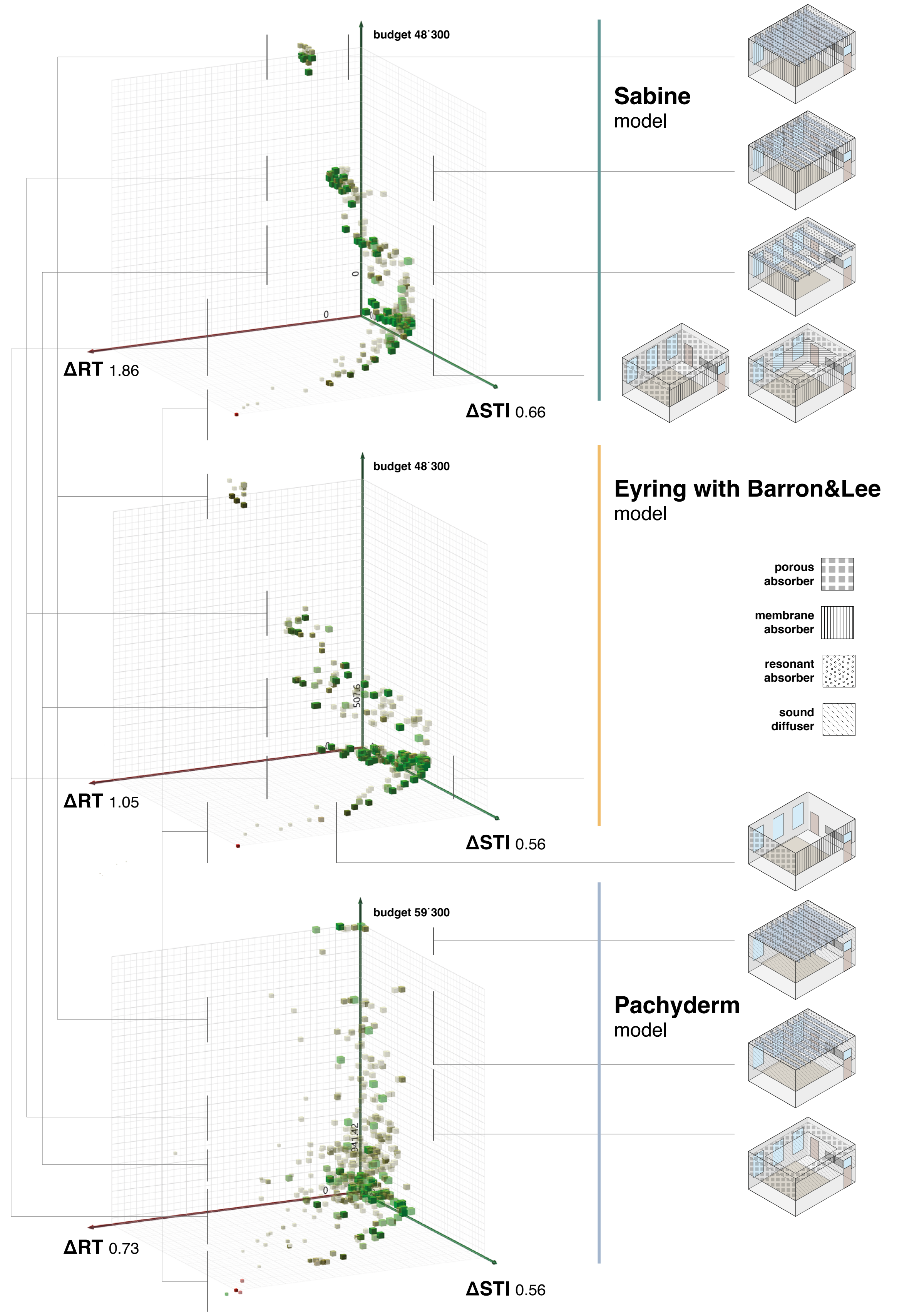


Figure 59. *Final generation of Pareto-front solutions from RT-STI-budget based optimizations.*

Generally, in multi-objective optimization there is a single best solution for each objective value. However, in all the other objective values this solution might not fare that well. Therefore, in multi-objective optimization, the non-dominated solutions are the ones that form the set of most interesting solutions. Each solution will exhibit some type of trade-off, which cannot be decided a priori (i.e. combined into a single fitness value) but needs to be explored a posteriori.

A detailed statistical analysis of results has required to collect data in excel sheet, this task has been implemented into the algorithm through a GH plug-in, namely TT Toolbox [117]. In appendix D, an extract from the above excel sheet has been reported. In this case the routine has been drawn up in order to collect all the information needed to "re-build" the configuration analysed. The collected data have been filtered from similar instances and sorted according priority levels as follow:

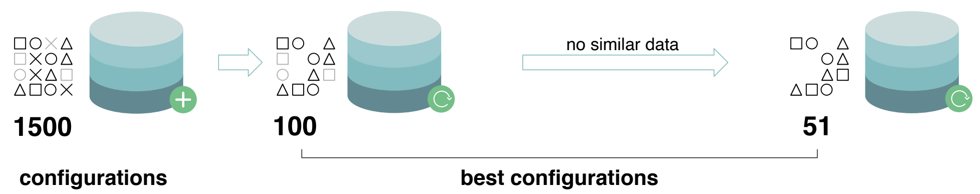
- average value of $\Delta RT_{(0.25\text{-}4kH)} = |RT_{opt}\text{-}RT_i|$;
- standard deviation of $\Delta RT_{(0,25\text{-}4kH)}$;
- $\Delta STI = STI_{max} - STI_i$
- C50 descriptor (maximized);
- budget (minimized)

where

i is the number of the run performed.

As far as the acoustic performance and design costs are concerned, results of all runs indicated that regardless of the walls treatment, solution with a totally absorbent ceiling confirms to be the most cheap solution and compatible with the target values to be achieved in a classroom. Moreover, it was observed that the acoustic targets can be reached also applying absorbing and diffusing materials at different locations on walls.

A combination of resonant and membrane absorbers, indeed, reach similar values, being so more effective. In the following pages two data-sheet are shown for each model built(two theoretical and one geometric): the former collects statistical data on the configuration carried out in the optimization process, these are firstly grouped according to the reference budget (5000€) and then in terms of: number of wall treatments used , extension of acoustic treatment on walls and typology of ceiling treatment; the latter compares the best solutions depending on the adopted ceiling treatment solution(AC100, AR-C, baffles) and for each the best low-cost alternative is show.



All the configurations examined meet the acoustic requirements, in particular, the values are within ± 6% of the optimal RT one and within -4% of the best STI value.

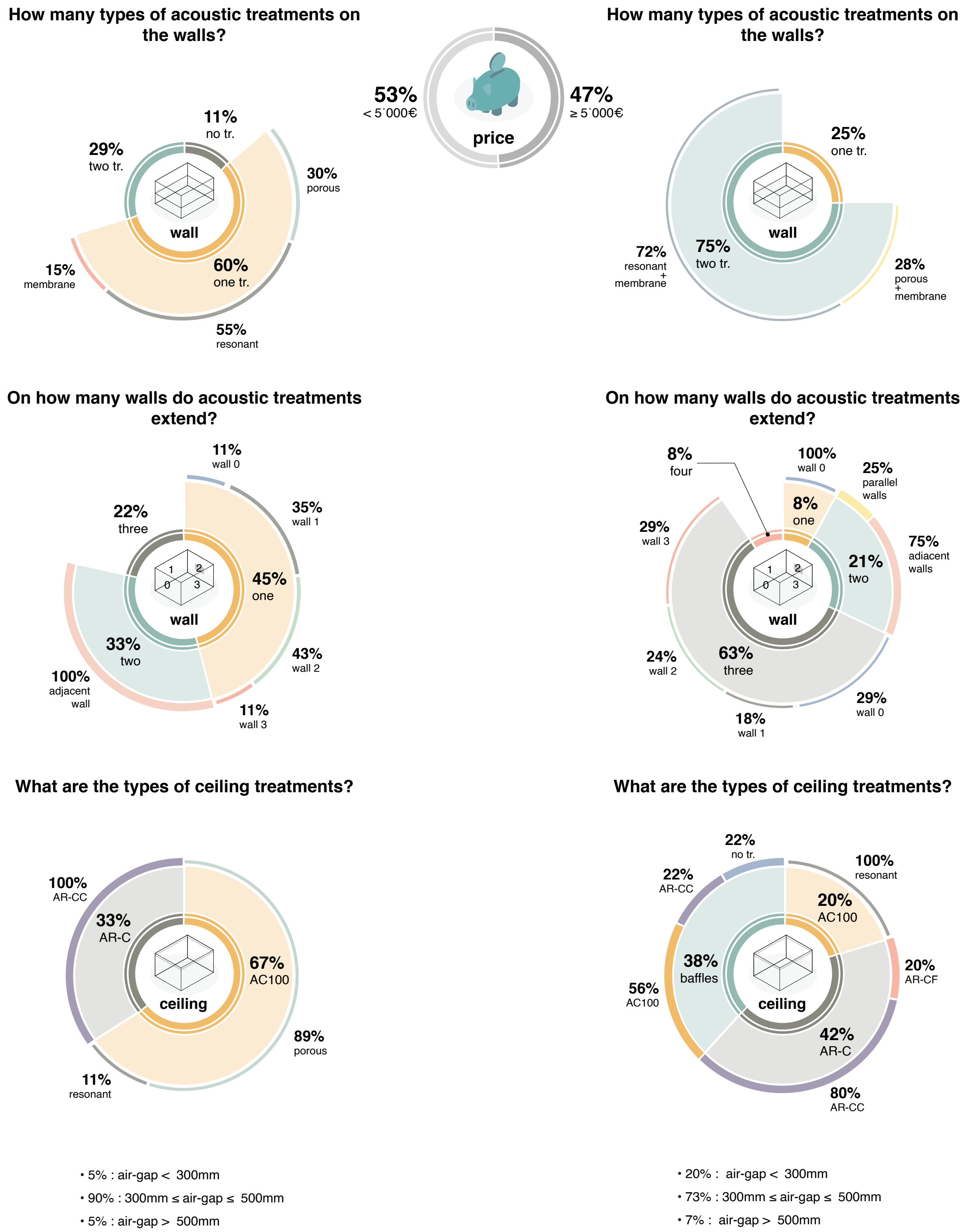


Figure 60. *Data analysis of the Sabine model best configurations.*

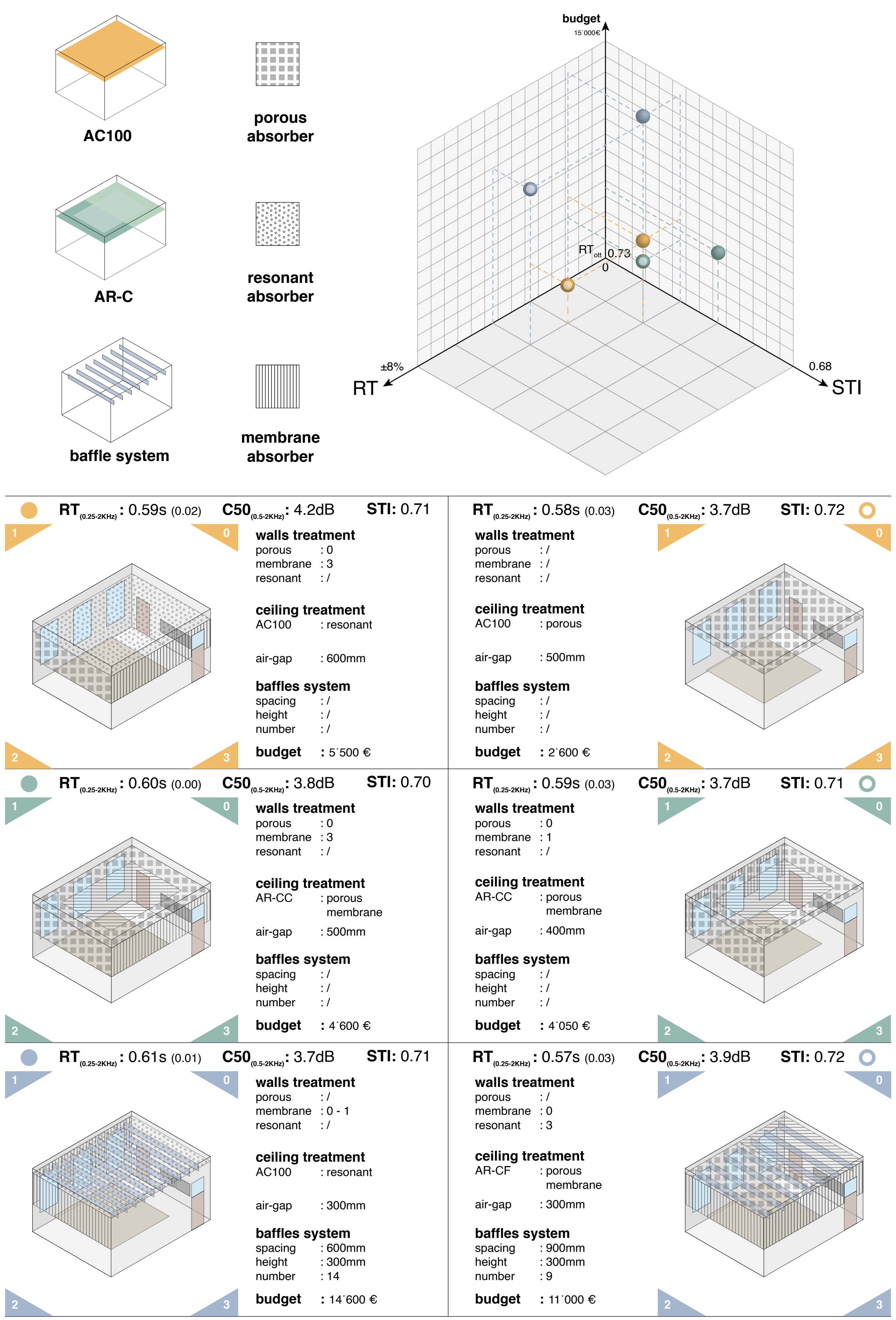
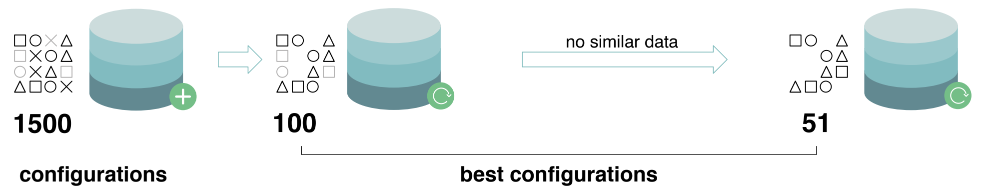
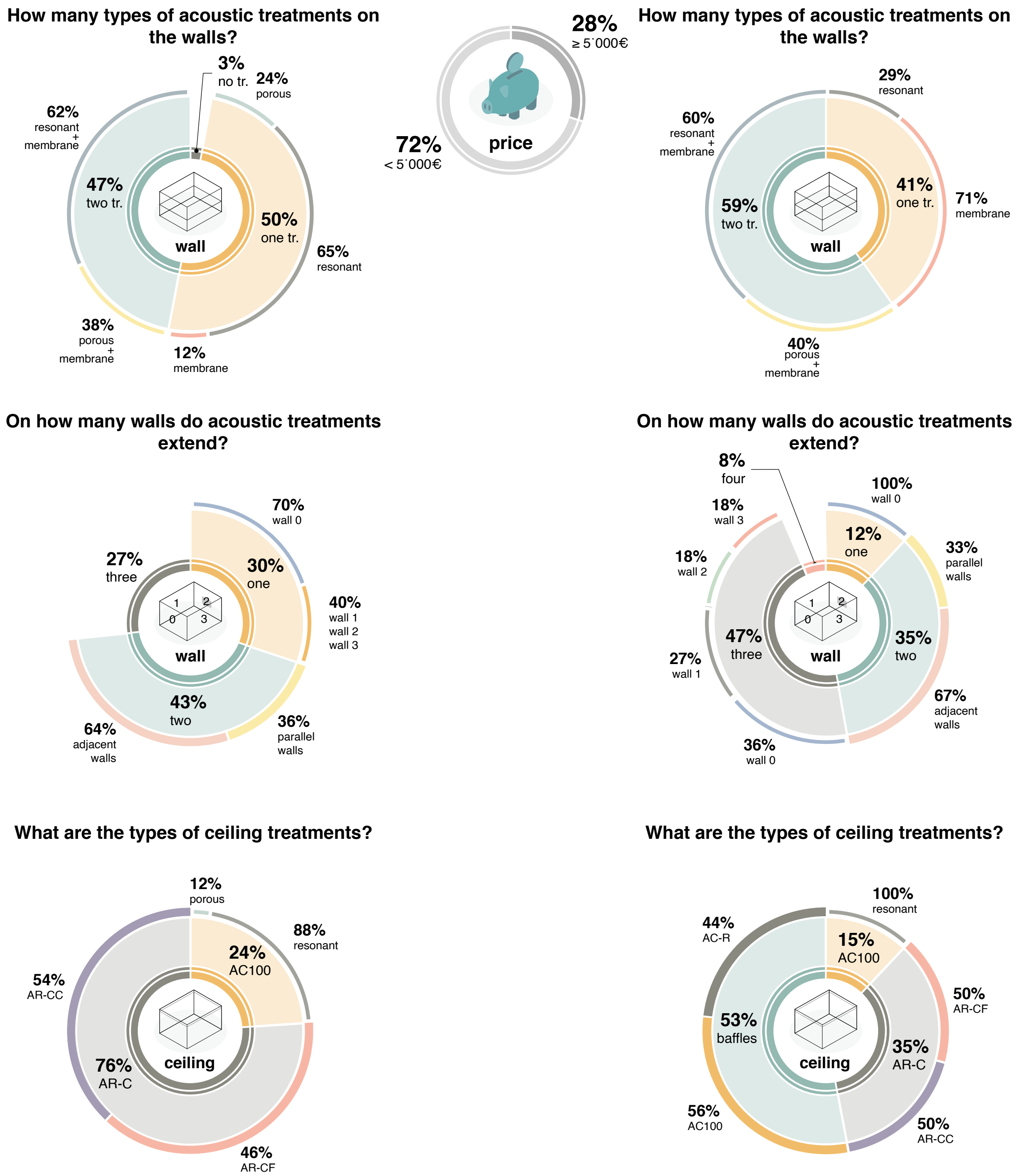


Figure 61. *Sabine model best configurations.*



All the configurations examined meet the acoustic requirements, in particular, the values are within ± 8% of the optimal RT one and within -6% of the best STI value.



