PERSONALISED CONTROL OF INDOOR ACOUSTICS

in middle schools

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M.Sc. Architecture, Urbanism, and Building Sciences
[Building Technology Track]

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Lastly, thank you, dear reader, for taking the time to peruse through the summary of my two years of education in the form of this thesis. I hope it is useful and that you benefit from the research.

Have a wonderful day!

With warm regards,
Meghana Raghunathan

ABSTRACT

Architecture is much more than just built forms on a piece of land. Architecture hinges on user experience and comfort. As such, it is up to us, as designers and engineers to be mindful of the quality of the conceptualised space.

Building physics is one such field that addresses the concerns of users. It outlines topics that play an integral role in the quality of life; thermal comfort, ventilation, lighting, and acoustics. The first three factors have something in common. They have evolved and been developed to the point where the user has the luxury of controlling this factors at a scale local to the user itself. This creates an enhanced user experience. Acoustics, on the other hand, poses numerous problems when the topic of personal control is broached. There are many factors that impact the quality of sound in a space. That is, there are simply too many variables one must take into account while addressing the topic of personalised control of sound in a room. Acoustic control systems, while existent, heavily hinge on the usage of technology to provide user control, resulting in bulky or expensive systems that makes this very concept of personalised control a distant reach to the average user.

Schools, particularly primary schools and middle schools pose an interesting challenge. In addition to the varying functions that happen in a classroom over the span of a day or a lesson plan, the users also have differing sound demands. Teachers' main concern is related to vocal strain and fatigue, while the poor acoustic conditions affect students' learning and social development.

While acoustic standards are largely enforced in the built environment during and post construction, it is imperative that we acknowledge that these standards are set for adults, by adults. They are values that make sense to a person with fully developed auditory and sensory systems. They are limited by the general function of a space and do not necessarily address the nuances of spatial usage. As a result, applying these standards as an unwavering rule to architectural typologies aimed at children might not be the most ideal approach. The still developing auditory and sensory systems of children, and the resulting requirements must be taken into account in spaces aimed at them.

This thesis aims to explore the possibilities that passive (dynamic) systems offer in the realm of acoustic and sound control set in the context of a middle school classroom. This process is done by theoretical calculations and digital simulations.

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1.1 Problem Statement

In the goals of achieving a comfortable indoor climate that affords the user control over it, one indoor environment factor, acoustics, remains underdeveloped in comparison to the others (heating, ventilation, and lighting). Noise can be understood as any sound unwanted by the listener. The definition represents a subjective understanding of noise that warrants some personal control over it. Furthermore, individual preferences for acoustic comfort vary widely, depending on a range of personal and environmental factors. Providing additional control over their environment could significantly impact learner satisfaction and productivity in the said space.

In the wake of the pandemic, COVID-19, the hybrid learning system has seen an increase in popularity. This approach requires learners to work across multiple platforms, including online and in-person classes, as well as shared workspaces with simultaneous requirements. Newer teaching methods result in students working in smaller groups, breaking out, and re-joining the class at various frequencies. The different learning systems require different acoustic interventions, tuned specifically for the then-occurring function. The existing infrastructure is ill-equipped to manage all the challenges posed by the evolving modes of learning and necessitates either a complete rework or strategic interventions.

The standards developed for schools are set based on the requirements of adults. This proves to be insufficient when one pauses to consider that children have still-developing auditory and sensory systems; they are more sensitive to certain noises and frequencies than adults. Poor acoustics has a long-term impact on children, affecting their memory retention, recall, language skills, and concentration in a classroom. Students require a steady acoustic environment that supports clarity of message and communication. In addition, mismanaged room acoustics of classrooms also result in an increase in stress and fatigue in teachers, with studies showing that they have a larger number of problems related to hearing and voice in comparison to the general population.

Acknowledgement and remediation of the acoustic challenges posed by classroom acoustics can only result in an enhanced productivity of learners, and an improvement in the physical and mental health of both students and teachers, thus resulting in an environment conducive to the required learning activities that foster the next generation of thinkers and doers.

1.2 Research Question

“How do the various teaching styles, and the acoustic requirements of a middle school learning environment influence the implementation of acoustic control systems?”

The following questions are used to elaborate and support the main research question.

Literature Research Questions:
1. What are the different teaching/learning styles in a middle school?
2. How often are the different teaching/learning styles employed?
3. What is the influence of room acoustics on a student’s/teacher’s comfort and performance/productivity?
4. To what extent can providing control over a student’s/teacher’s room acoustic environment improve their task performance?
5. What type of acoustic measures exist to support users in their hybrid working systems?

Practical Research Questions:
1. What are the key (acoustic) factors that play a vital role in evaluating acoustic comfort in (middle) schools?
2. To what extent can users have control over their acoustic environment?
3. To what extent does acoustic control affect the (perceived) acoustics in middle schools?

Evaluative Questions:
1. How affordable/accessible/user-friendly is the proposed acoustic (control) measure?
2. How does the proposed solution affect other indoor environment quality factors?

1.3 Objective

This research aims to look at existing technology and techniques for enhancing acoustic control, focusing on middle school classrooms. If the current technology is discovered to be insufficient, the research aims to develop a product that meets these needs. The established scope of the research demands a dual-pronged approach.

1. Literature Research
a. It requires constant reading and updating oneself on the on-going research, technology, and standards established.

Objective: establish gaps in existing research, understand the potential for future research and product development, and understand the existing standards for different indoor (learning) requirements. Establish prerequisites of a space.

2. Practical Research
The next is the regular testing of proposed methods qualitatively; it employs the use of simulation software to test proposed designs and ideas.

Objective: Understand user requirements, problems posed by the listener's environment, and understand the state of acoustics in a classroom.
Establish simulated evidence for the proposed solutions and their integrability at various scales. Also understand the impact of proposal on the other indoor environmental quality factors.

1.4 Scopes and Limitations

The research focuses on indoor building (room) acoustics. It will make use of the requirements of the space in terms of general building (installations, insulations, and impact) acoustics to establish prerequisites for the designed space for the proposed solution to be effective and appropriate in the applied context. The research assumes that the environmental acoustics are good and are up to the required standards. The research also relies on data and statistics from the Netherlands for determining the standard base classroom, and speaker/receiver heights.

It also aims to answer the question of its impact on other Indoor Environmental Quality [IEQ] factors, establish a system of spatial requirements in order for the product usage to be optimal, and also expects to analyse the psychoacoustics of the space in question.

1.5 Research Approach

The research methodology consists of 6 parts, starting with literature research, continued by the research phase, and ending with the analysis of the research results.

Part 1: Research Framework
The research topic is analysed an evaluated on its contribution to the field of Building Technology and its relevance in the field of building physics. It is also analysed based on its impact on users. The research topic is also broken down into sizeable parts to ensure proper addressal of the sub-parts. This is used to determine the starting point of the literature research, establish a proper framework of research, and create a time-line of the entire process.

Part 2: Literature Research and Framework
Every good investigation begins with the establishing of facts, and that is exactly what this step of the research focuses on. It seeks to answer the various sub-questions brought forth by the research question and create a basis from which the research intends to continue. This theoretical portion covers the reading and analysing of conference papers, various reports, standards, books, theses, and products that have a relevance to the chosen topic in either the same field of study or in allied fields. These topics include the following:

1. Acoustic factors that determine room acoustic conditions
2. Problems faced by school students and teachers in terms of acoustics.
3. Psycho-acoustical analysis
4. Standards from around the world for schools and educational systems as well as for distinct types of learning systems
5. Advances in different teaching styles employed in the education sector.
6. Accommodations required for individuals with impaired hearing or additional hearing requirements.

Since at this stage the exact end product of the research is unknown, the literature research phase casts a wide net into the possible realm of topics and solutions. They are as follows:

1. System development
2. Product development
3. Research – architectural typologies

Part 3: Qualitative & Quantitative Research
The qualitative step of the research develops on the established facts of the previous

step but can still be understood as part of the 'information collection' stage. It focuses on talking to industry professionals and quantitatively establishing a base comparison model for the testing of the design based on the data collected from the previous stages. It aims to put data to the emotional/psychological understanding of the studied space by means of digital simulation using CATT and Treble.

Part 4: Product Development
This stage takes all the data provided from the previous stages combined and puts it towards the development of a system that allows a user to control the application of the acoustic solution. It is developed and designed to address the unique needs of the indoor space under question.

Part 5: Product Testing
The developed product is constantly tested qualitatively and quantitatively using simulations carried out through an acoustic simulation software, either CATT or Treble.

Part 6: Results, Analyses, Conclusions
The last step of the research is to analyse the mountains of data accumulated by means of measurements and simulations. This data is visualised and interpreted, and conclusions are drawn based on it. This section also goes into depth about the limitations of the research and results, and potentials for further research/development are highlighted. It is the proverbial bow on the top of the research, here to tie everything up neatly.

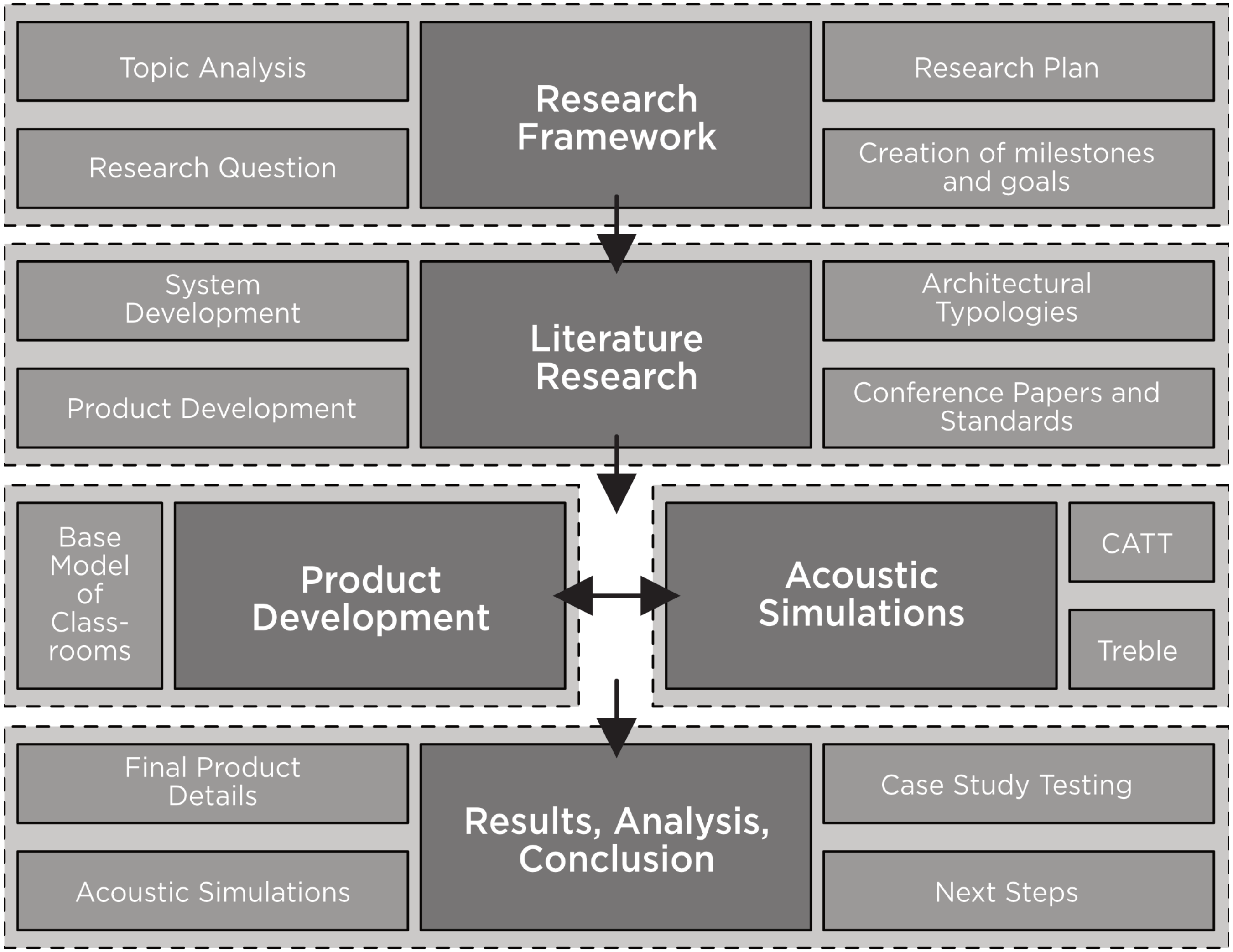


Image 1.1: Raghunathan, M. (2023). *Graphic showing research methodology* [graphic].

An obvious question to ask after reading this chapter is "why middle schools?" Rest assured, this typology has not been chosen lightly. It has come up after an extensive analysis into environments that would stand to benefit from adaptable indoor acoustics. The options considered are as depicted in the chart on the right. An elaboration is presented in the form of a literature research (See Chapter 3, Section 3.3, Parts 3.3.1 - 3.3.3).

Classrooms provide a unique challenge. Different types of education demand different approaches to teaching styles. These differences then require distinct approaches to acoustic treatment of a space. Now what happens when the same space uses different teaching styles over the span of one workday?

Children also pose a unique problem in the field of acoustics. Their on-going development means they are more susceptible to acoustic interferences. The standards set by adults for adults do not hold good for the younger age groups.

Literature studies revealed that the spaces that summarise these problems are mostly primary and middle schools. From here, discretion was used to choose middle schools as the subject of study due to the available data and prior studies into the subject albeit limited.

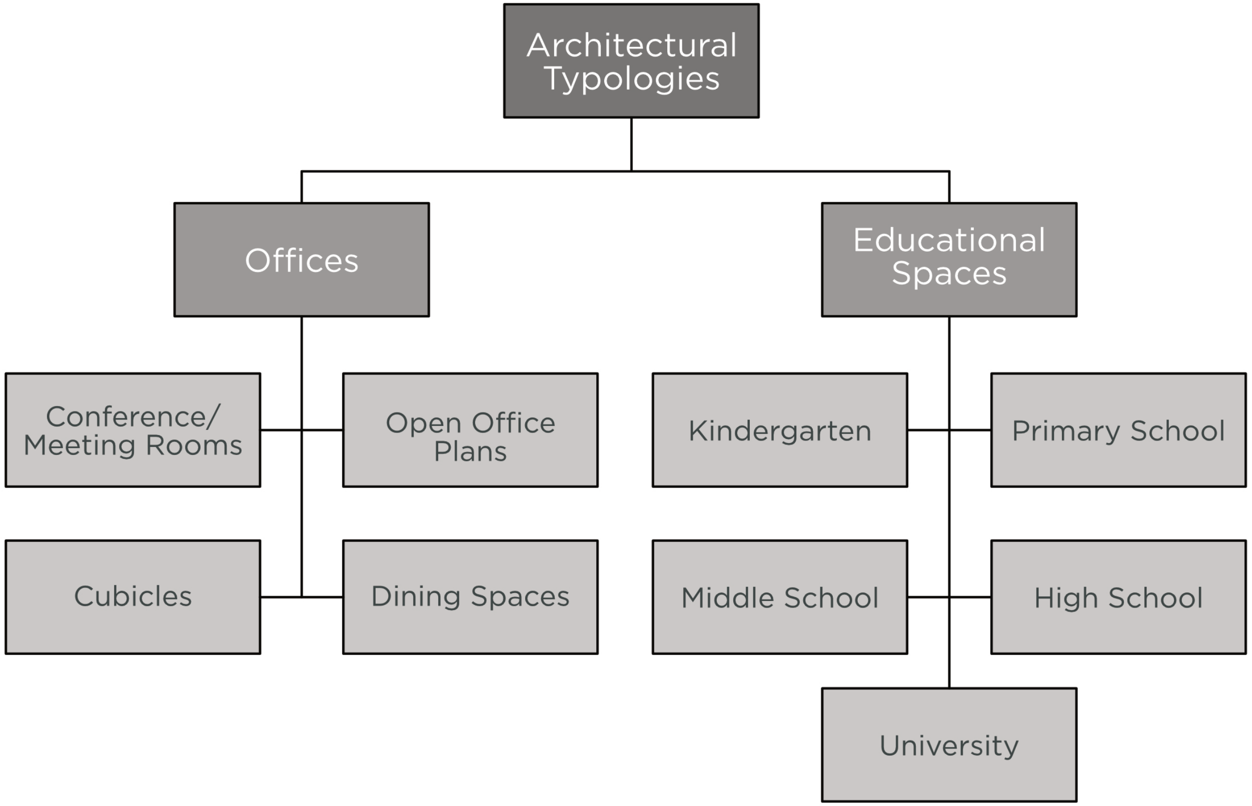


Image 1: Raghunathan, M. (2023). *Graphic showing architectural typologies* [graphic].

2.1 Acoustics and Acoustic Comfort: An Introduction

Acoustics is one of four indoor environment quality factors that helps determine the quality of a space.

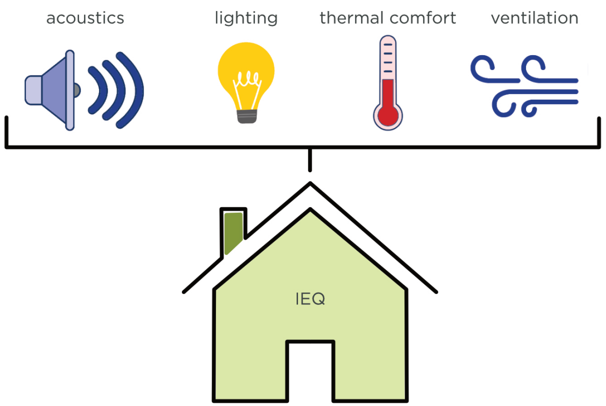


Image 2.1: Raghunathan, M. (2023). *Indoor Environmental Quality Factors* [graphic].

Acoustic comfort can be understood as the perceived state of well-being and satisfaction with the acoustical conditions of an environment. They are broadly affected by structure-borne impact noise, and airborne noise. Sound levels can have a physiological, and psychological effect on people *(Oseland et al., 2015)*.

The human ear can perceive a broad range in frequencies - between 20 Hz to 20kHz, with the speech frequencies ranging from 500 Hz to 5kHz *(Kryter, 1985 as cited in Navai & Veitch, 2003)*. Laird and Coyle, (1929) *(as cited in Navai & Veitch, 2003)* establishes that despite this large range of audible frequencies, annoyance and perceived discomfort increases with the increase in frequency, with the higher frequencies even having the capacity to have long term impact on a person's health. Raised sound levels (exposure to 85dB + for extended periods of time) can affect a person's biology, inducing stress, heart conditions, and affecting hearing in the long term. Physical effects are seen with continuous exposure to sound levels above 140 dB (typically unheard of in a typical office space). Psychological effects present themselves in user-specific ways; A steady, persistent sound could be annoying to some and comforting to others (such as the low hum of a HVAC system).

This chapter covers the definition of terms that the thesis primarily talks about. Other relevant (and secondary) terms that are discussed over the course of the literature research or the thesis itself are included in Appendix 02.

2.2 Reverberation Time, [RT]

It is the amount of time required for a sound [from a given source] to "fade away" or decay in a closed space. This is commonly studied as T-60 (the amount of time required for a 60dB decay). It is commonly calculated using Sabine's formula (as follows).

$$T = \frac{55.3V}{C_0 \,\bar{\propto}\, S} = \frac{V}{6A} \;(seconds)$$

where
T = reverberation time (s)
V = volume of the room (m^3)
C_0 = speed of sound in air (m/s)
$\bar{\alpha}$ = surface sound absorption coefficient
S = surface area (m^2)
A = total room absorption = $\sum S \,\bar{\propto}\, (sabins)$

2.3 Sound Pressure Level, [SPL]

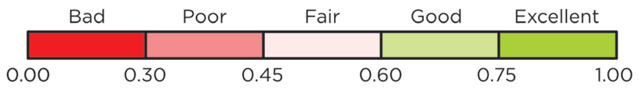
It can be defined as the pressure deviation from the ambient atmospheric pressure caused by a sound wave. It allows for an understanding of the intensity of sound in a given space. It can be calculated with the following formula (SFJ theory with Barron's correction).

$$L_p = Lw + 10\log\left(\frac{Q}{4\pi r^2} + \frac{4(1-\bar{\propto})^{\left(\frac{r}{mfp}\right)}}{A}\right)(dB)$$

where
L_p = sound pressure level (dB)
Q = directivity of sound
$\bar{\alpha}$ = surface sound absorption coefficient
r/mfp = Barron's correction (accounting for distance in the reverberation part of the sound field)
A = total room absorption = $\sum S \,\bar{\propto}\, (sabins)$

2.4 Sound Transmission Index, [STI]

It is a measure of the quality of speech in a given space. It ranges from 0 (bad) to 1 (excellent). This factor is dependent on speech sound level, reverberation time, background noise, frequencies of the sound, and the other psychoacoustic effects of sound.