- 12% :air-gap < 300mm
- 55% : 300mm ≤ air-gap ≤ 500mm
- 33% : air-gap > 500mm

- 23% :air-gap < 300mm
- 60% : 300mm ≤ air-gap ≤ 500mm
- 17% : air-gap > 500mm

Figure 62. *Data analysis of the Eyring with Barron&Lee theory model best configurations.*

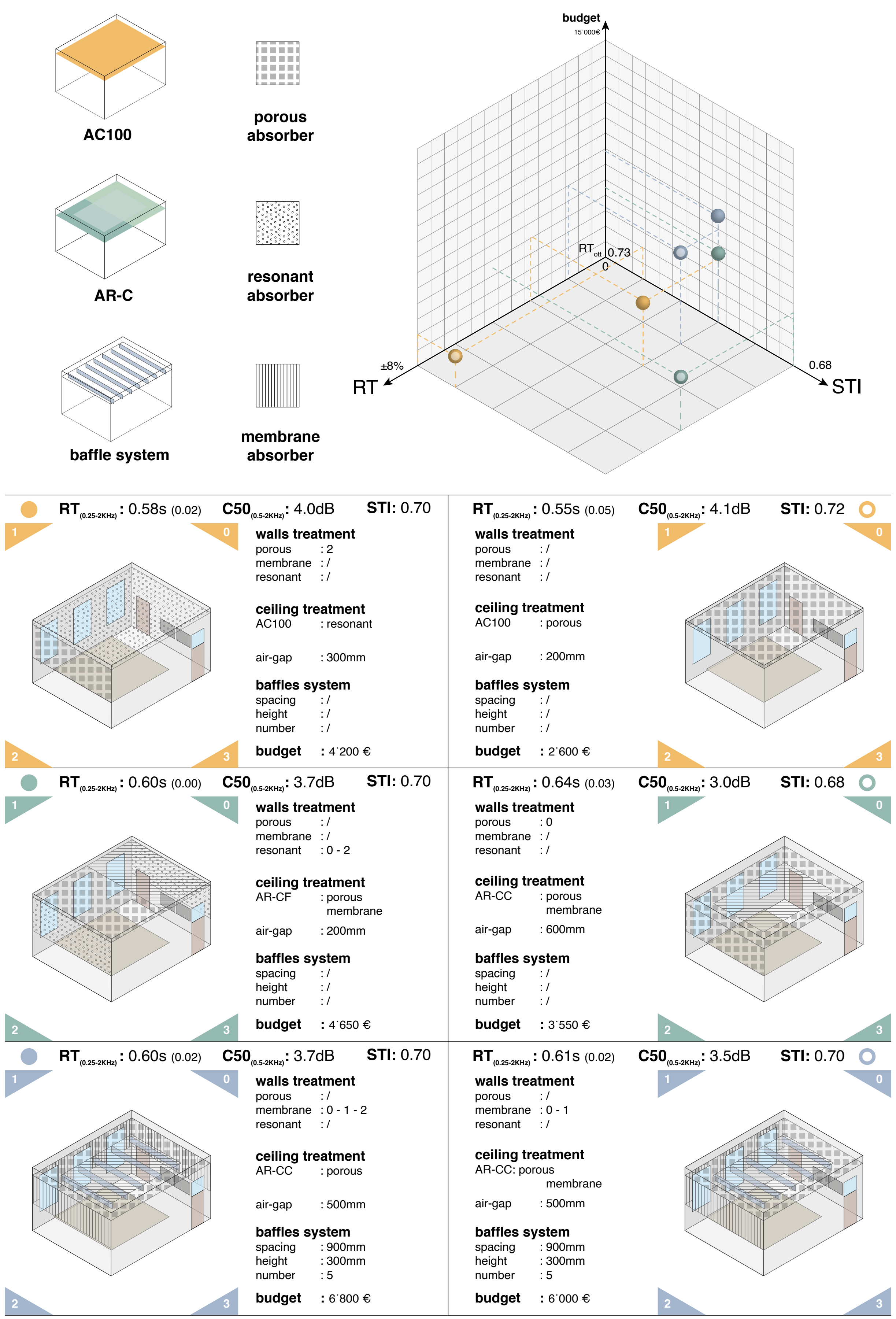
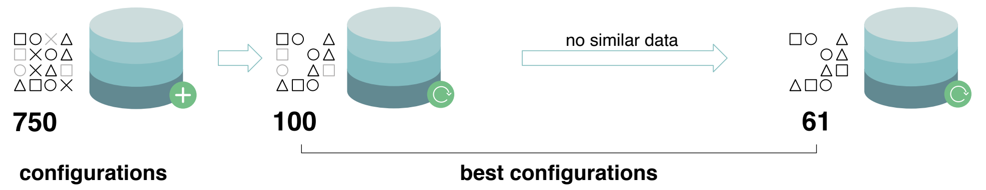
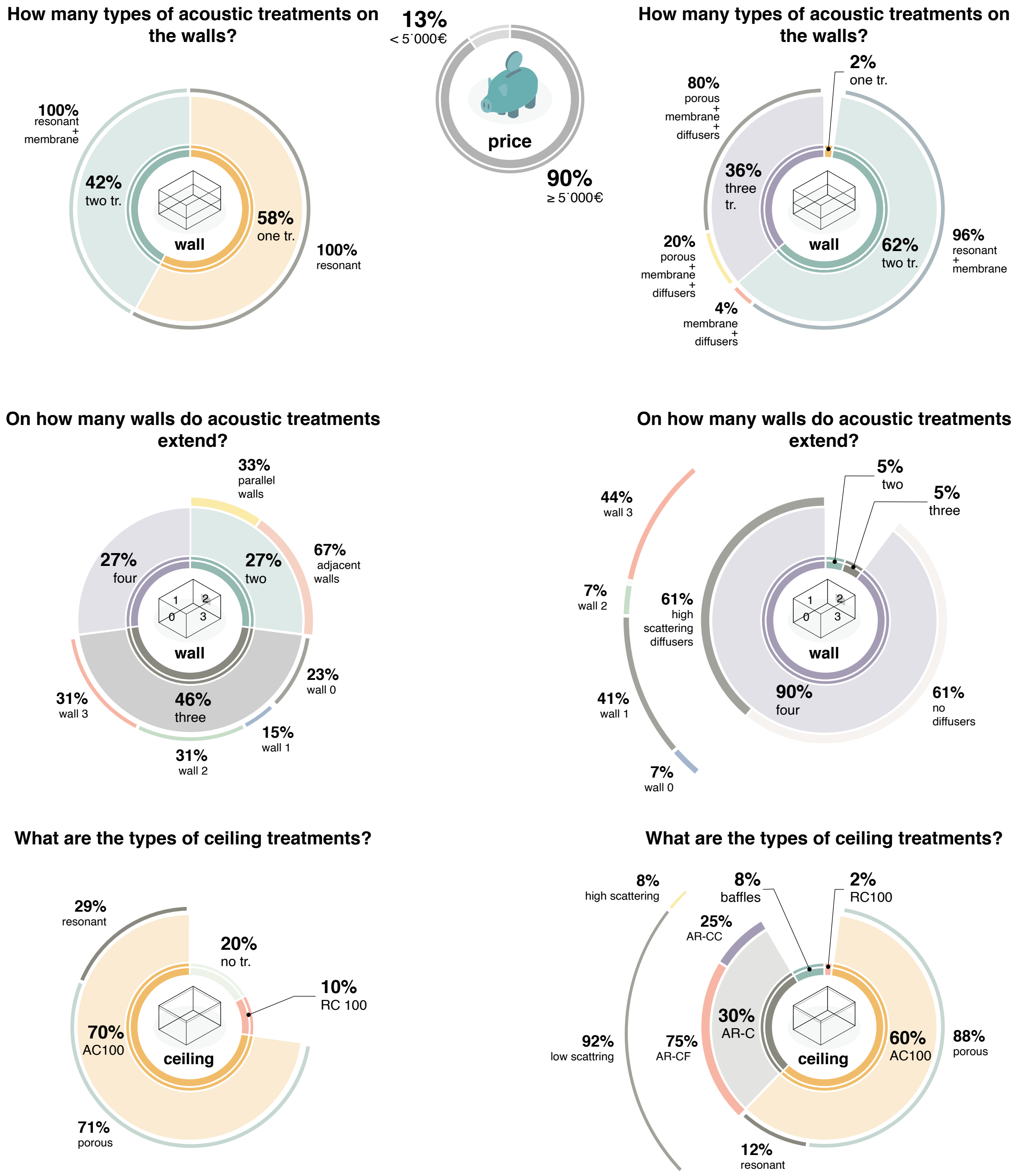


Figure 63. *Eyring with Barron&Lee theory model best configurations.*



All the configurations examined meet the acoustic requirements, in particular, the values are within ± 10% of the optimal RT one and within -12% of the best STI value.

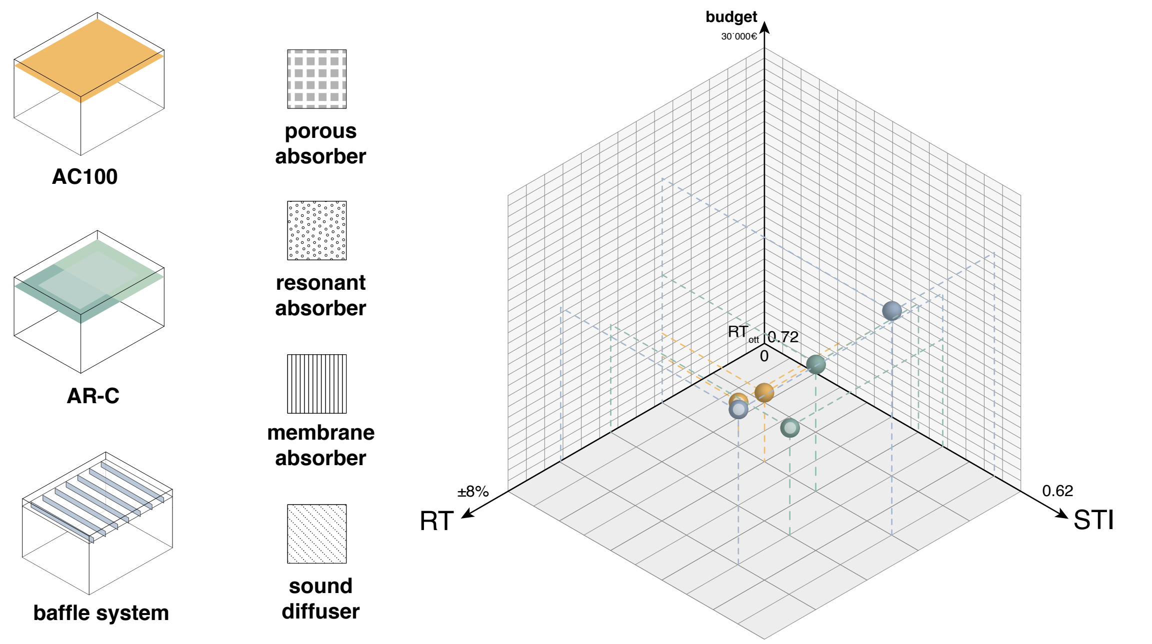


- 20% : no air-gap
- 20% :air-gap < 300mm
- 20% : 300mm ≤ air-gap ≤ 500mm
- 30% : air-gap > 500mm

- 37% :no air-gap
- 6% :air-gap < 300mm
- 9% : 300mm ≤ air-gap ≤ 500mm
- 72% : air-gap > 500mm

Figure 64. *Data analysis of Pachyderm model best configurations.*

ACOUSTIC OPTIMIZATION



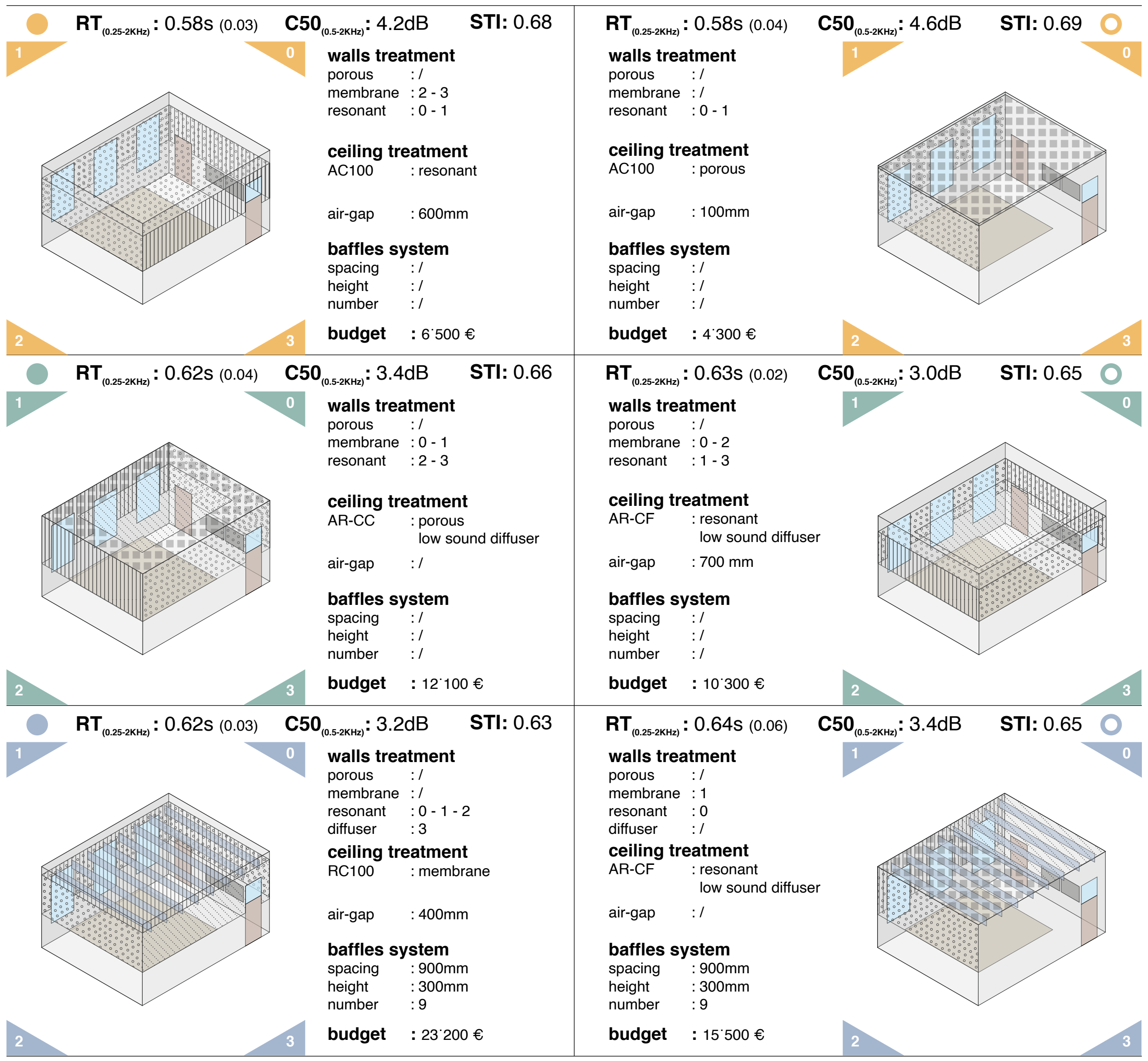


Figure 65. *Pachyderm model best configurations.*

However, the most significant indicators were obtained when, due to constraints, was impossible to treat the ceiling. In this case the combination of absorbent and diffusing materials on walls has been the best but not the cheapest. A combination of sound reflecting and absorbing materials, indeed, reach similar values, being so more effective. In the following the best configurations and the low-cost ones are shown and the respective results of the Octopus optimization.

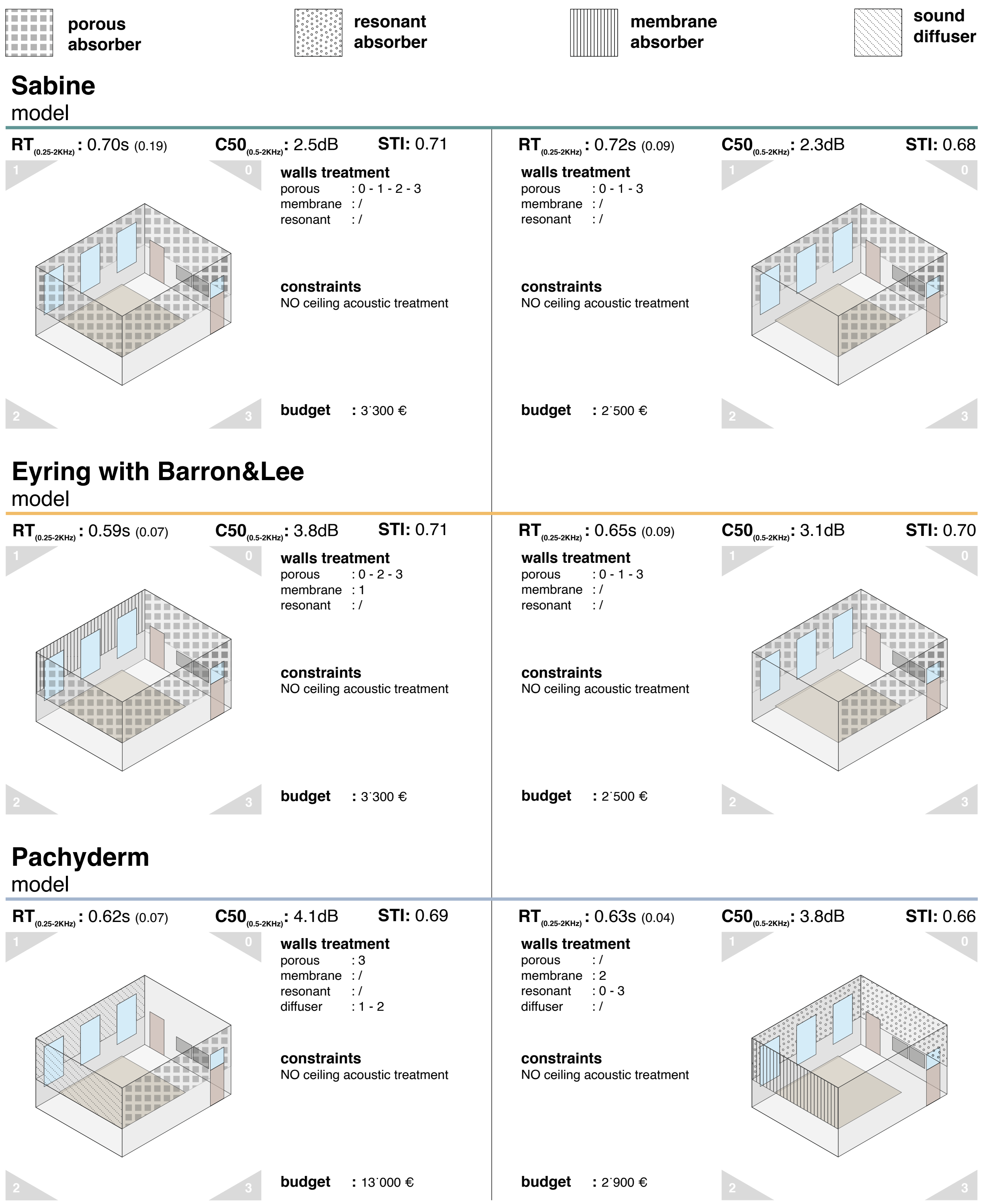


Figure 66. *Comparison between the best and low-cost configurations in the three models.*

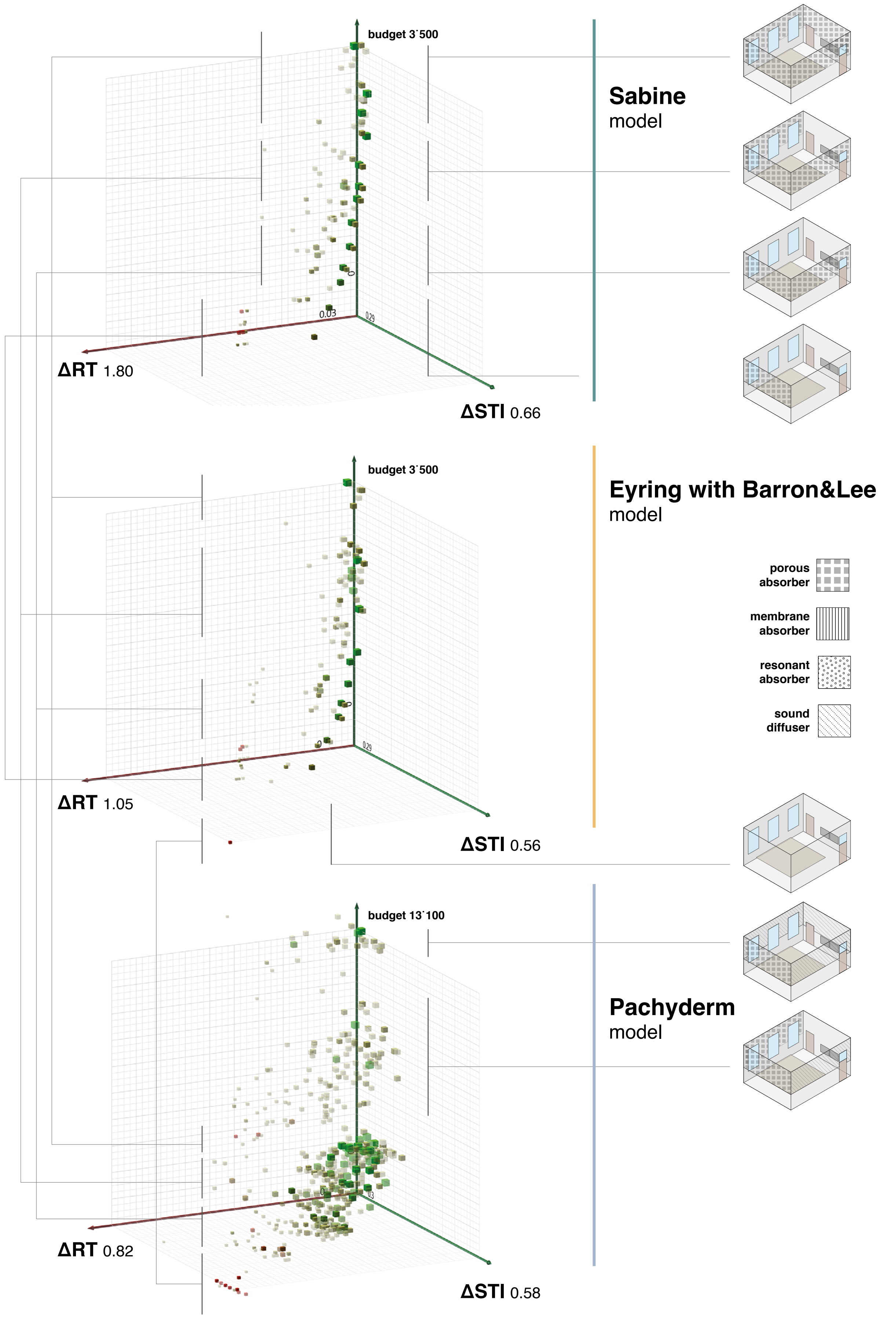


Figure 67. *Final generation of Pareto-front solutions from RT-STI-budget based optimizations, with the constraint of no ceiling acoustic treatment.*

6.4. Comparison with the best configurations of previous studies

So far, combinations testing of acoustic materials has been restricted to scenarios with few changes. All the previous studies [118, 119] have been key to undertake the research for classroom acoustic design, especially regarding the general idea to not completely use absorbent surfaces. Recent studies have investigated the effects of periodic type diffusers in a classroom to determine if the diffusers were beneficial for obtaining preferred acoustical conditions for speech communication: periodic type diffusers were installed on either the front or the side walls of a model classroom. Significant improvement in C50 values were achieved at the most distant seats when the diffusers were added on the front wall around the platform of the classroom. Above studies have found that adding diffusers on the front walls around the platform were more effective for improving the acoustics for speech at distant receiver positions. In the following paragraph, configurations suggested in these studies have been tested in the classroom case study and compared with two (with and without sound diffusers) of the best configuration obtained in this work. These are shown in the figure below.

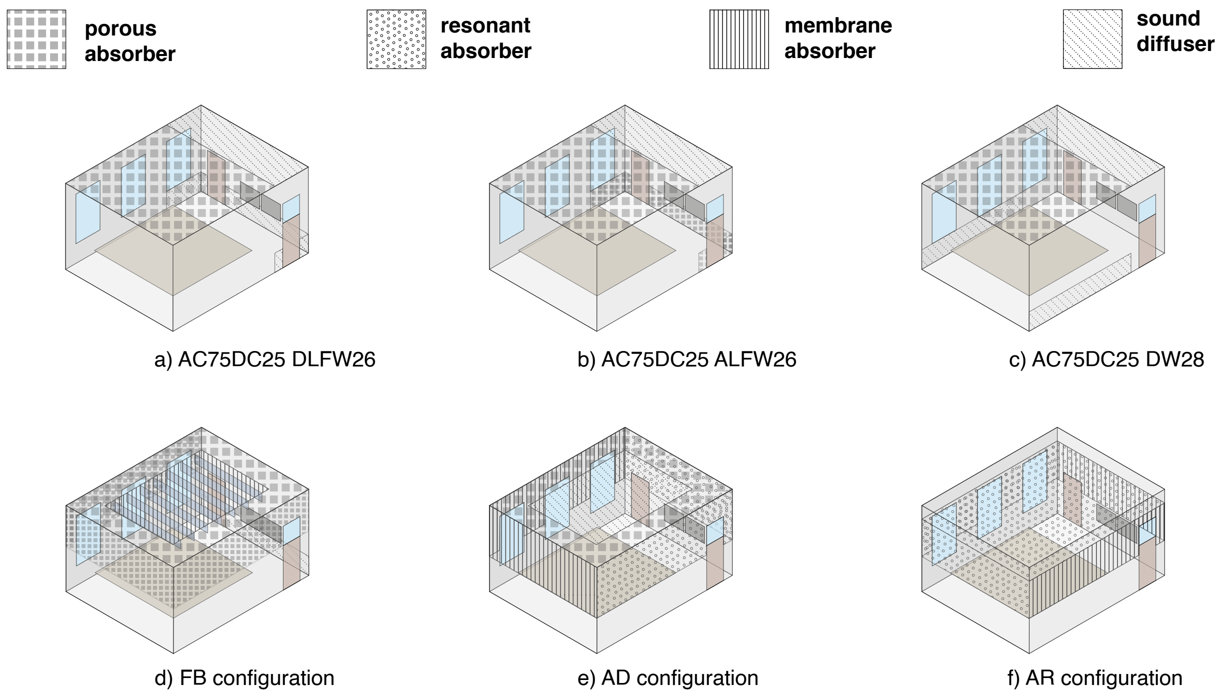


Figure 68. *Comparison between the configurations of previous studies.*

The notation AC75DC25 indicates a classroom treatment consisting of 75% of the ceiling being sound absorbing material and 25% of the ceiling diffusing material. The first configuration adds diffusers on lower front wall (figure 68a), the second one adds absorptive materials on the lower front wall (figure 68b) while the third one adds sound diffusers on the lower side walls (figure 68c). The BF configuration (figure 68d) combines an absorbent frame at the ceiling filled with sound baffles, absorptive panels on the side walls and on the higher back wall, sound diffusers on the lower front wall. The last two configurations (figure 68e-f), found in this work, combine absorbing materials with reflective and diffusing ones, respectively.