2.5 Sound Strength, [G]

It is the ratio of the sound energy that comes from a non-directive source measured at a seat, relative to the same sound energy from the same source measured in a free field at 10m. To put it simply, it gives an indication as to the 'loudness' of a sound. This factor is inversely dependent on the amount of sound absorption in a room.

2.6 Signal-to-Noise Ratio, [SNR]

SNR compares the level of desired signal to the level of background noise (i.e., the ratio of signal power to noise power) given in decibels.

2.7 Speech Clarity, [C_{50}]

Comparison of sound energy in early sound reflections (within 50ms) with later reflections (after 50ms) for speech.

2.8 Percentage of Articulation Loss of Consonants, [%ALCons]

This factor calculated the articulation loss of consonants as a percentage. It is an indication of the loss of speech intelligibility (henceforth also referred to as SI) that is brought about by a poor acoustic environment. A value of 0% means an error-free transmission (no lost consonants).

$$\%AL_{\text{cons}} = 0.73 * \frac{T}{r_g{}^2/r^2}\ (\%) \quad \text{for } r \leq 3.5\, r_g$$

$$\%AL_{\text{cons}} \approx 9T\ (\%) \quad \text{for } r > 3.5\, r_g$$

where
T = reverberation time (s)
r_g = reverberation radius (m)
r = distance between speaker and listener (m) (Cauberg, 2013)

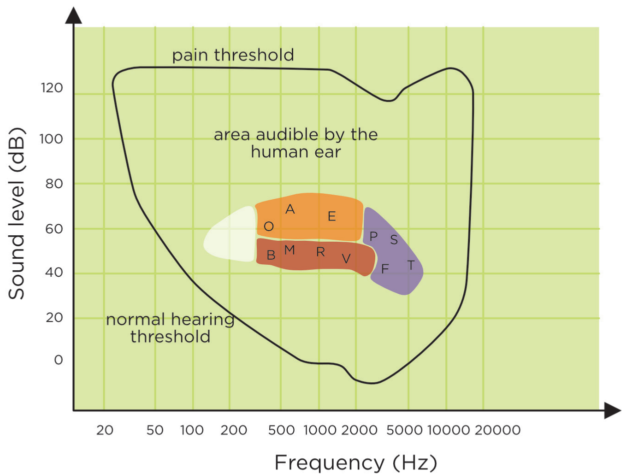


Image 2.2: Ecophon (n.d.) redrawn by Raghunathan, M. *Sound level vs. Frequency* [graphic]. https://www.ecophon.com/en/about-ecophon/acoustic-knowledge/basic-acoustics/

2.9 Transition Frequency

a.k.a. Schroeder frequency

The sound frequency zone which ranges from 100 to 200 Hz that is the crossover zone in which room resonances dominate until wavelengths adjust to the size of the room, i.e., the frequency at which rooms go from being resonators to being reflectors/diffusers.

It is given by:

f = 2000 * sqrt. (T/V) (Hz)

where
f is the transition frequency (Hz),
T is the reverberation time (s) and
V is the volume of the room (cu. m.)

"Despite huge advances in almost every area of architecture and interior design ... sound and acoustics, for the most part, have remained secondary concerns. They are possibly the two most pressing issues in architecture today,"

- Julian Treasure (2012) *(as cited in Oseland et al., 2015).*

To understand all the topics listed previously (Chapter 1, Section 1.5, Part 2), the following search terms were used to cast a wide net into relevant sources such as Google Scholar, Research Gate, Elsevier, Science Direct, and TU Delft Repository.

1. Offices
(Acoustics OR sound OR noise) AND (office OR work OR workplace)
(acoustics OR sound OR noise) AND (open plan OR OOP)

2. Schools
(acoustics OR sound OR noise) AND (class OR school OR classrooms OR students)

3. Acoustics
(acoustics OR sound OR noise) AND (personal control OR control OR systems)

The research first started with an open-ended question, "to what extent can a user control their indoor acoustic atmosphere?" To answer this, both, offices, and schools were taken into consideration and narrowed down in the due course of the literature review (you may have already seen a summary in the Author's Note 01). It is also important to note that of the 40 papers referred in the due process of this master thesis, some are covered in the chapter "Literature Review" and some are referred to in the chapters that have the most need and relevance for the information.

What is noise?
Noise, simply put is any undesirable auditory signal. Noise perception starts with the receiving of sound waves by the ear drum. It is converted into understandable signals by the human brain and is processed as audio, applying meaning to it. This makes sound a subjective experience. If the interpreted waves are found to be desirable, it can enhance the quality and productivity of work. If not, it can take away just as much from the aforementioned factors *(Oseland et al., 2015)*. This psychophysical aspect of noise increases the difficulty in adding control to it.

Do we really need personalised control?
There is an increased satisfaction with the office environment when occupants are given control over their behaviour and interactions in the workplace with both, their peers, and their environment in terms of IEQ factors *(Harvie-Clark & Hinton, 2021)*.

3.1 Offices

Offices present a unique challenge. The function demands synergies across multiple functions and work. This section will go in depth into the challenges posed by offices, the impact it has on people and the suggested solutions.

3.1.1. Sources of Noise

The modern approach to office spaces is treating it as a collaborative space (think open office plans with flex work spaces). There is also the traditional approach - usage of fixed places, fixed work schedules and rigid planning. Each typology comes with its own challenges. For example, employees working in open office environment experience more speech/acoustic problems as compared to an employee in a traditional office layout. In open plan offices [OOP], situations where sound levels exceed 45dB(A) result in lower acoustic satisfaction levels *(Bradley, 2003)*.

In order to understand the demands of an office space, it is broken down into four parts:

1. Individual work (task-based) – minimal collaboration. This could however include the need to make regular calls or attend online meetings/seminars.
2. Collaborative work (group tasks) – meetings
3. Communicative work - telephones, video conferencing
4. Relaxation – breaks for food, physical and mental well-being

Each task has separate standards for acoustic intervention. The demands, however, are not only dictated by task performed, but also the type of construction the user is surrounded by.

Green office buildings (LEED specific) also report a poor acoustic quality. Natural ventilation systems reduce the background levels to such an extent that there is a visible impact on speech privacy leading to a required intervention of engineered noise-control systems. Natural ventilation systems also mean that there is poor sound insulation from the exterior when the windows are open resulting in higher background noise levels for that period. There is also inadequate placement of sound absorption panels due to thermal ceiling slabs which need to remain unobstructed. This problem is further heightened by the fact that there are not enough standards and measures set in place by the LEED rating system to sufficiently assess the acoustic conditions of the building during and post construction *(Hodgson, 2011)*.

3.2.1. Noise, People, and Disturbance

First, can we use noise annoyance and noise disturbance interchangeably?
Kjellberg et al. (1996) suggests that noise annoyance and disturbance are not interchangeable terms to talk about annoyance with acoustic conditions, i.e. annoyance is one of the several consequences of being disturbed. However, both are prominent factors in the self-evaluation of reaction to an (acoustic) environment.

To quote Jones (2014) *(cited in Oseland et al., 2015)*, “Distraction is the price we pay for being able to focus on an event of interest while also gleaning some information from other sources of information...we can quickly move to new or potentially significant events – but it does mean that extraneous events of no significance can ‘capture’ attention. Distraction from sound is particularly pervasive because we are obliged to process sound – whether we want to or not.” In short, what Jones is trying to say is that no matter how pervasive a sound is, if the perception of it is negative, it has a direct impact on our ability to focus.

However, since we have already established that noise is subjective, personal experience must also be taken into account while talking about disturbance by noise. The German Standard VDI 2569 also states that while only 30-40% of the annoyance of sound is due to technical reasons, the remaining can be attributed to psychosocial aspects of acoustics such as

1. Noise control/handling,
2. Attitude towards the source,
3. Predictability of the event,
4. Activity profile of the listener,
5. Other IEQ factors, and
6. The individual’s noise sensitivity and tolerance

It is also important to note that older research (circa 1940s and 1970s) as well as Oseland et al. (2015) supports the idea that not all ambient sound levels cause annoyance but rather intermittent peak noises that fluctuate above the average levels with a lack of predictability *(Hay & Kemp,1972; Keighly, 1970; Kjellberg & Landstrom, 1944 cited in Oseland et al., 2015)*.

Broadbent (1979) *(cited in Oseland et al., 2015)* provides us with a further understanding of the relationship between people, noise, and disturbance (Image 3.1).

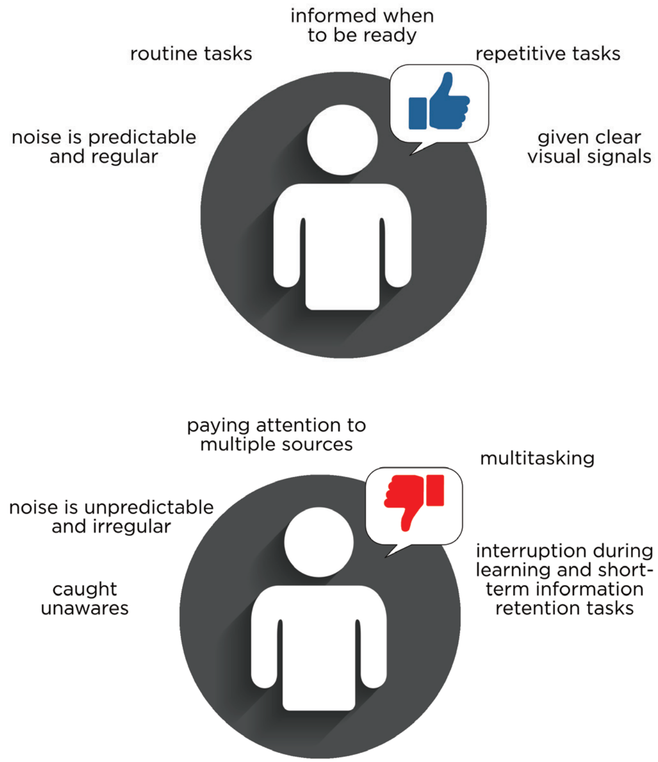


Image 3.1: Raghunathan, M. (2023). *Person’s response to external noise* [graphic].

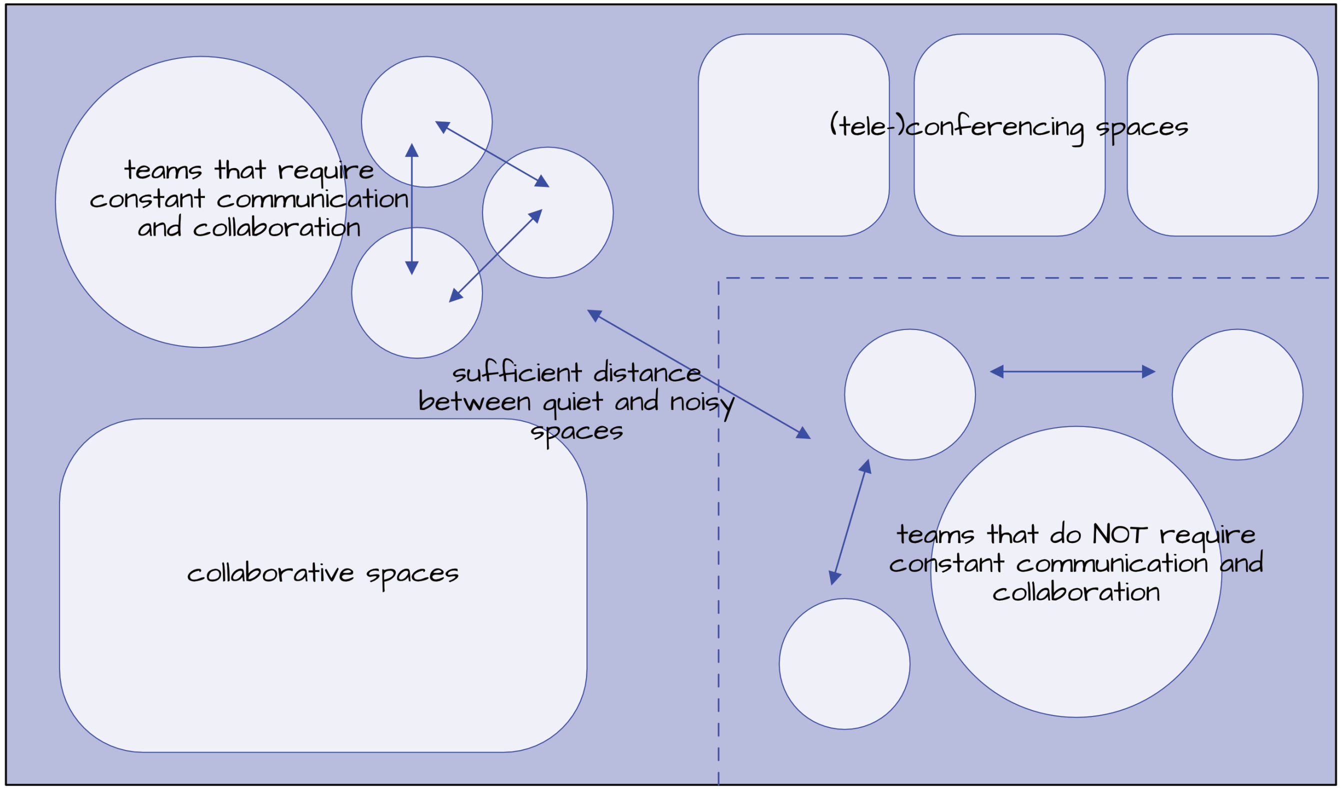
Matthews et al (2013) *(as cited in Oseland et al., 2015)* also says “The study of noise effect on performance is deceptively difficult; noise can affect the efficiency of task performance, usually for the worse but occasionally for the better...Individuals may not find a particular noise level annoying, but their task performance may nevertheless be impaired. Conversely, they may find a particular noise level extremely annoying and yet their task performance may be unaffected.”

This establishes that distraction is a factor unrelated to sound level but remains related to individual sound events themselves.

3.1.3. Noise Acceptance, Planning, and Architecture
Oseland et al., (2015) connects noise acceptance to the social expectations of the space (e.g.: silence is expected in a church but is uncharacteristic at the weekly farmer's market) - "The solution to noise distraction is as much to do with the management of the space and guidance on behaviour as it is about the design and acoustic properties". The report suggests the following 4-step process to designing people-centric acoustic solutions.

1. D – Displace
Use of spatial planning to locate quiet and conversation areas. It suggests using visual cues and suggestive designs to indicate the use of the space.

2. A – Avoid
Avoid sources of noise distraction (speakers, lack of private space for video conferencing).



Refer to the previous step for spatial planning of teams that need communications versus the teams that do not.

3. R – Reduce
Reduce the noise distraction by strategizing density and sizing of desks. Usage of good acoustical interventions to limit noise interference and infiltration.

4. E – Educate
Enforce policies and introduce office etiquettes to reinforce understanding and consideration towards colleagues. Explain the interventions from the previous steps and outline what is required of the employees.

The next step is to treat the rooms themselves, according to the designed function. Acoustic treatment of a room is subject to its placement and function *(NEN-ISO 22955, 2021)*.

1. Ceilings – as absorptive as possible (high weighted absorption coefficient) with a preferred full coverage of the ceiling.
2. Walls – absorbers placed strategically and at the height of a seated person's ears to limit reflections to workstations (especially in room corners), and to reduce the flutter effect.
3. Floors – limited absorption performance. Can be used for broad band absorption and to reduce impact noise.
4. Furnitures – placed to provide as much distance between workstations as possi-

Image 3.2: Raghunathan, M. (2023). *Suggested Zoning in Offices to Reduce Noise* [graphic].

ble (unless the space is designed for collaborative work). Includes the usage of dividers for sound attenuation between workspaces.

3.1.4 Additional Considerations
Hongisto et al. (2008) talks about introducing a model that co-relates the decrease in work performance as a function of STI. It (STI) serves as a connection between environmental psychology and acoustic design (although task demands, habituation and loudness of speech is unaccounted for).

The paper the inverse proportionality of STI with increase in room absorption, masking sound levels, and screen heights. It promotes the intervention of acoustic design (while emphasising the need for other physical interventions such as call booths and designated workspaces for meetings and such).

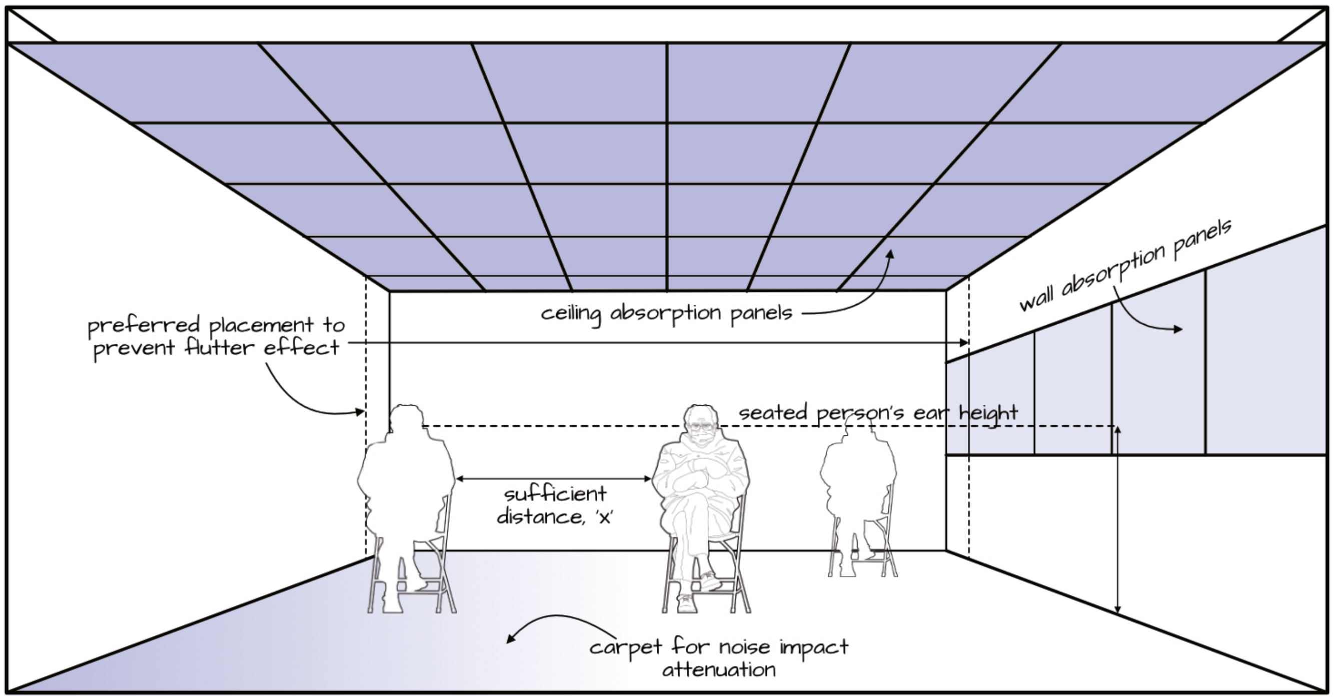


Image 3.3: Raghunathan, M. (2023). *Suggested Placement of Acoustic Absorbers/Reflectors in an office* [graphic].

3.2 Schools

The acoustic design for schools for a long time has been evaluated against the standards set for adults. This approach disregards the requirements of a still-developing child with an underdeveloped auditory system. There is a strong relationship between poor classroom acoustics and reduced scholastic achievements *(Sutherland & Lubman, n.d.)*. Poorly treated classrooms result in an increase in working noise of the space as a result of the Lombard effect, and consequentially cause an increase in fatigue and stress for students and teachers alike *(Tiesler et al., 2015b)*.

The last decade has seen an increase in modern learning environments in the form of technology based learning and open plan learning spaces. While there are many advantages to both, they also bring with them problems related to noise and acoustics. The progressive changes are directing classrooms away from a didactic teaching and towards a student/child centric learning. The furniture in classrooms also reflect this shift, with informal seating and arrangements being preferred over the usual grid pattern of desks facing a central speaker *(Donn et al., 2015)*.

This literature review considers only the educational teaching spaces and avoids a study into spaces affiliated with large congregations such as assembly halls and auditoriums, and music rooms.

3.2.1. Sources of Noise in Schools & Impact
Noise sources commonly present in a classroom are as follows (and illustrated in Image 3.4):

1. Noise from the environment
   (traffic, airplanes, playgrounds). Long term exposure to aircraft noise can impair students' attention and behaviour. Traffic noises interfere with learning efficiency, memory and recall (Liu et al., 2023).