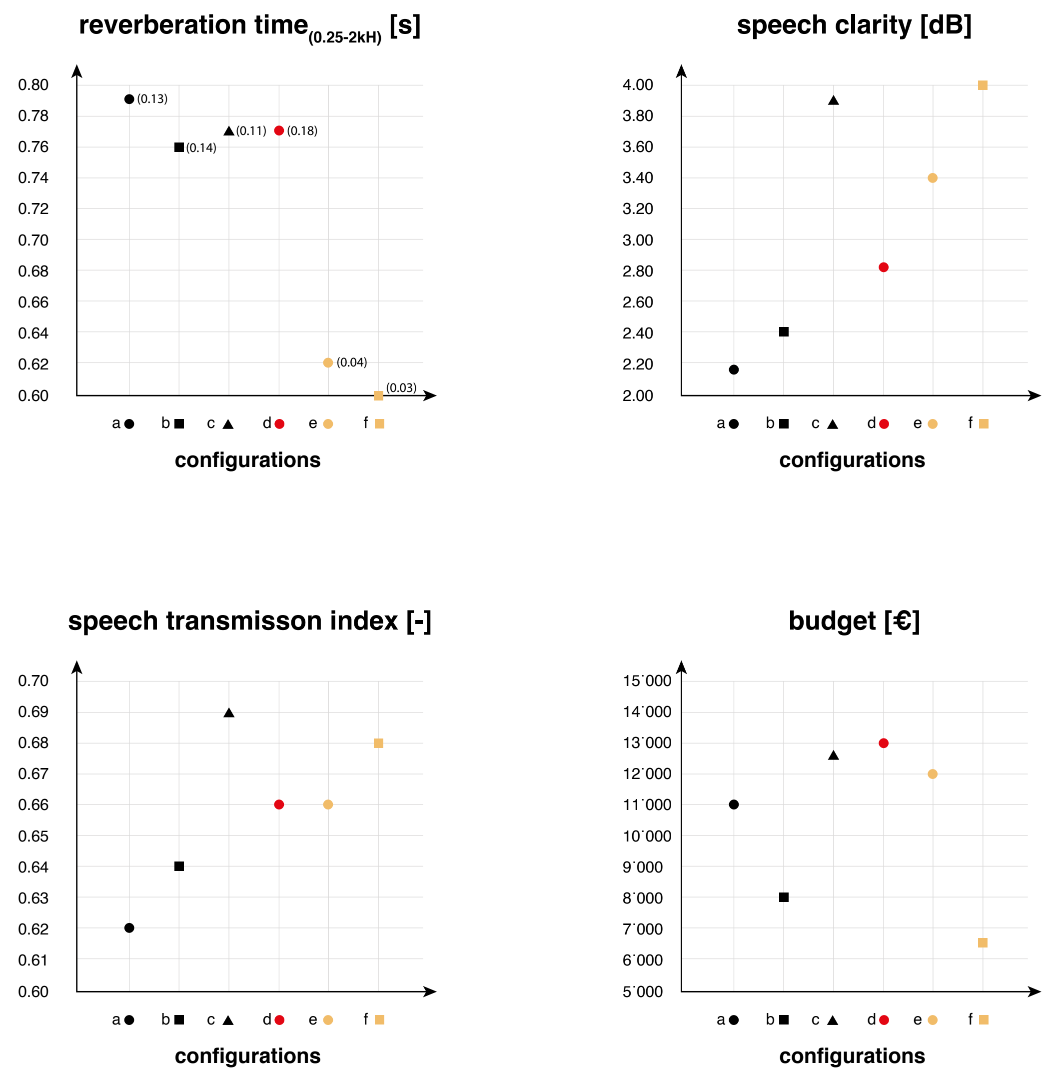


Figure 69. *Comparison between the acoustic and objective parameters of the Pareto-front optimization.*

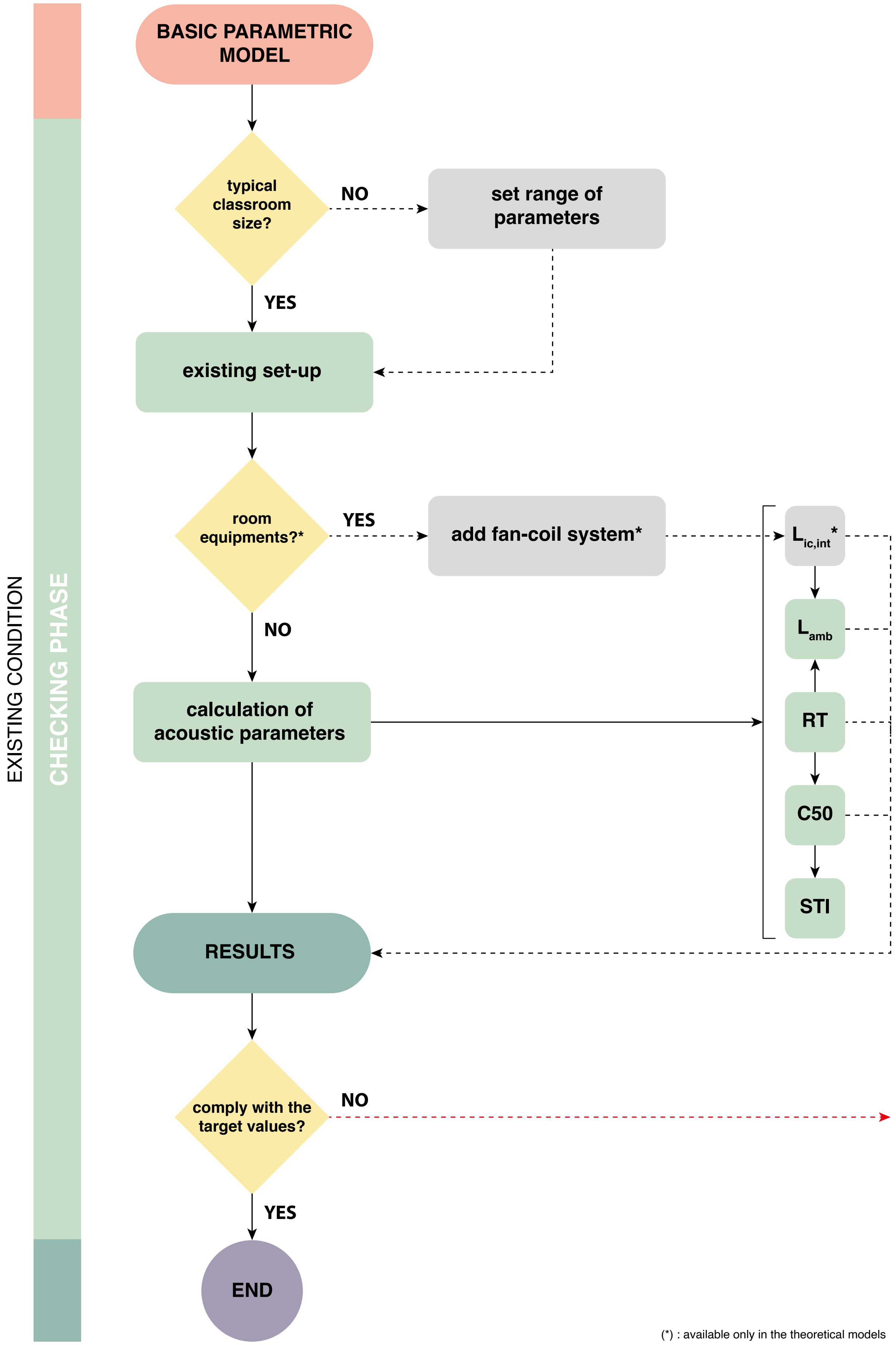


Figure 70. Simplified flow chart of the developed algorithm: existing condition.

ACOUSTIC OPTIMIZATION

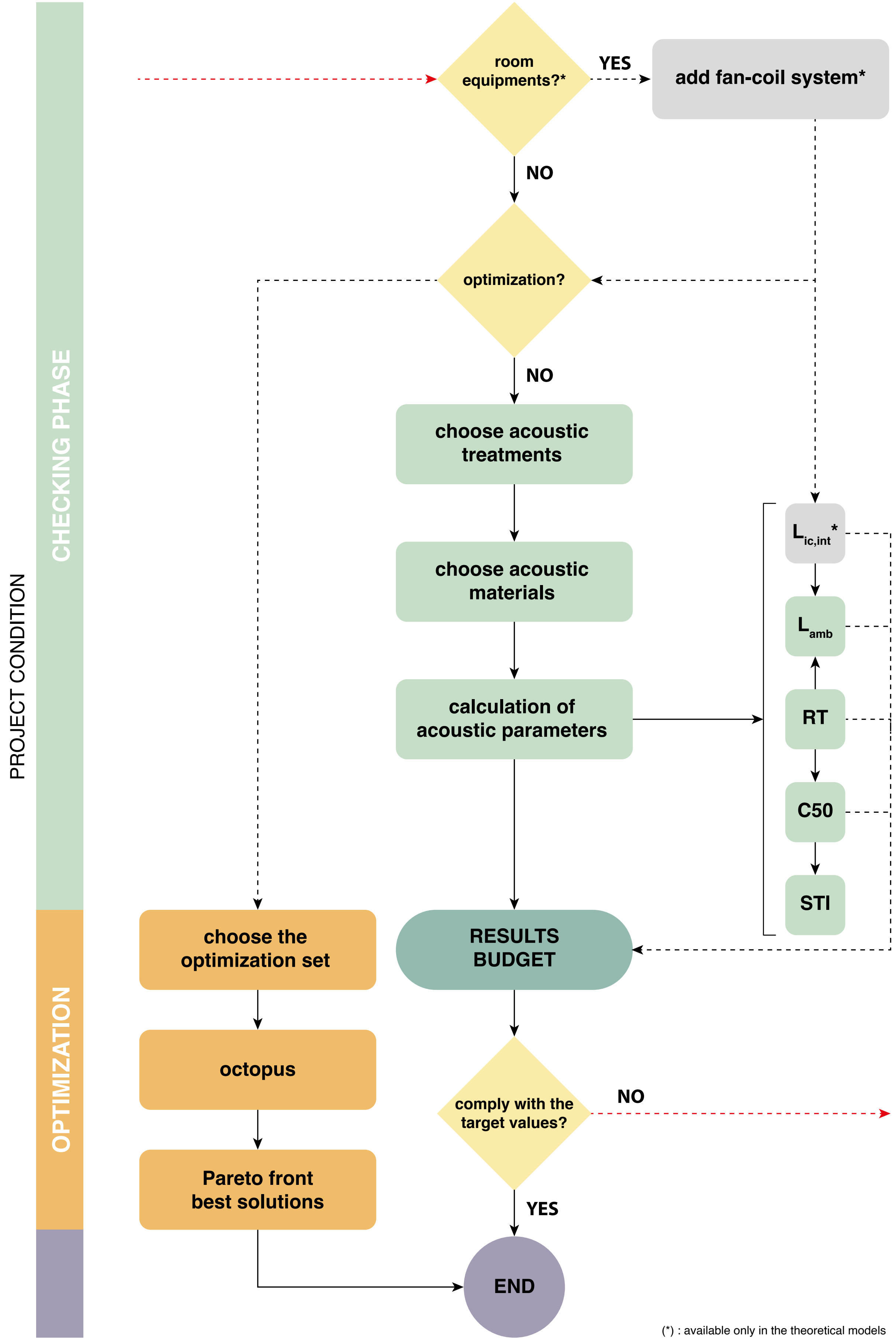


Figure 71. Simplified flow chart of the developed algorithm: project condition.

7. CONCLUSIONS

The above models provide essential information on a valid approach that could be helpful to assess the acoustic quality of classrooms and recommendations on how to increase it by improving teaching-learning activities. This work has shown how GA simulations and theoretical calculations are compatible for the solutions without scattering properties: results show that some low-cost solutions are comparable among the three models, even though GA simulation should be considered the most accurate.

Parametric modelling is far from commonplace in this kind of works. Though there is great interest in the potentials of parametric analysis, most practitioners in these fields of work tend not to be particularly well-versed in Grasshopper or similar programs. It does not help that parametric models are fairly time consuming to set up the first time, plus the search algorithms often running overnight. A culture shift in this practice needs to be in order before parametric tools, like this, will be ordinary in use.

Six areas of improvement have been identified for the above tool, likely: support for wider range of programs, calculation speed, ease of use, accuracy, more visualization features and expanding the number of acoustic parameters. In further development priority should perhaps be given to creation of an easier interface and coupling with faster GA simulation, in particular, include a user-friendly interface allowing an easy approach for non-expert practitioners; so, a definition faster (both in use and in calculation time). These are the most evident weak point of the tool, to this regard this the modularity of Grasshopper becomes a big disadvantage, also in terms of computation time as vast amounts of data need to be sent from one component to another. Future study could also focus on assessing in real cases of the limits of validity of the several methods proposed in this study and the trade-off between the room shape, acoustic materials arrangement and the assumption of existence of a diffuse sound field.

It needs further development to extend its application field in order to parametrically analyse the acoustic environment of different types of rooms in search of a common trend; in fact, right now this task would require operating on the Grasshopper canvas and significant knowledge on the designer's behalf concerning parametric design and acoustics.
During this study a large amount of design alternatives and a dataset were created, the latter should be evaluated more closely, perhaps through in-depth statistical analysis, to uncover any relationships between the future parameters that will be assessed and results of the parametric optimizations.
In short terms, the tools and knowledge yielded from this study will likely be confined to academics, but they have already produced useful tools to be used for didactic activity.
In conclusion, the need, repeatedly stressed in this work, to requalify our schools with their spaces and the fundamental role that they play in teaching-learning processes, favouring or hindering educational innovation and influencing the well-being of who is in the building, is the focus of the report [120], realized by Fondazione Agnelli and introduced in early December 2019. It has taken into account all the relevant dimensions, to focus on the future of school buildings in Italy. The report is based on in-depth and unpublished analyses to provide policy indications in view of the interventions necessary for school construction in the coming years. To this regard, the experience of "Torino fa scuola" project, has been fundamental: it led to the requalification of two secondary schools in Turin and shows again the need of an integrated approach to pursue the safety, sustainability and orientation towards educational innovation. Although the references to acoustics in the above report are not explicit, since I have partially followed the acoustic renovation work of one of the two schools, the G.Pascoli secondary school in Piazza Bernini in Turin (Figure 72), I can testify that there has been a great attention to this aspect.

CONCLUSIONS

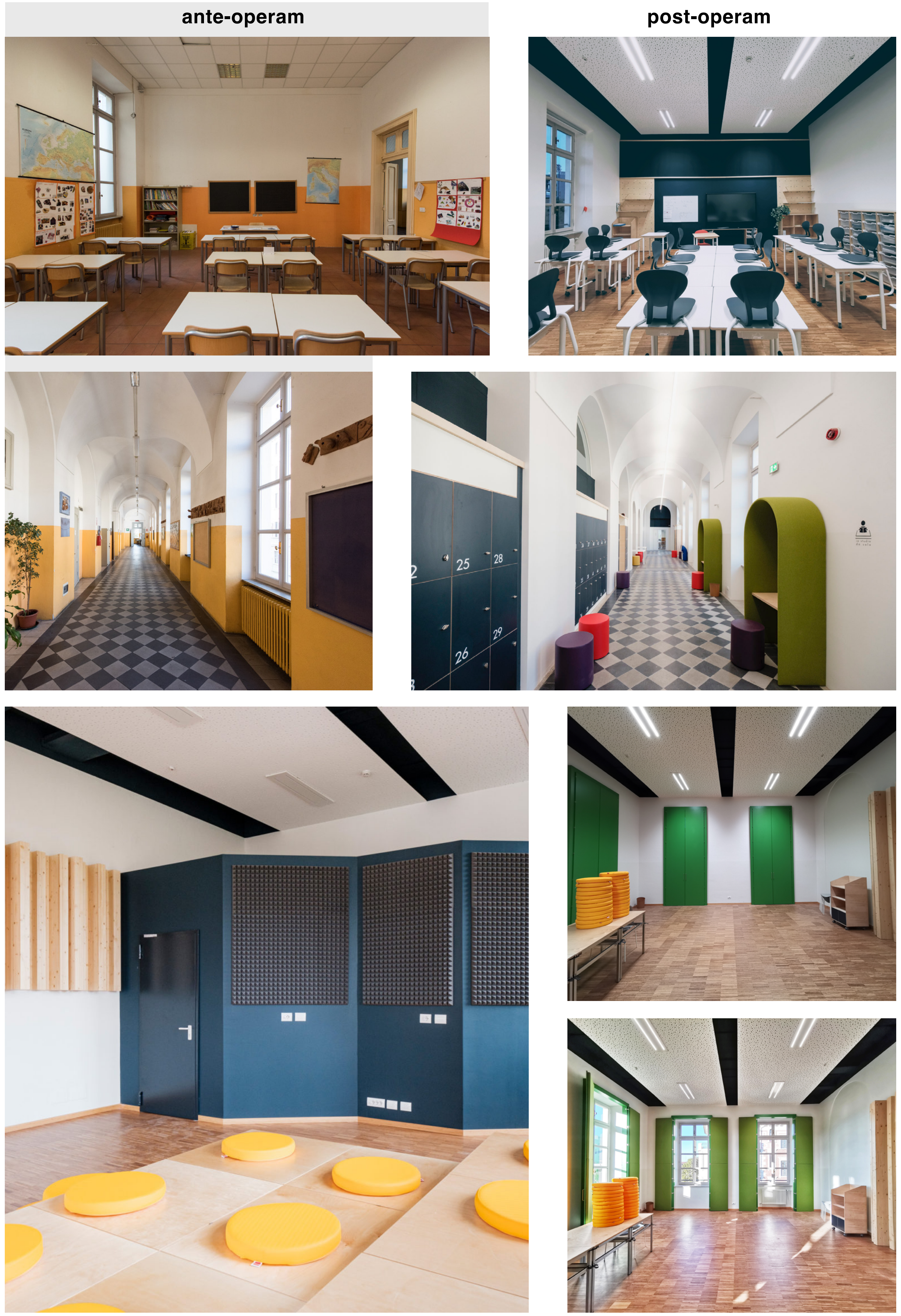


Figure 72. *Several spaces of G. Pascoli secondary school in Turin, ante and post operam: a) classroom b) hallway c) music room.*

APPENDIX A

The following appendix contains the python code used to calculate the absorption coefficients of the acoustic materials in the algorithm.