2. Installations *(HVAC, lights, machinery)*

3. Noise from adjacent spaces
   (classrooms, corridors, movement)

4. Conversations inside the classroom
   (babble, discussions)

5. Technology
   (computers, projectors, smart screens, printers, keyboards)(Madbouly et al., 2016b)

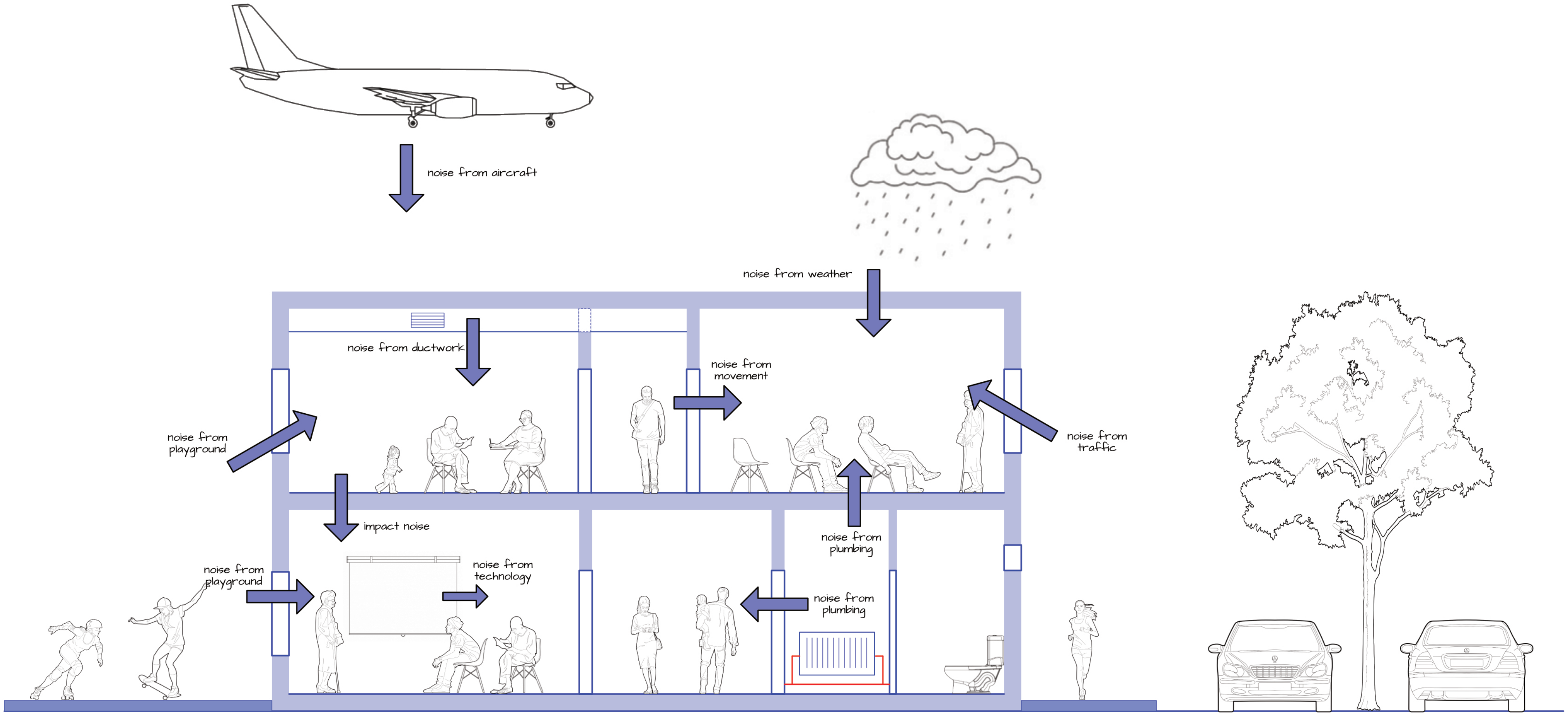


Image 3.4: Raghunathan, M. (2023). *Sources of Noise in a School* [graphic].

Other problems are also caused by over/under reverberant classrooms *(James & Canning, 2010)*. Bradley and Sato (2008) show that student activity is the dominant noise source during teaching activities. They have been shown to increase their noise level by 0.22dB in the presence of competing noise *(Donn et al. (2015) as cited in Whitlock and Dodd (2008))*, increasing the average noise levels by values up to 10dB.

3.2.2. Teaching Styles and Acoustic Requirements

Canning et al. (2015) talks about the various requirements expected of a student in a standard learning day. The listening demands are as follows: Listening to/when

1. The teacher when they are facing away
2. The class is engaged in activities
3. The teacher is moving around
4. Other students answering questions
5. Others are talking in the same room
6. Peers when working in groups
7. There is noise from installations/equipments

They can be summarised as hearing demands that occur in the following teaching styles.

1. Didactic learning (teacher centred)
2. Group learning (peer-to-peer)
3. Technology centred
4. Individual learning

Didactic learning (teacher centred)

This is the most popular teaching style present. One speaker, the teacher, addresses a collective group of students at once. The children are expected to direct all their listening efforts towards their teacher.

Speech intelligibility is a factor that is dependent on distance from the speaker. This means that the students seated furthest away from the teacher experience the most strain in listening. Sound amplification systems can be beneficial in ensuring that students seated furthest away from the teacher also receive the same level of education as their peers seated closer. However, it performs poorly in open plan spaces *(Mealings et al., 2014)*.

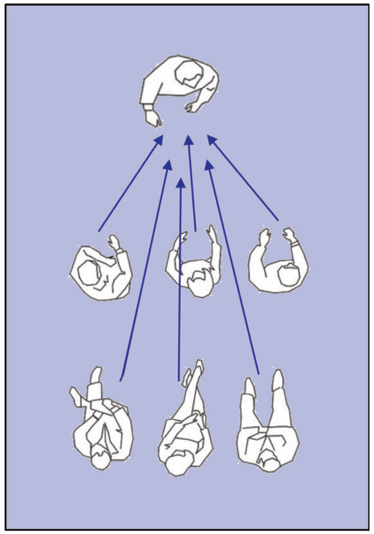


Image 3.5: Raghunathan, M. (2023). *Teaching Style - Teacher Centred, Showing Direction of Attention* [graphic].

Group Based Learning

The NZCRG found that the most popular classroom activity is group work (38% of classroom activities in New Zealand schools). This activity demands a more complex focus; students need to be able to hear their group partners without being disturbed by the work of other groups. This leads to the occurrence of both, the cafe effect and the Lombard effect. The space needs to ensure sufficient speech intelligibility during plenary sessions and should control the Lombard effect during break-out sessions.

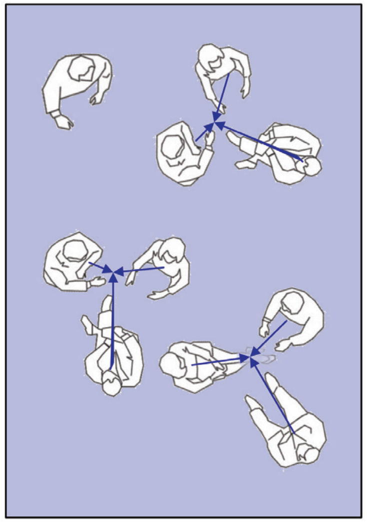


Image 3.6: Raghunathan, M. (2023). *Teaching Style - Group Learning, Showing Direction of Attention* [graphic].

Technology Based Learning

The integration of technology into education has seen a spurge in popularity with increase in technological developments. New teaching methods utilise multimedia learning systems. This comes with challenges of its own. The clarity of voice from a TV lies in the (boost of) mid-frequencies [roughly from 2kHz - 6kHz] or in the (cut of) bass frequencies [300Hz - 800Hz] *(Brant, 2023)*. Thus, depending on the type of activity being carried out, the focus on the required frequencies also change.

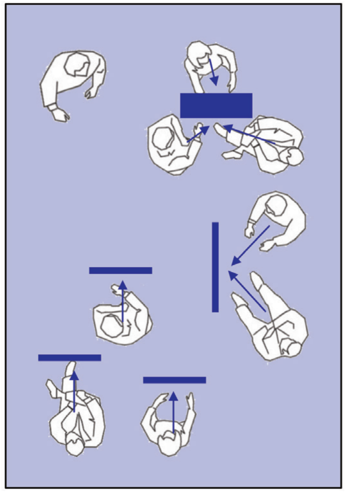


Image 3.7: Raghunathan, M. (2023). *Teaching Style - Technology Based Learning, Showing Direction of Attention* [graphic].

3.2.3. Impact of Poor Acoustics on Teachers

Vocal effort is a key indicator in the quality of the acoustic environment of a space. It talks about the impact of the acoustical environment on the speaker (in this case, the teacher) in terms of strain on the vocal chords.

The NZCRG discovered that 80% of teachers experience vocal fatigue when compared against 5% of the general population (Sapienza et al. as cited in Whitlock & Dodd, 2008). In a study conducted among 487 teachers across 22 schools in Sweden, it was found that 13% of teachers suffered from voice problems as a direct consequence of their line of work *(V. Lyberg-A hlander, R. Rydell, A. Löfqvist as cited in Garcia et al., 2014)*.

Bradley and Sato (2008) support the results of the research, showing that teachers must actively increase their vocal effort to reach their students effectively, often corresponding to levels louder raised voice levels. With a reduction in student-activity noise, teachers are expected to experience a higher work satisfaction with clear benefits to their physical and mental health conditions *(Garcia et al., 2014)*.

3.2.4. Impact of Poor Acoustics on Students

Children show greater sensitivity to acoustic disruptions which can be attributed to age-related developmental demands (Iglehart, n.d.). In a study conducted by Klatte and Hellbruck (2010) *(as cited in Donn et al. (2015))*, it was shown that more reverberant classrooms resulted in students performing poorly in phonological processing tasks while also experiencing inconvenience related to noise. This also impacted their relationship negatively with their mentors and peers as compared to students from a less reverberant room.

Mealings et al. (2014) over the course of their research establishes that students seated towards the back of an open plan classroom experiences an STI of 0.3 as compared to a value of 0.7 for the students seated at the front. They use this data to reiterate the fact that open plan classrooms perform poorly in terms of acoustic comfort for both teachers and students due to their intrusive noise levels.

Liu et al. (2023) shows a direct co-relation between increase in SPL and the decrease in the learning efficiency of the students in the classroom. This relationship remains non-linear with the decreasing trend being more prominent when the environmental sound exceeds 50dB. Tiesler et al. (2015) also correlates increasing SPL with fatigue, concentration loss, and an increase in “dysfunctional” activities such as heckling and crying.

3.2.5. Redefining Standards for Children

The standards created for various constructions is set for adults by adults. This approach to acoustic solutions does not hold good when we take into consideration the function of schools. Children spend a minimum of 7-8 hours everyday in this institution. This requires a special attention to the requirements of their still-developing auditory systems.

Speech integration time refers to the point in time after which speech signal reflections no longer add to the direct signal and become a hindrance the later they arrive. This can be understood using factors such as C_{50}. The speech integration time in 7–9-year-olds is much smaller in comparison to an adult. Whitlock and Dodd (2008) measure the integration time of speech for adults and children and suggests that the useful early reflections are under 35ms for children rather than the suggested 50ms for adults. This requires a room with even lower RT than expected since it will have lesser unwanted sound energy (sound outside the integration time).

They also establish the difference in the Lombard reflex in children and adults; children are affected by masking noise above 15 dB(A) (Lombard coefficient of 0.19dB/dB) while adults are affected by levels above 4 dB(A) (Lombard coefficient of 0.13 dB/dB). A low RT inadvertently also helps suppress the cafe effect occurring due to children interacting in a classroom.

3.2.6. Suggestions for Designing Classrooms
Madbouly et al. (2016b) establishes certain pre-requisites for classroom zoning such as locating the class far away from the noise sources mentioned in the previous section. Proper zoning and planning can drastically affect the impact of environmental noise from the get-go. HVAC systems should be placed away from learning spaces with the ductwork being lined with sound absorbent material.

Once zoning is taken care of, the classroom geometry can be worked upon. J. Singer (2003) advices on the limitation of classroom height to 9 feet [2.7 m] in height. Rooms with one dimension significantly greater than the other and rooms with uneven sound absorption tend to result in spaces with a non-uniform sound field that is heavily dependent on source and receiver locations *(Canning et al., 2015)*. The publication also suggests limiting the room depth to 8.5m to reduce the late reflections from the rear wall. If in case this is exceeded, the rear wall would require acoustic interventions as well – either absorption or diffusion. A suggestion is also made to tilt windows in such a way that reflections are directed away from speakers and listeners.

Classrooms can be classified as ‘dry’ acoustic spaces and should be treated as such; the RT should be short, clarity of speech must be good, and should supported by sufficient loudness and speech intelligibility.

The ceilings and walls should be lined with acoustic materials strategically, preferably in the room corners, and staggered on opposite walls, ceilings should allow for reflectors in the centre of the room to enhance early reflections. Ambient noise levels need to be the first target while working on improving the SNR in classrooms *(Bradley, 2003, supported by Donn et al., 2015)*.

Addition of diffusers to surfaces of a classroom enhances the C50 value to achieve a higher clarity and are also useful in enhancing the early arriving reflection energy (G50) value for distant seats, helping in creating a more uniform acoustic condition across the room. Diffusers be placed on the ceiling, lower front/side wall, and absorptive materials on the lower front wall *(Choi, 2015)*.

Whitlock and Dodd (2008) suggests the careful placement of sound reflectors/absorbers based on the teaching style in use.
1. For group work, there is an expectation of being able to hear your fellow group mates, and thus the workspace demands the usage of reflectors above it.

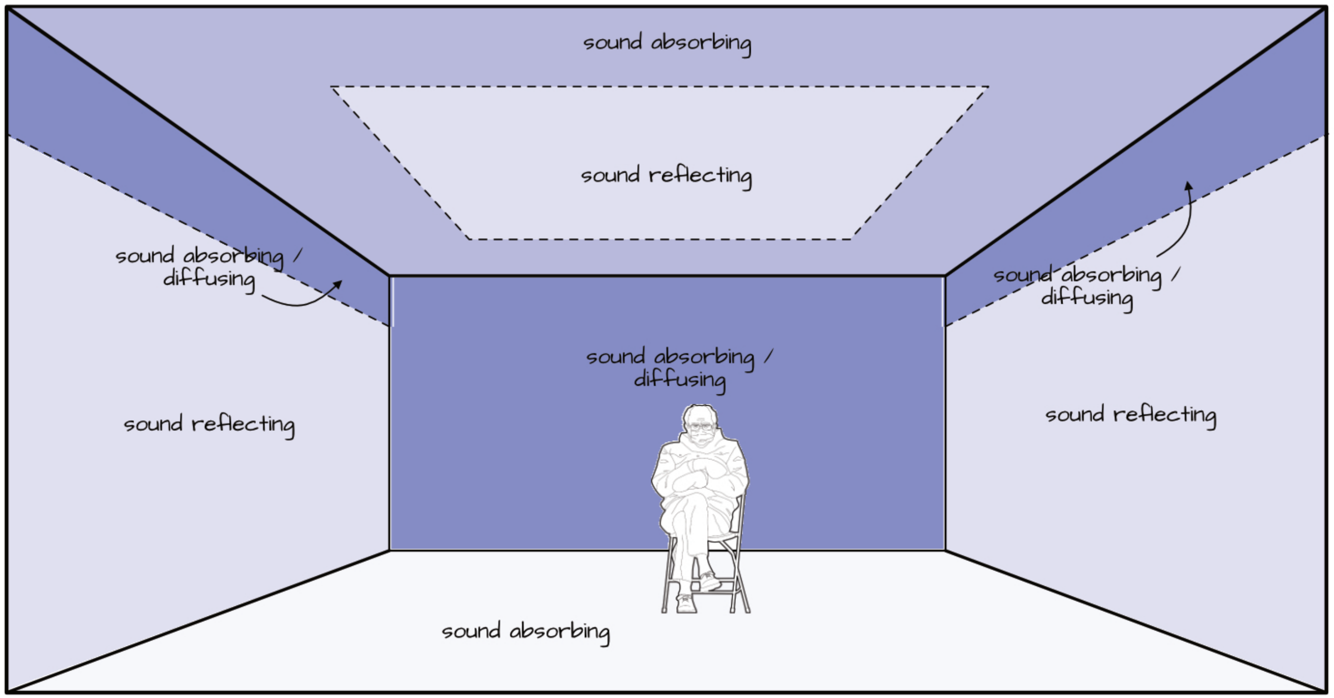


Image 3.8: Raghunathan, M. (2023). *Suggested Placement of Acoustic Absorbers/Reflectors in a Classroom* [graphic].

2. For a teacher-centric class, late arriving sound needs to be dampened by means of sound absorbing panels on the rear wall. Additionally, J. Singer (2003) suggests placing angled panels behind the source to enhance speech clarity during lessons.
3. Liu et al. (2023) proves that for individual tasks, a higher RT is preferred to mask the background speech, making it unintelligible, while a lower RT is preferred for tasks that require active listening, memory, recall and retention.

Dodd et al. (n.d.) also states that acoustic interventions on the ceiling can be the deciding factor in a room having "good" and "poor" acoustics.

Improved room acoustics results in better communication in the classroom, reducing the working SPL and speech effort, culminating in lower levels of stress in students and teachers, and improved behaviours in students *(Tiesler et al., 2015)*.

3.2.7. Considerations for Hearing Impairments, Autism, and Other Educational Requirements

Under the umbrella of research concerning students and children, there are limited studies into children using hearing aids or children who would benefit from additional hearing considerations. Hearing loss in humans is described in relation to an audiogram, specifically the measure of an individual's threshold of hearing for pure tones of 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, and 8 kHz presented to each ear by means of a headphone *(Canning et al., 2015)*.

James and Canning (2010) investigated the noise sources as outlined in the Building Bulletin 93 (BB93) and found the following for the acoustic requirements for schools that teach children on the autism spectrum.

1. Airborne noise from outside the building can be the same as in mainstream schools.
2. Rain noise was not a particular source of discomfort and problem to children with ASD.
3. Noise from machinery and equipment was found to be problematic if the noise contained tones, regular impulses or other characteristics that make it noticeable. They suggest incorporating an NR25 measured in terms of $L_{eq,30\ mins}$ in a teaching space.
4. Open plan design is discouraged for acoustic comfort alongside other relevant reasons (not described).
5. Less reverberant classrooms (RT < 0.7s in 250 Hz, and < 1.0s in 125 Hz - unfurnished) are highly preferred and suggested for ASD schools.

High reverberation blurs acoustic details of speech, with further masking brought about by the amplitude and timing of the noise. There is a visible decrease in speech perception with an increase in RT (that could then be offset, to a limited extent, by a higher SNR) *(Iglehart, n.d.)*. Greenland et al. (2019) suggests a RT of 0.5s (unoccupied) and 0.45 s (occupied) in combination with +15 dB SNR for students with SCHN. For students with hearing impairments, they suggest a shorter RT with a boosted SNR of +20 dB, in combination with personal/general hearing aids/ systems. The last-mentioned measure can help reduce listening difficulties by enhancing SNR, and reducing unneeded reverberations *(Canning et al., 2015)*. The paper also suggests using technological solutions as and when required, keeping in mind its advantages and disadvantages.

It incorporates the usage of technology as part of the curriculum. This in turn creates a demand of attention from acoustic systems geared towards addressing this.

3.3 Acoustic Control Systems

Acoustic control systems are of two types: passive and active. Passive measures are most effective when worked into the space at the design stage of the project. Active systems are more flexible in their intervention. They can be integrated at a later stage or can be personalised to the users, adhering to their requirements. Moreover, certain measures afford users control over the device and other measures are large scale interventions that are technology and system dependent. It is as illustrated below.