A.1 Porous absorber

```
__author__ = "Angelo_Lombardo"
__version__ = "2019.06.06"

#porous absorber_design

c=343 #[m/s] speed of sound in air at 20°C
#s=float(0.04) #absorber thickness
#d=float(0.00) #air gap
d1=s+d
λmax=4*d1
#print(round(λmax,2),"m")
fmin=c/λmax #minimum frequency of maximum absorption
#print(int(fmin))
#print('\nminimum frequency of maximum absorption of the acoustic panel= ',int(fmin),"Hz")

f=[125,250,500,1000,2000,4000]

f_abs=[0.05,0.1,0.13,0.2,0.4,0.7,0.85,0.85,0.85,00.85]

rif_1000=(f.index(2000))
#print(rif_125)

rif_fmin_=min(f, key=lambda x:abs(x-fmin))
#print(rif_fmin_)

rif_fmin=(f.index(rif_fmin_))
#print(rif_fmin)

def shift(seq, n):
    return seq[n:]+seq[:n]

n=int(rif_1000-rif_fmin)
#print(n)
```

```
seq=f_abs

abs_f_shift=shift(f_abs,n)

abs_coefficients=(abs_f_shift[2:8])

#print(abs_f_shift[2:8])
```

A.2 Resonant absorber

```
__author__ = "Angelo_Lombardo"
__version__ = "2019.06.06"

#resonant absorber_design

#reference gyptone AirActive 15-30

import math

c=343 #[m/s] speed of sound in air at 20°C
h=float(0.0125) #panel thickness
#d=float(0.2) #air gap
#p=19.6 #perforated area 14%

pi_greco=math.pi

fmin=(c/(2*pi_greco))*((p/100)/(d*h))**0.5 #frequency of maximum absorption
#print(int(fmin))
#print('\nresonant frequency of the acoustic panel= ',int(fmin),"Hz")

f=[125,250,500,1000,2000,4000]

f_abs=[0.25,0.30,0.40,0.65,0.85,0.7,0.55,0.50,0.50,0.45,0.45]

rif_1000=(f.index(500))
#print(rif_125)

rif_fmin_=min(f, key=lambda x:abs(x-fmin))

rif_fmin=(f.index(rif_fmin_))

def shift(seq, n):
    return seq[n:]+seq[:n]

n=int(rif_1000-rif_fmin)
#print(n)

seq=f_abs

abs_f_shift=shift(f_abs,n)

abs_coefficients=(abs_f_shift[2:8])
```


A.3 Membrane absorber

```
__author__ = "Angelo_Lombardo"
__version__ = "2019.06.06"

#membrane panels_design

ρ=int(700) #density[kg/m3]
s#=float(0.025) #width
m=round(ρ*s,2) #surface mass
d#=float(0.2) #distance from the ceiling/walls
#md=roundm*d
f0=60/((m*d)**0.5) #resonance frequency of the acoustic panel ---> max acosutic absorption
print('\nresonance frequency of the acoustic panel= ',int(f0),"Hz")

three_o=[25,31.5,40,50,63,80,100,125,160,200,250,315,400,500,630,800,1000,1250,1600,2000,2500
,3150,4000,5000,6300,8000,10000] #one-third-octaves
#print(len(three_o))

abs_tree_o=[0.13,0.14,0.16,0.18,0.22,0.30,0.40,0.42,0.37,0.30,0.22,0.18,0.16,0.14,0.13,0.11,0.10,0.
09,0.08,0.07,0.06,0.06,0.05,0.05,0.05,0.05,0.05,0.05,0.04,0.04] #absrption coefficients for one-third_
octaves
#print(len(abs_tree_o))

rif_125=(three_o.index(125))
#print(rif_125)

rif_fo=min(three_o, key=lambda x:abs(x-f0))
#print(rif_fo)

rif_o=(three_o.index(rif_fo))
#print(rif_o)

def shift(seq, n):
    return seq[n:]+seq[:n]

n=int(rif_125-rif_o)
#print(n)

seq=abs_tree_o

abs_tree_o_shift=shift(abs_tree_o,n)

#print(abs_tree_o_shift)

n=3
three_o_sublist=[abs_tree_o_shift[i:i+n] for i in range(0, len(abs_tree_o_shift), n)]
#print(three_o_sublist)

#print(type(three_o_sublist))
abs_coefficients_0=[]
for i in three_o_sublist:
    sum_sublist=round((sum(i))/3,2)
    #print(sum_sublist)
    abs_coefficients_0.append(sum_sublist)
abs_coefficients=abs_coefficients_0[2:8]
#print(abs_coefficients)
```

A.4 Baffle system

```
__author__ = "Angelo_Lombardo"
__version__ = "2019.06.06"

###a=input()
##print("insert baffle height")
#h=input()

a_primo = float(a)/float(h)
#print(round(a_primo,2))

ak_0= 1-((math.sqrt(1+a_primo**2)-1)/a_primo)
#print(ak_0)


#type(ak_0)

# In[4]:

list_alfa_b=[0.15,0.35,0.80,0.97,0.97,0.97] #from Test Certificate

# In[5]:

#print("insert number of baffles")
#n_baffles=input()
#n_baffles=int(9)
n_baffles

n_baffles_f=n_baffles+1

ak_s=[]
for alfa_b in list_alfa_b:
        ak_1=[((1-alfa_b)**n)*(math.sqrt(1+((n-1)*a_primo)**2)+math.sqrt(1+((n+1)*a_primo)**2)-2*math.
sqrt(1+(n*a_primo)**2)) for n in range(1,n_baffles_f)]
    ak_n=[sum(ak_1)]
    #print(ak_n)
    ak_s.extend(ak_n)

#print(ak_s)

ak_2=[(1/a_primo)*i for i in ak_s]
#print(ak_2)

ak=[ak_0-s for s in ak_2]
#print(ak)
for elem in ak:
    ak_coefficients=round(elem,2)
    print(ak_coefficients)
```

APPENDIX B

The following appendix shows the python code used to calculate the absorption coefficients of the acoustic materials in the algorithm.

B.1 Reverberation Time

```
__author__ = "Angelo_Lombardo"
__version__ = "2019.06.06"

a=x*math.log10(V)-y
RT_opt=round(a,1

RT0=0.16*V/Aeq
RT_occ=round(RT0,2)

RT_inocc0=RT_occ/(1-RT_occ*(Aeq_pupils-chairs_desks)/(0.16*V))
RT_inocc=round(RT_inocc0,2)
```

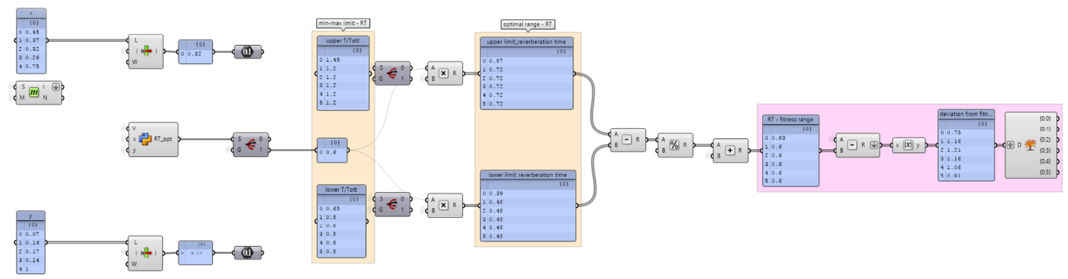


Figure A01. *Optimal reverberation time calculation on GH canvas.*

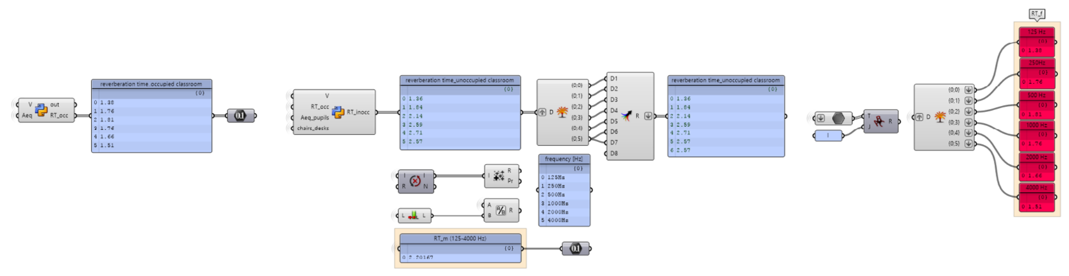


Figure A02. *Reverberation time calculation on GH canvas.*

B.2 Speech Clarity

```
__author__ = "Angelo_Lombardo"
__version__ = "2019.06.06"

a=100/r**2
b=math.exp(-0.691/T)
c=math.exp(-0.04*r/T)
d=31200*T/V
e=10*math.log10((a+d*(1-b)*c)/(c*d*b))
C50=round(e,1)

list_split=x.split(";")
c=list_split[1]
d=list_split[2]
e=list_split[3]

h=float(C50_500)+float(C50_1000)+float(C50_2000)
C50m=round(h/3,1)
```

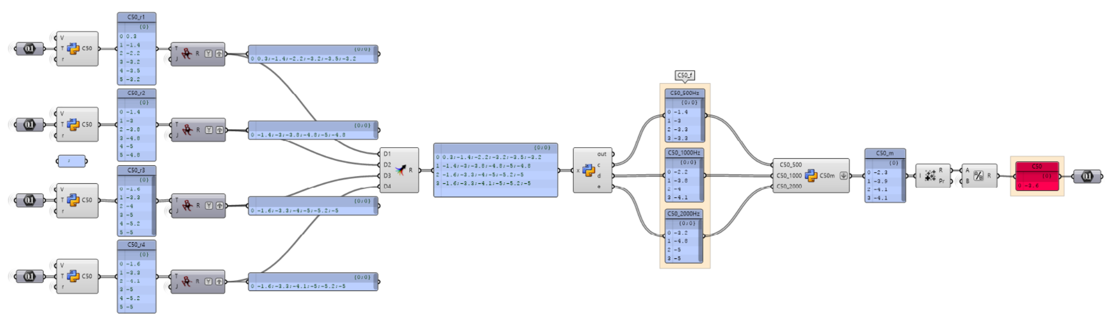


Figure A03. *Clarity speech calculation on GH canvas.*

B.3 Speech Transmission Index

```
__author__ = "Angelo_Lombardo"
__version__ = "2019.06.06"

import math
import numpy as np

####print("insert volume")
###V=input()
##print("insert talker to listener distance")
#r=input()
# In[5]:

Hz=([125,250,500,1000,2000,4000,8000])

# In[7]:
#index_spectrum=1
#index_sex=0

if index_spectrum==0:
    Ls_A_1m=int(54)
else:
    if index_spectrum==1:
        Ls_A_1m=int(60)
    else:
        if index_spectrum==2:
            Ls_A_1m=int(66)
        else:
            if index_spectrum==3:
                Ls_A_1m=int(72)
            else:
                if index_spectrum==4:
                    Ls_A_1m=int(78)
#print(Ls_A_1m)

male_spectrum=[2.9,2.9,-0.8,-6.8,-12.8,-18.8,-24.8]
male_spectrum_=np.asarray(male_spectrum)
#print(male_spectrum_)
female_spectrum=[0,5.3,-1.9,-9.1,-15.8,-16.7,-18]
female_spectrum_=np.asarray(female_spectrum)
#print(female_spectrum_)
if index_sex==0:
    Ls_f_1m=Ls_A_1m+male_spectrum_
else:
    if index_sex==1:
        Ls_f_1m=Ls_A_1m+female_spectrum_
        Ls_f_1m[0]=0
        #print(Ls_f_1m[0])
#print(Ls_f_1m)

def sti(r):
    pi_greco=math.pi
    #print(pi_greco)

      Tf=[float(i) for i in y]
    #if len(Tf)==7:
        #print("keep on!")
```

```
    rc_f=[0.0032*V/i for i in Tf]
    #print (rc_f)
    rc_ff=[round(elem, 2) for elem in rc_f]
    #print("\nrc_f=",rc_ff)

    IDf=[2,2,2,2,3,3,3]
    Qf=[round(10**(i/10),2) for i in IDf]
    F=[0.63,0.8,1,1.25,1.6,2,2.5,3.15,4,5,6.3,8,10,12.5]
    #if len(F)==14:
        #print("keep on!")

    #Ln_f=[25.5,31.5,27.5,19.4,13.1,7.7,6.7]
    #if len(Ls_f_1m) and len(Ln_f)==7:
        #print("keep on!")

    #A=(Qf[0]/r**2)+(1/rc_f[0])*(1+(2*pi_greco*F[0]*(Tf[0]/13.8))**2)**-1
    #print(round(A,2))

    #B=(2*pi_greco*F[0]*Tf[0]/(13.8*rc_f[0]))*(1+(2*pi_greco*F[0]*Tf[0]/13.8)**2)**-1
    #print(round(B,2))

    #C=(Qf[0]/r**2)+(1/rc_f[0])+Qf[0]*10**((Ln_f[0]-Ls_f_1m[0])/10)
    #print(round(C,2))

    #mf_F=math.sqrt(A**2+B**2)/C
    #print(round(mf_F,3))

#print("\n\n---------------------")
    Qf_=np.asarray(Qf)
    rc_f_=np.asarray(rc_f)
    Tf_=np.asarray(Tf)
    Ln_f_=np.asarray(Ln_f)
    Ls_f_1m_=np.asarray(Ls_f_1m)
    IDf_=np.asarray(IDf)
    print("\n\nQ_f=",Qf_)#len(Qf_))
    print("\nrc_f=",rc_ff)#len(rc_f_))
    print("\nTf=",Tf_)#len(Tf_))
    print("\nLs_f_1m=",Ls_f_1m_)#len(Ls_f_1m_))
    print("\nLn_f=",Ln_f_)#len(Ln_f_))

    A__=[]
    for i in range(0,len(F)):
        A_=(Qf_/r**2)+(1/rc_f_)*(1+(2*pi_greco*F[i]*(Tf_/13.8))**2)**-1
        #print(A_)
        A__.extend(A_)
    #print(A__)

    A___=np.reshape(A__,(14,7))
    #print(A___.round(3))

    B__=[]
    for i in range(0,len(F)):
        B_=(2*pi_greco*F[i]*Tf_/(13.8*rc_f_))*(1+(2*pi_greco*F[i]*Tf_/13.8)**2)**-1
        #print(B_)
        B__.extend(B_)
    #print(B__)
```



```
    B___=np.reshape(B__,(14,7))
    #print(B___.round(3))

    C__=[]
    for i in range(0,len(F)):
        C_=(Qf_/r**2)+(1/rc_f_)+Qf_*10**((Ln_f_-Ls_f_1m_)/10)
        #print(C_)
        C__.extend(C_)
    #print(C__)

    C___=np.reshape(C__,(14,7))
    #print(C___.round(3))

    mf_F_=(A___**2+B___**2)**0.5/C___
    #print(mf_F_)

    mf_F__=np.reshape(mf_F_,(14,7))
    print("\nmf_f:\n",mf_F__.round(3))

    print("\nmatrix_shape=",mf_F__.size)
    #if mf_F__.size==98:
        #print("keep on!")

    Lsd_f=Ls_f_1m-20*np.log10(r)
    #print(np.round(Lsd_f,1))
    Lsr_f=Ls_f_1m-IDf_-10*np.log10(rc_f_)
    #print(np.round(Lsr_f,1))

    Ls_f=(10*np.log10(10**(Lsd_f/10)+10**(Lsr_f/10)))
    print("\nLs_f=",np.round(Ls_f,1))

    Leq_tot=(10*np.log10(10**(Ls_f/10)+10**(Ln_f_/10)))
    print("\nLeq_tot=",np.round(Leq_tot,1))
    If=10**(Leq_tot/10)
    print("\nI_f=",np.round(If,1))

    Lf_1=np.roll(Leq_tot,1)
    Lf_1[0]=0
    #print(np.round(Lf_1,2))
    If_1=10**(Lf_1/10)
    If_1[0]=0
    print("\nI_f-1=",np.round(If_1,1))

    amdB_=[]
    for i in Lf_1:
        if i<63:
            amdB=0.5*i-65
        else:
            if i>=63 and i<67:
                amdB=1.8*i-146.9
            else:
                if i>=67 and i<100:
                    amdB=0.5*i-59.8
                else:
                    if i>=100:
                        amdB=-10
        #print(i)
        amdB_.append(amdB)
```

```
#print(amdB_)
amdB__=np.asarray(amdB_)
amdB__[0]=0
print("\namdB=",np.round(amdB__,1))
amf=10**(amdB__/10)
amf[0]=0
print("\namf=",np.round(amf,6))

Lrs_f=np.array([46, 27, 12, 6.5, 7.5, 8, 12])
print("\nLrs_f=",Lrs_f)
type(Lrs_f)
Irs_f=10**(Lrs_f/10)
print("\nIrs_f=",np.round(Irs_f,2))

Iam_f=If_1*amf
print("\nIam_f=",Iam_f)

m1f_F=mf_F__*(If/(If+Irs_f+Iam_f))
print("\nm'f_f:\n",np.round(m1f_F,3))

m1f_F1=np.clip(m1f_F,0,1)
print("\nm'f_f  <=1:\n",np.round(m1f_F1,3))

S_N_eff_f=10*np.log10(m1f_F1/(1-m1f_F1))
print("\nS_N_eff_f:\n",np.round(S_N_eff_f,2))

S_N_eff_f15=np.clip(S_N_eff_f,-15,15)
print("\nS_N_eff_f  >=-15 <=+15:\n",np.round(S_N_eff_f15,2))

TI_f=(S_N_eff_f15+15)/30
print("\nTI_f:\n",np.round(TI_f,3))

MTI_f=TI_f.mean(axis=0)
print("\nMTI_f:\n", np.round(MTI_f,3))
sum_MTI_f=np.sum(MTI_f)

if index_sex==0:
    alfa=np.array([0.085,0.127,0.23,0.233,0.309,0.224,0.173])
else:
    if index_sex==1:
        alfa=np.array([0,0.117,0.223,0.216,0.328,0.25,0.194])
print("\nalfa_f:\n", alfa)
if index_sex==0:
    beta=np.array([0.085,0.078,0.065,0.011,0.047,0.095])
else:
    if index_sex==1:
        beta=np.array([0,0.099,0.066,0.062,0.025,0.076])
print("\nbeta_b:\n", beta)

alfa_MTI_f=alfa*MTI_f
#print(np.round(alfa_MTI_f,4))
#print("\nTotal:",np.round(np.sum(alfa_MTI_f),2))
sum_alfa_MTI_f=np.sum(alfa_MTI_f)

MTI_f0=MTI_f
MTI_f0_=np.delete(MTI_f0,-1)
#print(np.round(MTI_f0_,4))
MTI_f1=MTI_f
```



```
    MTI_f1_=np.delete(MTI_f1,0)
    #print(np.round(MTI_f1_,4))

    MTI_f_0_1=(MTI_f0_*MTI_f1_)**0.5
    #print(np.round(MTI_f_0_1,4))
    sum_MTI_f_0_1=np.sum(MTI_f_0_1)

    beta_MTI_f_0_1=beta*MTI_f_0_1
    #print(np.round(beta_MTI_f_0_1,4))
    #print("\nTotal:",np.round(np.sum(beta_MTI_f_0_1),2))
    sum_beta_MTI_f_0_1=np.sum(beta_MTI_f_0_1)

    w_sum_alfa_MTI_f=sum_alfa_MTI_f/sum_MTI_f
    #print(np.round(w_sum_alfa_MTI_f,4))

    w_sum_beta_MTI_f_0_1=sum_beta_MTI_f_0_1/sum_MTI_f_0_1
    #print(np.round(w_sum_beta_MTI_f_0_1,4))

    STI=sum_alfa_MTI_f-sum_beta_MTI_f_0_1

    return STI
if V<=250:
    s_a_distances_0=x.split(";")
    s_a_distances_=[s_a_distances_0[0],s_a_distances_0[3]]
else:
   s_a_distances_=x.split(";")

list_sti=[]
#print("values STI list:"), print(list_sti)
d=s_a_distances_
for i in d:
    sti__=sti(float(i))
    sti___=round(sti__,2)
    #print("\n",sti___)
    #print("\n---------------------")
    list_sti.append(sti__)
#print(list_sti)
#print(type(list_sti))
sum_list_sti=sum(list_sti)
#print(sum_list_sti)
#print("\n\nThe total sum is: "+str(round(sum_list_sti,3)))
mean_list_sti=sum_list_sti/len(list_sti)
#print("\nThe mean value is: "+str(round(mean_list_sti,3)))

__STI=round(mean_list_sti,2)

print("\n",__STI)

if sti__>0 and sti__<=0.3:
    speech_quality=("BAD")
else:
    if sti__>0.3 and sti__<=0.45:
        speech_quality=("POOR")
    else:
        if sti__>0.45 and sti__<=0.6:
            speech_quality=("FAIR")
        else:
            if sti__>0.6 and sti__<=0.75:
```

```
                speech_quality=("GOOD")
            else:
                if sti__>0.75 and sti__<=1:
                    speech_quality=("EXCELLENT")
```