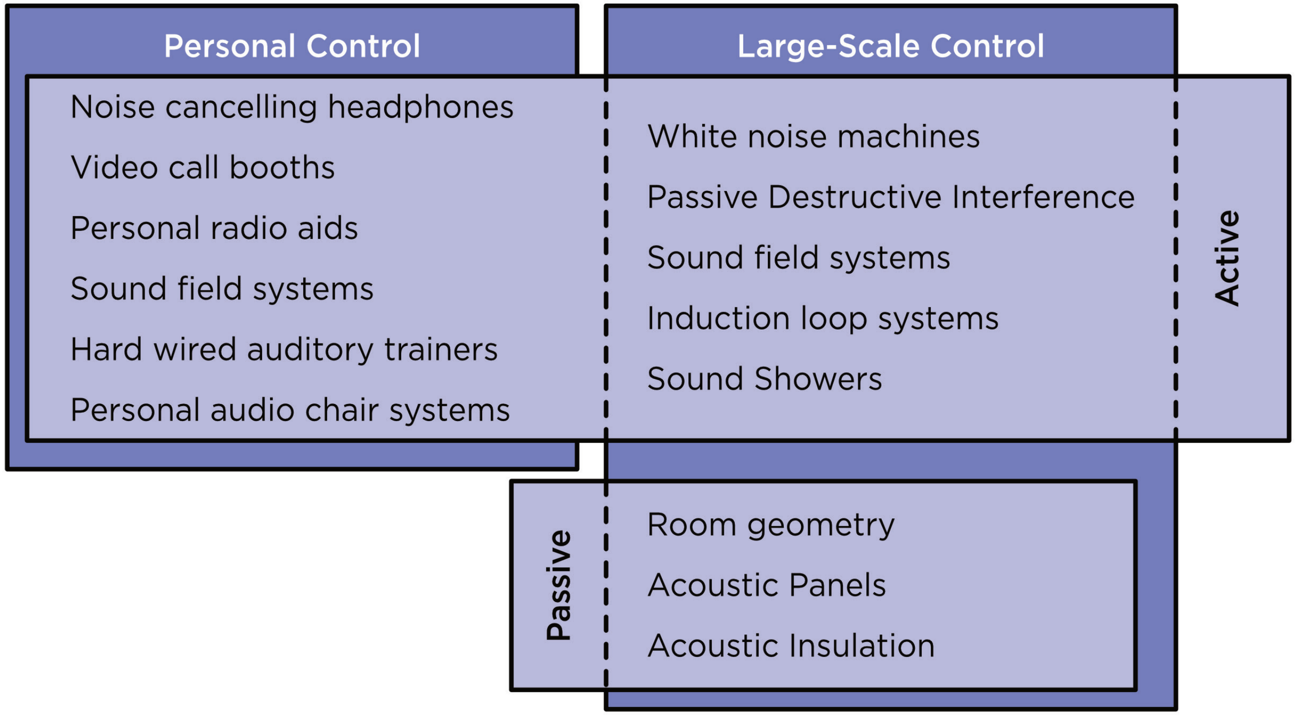


Image 3.9: Raghunathan, M. (2023). *Graphic showing personal and large-scale acoustic control systems* [graphic].

3.3.1. Personal Control Systems

Noise cancelling headphones
This measure is most effective for offices and individual learning periods. However, it is at most a short-term intervention with usage for longer periods resulting in physical and auditory fatigue.

Video call booths
The booths are a reliable intervention for offices where people regularly need to telecommute as a part of their work. However, if there are too many people who have a work profile that mandates the usage of the booth, it could prove to be insufficient. Acquisition of enough booths for the many employees could be both, expensive, and an overkill in terms of office funds and available space.

Personal radio aids
These aids can reduce the effect of distance between the speaker and listener, negating the effects of poor SNR. It can also be portable, and thus convenient. This measure can be expensive to obtain and addresses the requirements of the individual acoustics and not the class acoustics as a whole. These systems can also fail in noisy environments, with the microphone being unable to pick up on the required signal *(Canning et al., 2015)*.

Sound field systems
This system is also advantageous in the sense that it is portable and addresses the reduction in SNR due to the speaker-learner distance. It can also be bulky and difficult to carry around while also being unreliable in the SNR amplification to sufficiently meet the auditory needs of the user *(Canning et al., 2015)*.

Hard wired auditory trainers/systems
This is one of the more reliable personal acoustic control systems with it providing excellent SNR levels, working with cochlear implants, providing sound insulation, and being adaptable to group needs. This system is also bulky and can be uncomfortable to use *(Canning et al., 2015)*.

Personal audio chair systems
These systems create acoustics ‘islands’ with speaker systems tuned to each chair indi-

vidually. They allow (limited) control to their users and can also be extremely expensive systems to install and maintain.

3.3.2. Passive Control Systems

Room geometry
The room geometry plays a pivotal role in the acoustics of the space. The direct sound from speaker to listener must be without any obstructions for it to be most effective. This intervention is crucial since it has to be accounted for during the design stage.

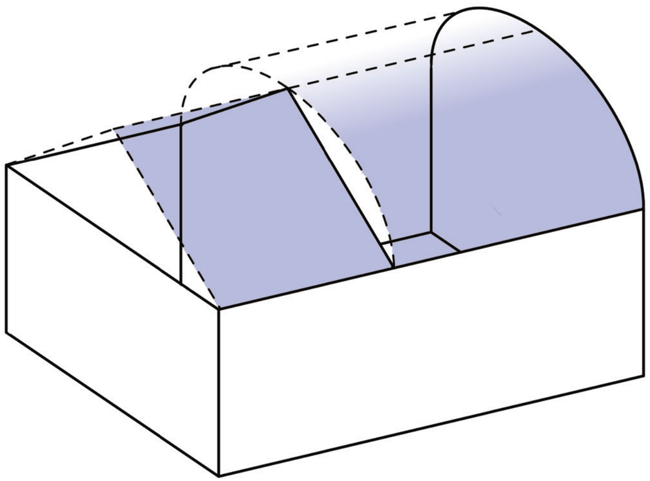


Image 3.10: Raghunathan, M. (2023). *Room Geometry* [graphic].

Acoustic panels & insulations
They are sound absorbing boards that can affect the reverberation time of a room. These panels have a pre-engineered effect on the noise dampening across the frequency bands (250 Hz to 8000 Hz). This specificity in its absorption values means that a room is fixed in its acoustic quality after the placement of the panels resulting in limited flexibility in its usage. Insulation dampens the unwelcome sound from adjacent spaces by adding a barrier in the direct line of sound from the speaker to the listener. It can supress indirect sound waves that result in echoes and excessive reverberation.

3.3.3. Active & Large-Scale Control Systems

White noise machines
It helps reduce distracting noise by producing (natural) soundscapes. These machines are designed for muting out unwanted sound from the surroundings when placed between the listener and noise source.

Induction loop systems
The induction loop systems are discreet and cheap. It can be integrated into spaces geared towards community activities. However, this system is unpredictable in its acoustic response, spilling over of signal into adjacent spaces, and is susceptible to electromagnetic interferences. It also is designed for the individual needs and can result in isolating the user from the environmental sounds, making it inappropriate for classroom applications *(Canning et al., 2015)*.

Passive destructive interference
Systems that use passive destructive interference make use of interfering sound waves that are in counter-phase to cancel the incoming sound. This is also used to mute out unwanted sounds from the environment. These systems can be expensive to install and maintain.

Sound field systems
Classroom sound field systems reduce the effect of distance from speaker and listener while also being inclusive. It answers the concerns of the larger group/class and can maintain SNR levels across the classroom. This however could cause poor classroom acoustics and might not satisfy the needs of a student with special healthcare needs (SCHN) *(Canning et al., 2015).*

Sound Showers
They are directional loudspeakers that are designed to transmit clear audio across longer distances even in noisy environments (without adding to the ambient noise levels). It creates a confined audio zone without the aid of personal systems such as headphones. They allow for precision sound localisation, cause minimal sound interference, and create a personalised audio experience *(Panphonics, 2023)*.

3.4 Products in the Market

This covers the study into the current state of acoustic products which was deemed necessary in order to understand the current state of acoustic (control) systems. The images of the products covered in this section can be found under Appendix 03.

3.4.1. Silentium
System: Active Noise Control
Type: Passive Destructive Interference

The company has developed an Active Noise Control (ANC) system that boasts a noise reduction of up to 10 dB(A). This product is a broadband ANC, effective for low/medium frequency noises up to 1.8 kHz. Moreover, it can create personal sound bubbles even in group spaces, reducing the need for passive control measures. This zonal control measure works by capturing the ambient noise of the space and creating the afore-mentioned personal sound bubbles. They also offer a point noise control system where the noise and its source are already identified and controlled at the point of origin before it has a chance to spread.

The sensors of the system relay the noise source to the controller which in turns produces anti-noise to counter this. It also has error microphones in place to receive feedback on the sound signature of the noise and subsequently refine it (Active Noise Control Technology, n.d.).

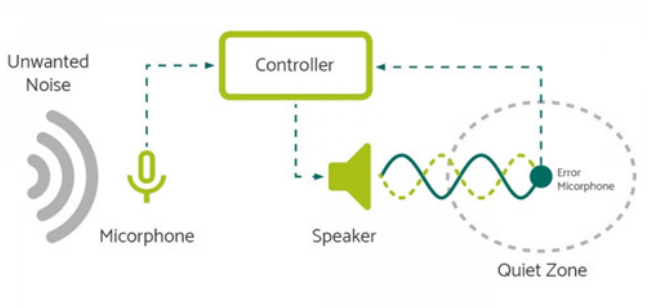


Image 3.11: Silentium (n.d.). *Silentium S-Cube, Broadband ANC* [graphic]. Silentium https://www.silentium.com/technology-2/.

3.4.2. Modio
System: Active Noise Control
Type: White Noise Machine/ Noise Masking

The company creates a device that generates a continuous soothing background sound, allowing its users to drown out external noise. It is small and easily mountable which makes it perfect for use in the hospitality sector. The device also allows its users to set the background sound level according to their personal preference *(Modio, n.d.)*.

3.4.3. ADAM
System: Passive Noise Control
Type: Passive Destructive Interference

The Acoustics by Additive Manufacturing, ADAM, project combines passive destructive interference tech with additive manufacturing to create components geared towards acoustic control. The system makes use of sound waves in the counter-phase to counter the incoming noise sound waves. It utilises different quarter wavelength tubes to achieve broad spectrum absorption via fiscal thermal damping. The usage of additive manufacturing means that complex shapes of diverse types are easy to produce, while also ensuring a customised acoustic solution, unique to the designed space *(Acoustic Control of Your Environment, n.d.)*.

3.4.4. NOWN
System: Passive Noise Control
Type: Acoustic Panels and Systems

The company (NOWN – Simply Elevated, n.d.) offers a range of acoustic solutions in the following categories: ceiling baffles, clouds, and panels, lighting integrated systems, acoustic partitions and wall panels.
They offer customisable and adaptable sizes for most of their designs. NOWN makes it a point to make the solution modular and interesting aesthetically while maintaining the functionality of it.

INFIKNIT™
Intended for usage in large gathering spaces, it is designed to help reduce and control the reverberations in the room. They make use of 3D knitting to reduce waste while optimising performance of the system developed. They also have achieved a true NRC® of 0.75.
The entire system is 100% recyclable (with a pending bronze status in the cradle-to-cradle assessment).

Made of Air
The product is developed using a carbon-negative material, biochar obtained from wood waste. It has a carbon negative value of - 02.0 kgCO_2/kg.
This product as well is 100% recyclable (with a pending bronze status in the cradle-to-cradle assessment).

Recycled Materials
Soft Sounds® uses felted 100% PET plastics to achieve a true NRC® of 0.75 while still being 100% recyclable and 100% salvageable.

CircuLUM™ is designed from 75% recycled aluminium cans, averaging about 136 cans per module and achieves a true NRC® of 0.75. The usage of aluminium cans ensures that the product can be 100% salvaged at the end of its usage.

3.5 Literature Research Summary

The chapter addresses the importance of acoustics in different environments, focusing on open plan offices and schools. It compares and contrasts the information in order to hone into one topic to continue the research into personalised control of room acoustics.

Noise, simply put, is a sound or auditory signal that is unwanted or undesired. This means that psychoacoustics, age, tasks performed, and architectural limitations play influential roles in understanding the acoustic needs of the space and its users. Thus, it can be safely concluded that users can experience an increased satisfaction with their environment when afforded control over the same.

In order to hone in on the space that has the more demanding acoustic challenges, both offices and schools were taken into consideration.

Offices
Offices have changed in the way they approach work environments. Open plan and flex spaces are seeing an increase in popularity. This architectural choice results in more speech/acoustic problems as compared to a traditional cubicle work space. Green office buildings (LEED specific) also pose specific challenges. There is little attention to integration of acoustics and natural building systems resulting in poor sound environments for the users. The LEED system also needs to further supplement the standards and measures used to test the acoustic conditions of a building during and post construction.

In a working atmosphere, pervasive sound is particularly disturbing since people tend to process sound regardless of want. If this interrupting sound is registered as a negative event, it impacts the quality of work immediately. However, this disturbing noise makes up for only 30-40% of annoyance. The remaining depend on psychosocial aspects of acoustics such as predictability of event, noise sensitivity/tolerance, general quality of space, and the handling of the event. If the sound is predictable, it tends to become less distracting. This establishes that distraction is a factor unrelated to sound level but remains related to individual sound events themselves.

Strategic planning of spaces is an effective passive method to tackle this problem. Spatial planning should be the first step in effectively zoning the quiet and noisy spaces away from each other. The next step is to actively reduce the sources of noise such as placing speakers only where necessary, and strategically planning internal layouts. Lastly, introducing policies that will help maintain good acoustics.

After the external factors are under control, room acoustics can be addressed. The ceiling is the suggested primary placement of absorbers. Additionally, wall absorbers at the listener’s ear height can be placed. The floor has limited impact on sound absorption but can reduce the impact noise from that floor. Finally, if there is a large amount of sound infiltration from one workstation to another, sound barriers and spatial dividers can be considered.

Schools
There is a unique problem posed by acoustics in schools, particularly schools for younger children. The standards set for evaluation do not take into consideration the developing sensory systems of children. They tend to be more sensitive to noise and less tolerant to the effects of high levels of noise.

The modern schooling systems are seeing an increase in mixed modes of education including but not limited to group work, technology based systems, and independent learning. Each teaching style comes with its own listening demands. When the teacher is in focus, all the students are expected to listen to them and absorb information. During breakout sessions, students are expected to focus on their group alone, ignoring the classroom chatter. In individual sessions, concentration can be broken by any fluctuations in background noise levels.

In short, there are two main users in a school, the teachers and the students. The types of problems they experience due to noise vary vastly. Teachers experience more vocal strain and fatigue due to constantly having to talk above the noise of the classroom chatter. This negatively impacts their physical and mental health. Students, on the other hand, experience a poorer learning environment as a result of noise. The distraction caused impacts their scholastic achievements, affecting memory, recall, attention, and social relationships. Younger students are also particularly susceptible to dysfunctional behaviour.

In order to address the needs of children in the classroom, attention needs to be given to the early reflection time and the reverberation time. C_{35} must be used in place of C_{50}, and the reverberation time must be adjusted depending on the type of activity, function, and should take into account any other considerations required for hearing or learning impairments.

Addressing these problems in a classroom can be approached similar to the office solution. First, zone. Second, focus on internal planning and layouts, avoiding open plans, and irregular and disproportionate geometry as much as possible. Third, focusing on room acoustics. Diffusers can be used to enhance early reflections and to create a more uniform acoustic condition across the room. The suggested locations for the placement of diffusers are on the ceiling, the lower frontal and side walls. Absorptive materials are preferred at the listening height, on the ceiling, and on the surface opposite the source. These measures can help reduce late arriving sound. Reflectors can be used to enhance sound when needed. Placing reflectors at the point of first order of reflection can enhance the early reflections. Reflectors above a group discussing can enhance the sound strength, inadvertently reducing the Lombard and cafe effect.

The effects of noise are amplified in students with additional hearing or learning requirements. Treating a room to fit with the additional needs requires a focus on the SNR and reverberation time. The larger the SNR and the lower the reverberation time, the better the quality of the learning environment.

Acoustic Control Systems
There are many types of control systems in the market currently. They can be broadly classified as passive and active measures, and personal and large-scale measures. Each comes with their own advantages and disadvantages.

Personal control systems are heavily discouraged for long term use. Long term use can result in auditory fatigue if not mental and physical fatigue as well. However, they are portable and can be convenient in addressing the nuanced needs of a person.

Passive measures are primarily interventions in the design and construction phases of a project. This involves care in planning room geometry and accounting for acoustics at the design level, thus reducing the extent of intervention post construction. They can be further enhanced by means of acoustic panels and insulations.

Large-scale and active control systems address the needs of the space as a whole but cannot address the needs of the user in specific. They can be effective in implementing zonal control systems, or in curating specific conditions demanded by a space. They primarily use passive destructive interface or white noise to counter unwanted sound and to mask background noises respectively. This technology makes them expensive or difficult to install and maintain, thus limiting their implementation to institutions that can afford the costs related to the system.

3.6 Primary Takeaways

- Schools pose a pressing problem since children require an additional focus during acoustic design.
- The treatment of spaces can be approached similarly (zoning, internal planning) until the point of room acoustics.
- Different functions have different demands from a space (distraction is directly to the expected behaviour of sound and the deviation from the same).
- Diffusers can be used to enhance early reflections and to create even sound fields.
- Absorbers can reduce the late reflections, and echo and flutter effects.
- Reflectors can be used to enhance early/first reflections.
- Early reflections, SNR, and reverberation time can be extremely useful in assessing the quality of sound in a space.
- Existing personalised acoustic measures can be expensive or not suitable for long term use, making them un-viable for educational use.
- Ceilings can be the make or break point in room acoustics

The simulation model assumes information based on relevant data from the Netherlands in order to arrive at a standard representative model for middle school classrooms. This is necessary in order to have a reliable model to test the proposed solutions with. The dimensions are taken to be (an average of) 8 x 7 m *(Rantala & Sala, 2015)*.

The classroom is assumed to have Noise Reduction Coefficient [NRC] values that reflect current and popular practices in schools in the Netherlands as of 2023-24. This helps in understanding the quality of the environmental acoustics while shifting the focus towards and limiting it to room acoustics alone.

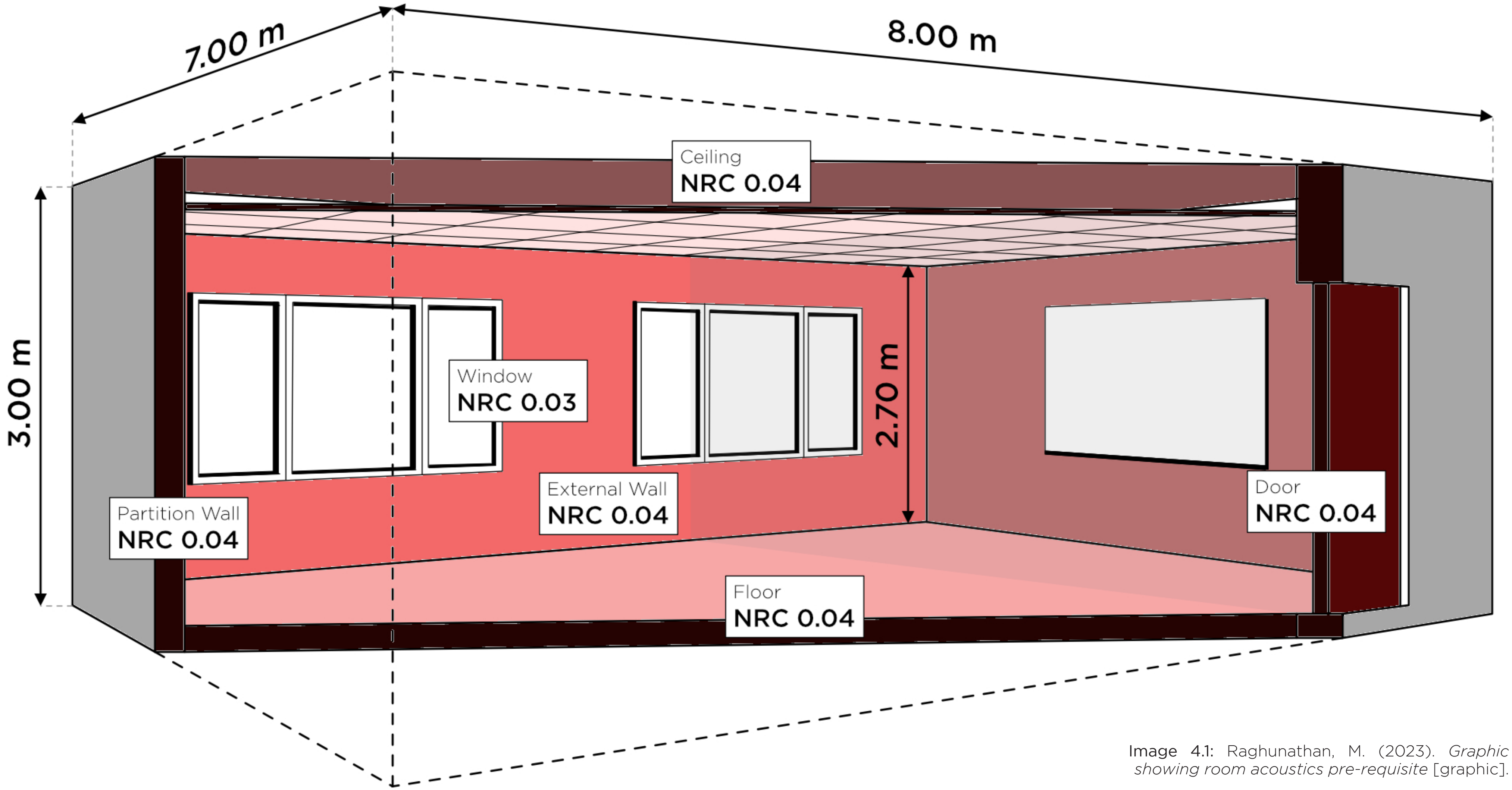


Image 4.1: Raghunathan, M. (2023). *Graphic showing room acoustics pre-requisite* [graphic].

4.1 Model Information Summary

1. The Dimensions
Height: 3m
Width: 7m
Length: 8m

2. Areas and Volumes
Square area: 56 sq. m.
Total volume: 168 cu. m.

3. Voids
No. of windows: 2
Sill Level: 0.9 m
Lintel Level: 2.1 m
Dimensions of each window: 2.5 m x 1.2 m
Type: Double Glazed Units
Total Area: 10% of wall
Dimensions of the door: 1.2 m x 2.1 m

4. Materials
Walls: Plaster finish
Ceiling: Plaster Finish
Floor: Linoleum
Door: Standard Plywood
Windows: Glass
Furniture: Standard Plywood
Other: Whiteboards

5. General Specifics
Relative Humidity: 50%
Indoor Temperature: 20 °C
Transition Frequency: 289 Hz

6. Software
Treble
CATT

4.2 Targets & Goals

The different acoustic requirements of each learning style are as follows (Also see Appendix 11):

1. Teacher Centred Learning
RT < 0.4 - 0.6 s *(standard: RT < 0.6 s)*
STI > 0.75 *(standard: STI > 0.6 [NC 25-30])*
SNR of +15 - +20 dB
L_{eq} of 35 dB *(standard: L_{eq} of 35-40 dB)*
%ALCons < 10 %

2. Group Based Learning
RT < 0.8 s
STI > 0.60 *[NC 25-30]*
SNR of +15 - +20 dB
L_{eq} of 35 dB

3. Technology Based Learning
RT < 0.4 - 0.6 s *(standard: RT < 0.6 s)*
STI > 0.75 *(standard: STI > 0.6 [NC 25-30])*
SNR of +15 - +20 dB
L_{eq} of 35 dB *(standard: L_{eq} of 35-40 dB)*

4. Special Learning Requirements
RT < 0.3 - 0.5 s *(standard: RT < 0.4 s)*
STI > 0.60 *(standard [NC 25-30])*
SNR of +15 *(750 Hz to 4 kHz)* - +20 dB *(250 to 750 Hz)*
L_{eq} of 30 dB *(standard)*

4.3 The Model - Simulations

This section will cover the stipulations of the various components that make up a model prepared for simulations.

4.3.1. Source - Receiver Positions & Audio Mapping Grid
The images below and in the upcoming pages outline the different combinations of source and receiver placements and the intended understanding expected to be gleaned from it.

The model relies on data specific to the Netherlands and as a result, the solutions and methods used retain a high relevance for this country.

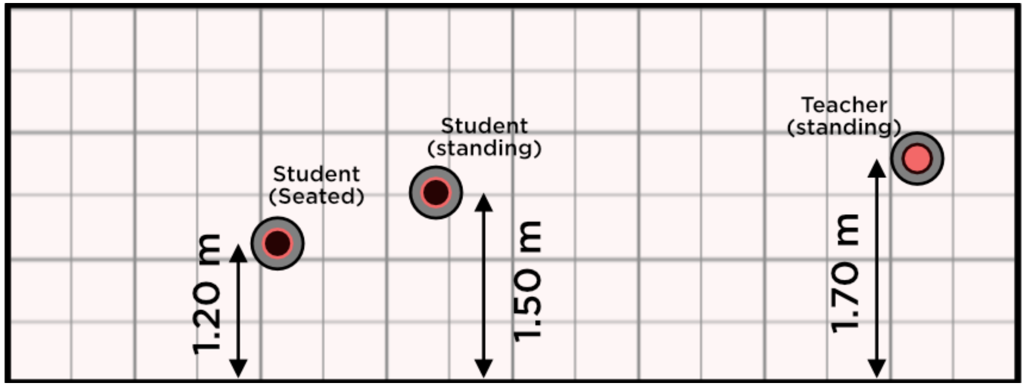


Image 4.2: Raghunathan, M. (2023). *Graphic showing the Source-Receiver heights for teacher and students* [graphic].

Scenario #1

A teacher addressing the class as a whole from the front of the classroom.

No. of Sources: 1
No. of Receivers: 30

Source Type:
Directional (Single Speaker)

Target:
Teacher Centred Learning,
Technology Based Learning

Scenario #2

A teacher addressing the class as a whole while walking around the classroom.

No. of Sources: 1
No. of Receivers: 30

Source Type:
Directional (Single Speaker)

Target:
Teacher Centred Learning,
Group Based Learning,
Technology Based Learning

Scenario #3

A student responding to a question from his seat.

No. of Sources: 1
No. of Receivers: 6
Source Type:
Directional (Single Speaker)

Target:
Teacher Centred Learning

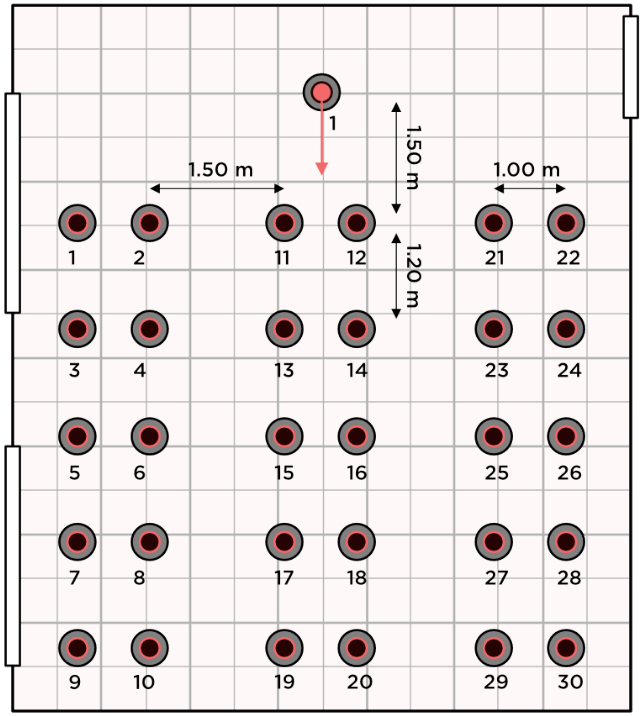


Image 4.3: Raghunathan, M. (2023). *Floor Plan showing the 1st set of Source-Receiver positions* [graphic].

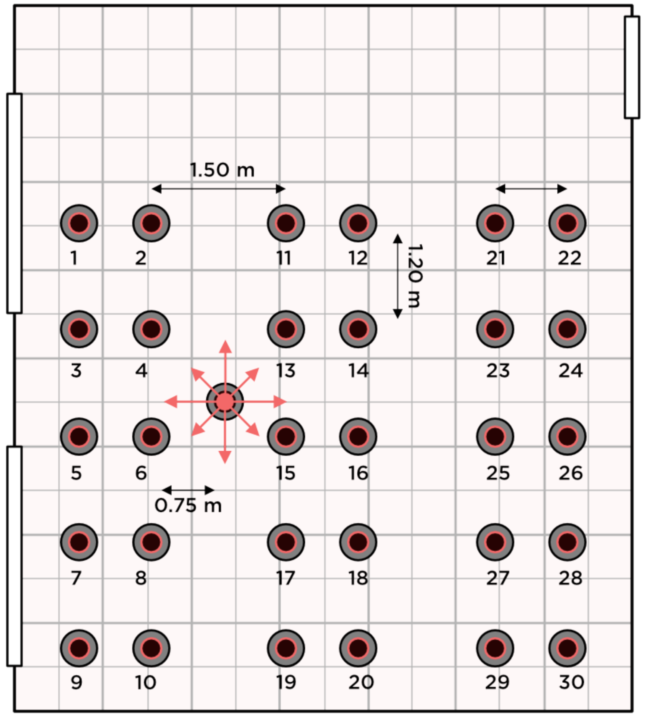


Image 4.4: Raghunathan, M. (2023). *Floor Plan showing the 2nd set of Source-Receiver positions* [graphic].

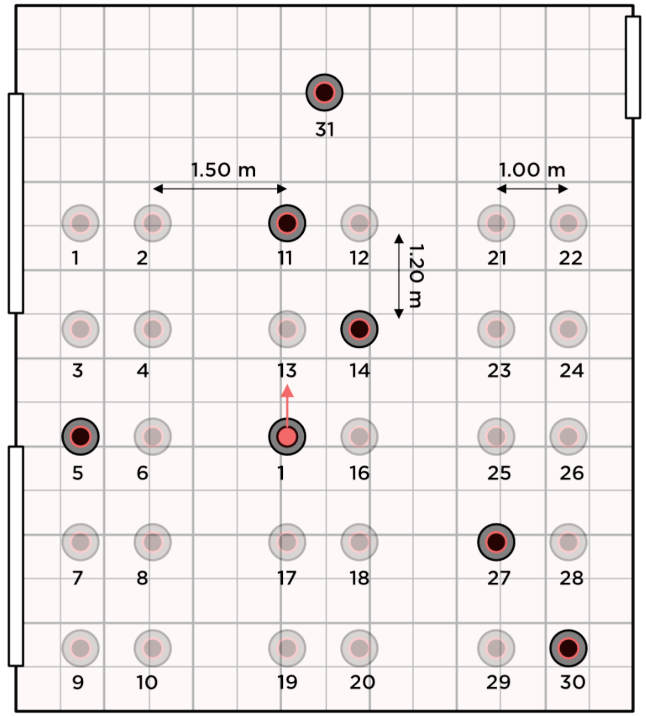


Image 4.5: Raghunathan, M. (2023). *Floor Plan showing the 2nd set of Source-Receiver positions* [graphic].

Scenario #4

A class in the process of a group project, working in pairs, talking out loud.

No. of Sources: 2
No. of Receivers: 9

Source Type:
Directional (Dual Speakers)

Target:
Group Based Learning

Scenario #5

A class in the process of a group project, working in pairs, talking out loud.

No. of Sources: 4
No. of Receivers: 15

Source Type:
Directional (Multiple Speakers)

Target:
Group Based Learning

Audio Mapping Grid

The classroom is divided into small grids of 0.50 x 0.50 m (for a total of 224 squares) in order to understand the effect of the source in scenarios 1-4 on the entire classroom. This is expected to assist in the evaluation of the space in relation with seating assignments, typology of work, surrounding furnitures/ materials, and direction of audio. Additionally it is expected to give a better understanding of SPL, STI and G values across the entire space. This method of data perception is important in the goals of achieving a personalised control system.

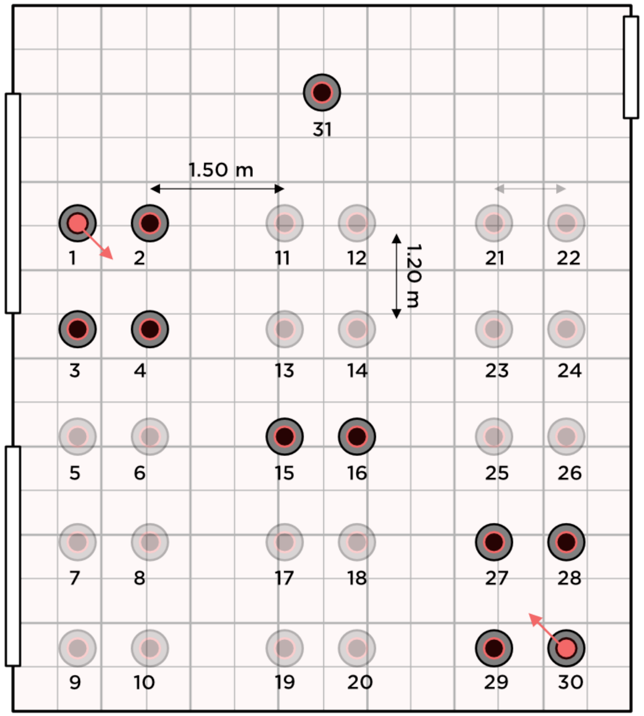


Image 4.6: Raghunathan, M. (2023). *Floor Plan showing the 2nd set of Source-Receiver positions* [graphic].

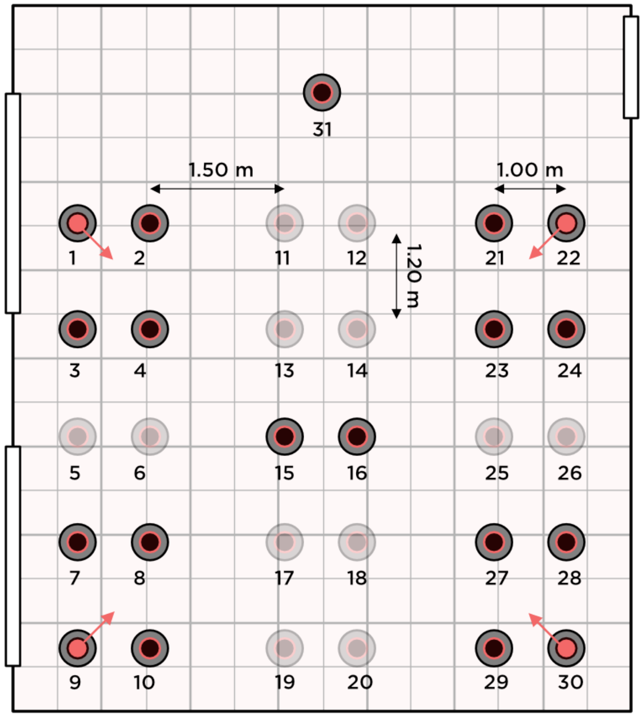


Image 4.7: Raghunathan, M. (2023). *Floor Plan showing the audio mapping grid* [graphic].

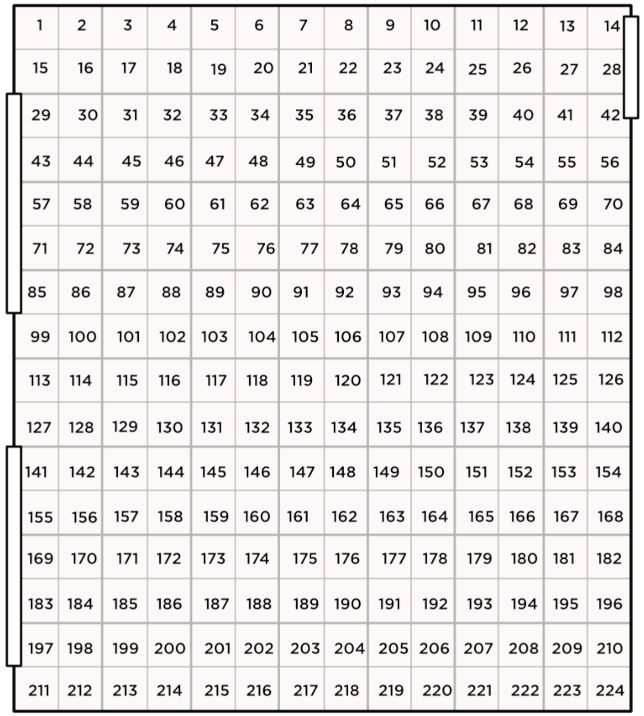


Image 4.8: Raghunathan, M. (2023). *Floor Plan showing the audio mapping grid* [graphic].

4.3.3. Material Definition
The following are the material assumptions. The absorption coefficients for these materials are as elaborated on the right. This data is fixed for the duration of the research.

Voids
Door: Standard Plywood of 2.5" thickness
Windows: Double Glazed Units

Vertical Planes
External: Masonry Construction with a plaster finish on the interior side
Internal Parition Walls: Plaster boards with wooden studs

Horizontal Planes
Floor: Linoleum
Ceiling: Concrete with plaster finish

4.3.4. Software
The software considered for use in the research are CATT and Treble. Each software comes with its own advantages and disadvantages which at times are complementary to each other.

CATT acoustics is unfriendly to newcomers and is largely uninfluenced by small fluctuations in the interior geometry. It utilises geometric solver to produce results and disregards the transition frequency of the acoustic environment. Treble is a newer software, designed to be user friendly. It accounts for the transition frequency, using a wave-based solver for frequencies below the transition frequency, and a geometric solver for the ones above. It is more sensitive to smaller changes in interior spaces.

Material Type	Location	Absorption Coefficient						NRC
		125	250	500	1000	2000	4000	
Linoleum	Floor	0.02	0.03	0.04	0.04	0.06	0.05	0.04
Glass	Window	0.07	0.03	0.03	0.03	0.03	0.02	0.03
Absorption	Ceiling	0.84	0.9	0.89	0.8	0.92	0.95	0.88
Plastered Masonry Wall	Walls	0.02	0.03	0.03	0.04	0.07	0.08	0.04
Wood	Furniture	0.02	0.03	0.04	0.08	0.15	0.2	0.08
Wood	Door	0.16	0.07	0.04	0.02	0.01	0.02	0.04

CATT Acoustics | Advantages
- User has final say in the input values of the simulation
- Easy to edit absorption coefficients, and source types (noise type, sound source type)
- Can enter scattering coefficients per frequency band
- Can average out the results from multiple sources

CATT Acoustics | Disadvantages
- Steep learning curve – it requires users to learn prompt codes in order to define sources
- Unreliable results in small spaces
- Uses only a geometric solver. It does not account for the wave behaviour of sound underneath the transition frequency of a room.
- Runs on the system of user. This results in the simulations with lengthy run times.
- Planes may be flipped and additional care needs to be taken to make sure model is right in the software.
- Any mistakes in material assignment to planes need to be fixed at the model level and cannot be changes in the software itself.

CATT Acoustics | General points
- Results are given in the following frequencies: 125, 250, 500, 1k, 2k, 4k, 8k, and 16k Hz.
- Requires different 'materials' to be assigned prior to exporting (and then later assigning absorption coefficients).
- Has a plug-in for SketchUp

Treble | Advantages
- Easy learning process
- Uses wave-based and geometric solvers for frequencies under and above the transition frequency respectively.
- Runs on the cloud. This results in shorter simulation run time and frees up the user's PC for other work.
- More reliable results for smaller, and unusual geometry of spaces
- Easy to go back and edit simulation inputs
- Can have multiple simulations for the same space without having to create multiple instances.
- Can assign different materials to planes under same layer classification
- Can enter scattering coefficients per frequency band or as an overall value (single

value scattering)
- Transition frequency can be manually adjusted
- Can compare the different simulation results on the same screen, see results for the different solvers independent of each other, or for specific source-receiver combinations
- Can upload/create custom source definitions

Treble | Disadvantages
- Cannot set the values the user wants for the absorption coefficients (material fitter fits the user given absorption coefficients to a reflection coefficient curve which may result in different values from the ones the user wants but it takes into account the impedance of the materials).
- Cannot enter absorption coefficients higher than 0.95. However this has limited impact as values above 0.95 are unrealistic.
- Cannot edit a material once created
- Cannot assign materials to different sides of the same plane (eg: floor/ceiling, walls with different materials on either side)

Treble | General points
- Uses only pink noise (omni source) but can create custom source definitions
- Results are given in the following frequencies: 63, 125, 250, 500, 1k, 2k, 4k, and 8k Hz
- Requires different 'materials' to be assigned to layers for exporting (and later assigning absorption coefficients)
- Uses geometric solver above the transition frequency (which is automatically determined), and a wave solver for the frequencies under the transition frequencies
- Has a plug-in for SketchUp
- If a geometry is not watertight, it can still be uploaded for ray tracing simulation.
- Visually shows the surfaces/places with error in sketchup
- Has a survey solver for a quick analysis
- Can choose which solver (geometric or wave based) is used to simulate. However, the geometric solver will not produce results for frequencies under the transition frequency, and the wave based, for frequencies above the transition frequency.

Considering all the advantages and disadvantages, Treble is chosen as the software most appropriate for the investigation that this thesis demands.

Image 4.9: Raghunathan, M. (2023). *Flowchart showing the work process invloved in using CATT and Treble.*

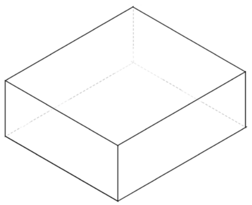
4.4 The Current Scenario

Before the thesis can proceed, an understanding of the situation prior to any intervention is warranted. This will outline the demands of a space, and the extent of intervention needed.

The model classroom is run through 5 simulations, one for each scenario outlined previously. There are 2 surface receivers for each scenario; one at the student's seated height, and another at 2.6 m. These will allow us to understand the impact of source-receiver combinations at the ceiling level as well as the receiver level, fostering a deeper understanding of the space.

The primary values studied are the reverberation time [T-30 in seconds], early decay time [EDT in seconds], C50 [in dB], G [in dB] and SPL [in dB]. These factors together provide a solid understanding of the acoustic conditions of the class.