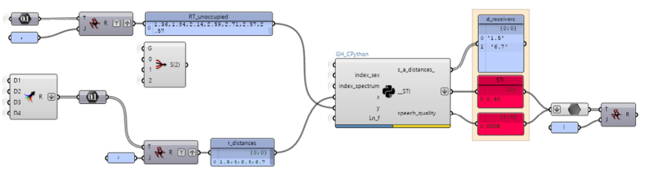


Figure A04. *Speech transmission index calculation on GH canvas.*

B.4 Room equipment noise

```
__author__ = "Angelo_Lombardo"
__version__ = "2019.06.06"

import math
import numpy as np

if fan_coil_==0:
    Lw=[35.5,42.7,39.1,30.3,23.1,14.8]
else:
    if fan_coil_==1:
        Lw=[43.5,43.3,40.6,34.8,32.3,16.7]
#print(Lw)

A_weighting_curve=[-16.1,-8.6,-3.2,0,1.2,1]
A_weighting_curve_=np.asarray(A_weighting_curve)

def Lp_d(d):
    def Lp_r(*r):
        #R=[57.6,72.9,85.2,91.4,92.7,96.6] #room constant
        Q=2 #directivity
        pi_greco=math.pi

        R_=np.asarray(R)
        Lw_=np.asarray(Lw)
        d_list= np.array([])

        for num in r:
            ###print(num)
            #print(type(num))
            Lp=np.round(Lw_+10*np.log10((Q/(4*pi_greco*(num**2)))+(4/R_)),1)
```



```
            #print(Lp)
            #print(type(Lp))
            d_list= np.append(d_list, Lp)
        return (d_list)
        #print(d_list)

    l_d1=len(d)
    #print(l_d1)
    Lp_d1=Lp_r(*d)
    #print(Lp_d1)

    Lp_d1.shape = (l_d1, 6)
    #print(Lp_d1)

    p=Lp_d1.transpose()
    #print(p)

    #---------------------------------

    list_n=[]
    for i in p:
        a=i.tolist()
        #print(a)
        #print(type(a))
        list_n.append(a)
        #print(list_n)

    def dB_sum(*args):
        z = 0
        y = 0
        for num in args:
            z += 10**(float(num)/10)
            #print(z)
        y += 10*math.log10(z)
            #print(y)
        return(y)

    sum2=[]
    for i in list_n:
        sum1=dB_sum(*i)
        #print(round(sum1,1))
        sum2.append(round(sum1,1))

    #print("\n")
    #return(sum2)
    #print(sum2)
    sum2_=np.asarray(sum2)
    sum2_A=sum2_+A_weighting_curve_
    #print(sum2_A)
    sum3_=dB_sum(*sum2_A)
    sum3=round(sum3_,1)

    return(sum3)

list_input=[]
if volume<250:
    list_input.append(d1)
    list_input.append(d4)
```

```
else:
   list_input.append(d1)
   list_input.append(d2)
   list_input.append(d3)
   list_input.append(d4)
#print(list_input)

Lp_d_tot=[]
#=[[10,10],[5,5]]
for i in list_input:
    out=Lp_d(i)
    #print(out)
    Lp_d_tot.append(out)

#print("*****",Lp_d_tot)

if volume<=100:
    T0=0.5
else:
    if volume>=2500:
        T0=2.5
    else:
        T0=0.05*volume**(0.5)

T0_=round(T0,2)

k2=-10*(math.log10(RT_m/T0))
k2_=round(k2,2)

Lp_d_ntot=[]
for i in Lp_d_tot:
    out_n=round(i+k2_,1)
    #print(out_n)
    Lp_d_ntot.append(out_n)
#print(Lp_d_ntot)

def E_conv(*args):
        E=[]
        for num in args:
            k = 10**(num/10)
            E.append(k)
        return (E)


l_Lp=len(Lp_d_ntot)

E_f=E_conv(*Lp_d_ntot)
#print(E_f)

mean_E=sum(E_f)/l_Lp
#print(mean_E)

Lic_int=round(10*math.log10(mean_E),1)
#print(mean_A)

LAeq_list=[]
LAeq_list.append(Lic_int)
LAeq_list.append(float(L2_A_tot))
```



```
def dB_sum(*args):
        z = 0
        y = 0
        for num in args:
            z += 10**(float(num)/10)
            #print(z)
        y += 10*math.log10(z)
            #print(y)
        return(y)

LAeq=dB_sum(*LAeq_list)
LAeq_=round(LAeq,1)
#print("\n")
#print("LA_eq=",round(LAeq,1),"dBA")
```

B.5 Overall noise in the environment

```
__author__ = "Angelo_Lombardo"
__version__ = "2019.06.06"

import math
import numpy as np

if fan_coil_==0:
    Lw=[35.5,42.7,39.1,30.3,23.1,14.8]
else:
    if fan_coil_==1:
        Lw=[43.5,43.3,40.6,34.8,32.3,16.7]
#print(Lw)

A_weighting_curve=[-16.1,-8.6,-3.2,0,1.2,1]
A_weighting_curve_=np.asarray(A_weighting_curve)

def Lp_d(d):
    def Lp_r(*r):
        #R=[57.6,72.9,85.2,91.4,92.7,96.6] #room constant
        Q=2 #directivity
        pi_greco=math.pi

        R_=np.asarray(R)
        Lw_=np.asarray(Lw)
        d_list= np.array([])

        for num in r:
            ###print(num)
            #print(type(num))
            Lp=np.round(Lw_+10*np.log10((Q/(4*pi_greco*(num**2)))+(4/R_)),1)
            #print(Lp)
            #print(type(Lp))
            d_list= np.append(d_list, Lp)
        return (d_list)
        #print(d_list)

    l_d1=len(d)
```

```
    #print(l_d1)
    Lp_d1=Lp_r(*d)
    #print(Lp_d1)

    Lp_d1.shape = (l_d1, 6)
    #print(Lp_d1)

    p=Lp_d1.transpose()
    #print(p)

    #---------------------------------

    list_n=[]
    for i in p:
        a=i.tolist()
        #print(a)
        #print(type(a))
        list_n.append(a)
        #print(list_n)

    def dB_sum(*args):
        z = 0
        y = 0
        for num in args:
            z += 10**(float(num)/10)
            #print(z)
        y += 10*math.log10(z)
            #print(y)
        return(y)

    sum2=[]
    for i in list_n:
        sum1=dB_sum(*i)
        #print(round(sum1,1))
        sum2.append(round(sum1,1))

    #print("\n")
    #return(sum2)
    #print(sum2)
    sum2_=np.asarray(sum2)
    #print(sum2_)

    return(sum2_)

list_input=[]
if volume<250:
   list_input.append(d1)
   list_input.append(d4)
else:
   list_input.append(d1)
   list_input.append(d2)
   list_input.append(d3)
   list_input.append(d4)
#print(list_input)

Lp_d_tot=[]
#=[[10,10],[5,5]]
for i in list_input:
```



```
    out=Lp_d(i)
    #print(out)
    Lp_d_tot.append(out)

#print("*****",Lp_d_tot)

l_Lp=len(Lp_d_tot)
#print(l_Lp)

def E_conv(*args):
        E=[]
        for num in args:
            k = 10**(num/10)
            E.append(np.round(k,2))
        return (E)

E_f=E_conv(*Lp_d_tot)

#print("\n")
mean_E=sum(E_f)/l_Lp
#print(mean_E)

Lp_m=[]
for i in mean_E:
    y = 10*math.log10(i)
    Lp_m.append(round(y,1))

#print(Lp_m)

list_input=[]
list_input.append(Lp_m)
list_input.append(L2_tot)
list_input_=np.array(list_input).T.tolist()

#print(list_input_)

def dB_sum(*args):
        z = 0
        y = 0
        for num in args:
            z += 10**(float(num)/10)
            #print(z)
        y += 10*math.log10(z)
            #print(y)
        return(y)

Ln_f=[]
for i in list_input_:
    sum1=dB_sum(*i)
    #print(round(sum1,1))
    Ln_f.append(round(sum1,1))

#print("\n")

#print(Ln_f)
```

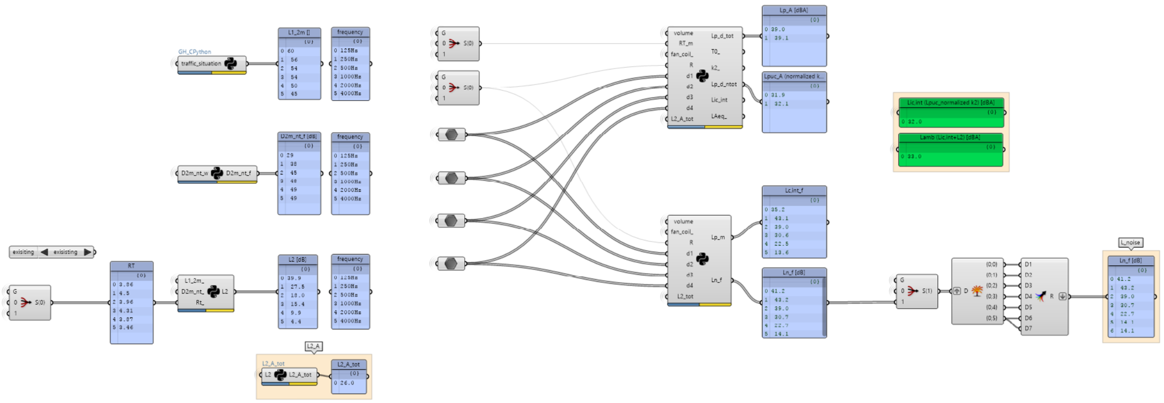


Figure A05. *Room equipment noise and overall noise in the environment calculation on GH canvas.*

APPENDIX C

The following appendix summarizes the materials used in the ray tracing model, their geometric characteristics and their absorption and scattering coefficients. Each one has been is assigned to a Rhino layer.

C.1 Ray-tracing model materials

RHINO LAYER	MATERIAL	ABSORPTION COEFFICIENTS [%] (125-4000Hz)	SCATTERING COEFFICIENTS [%] (125-4000Hz)
00	marble, tiles, clinker	1 1 2 2 3 3	
01	smooth plaster	2 2 3 3 4 5	
02	wooden door	10 8 6 5 5 5	15 20 25 28 30 30
03	windows, transom	28 20 11 6 3 2	
04	blackboard	30 24 19 14 8 5	
05a	primary school pupils	5 10 20 35 40 45	20 30 40 50 50 60
05b	desks and chairs	7 6 7 7 4 3	
06	porous absorber - a	10 13 20 40 70 85	
07	porous absorber - b	20 40 70 85 85 85	
08	porous absorber - c	40 70 85 85 85 85	
09	porous absorber - d	75 85 85 85 85 85	
10	membrane absorber - a	40 23 14 10 7 5	15 20 25 28 30 30
11	membrane absorber - b	23 14 10 70 6 5	
12	membrane absorber - c	23 14 10 7 6 5	
13	membrane absorber - d	19 13 9 6 5 5	
14	resonant absorber - a	40 65 85 70 55 50	
15	resonant absorber - b	30 40 65 85 70 55	

RHINO LAYER	MATERIAL	ABSORPTION COEFFICIENTS [%] (125-4000Hz)	SCATTERING COEFFICIENTS [%] (125-4000Hz)
16	resonant absorber - c	65 85 70 55 50 50	15 20 25 28 30 30
17	resonant absorber - d	40 65 85 70 55 50	
18	brick-proof ceiling - a	30 16 11 8 6 5	
19	brick-proof ceiling - b (i)	15 30 60 75 65 60	
20	brick-proof ceiling - b (ii)	45 60 70 60 55 55	
21	baffles - a	4 8 18 21 21 21	
22	baffles - b	8 17 35 40 40 40	
23	baffles - c	13 26 50 57 57 57	
24	baffles - d	20 40 65 72 72 72	
25	baffles - e	39 66 90 94 94 94	
26	scattering panel – 01a	2 2 3 3 4 5	15 20 44 73 84 93
27	scattering panel – 01b	2 2 3 3 4 5	23 26 91 86 88 94
28	scattering panel – 10a	30 23 14 10 7 5	15 20 44 73 84 93
29	scattering panel – 11a	23 14 10 7 5 5	15 20 44 73 84 93
30	scattering panel – 12a	23 14 10 7 6 5	15 20 44 73 84 93
31	scattering panel – 13a	19 13 9 6 5 5	15 20 44 73 84 93
32	scattering panel – 10b	30 23 14 10 7 5	23 26 91 86 88 94
33	scattering panel – 11b	23 14 10 7 5 5	23 26 91 86 88 94
34	scattering panel – 12b	23 14 10 7 6 5	23 26 91 86 88 94
35	scattering panel – 13b	19 13 9 6 5 5	23 26 91 86 88 94

These are actually "container" materials as presented below, since they include materials of the same type (porous, membrane, resonant, etc.) with the same absorption and scattering coefficients although they can assume different configurations in terms of thickness or air gap for example.