Due to the materials in the classroom, the room is mostly reverberant. This results in poor speech intelligibility and high levels of intrusive noise. The recommended RT is 0.8s (for a classroom with teaching functions). Currently the room indicates an RT of 3.17s - 4 times the recommended time. As expected, the C50 values are extremely low in the primary speech frequencies. This means that any conversation occurring in that classroom will be garbled, i.e. speech is



Scenario 1

Frequency	Source Averages				
	T-30	C50	G	SPL	EDT
125	6.28	-10.26	-13.84	53.61	5.68
250	5.44	-8.28	-12.17	61.8	4.45
500	2.66	-4.4	24.88	64.63	2.78
1000	2.14	-3.23	24.01	57.5	2.19
2000	1.42	0.01	19.11	47.91	1.38
4000	1.14	1.55	17.02	40.83	1.09
Averages	3.18	-4.1	9.84	54.38	2.93

Scenario 2

Frequency	Source Averages				
	T-30	C50	G	SPL	EDT
125	6.39	-9.35	-13.3	54.18	5.87
250	5.5	-6.87	-11.95	62.05	4.66
500	2.67	-4.18	25.06	64.81	2.79
1000	2.13	-2.53	24.35	57.84	2.19
2000	1.42	0	19.25	48.05	1.39
4000	1.14	1.62	17.28	41.09	1.09
Averages	3.21	-3.55	10.12	54.67	3

Scenario 3

Frequency	Source Averages				
	T-30	C50	G	SPL	EDT
125	6.14	-9.89	-12.38	55.1	5.67
250	5.54	-7.05	-11.85	62.15	4.8
500	2.65	-4.9	24.82	64.57	2.79
1000	2.12	-3.38	24.04	57.53	2.19
2000	1.42	-0.94	18.75	47.55	1.39
4000	1.14	0.26	16.41	40.22	1.1
Averages	3.17	-4.32	9.97	54.52	2.99

masked due to long reverberation time. The STI for the classroom is also 0.49 (averaged value over the receiver points) which is under the minimum requirement of 0.65. The SPL values look like they are well under the

Scenario 4

Frequency	Source Averages				
	T-30	C50	G	SPL	EDT
125	6.14	-9.89	-12.38	55.1	5.67
250	5.54	-7.05	-11.85	62.15	4.8
500	2.65	-4.9	24.82	64.57	2.79
1000	2.12	-3.38	24.04	57.53	2.19
2000	1.42	-0.94	18.75	47.55	1.39
4000	1.14	0.26	16.41	40.22	1.1
Averages	3.17	-4.32	9.97	54.52	2.99

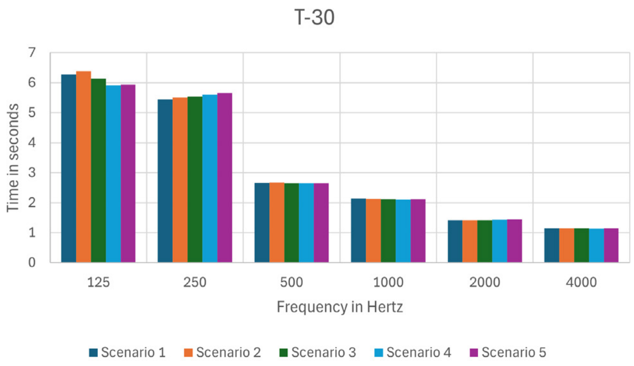
Scenario 5

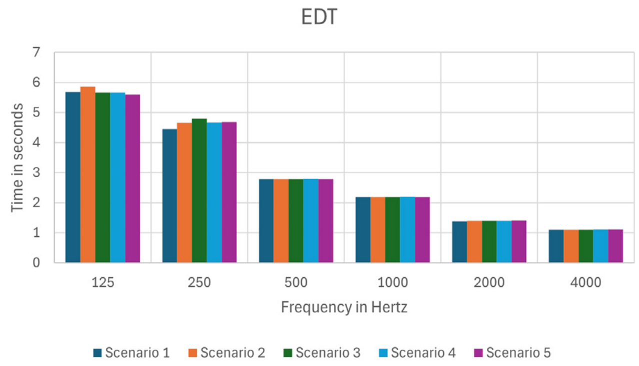
Frequency	Source Averages				
	T-30	C50	G	SPL	EDT
125	5.92	-8.985	-13.27	54.21	5.67
250	5.605	-7.485	-12.355	61.645	4.675
500	2.645	-3.42	25.35	65.1	2.8
1000	2.105	-1.79	24.72	58.21	2.195
2000	1.43	1.29	20.03	48.83	1.395
4000	1.135	2.945	18.145	41.955	1.11
Averages	3.14	-2.91	10.44	54.99	2.97

Summary

Frequency	Source Averages				
	T-30	C50	G	SPL	EDT
125	6.13	-9.61	-13.18	54.29	5.7
250	5.55	-7.36	-12.17	61.82	4.65
500	2.66	-4.15	25.04	64.79	2.79
1000	2.12	-2.65	24.3	57.79	2.19
2000	1.43	0.22	19.35	48.15	1.39
4000	1.14	1.74	17.29	41.1	1.1
Averages	3.17	-3.64	10.11	54.66	2.97

minimum but one must take into consideration that SPL is important in its relationship with distance. The classroom currently has a 0.6 dB drop per doubling of distance.





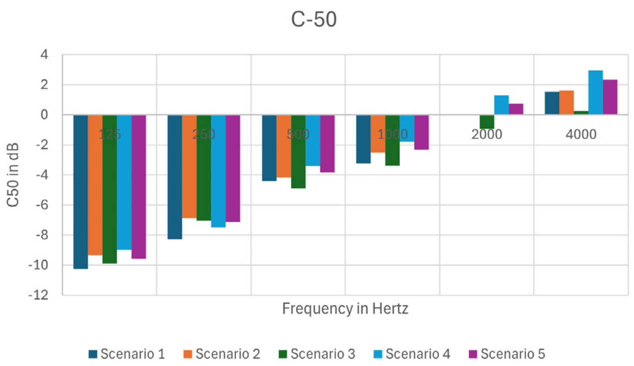
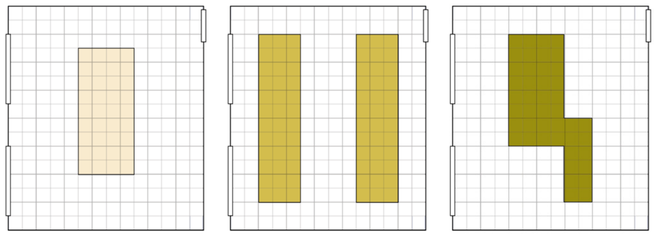


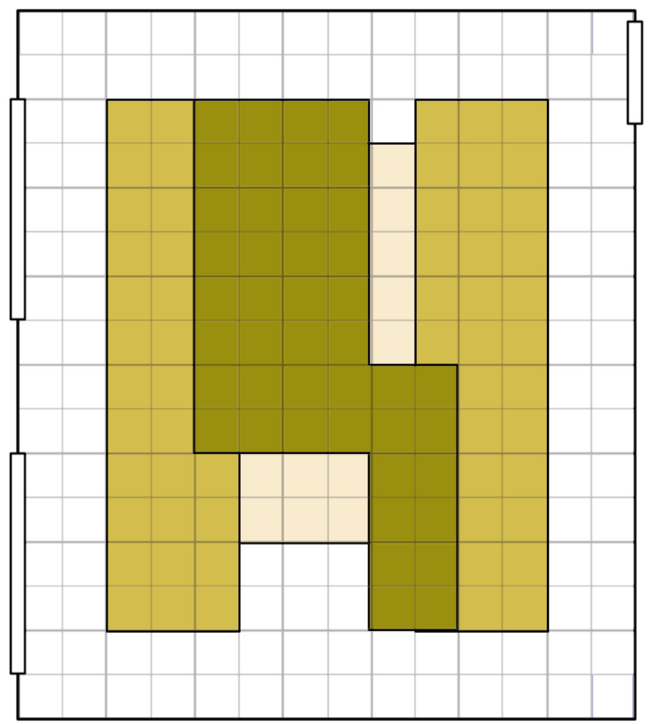
Image 4.10-4.15 [data tables]: Raghunathan, M. (2023). *Data tables showing the acoustic values for Scenarios 1 to 5, and a summary.*
Image 4.16-4.20 [graphs]: Raghunathan, M. (2023). *Graphs showing the results per frequency band for (clockwise) T-30, EDT, SPL, C50 and G.*



Additionally, the RT is studied on a surface rendered map. The results for the different scenarios and sources under each scenario are averaged and combined into a single map.

The hotspots for the bass speech frequencies are identified and mapped in order to understand the important positions for interventions. The hotspots are concentrated in the centre of the room, with the periphery being the least impacted.

Image 4.21-4.24 [surface maps]: Raghunathan, M. (2023). *Maps showing (L to R) hotspots for 125 Hz, 250 Hz, 500 Hz, and a summarised map of all 3 frequencies.*



This section will cover the initial proposed designs for acoustic interventions in a middle school classroom.

5.1 Design Criteria

Important aspects taken into account while designing a system are as follows:

1. Ease of production
2. Usage of pre-existing mechanics
3. Ability to fit into existing construction style & system
4. Regularity of modules
5. Modularity and replaceability

The designs are analysed based on certain factors such as:

1. **Mechanisms**
    a. Type
        i. Level of control
        ii. Active/passive systems
    b. Complexity
        i. Extent of intervention
        ii. Production cost
        iii. Kid proof-ness

2. **Aesthetics**
    a. Profile/Pattern flexibility
        ii. Geometry
        iii. Configurations
    b. General aesthetics
        i. Material
        ii. Geometry

3. **Acoustic Factors**
    a. Absorption Percentage
        i. Ceiling coverage
    b. Amount of absorbers/reflectors
        i. No. of materials
        ii. Variability

5.1.1 Design Approach

The designs were developed based on the following principles:

1. A reflector plate in direct contact with an absorber acts in addition to the absorber. In other words, it can enhance the properties of the absorber.
2. Pre-existing movement mechanisms - curtains, sit/stand tables
3. Impact of different geometries at the design level and at the product level.

5.1.2 Limitations & Important Considerations

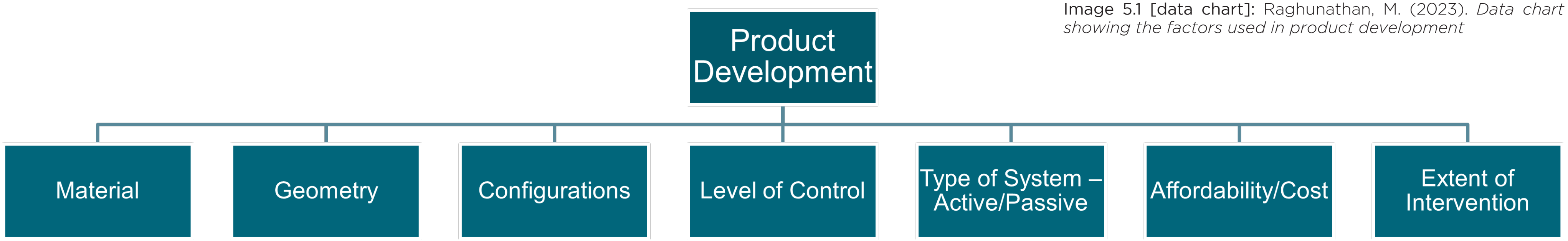
The grading scale on the bottom right of each page of the design is a purely subjective grading. It serves as a method to assess and filter out options that will be most viable for future analysis and development.

The goal of the designs is to achieve varying absorption levels in the classroom. As such, it can be said that the primary takeaways from this section are the specific demands in the placement of absorbers and reflectors, and the method of addressal of the various demands of a space.

Cost and production factor is not yet a primary factor of consideration at this stage. It will be taken into account during the validation and the verification section of this report.

The primary point of intervention is the ceiling. The walls are the final consideration for intervention. This is so that the internal planning of the space can be as flexible as the teaching styles demand.

Image 5.1 [data chart]: Raghunathan, M. (2023). *Data chart showing the factors used in product development*



5.2 Design Options

It is important to note that the rating system visible on the bottom right of the pages are subjective and act as a preliminary selection criteria.

5.2.1 Option #1
Mechanism: Hinge
Module Size: 0.9 x 0.9 m
Design Principle: 1

A (perforated) reflector plate enhances the performance of an absorber if and only if it is in direct contact with the absorber material. Separate them and you break them down into their individual components: an absorber and a reflector.

This relies on the integration of hinges in a standard absorber + plate acoustic panel. It can continue to use existing systems for installation.
Existing technology (such as tension cables, hydraulic systems, magnetised systems) can be used to operate the hinges of the system.

Advantages
- Mimics design of existing acoustic panels
- Easy installation
- Easy to replace
- Modular

Disadvantages
- Aesthetically bland
- Minimal variability of absorbers/reflectors
- Objects stuck in the hinges could affect the movement

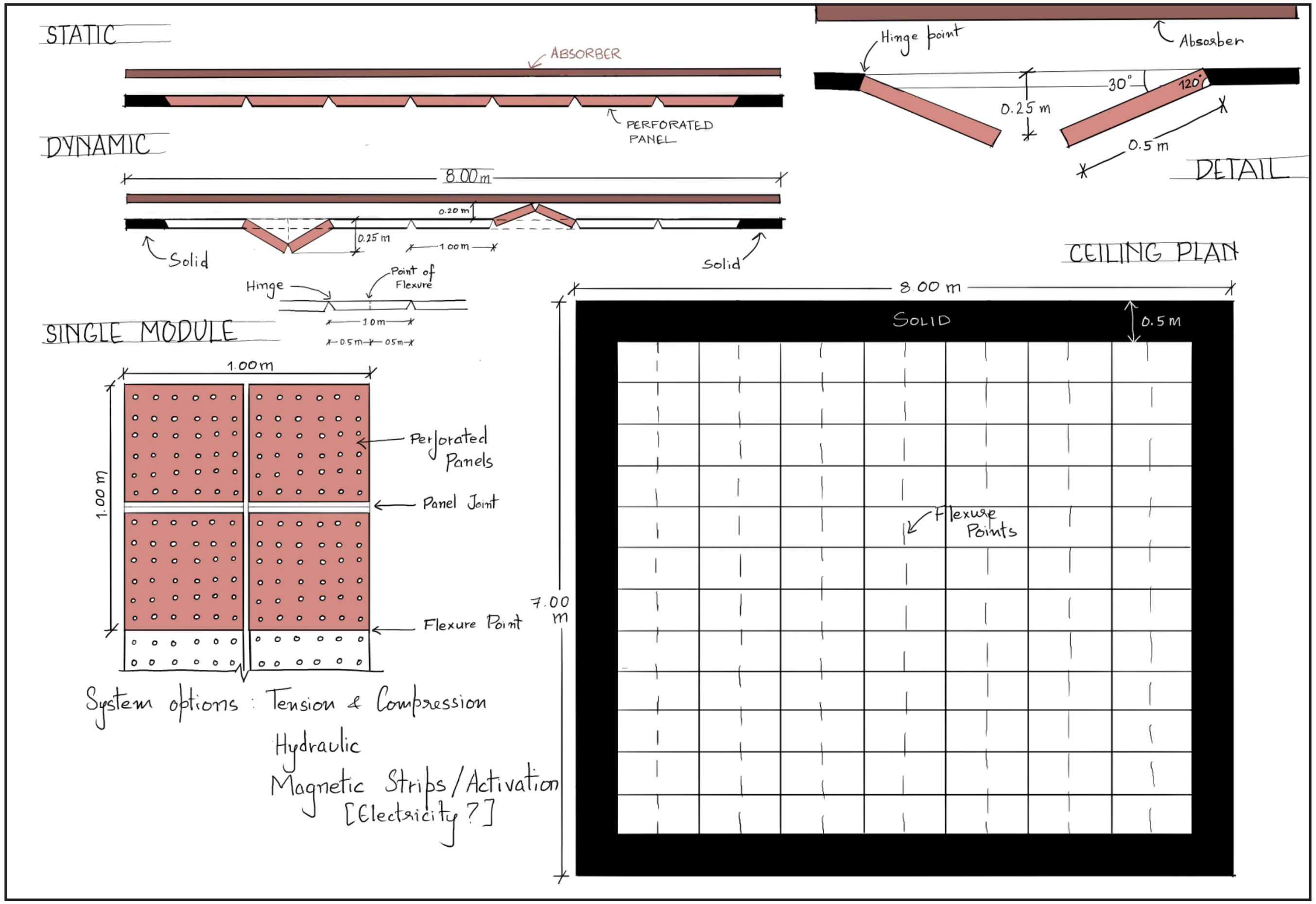
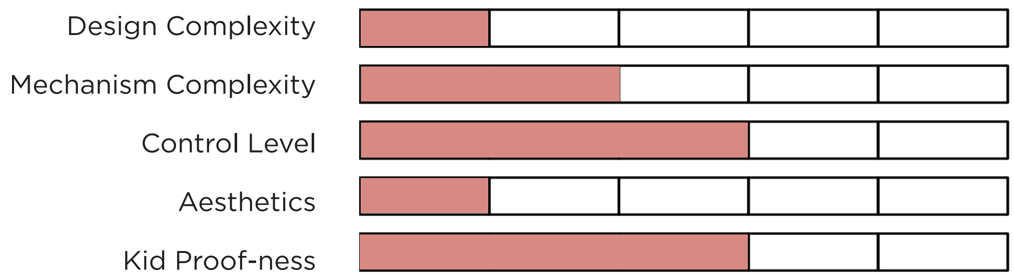


Image 5.2 [illustration]: Raghunathan, M. (2023). *Design Option #1*



5.2.2 Option #2
Mechanism: Deployable - push/pull
Module Size: 0.9 x 0.9 m
Design Principle: 1

This design also works on the principle of change in behaviour of a reflector plate that is in conjecture with the absorber surface. This relies on the usage of technology that allows for constant push/pull of the reflector plate. Similar technology can be seen in manually cranked sit/stand tables, hydraulic sit/stand tables, winding by means of cables, and in gym equipment (adjustment of the various moving components of a machine).

Advantages
- Mimics design of existing acoustic panels
- Easy installation
- Easy to replace
- Modular
- Adjustable patterns - solids and voids - allowing for a customisable acoustic profile
- Can create absorbent and reverberant sections

Disadvantages
- Aesthetically limited
- Requires a user intuitive interface for optimal usage and performance
- Performance can be affected if objects are trapped in the mechanism

QUICK NOTE

The design elaboration and illustration is available under “Appendix 04 - Proposed Design Elaboration”.

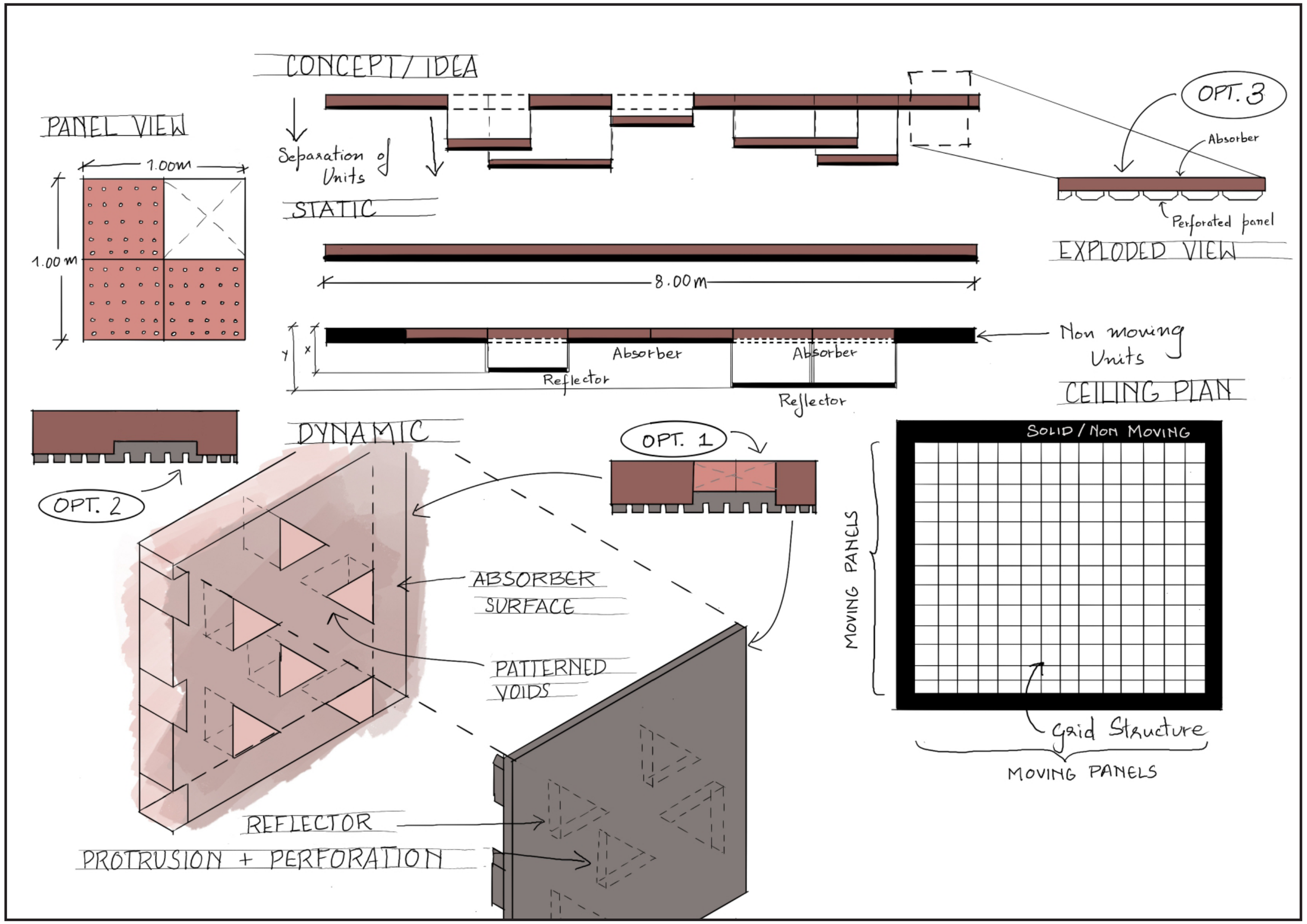


Image 5.3 [illustration]: Raghunathan, M. (2023). *Design Option #2*

5.2.3 Option #3

Mechanism: Deployable
Module Size: Variable
Design Principle: 2

This design is based on the concept of expanding tables. Just as a (specifically designed) table can be extended to accommodate more users, these panels can also expand to reveal more absorber or reflector material, chosen in accordance with the requirements and sound profile of the room.

Advantages

- Mimics design of existing acoustic panels
- Can contain more absorber/reflector material than a standard panel
- Can create absorbent and reverberant sections
- Aesthetically interesting

Disadvantages

- Requires a user intuitive interface for optimal usage and performance
- Need not be modular

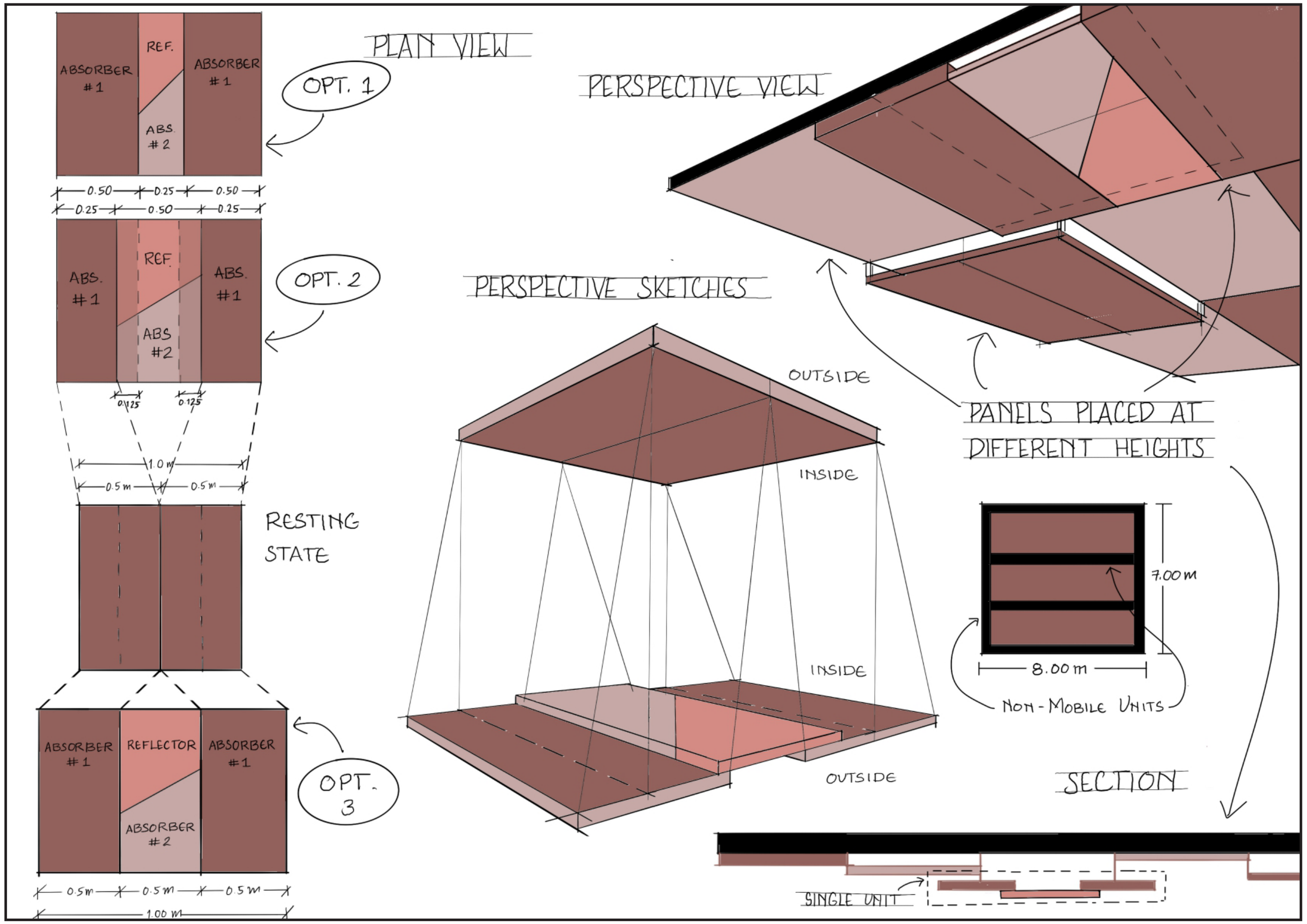


Image 5.4 [illustration]: Raghunathan, M. (2023). *Design Option #4*

5.2.4 Option #4
Mechanism: Deployable - Hinge
Module Size: 0.9 x 0.9 m
Design Principle: 3

This proposal is based on the concept of pop-out pockets. If the panel has pockets that can be 'popped' out, then by the strategic placement of absorber or reflector on the inner surface of the popped out panel, the sound waves can be 'trapped' as required.

The idea is that by 'popping' out these units, the amount of absorptive surface area can be increased while also using the angle of the open unit to optimally target incoming sound waves.

Advantages
- Mimics design of existing acoustic panels
- Can contain more absorber/reflector material than a standard panel
- Easy replace-ability

Disadvantages
- Requires a user intuitive interface for optimal usage and performance
- Many moving parts
- Aesthetically minimal

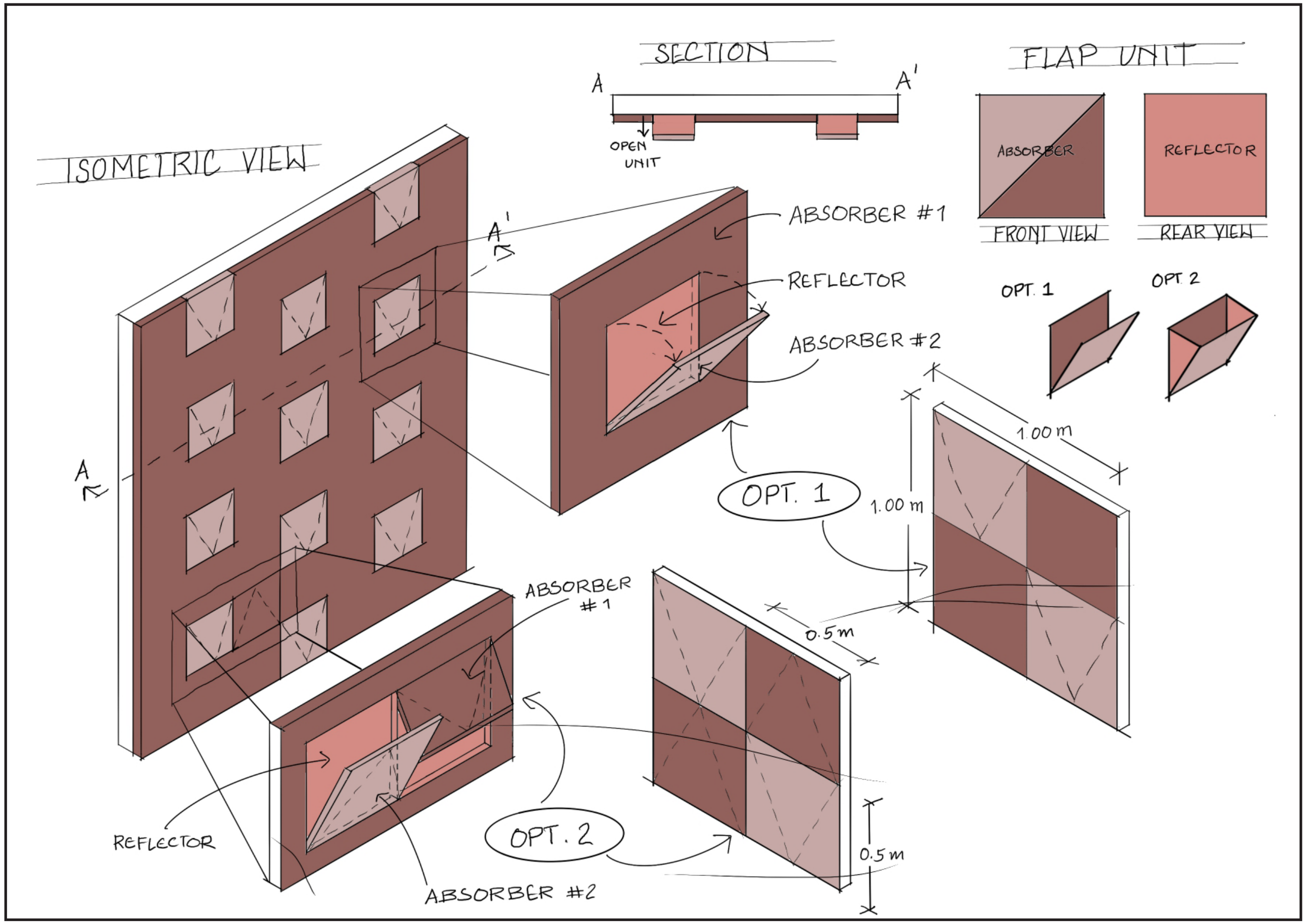


Image 5.5 [illustration]: Raghunathan, M. (2023). *Design Option #4*

5.2.5 Option #5
Mechanism: Deployable - rolling
Module Size: Variable
Design Principle: 2

This design is conceptualised based on the (automated) curtain systems and external blinds. Two rails on either side of the panel house tracks that slide the acoustic textile back and forth, much like a curtain, revealing the reflector plate hidden behind it.
This results in an adjustable sound profile that is heavily dependent on the extent of visible reflector plates.

Advantages
- Simple mechanism
- Can use existing methods of acoustic panel installation
- Can create absorbent and reverberant sections
- Aesthetically interesting
- Replaceable and modular

Disadvantages
- Requires a user intuitive interface for optimal usage and performance
- Drives up cost of material
- Maintenance of acoustic textile could be a problem

QUICK NOTE

The early design elaboration and illustration is available under "Appendix 04 - Proposed Design Elaboration". It goes over the initial thought process of function and mechanism.

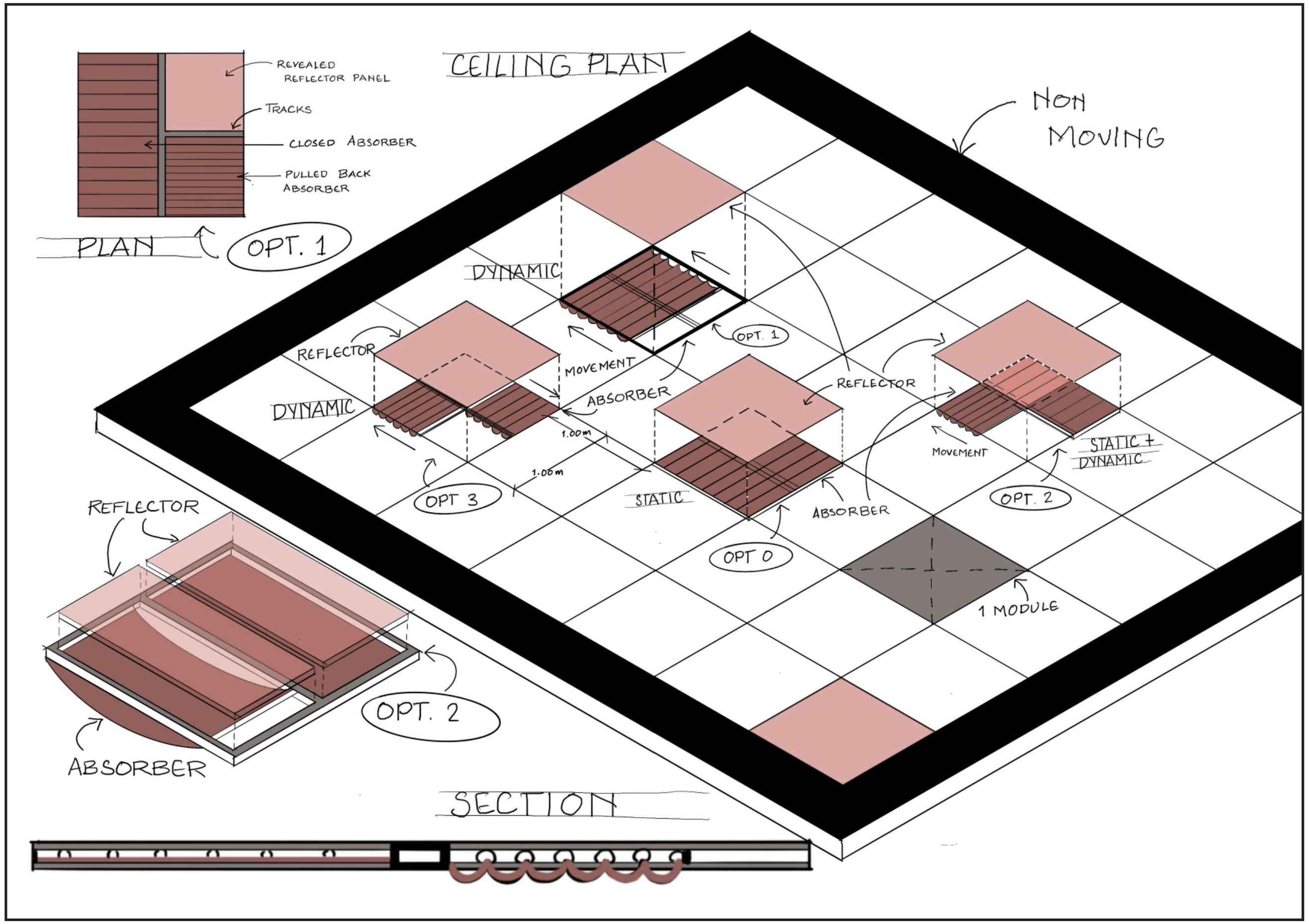
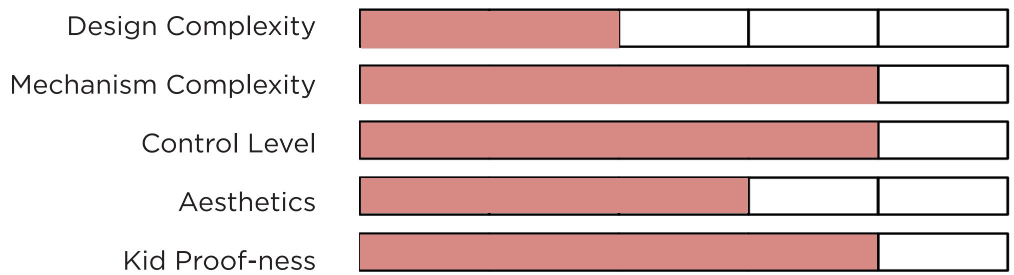


Image 5.6 [illustration]: Raghunathan, M. (2023). *Design Option #5*



5.2.6 Option #6

Mechanism: Sliding
Module Size: 0.9 x 0.9 m
Design Principle: 3

This design is conceptualised based on one question. The sound profile of a room is usually influenced by the combination of absorbers and reflectors in a room. The planes that come together to form a room remain static. So, what happens if we can control the profile of a ceiling?

The panel is made up of smaller cubes that move relative to each other, allowing a user to create multiple ceiling profiles using a single system. Additionally, each 'cube' can also vary in terms of its contents (as indicated in the image), allowing vast control over the adaptability of sound in a room.

Advantages

- Aesthetically interesting
- Replaceable and modular
- High level of control offered to user

Disadvantages

- Complex mechanism
- Complex production and usage
- Maintenance could be a problem

AUTHOR'S NOTE 02

The ideation of this design brought up an interesting question. Why should the other interventions be installed on a flat ceiling? This thought is elaborated in the next chapter.

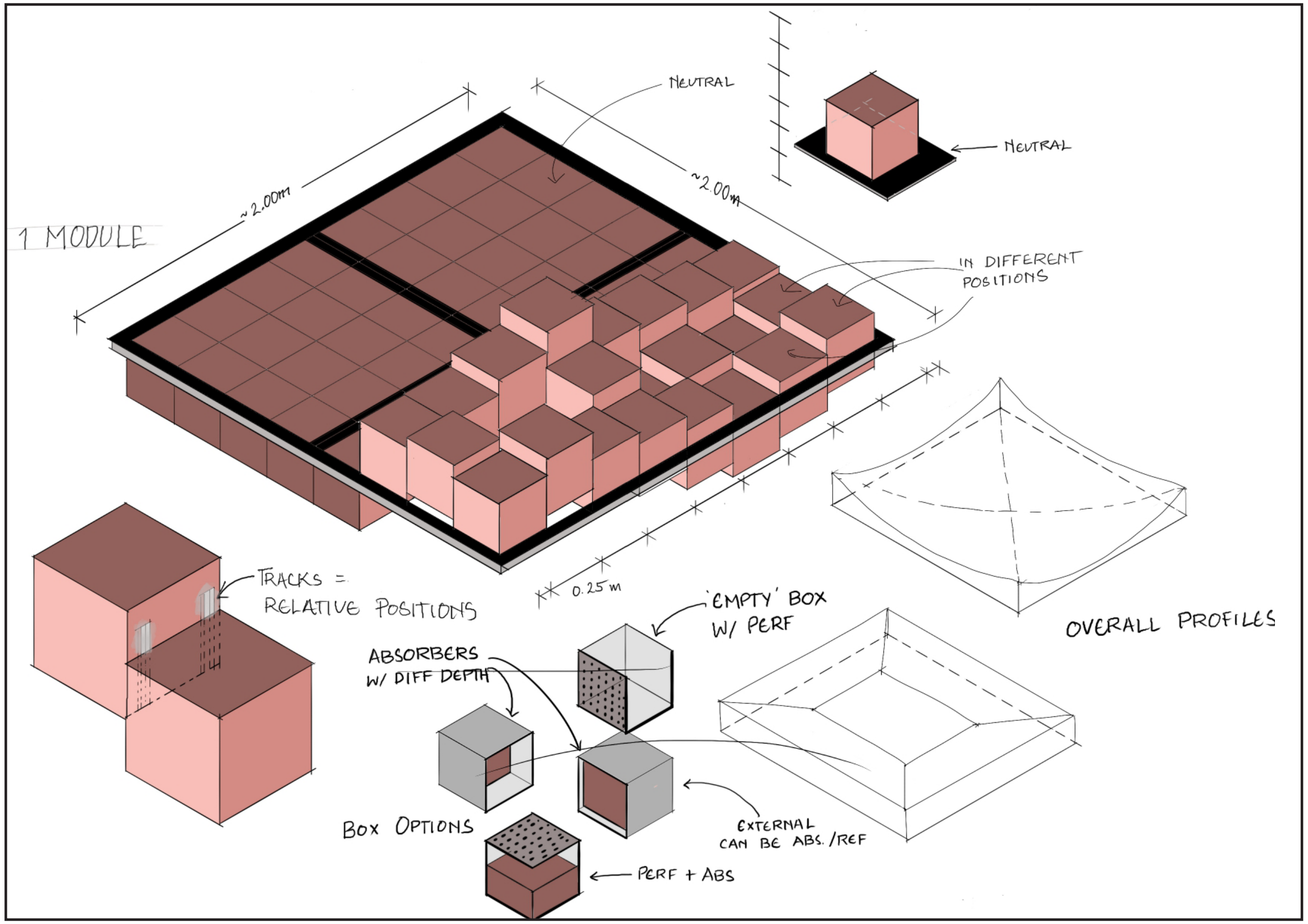


Image 5.7 [illustration]: Raghunathan, M. (2023). *Design Option #6*

5.2.7 Option #7
Mechanism: Pivot
Module Size: 0.9 x 0.9 m
Design Principle: 3

The proposal explores the idea of multiple acoustic materials encased in a singular geometry; enabling it to be rotated in order to be revealed. This option allows for multiple acoustic profiles for a singular space.