< absorption coefficients >

[scattering coefficients]

(*) :negligible

7. porous absorber:

wall — air gap [0÷120mm]

ceiling/false-ceiling — air gap [0÷(h_{max})mm]

thickness* [25÷50mm]

a) - air gap≤20mm — <0.10 0.13 0.20 0.40 0.70 0.85>

b) - 20mm<air gap≤80mm — <0.20 0.40 0.70 0.85 0.85 0.85>

c) - 80mm<air gap≤250mm — <0.40 0.70 0.85 0.85 0.85 0.85>

d) - air gap>250mm — <0.75 0.85 0.85 0.85 0.85 0.85>

[0.15 0.20 0.25 0.28 0.30 0.30]

8. membrane absorber:

wall — air gap [40÷120mm] — thickness [9÷25mm]

ceiling/false-ceiling — air gap [40÷(h_{max})mm] — thickness [9÷25mm]

a) - air gap<80mm thickness<15mm — <0.40 0.23 0.14 0.10 0.07 0.05>

b) - air gap<80mm thickness≥15mm — <0.23 0.14 0.10 0.07 0.05 0.05>

c) - air gap≥80mm thickness<15mm — <0.23 0.14 0.10 0.07 0.06 0.05>

d) - air gap≥80mm thickness≥15mm — <0.19 0.13 0.09 0.06 0.05 0.05>

[0.15 0.20 0.25 0.28 0.30 0.30]

9. resonant absorber:

wall — air gap [40÷120mm]

ceiling/false-ceiling — air gap [40÷(h_{max})mm]

thickness [12,5mm] — perforated area [9÷19%]

a) - air gap<200mm perf. area<15% — <0.40 0.65 0.85 0.70 0.55 0.50>

b) - air gap<200mm perf. area≥15% — <0.30 0.40 0.65 0.85 0.70 0.55>

c) - air gap≥200mm perf. area<15% — <0.65 0.85 0.70 0.55 0.50 0.50>

d) - air gap≥200mm perf. area≥15% — <0.40 0.65 0.85 0.70 0.55 0.50>

[0.15 0.20 0.25 0.28 0.30 0.30]

10. brick-proof ceiling:

a) - in adherence <0.30 0.16 0.11 0.08 0.06 0.05>

b) - lowered : air gap [65-200mm]

i. - air gap=65mm <0.15 0.30 0.60 0.75 0.65 0.60>

ii. - air gap=200mm <0.45 0.60 0.70 0.60 0.55 0.55>

[0.15 0.20 0.25 0.28 0.30 0.30]

11. baffles:

spacing [300-600-900-1200mm]

height [300-600mm]

a) spacing=900mm; height=300mm; no-suspension

spacing=1200mm; height=300mm; no-suspension <0.04 0.08 0.18 0.21 0.21 0.21>

b) spacing=600mm; height=300mm; no-suspension

spacing=900mm; height=300mm; suspension

spacing=900mm; height=600mm; no-suspension

spacing=1200mm; height=300mm; suspension

spacing=1200mm; height=600mm; no-suspension <0.08 0.17 0.35 0.40 0.40 0.40>

c) spacing=300mm; height=300mm; no-suspension

spacing=600mm; height=300mm; suspension

spacing=600mm; height=600mm; no-suspension

spacing=1200mm; height=600mm; suspension <0.13 0.26 0.50 0.57 0.57 0.57>

d) spacing=300mm; height=300mm; suspension

spacing=300mm; height=600mm; no-suspension

spacing=600mm; height=600mm; suspension

spacing=900mm; height=600mm; suspension <0.20 0.40 0.65 0.72 0.72 0.72>

e) spacing=300mm; height=600mm; suspension <0.39 0.66 0.90 0.94 0.94 0.94>

[0.15 0.20 0.25 0.28 0.30 0.30]

26. scattering panel:

a) - in adherence <0.02 0.02 0.03 0.03 0.04 0.05>

[0.15 0.20 0.44 0.73 0.84 0.93]

b) - in adherence <0.02 0.02 0.03 0.03 0.04 0.05>

[0.23 0.26 0.91 0.86 0.88 0.94]

28. scattering panel:

wall air gap [40÷120mm] thickness [9÷25mm]

ceiling/false-ceiling air gap [40÷(h_{max})mm] thickness [9÷25mm]

a) - air gap<80mm thickness<15mm <0.30 0.23 0.14 0.10 0.07 0.05>

b) - air gap<80mm thickness≥15mm <0.23 0.14 0.10 0.07 0.05 0.05>

c) - air gap≥80mm thickness<15mm <0.23 0.14 0.10 0.07 0.06 0.05>

d) - air gap≥80mm thickness≥15mm <0.19 0.13 0.09 0.06 0.05 0.05>

[0.15 0.20 0.44 0.73 0.84 0.93]

32. scattering panel:

wall air gap [40÷120mm]

ceiling/false-ceiling air gap [40÷(h_{max})mm]

thickness [12,5mm] perforated area [9÷19%]

a) - air gap<200mm perf. area<15% <0.30 0.65 0.85 0.70 0.55 0.50>

b) - air gap<200mm perf. area≥15% <0.30 0.40 0.65 0.85 0.70 0.55>

c) - air gap≥200mm perf. area<15% <0.65 0.85 0.70 0.55 0.50 0.50>

d) - air gap≥200mm perf. area≥15% <0.40 0.65 0.85 0.70 0.55 0.50>

[0.23 0.26 0.91 0.86 0.88 0.94]

A Python code, based on the *if* function has been written to correctly assign layer to surfaces in Grasshopper, considering the material properties, an example is show below:

```
__author__ = "Angelo_Lombardo"
```

```
__version__ = "2019.06.06"

#x:air gap
#y:thickness

x1=x*1000
if z==0:
    if x1<80 and y==0:
        out=0
    else:
        if x1<80 and y==1:
            out=1
        else:
            if x1>=80 and y==0:
                out=2
            else:
                if x1>=80 and y==1:
                    out=3
else:
    if z==1:
        if x1<80 and y==0:
            out=5
        else:
            if x1<80 and y==1:
                out=6
            else:
                if x1>=80 and y==0:
                    out=7
                else:
                    if x1>=80 and y==1:
                        out=8
    else:
        if z==2:
                if x1<80 and y==0:
                    out=9
                else:
                    if x1<80 and y==1:
                        out=10
                    else:
                        if x1>=80 and y==0:
                            out=11
                        else:
                            if x1>=80 and y==1:
                                out=12
        else:
            out=4
print out
```

APPENDIX D

The following figure shows the excel sheet used to collect the information derived from the optimization process.

Case study	Dimensions [l*w*h	Volume
Primary School Luc	8.4*6.7*4.4	248m³

fitness-125Hz	fitness-250Hz	fitness-500Hz	fitness-1000Hz	fitness-2000Hz	fitness-4000Hz	C50	STI	fitness-STI	fitness-BUDGET
0,61	0,28	0,05	0,06	0,11	0,11	2,45	0,66	0,34	4079,83
0,84	0,49	0,01	0,19	0,25	0,25	3,7	0,78	0,22	16134,58
0,72	0,41	0,09	0,06	0,11	0,12	2,675	0,72	0,28	7461,89
0,09	0,04	0,04	0,06	0,07	0,08	4,475	0,73	0,27	4546,22
0,67	0,21	0,16	0,26	0,29	0,3	5,9	0,81	0,19	24479,9
0,08	0,02	0,03	0,05	0,06	0,07	4,25	0,72	0,28	4270,16
0,6	0,32	0,01	0,15	0,19	0,2	3,8	0,76	0,24	16260,31
0,53	0,42	0,14	0,07	0,04	0,03	1,85	0,68	0,32	12174,61
1,06	1,06	0,5	0,23	0,14	0,11	-0,525	0,62	0,38	8846,11
0,25	0,17	0,26	0,35	0,35	0,31	1,1	0,59	0,41	4163,47
1,47	0,88	0,25	0,03	0,03	0,05	0,95	0,68	0,32	7786,75
1	0,42	0,01	0,15	0,18	0,19	3,6	0,76	0,24	10398,23
0,45	0,29	0,2	0,07	0,01	0,01	1,975	0,68	0,32	4720,79
1,35	0,78	0,19	0,03	0,09	0,1	1,55	0,71	0,29	8266,03
0,48	0,81	0,93	0,88	0,77	0,75	-2,4	0,47	0,53	5732,04
0,05	0,02	0,07	0,07	0,06	0,06	3,2	0,68	0,32	5629,36
0,09	0,23	0,14	0,03	0,1	0,09	2,775	0,72	0,28	6649,25
0,02	0,01	0,12	0,18	0,21	0,2	5,7	0,78	0,22	15632,2
0,49	0,84	0,97	0,9	0,81	0,78	-2,725	0,46	0,54	4501,18
1,1	0,71	0,15	0,07	0,13	0,14	1,975	0,72	0,28	14484,21
0,04	0,24	0,39	0,4	0,35	0,38	0,375	0,57	0,43	5418,49
2,75	2,26	1,35	1	0,84	0,71	-4,275	0,45	0,55	507,6
0,05	0,02	0,04	0,07	0,09	0,1	4,35	0,73	0,27	2994,58
0,66	0,43	0,27	0,22	0,19	0,16	0,875	0,63	0,37	3863,98
0,09	0,02	0,05	0,12	0,13	0,1	3,125	0,66	0,34	3853,9
0,61	0,56	0,12	0,08	0,14	0,14	2,375	0,73	0,27	15767,59
0,72	0,72	0,59	0,55	0,52	0,46	-1,025	0,54	0,46	3861,98
1,66	1,11	0,75	0,63	0,53	0,46	-1,95	0,52	0,48	930,6
0,05	0,13	0,26	0,28	0,29	0,29	8,45	0,83	0,17	24885,64
0,27	0,26	0,21	0,12	0,08	0,06	1,75	0,66	0,34	5182,29
1,69	1,37	0,76	0,54	0,47	0,4	-2,05	0,54	0,46	1849,35
0,23	0,17	0,26	0,36	0,37	0,33	1,1	0,59	0,41	4689,8
0,66	0,24	0,11	0,18	0,19	0,2	4,775	0,77	0,23	23636,93
0,64	0,87	0,49	0,19	0,1	0,08	-0,15	0,64	0,36	6730,31
1,86	1,41	0,58	0,15	0,02	0	-0,8	0,64	0,36	2605,68
0,08	0,09	0,26	0,3	0,32	0,32	8,45	0,84	0,16	26067,88
0,19	0,07	0	0,02	0,03	0,05	3,675	0,71	0,29	10718,64
3,42	3,46	2,42	1,89	1,5	1,24	-6,9	0,34	0,66	0
0,22	0,27	0,41	0,48	0,46	0,45	0,125	0,55	0,45	5166,54
0,33	0,47	0,61	0,73	0,71	0,63	-1,05	0,51	0,49	3820,92
0,03	0,08	0,14	0,16	0,17	0,18	5,875	0,77	0,23	9892,26
0,08	0,11	0,09	0,15	0,2	0,22	2,55	0,64	0,36	6093,31
0,43	0,63	0,71	0,66	0,56	0,54	-1,35	0,53	0,47	2070
0,29	0,21	0,06	0,19	0,23	0,23	4,675	0,78	0,22	18705,49
0,46	0,32	0,41	0,5	0,49	0,43	0,125	0,56	0,44	3162,81
0,8	0,56	0,1	0,04	0,09	0,1	2,225	0,72	0,28	13359,85
0,66	0,95	0,87	0,65	0,51	0,49	-2,1	0,52	0,48	4420,26

Figure A06. *Extract from the excel data sheet derived from the optimization process.*

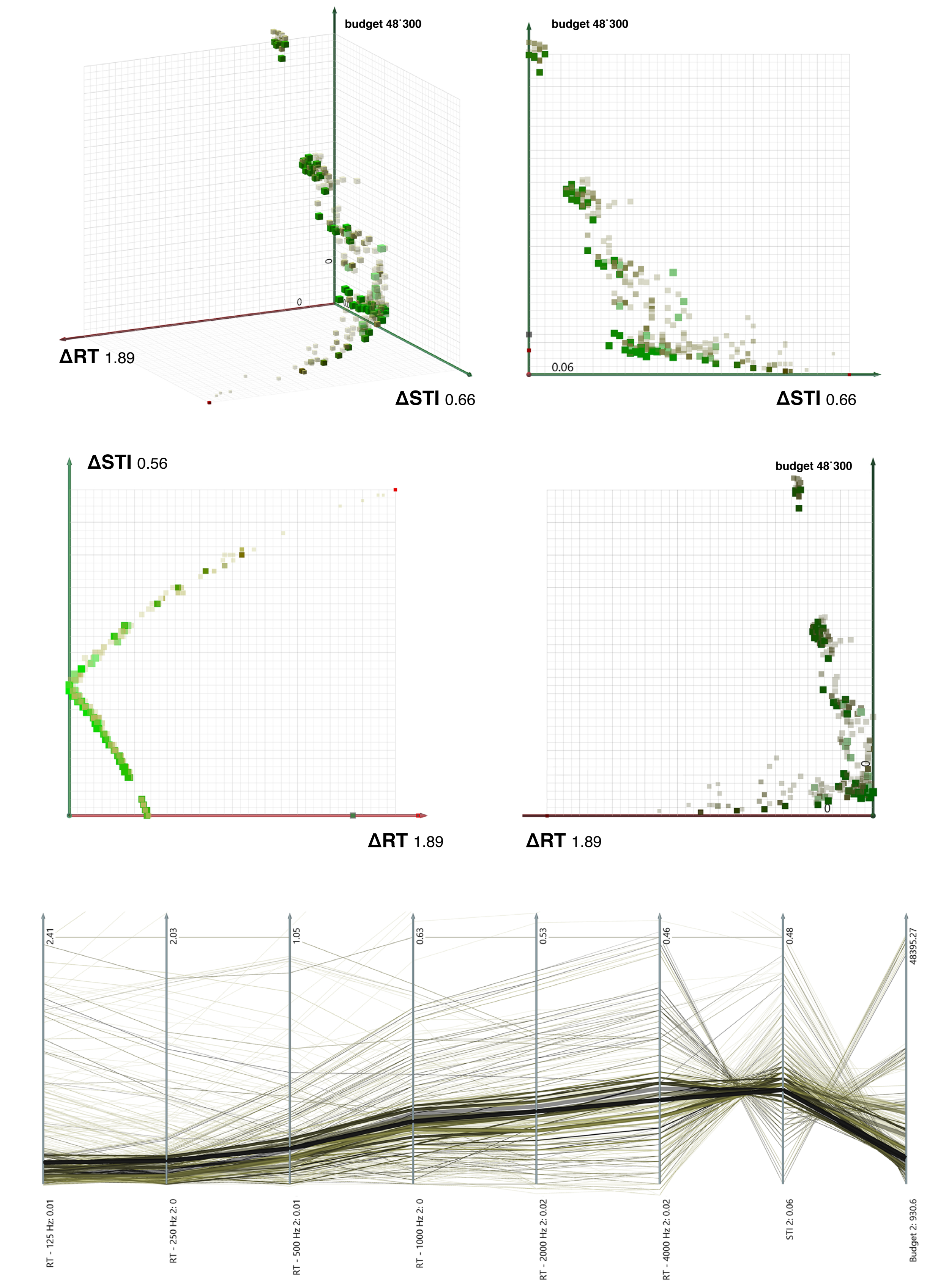


Figure A07. *2D and 3D views of Pareto-front optimization from Sabine model.*

APPENDIX D

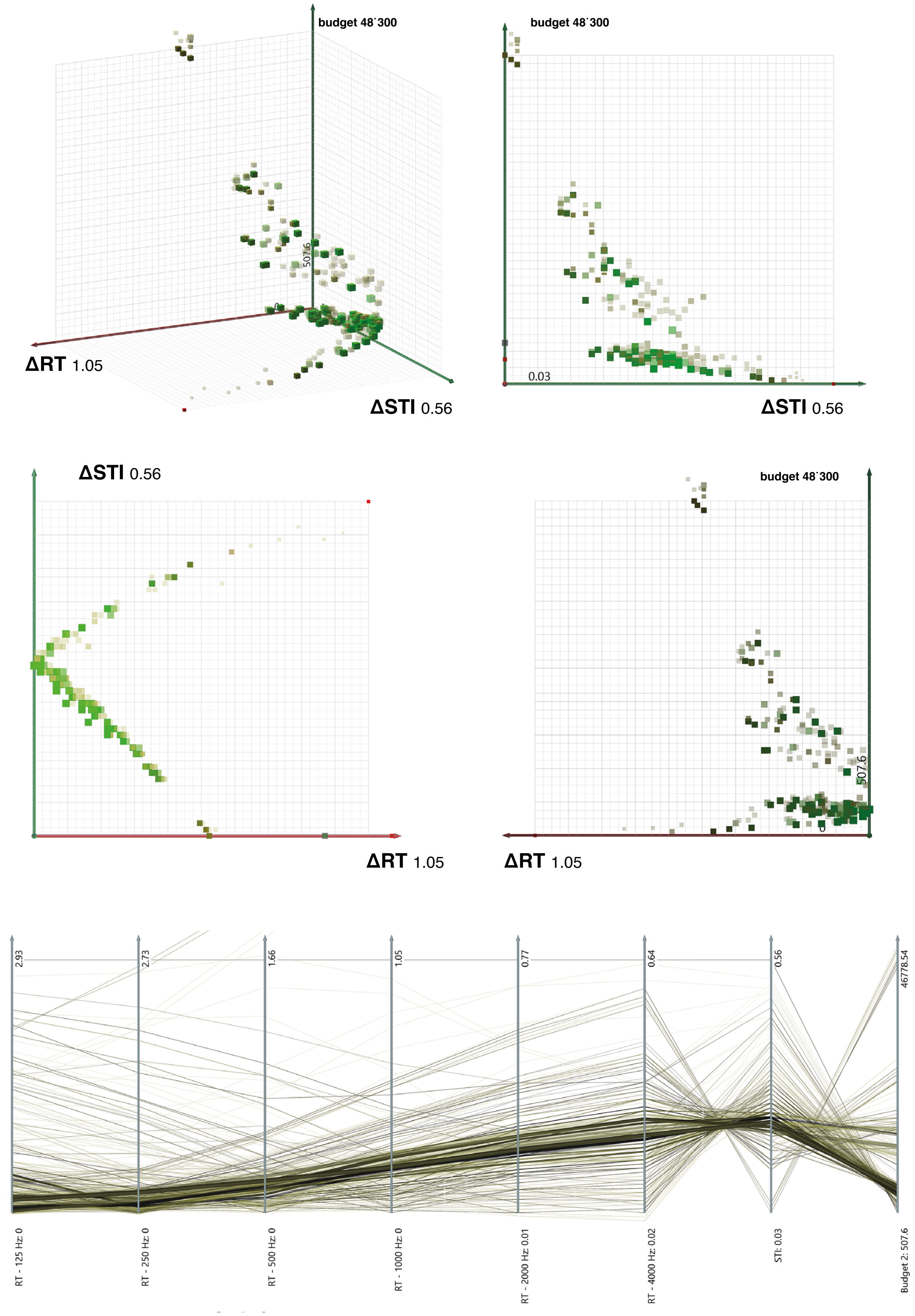


Figure A08. *2D and 3D views of Pareto-front optimization from Eyring with Barron&Lee mod el.*

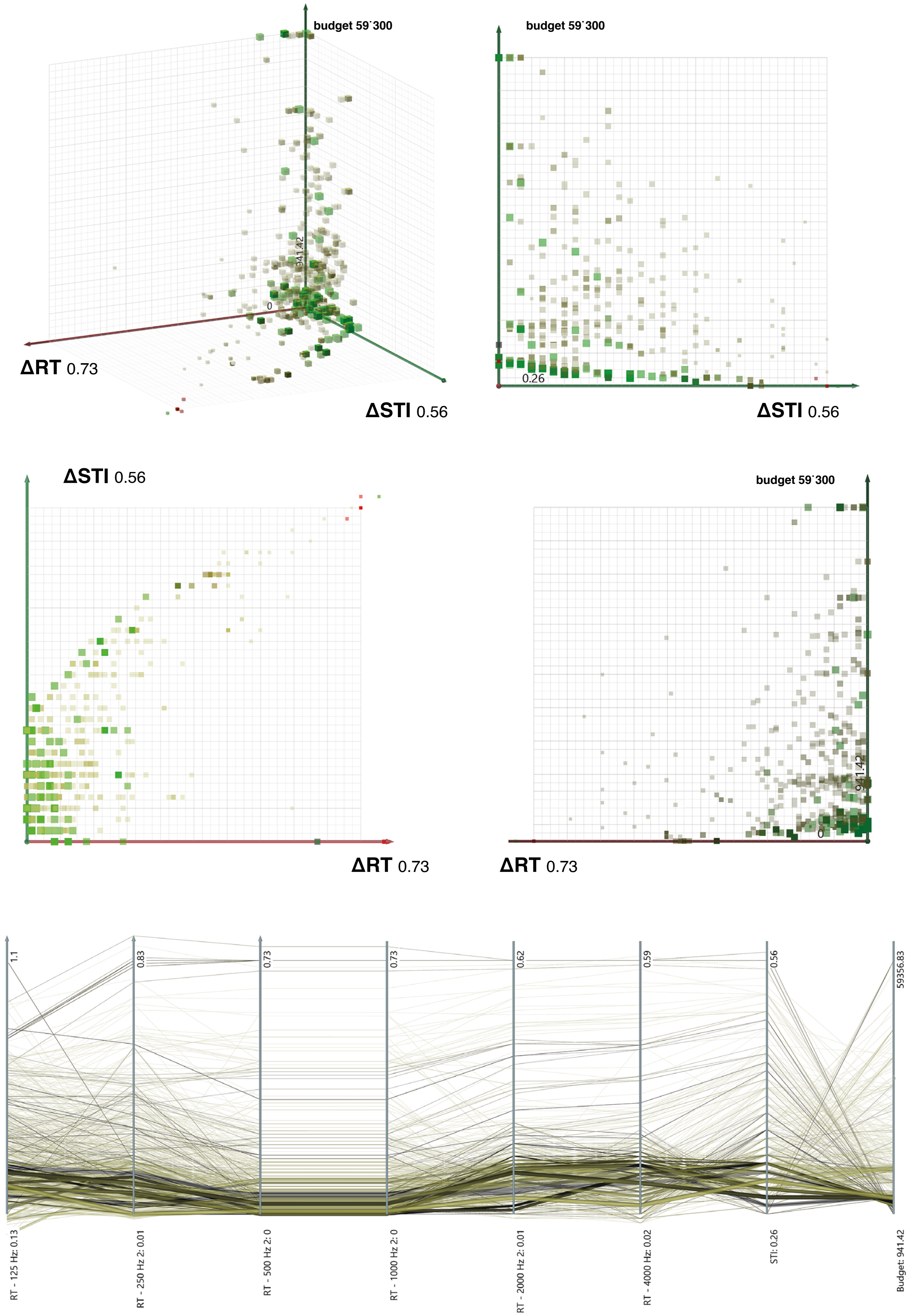


Figure A09. *2D and 3D views of Pareto-front optimization from Pachyderm model.*

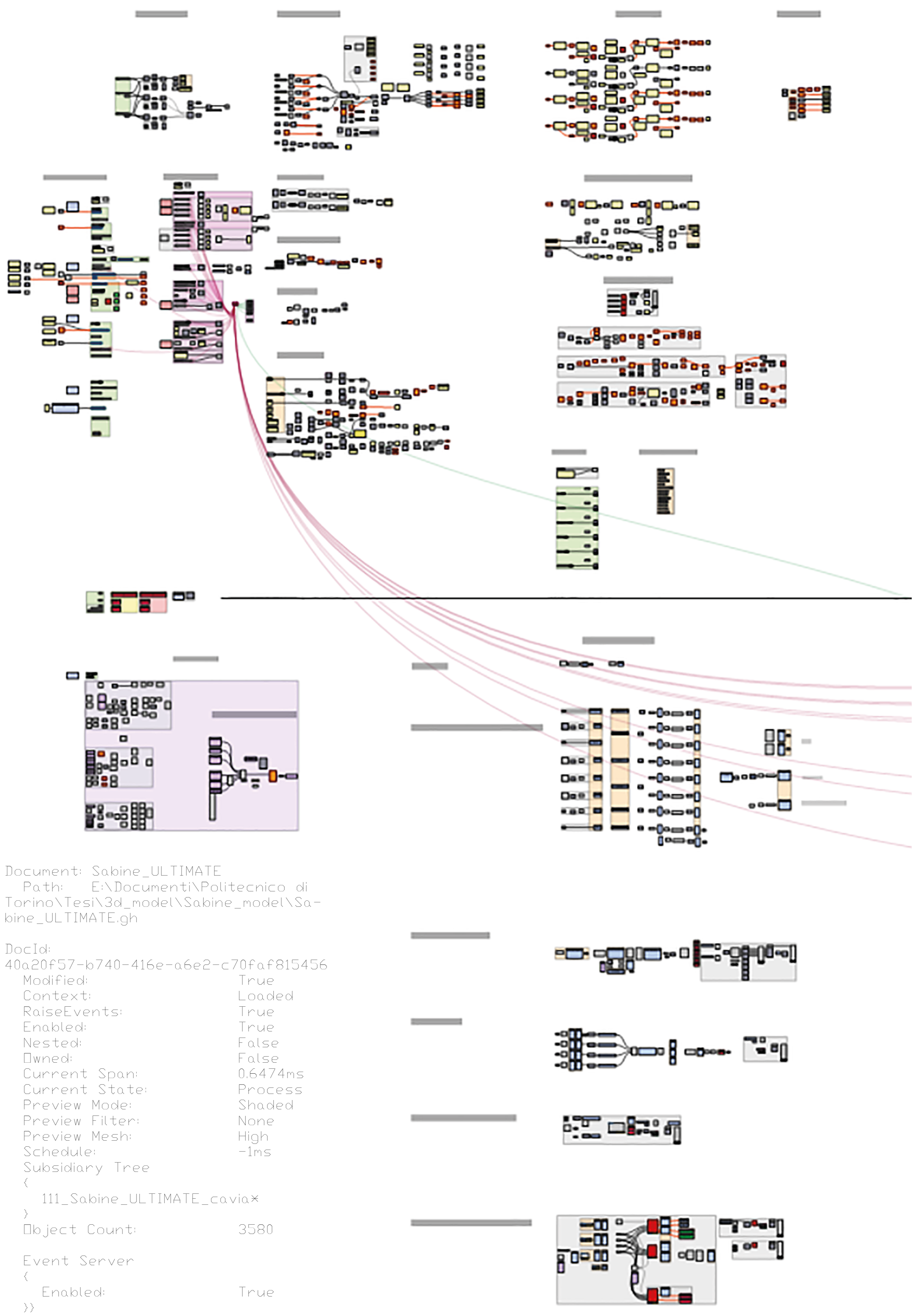


Figure I. *Overview of the algorithm on GH canvas: part 1.*

ALGORITHM ON GH CANVAS

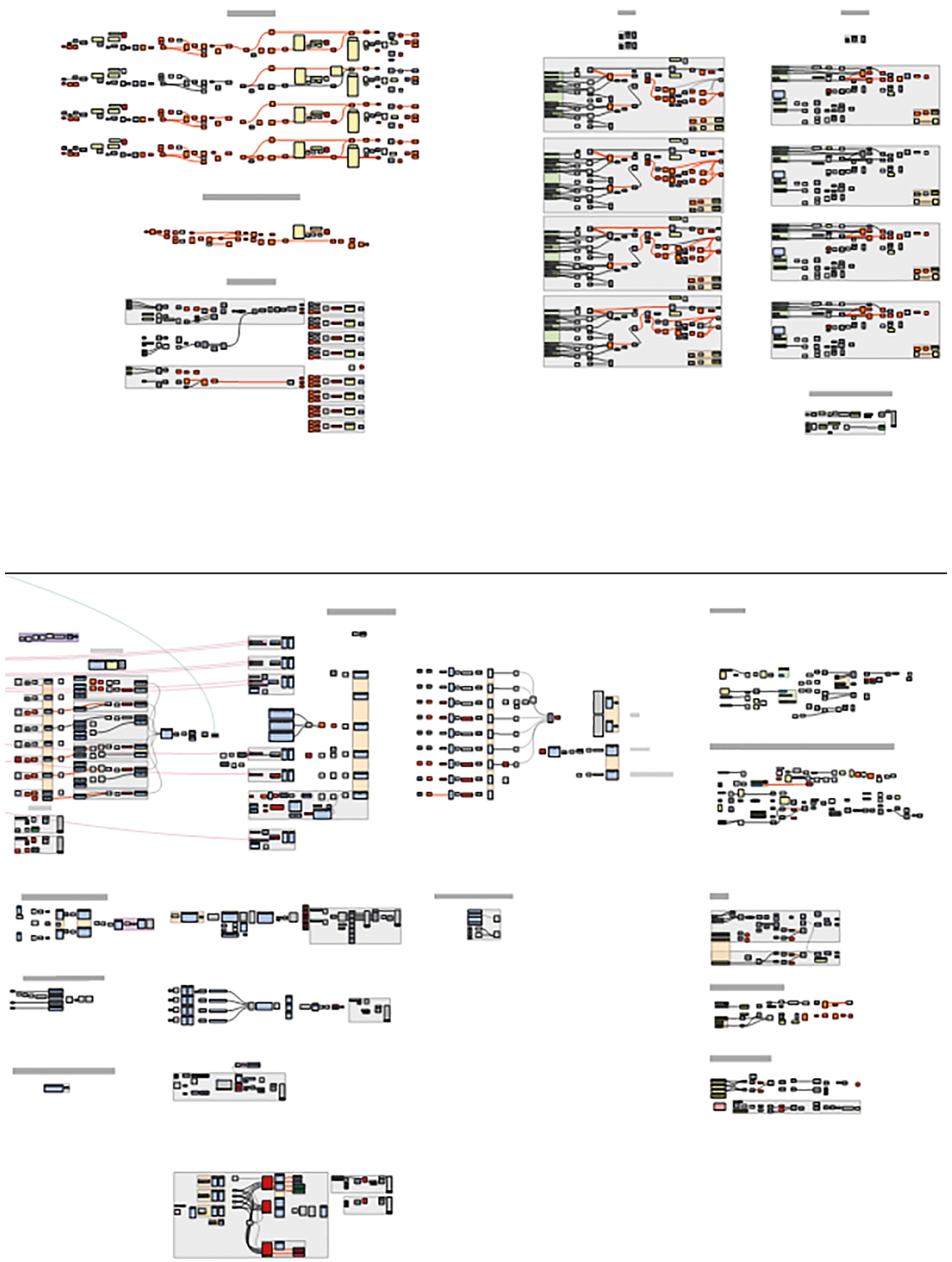


Figure II. *Overview of the algorithm on GH canvas: part 2.*

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