Advantages
- Simple mechanism
- Can use existing methods of acoustic panel installation
- Can create absorbent and reverberant sections
- Replaceable and modular
- Can effectively double the amount of acoustic material in a space
- Flexible base geometry
- Flexible installation
- Customisable modules

Disadvantages
- Increases material cost
- Aesthetically neutral
- Could have too many small moving parts
- Could need large scale control instead of control at user level

QUICK NOTE

The early design elaboration and illustration is available under “Appendix 04 - Proposed Design Elaboration”. It goes over the initial thought process of function and mechanism.

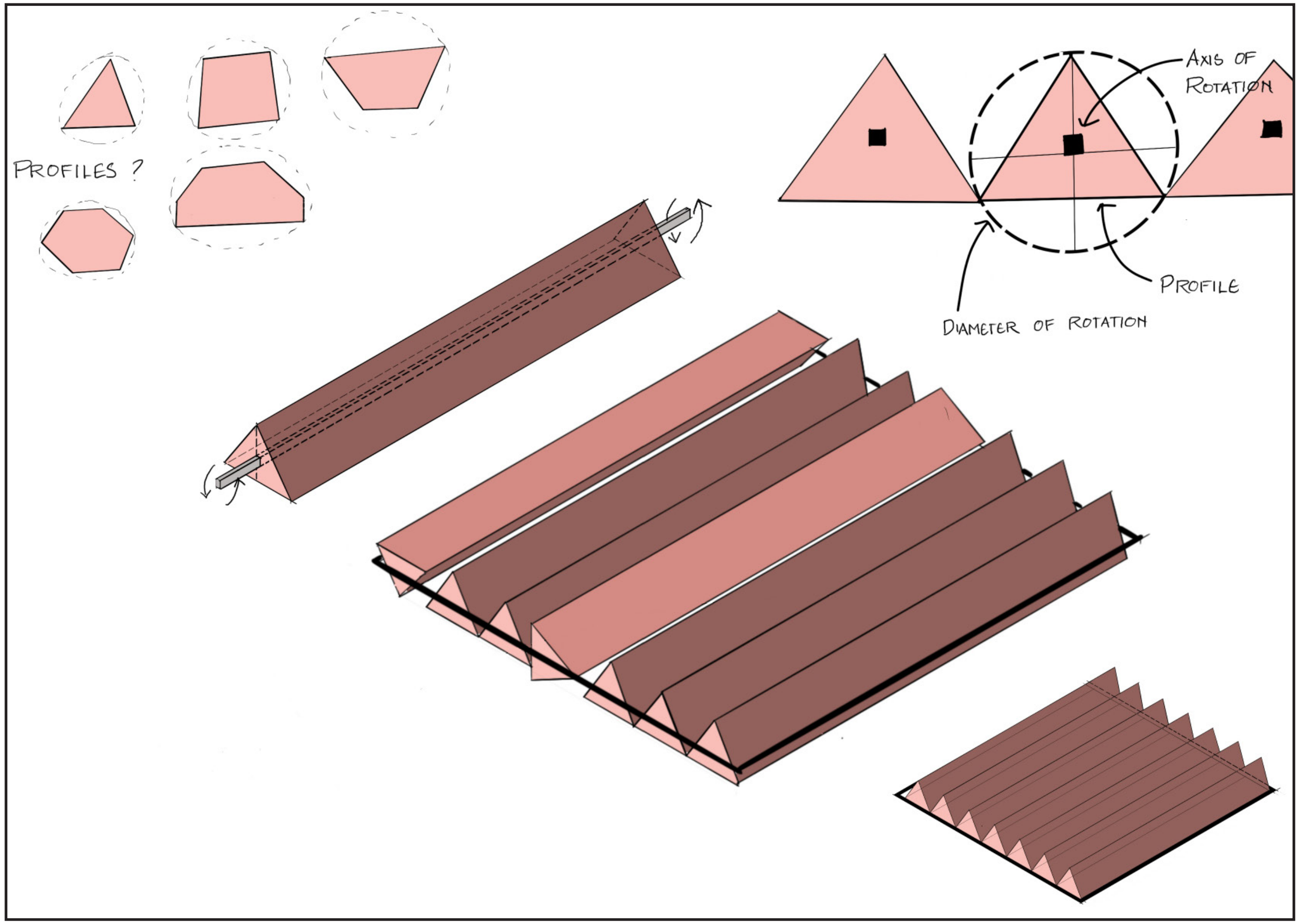
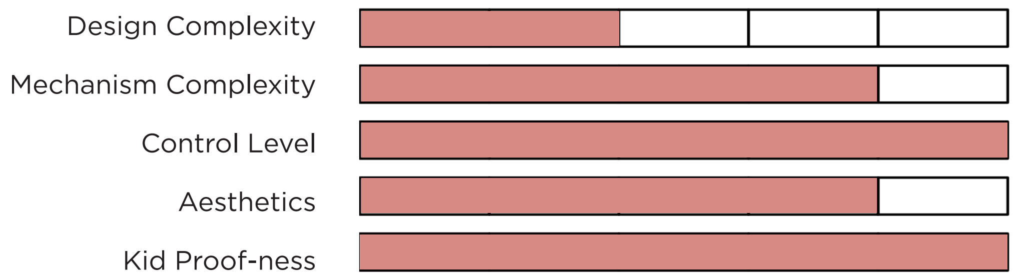


Image 5.8 [illustration]: Raghunathan, M. (2023). *Design Option #7*



5.2.8 Option #8
Mechanism: Deployable - rolling
Module Size: Variable
Design Principle: 2

This design is also based on curtain systems. It integrates the concept of curtains with the appearance of baffles. If these baffles have punctures in geometry and these baffles can then be moved on a set track, the combination of various perforations and solids will allow for the attenuation of direct sound.

Advantages
- Simple mechanism
- Can use existing methods of acoustic baffle installation
- Aesthetically interesting
- Replaceable and modular

Disadvantages
- Limited effect on sound profile of room
- Targets mostly direct sound
- Cannot provide more absorbent or reflective material

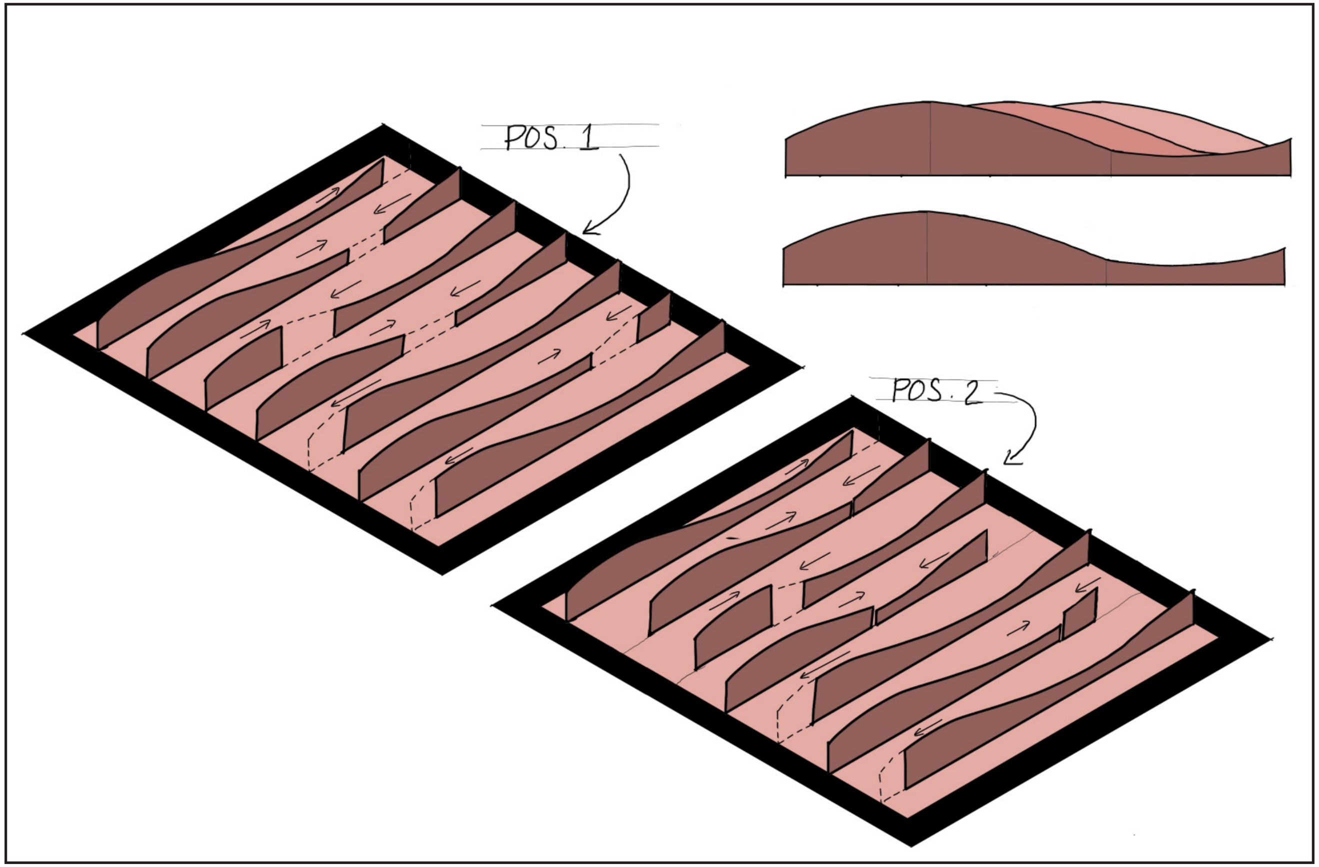
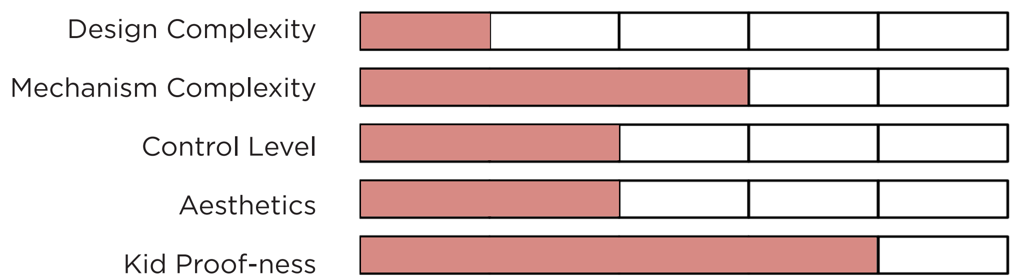


Image 5.9 [illustration]: Raghunathan, M. (2023). *Design Option #8*



5.2.9 Option #9
Mechanism: Deployable - rolling
Module Size: Variable
Design Principle: 3

This design is conceptualised based on a single directional rotational system. The system consists of 3 plates; 1st - a reflector plate, 2nd - absorber plate 1, and 3rd - absorber plate 2. The absorber plates themselves are split into 4 quadrants. There are 2 patterns of absorber material alternated over the quadrants - one more solid and one with more voids. The bottom most plate has the same pattern in the same order as the plate above. It is also the only rotational plate. Position 1 will allow the solids of both plates and the voids of both plates to overlap, revealing most of the reflector plate at the top (creating a more reflective space). Position 2 will require the bottom plate to rotate by 90 degrees. This will result in the solid of the middle plate to overlap with the void of the lower plate; least visibility of the reflector plate (thus, creating a more absorbent space).

Advantages
- Simple mechanism
- Can use existing methods of acoustic panel installation
- Can create absorbent and reverberant sections
- Replaceable and modular
- Can have localised and large-scale control

Disadvantages
- Drives up cost of material
- May not be user intuitive
- Aesthetically neutral

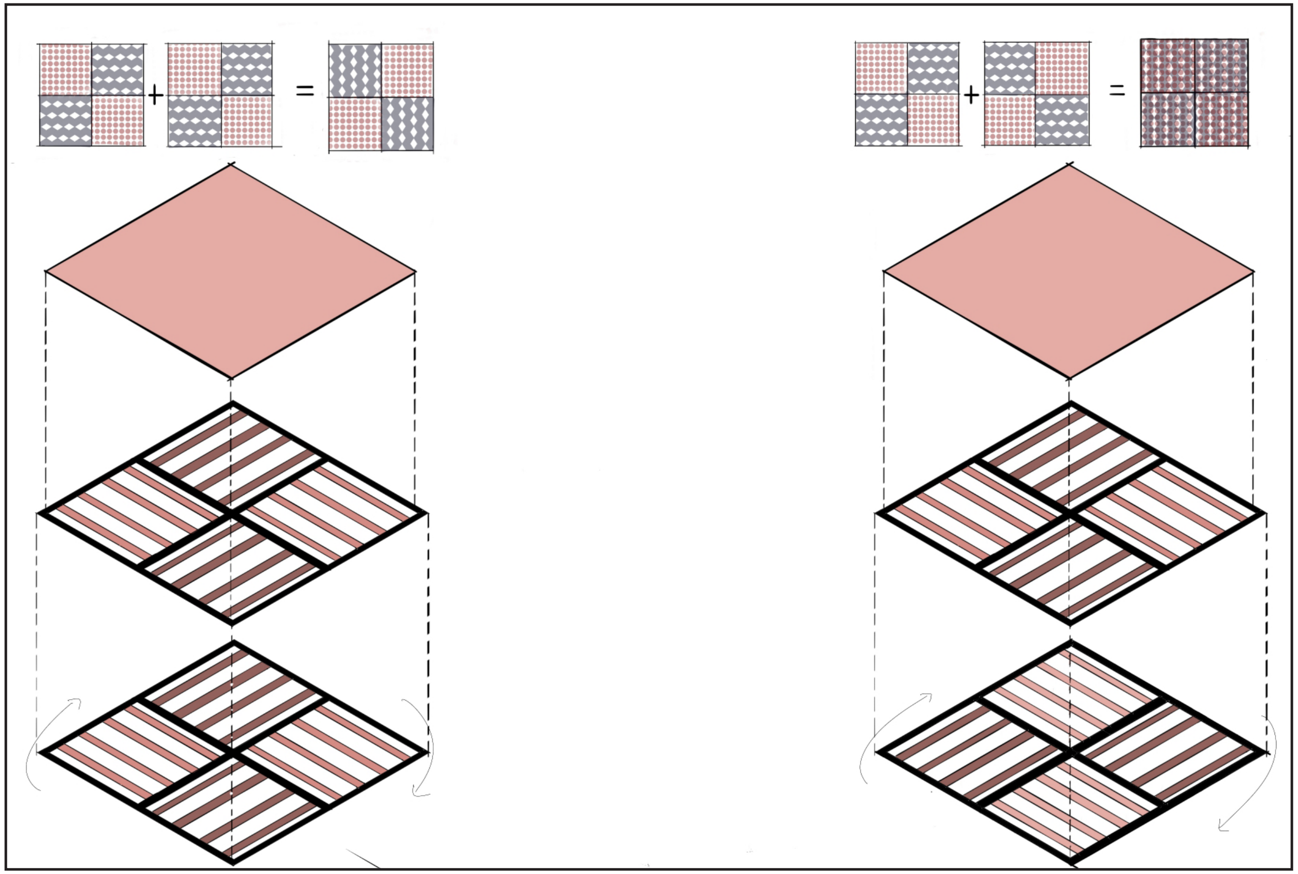


Image 5.10 [illustration]: Raghunathan, M. (2023). *Design Option #10*

5.2.10 Option #10
Mechanism: Deployable
Module Size: Design dependent
Design Principle: 3

This design is mostly just conceptual. It explores the concept of solids and voids as absorbers and reflectors respectively. It then adds the dimension of isolated control of the 2 types of acoustic interventions considered.

The design on the adjacent page (option 11) adds another aspect to the above; foldable geometry. This design in specific, has been developed by engineers at BYUCMR in an effort to explore the applications of origami engineering in designing solar arrays for space crafts. This design is also ideal for acoustic panel installations. It allows for a varying combination of absorbers and reflectors contained in a smaller footprint.

Advantages
- Simple mechanism
- Can use existing methods of acoustic panel installation
- Can create flexible absorbent and reverberant sections
- Aesthetically interesting
- Replaceable and modular
- Can be controlled at various scales

Disadvantages
- Could need a user intuitive interface for optimal usage and performance
- Drives up cost of material and production
- Maintenance of acoustic panel could be a problem

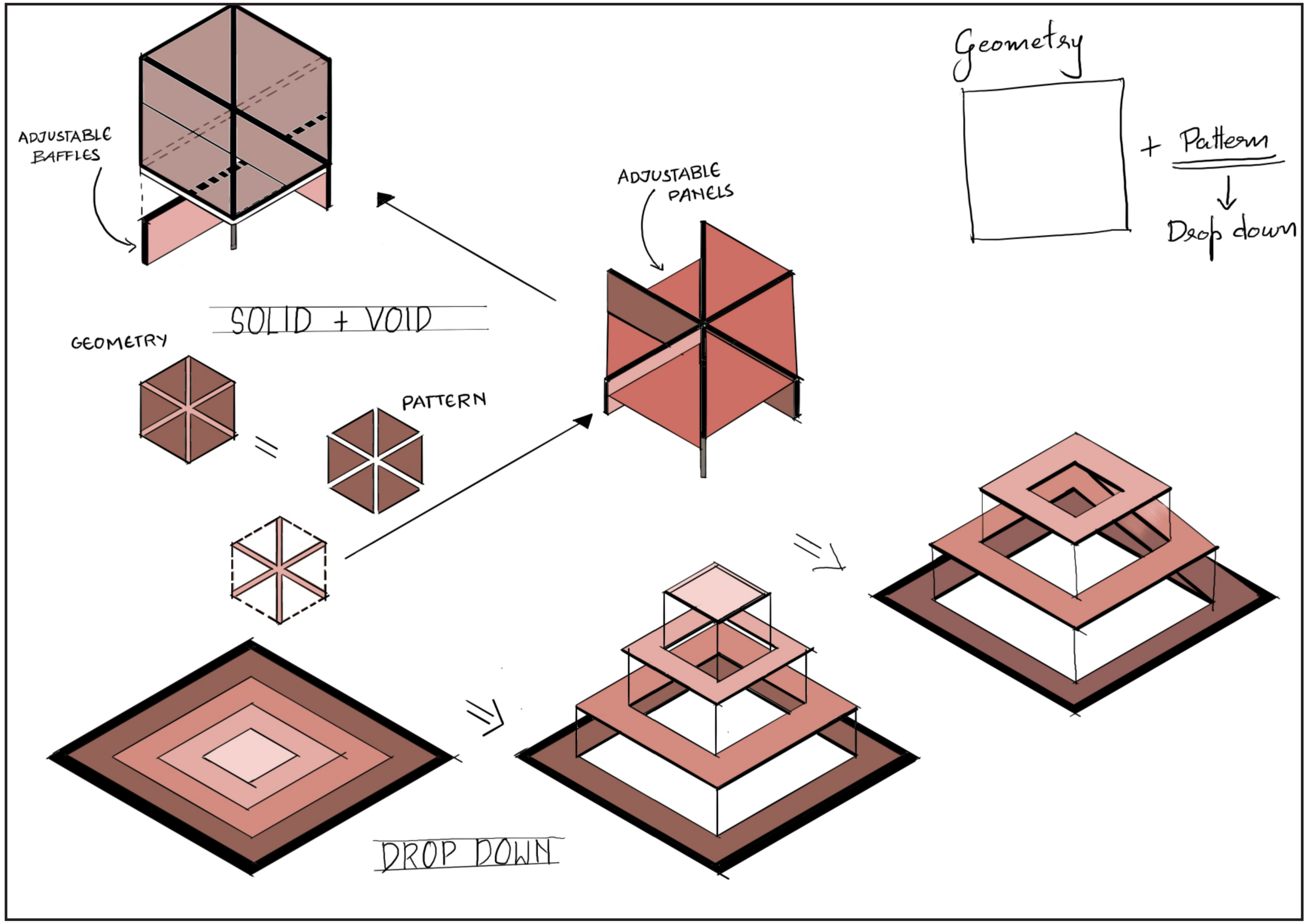


Image 5.11 [illustration]: Raghunathan, M. (2023). *Design Option #11*

5.2.11 Option #11

Mechanism: Deployable
Module Size: Design dependent
Design Principle: 3

The design on the adjacent page (option 11) adds another aspect to the previous; foldable geometry. This design in specific, has been developed by engineers at BYUCMR in an effort to explore the applications of origami engineering in designing solar arrays for space crafts. This design is also ideal for acoustic panel installations. It allows for a varying combination of absorbers and reflectors contained in a smaller footprint.

Advantages

- Easy to use
- Aesthetically interesting
- Replaceable and modular
- Can be controlled at various scales

Disadvantages

- Could need a user intuitive interface for optimal usage and performance
- Drives up cost of material and production

AUTHOR'S NOTE 03

Design 11 is also a combination of the concepts seen in option 3 (opening and deploying of more acoustic material) and option 10 (balance of absorbers and reflectors based on the approach of solids and voids). It in combination with the origami engineered deployment, makes for an ideal acoustic product.

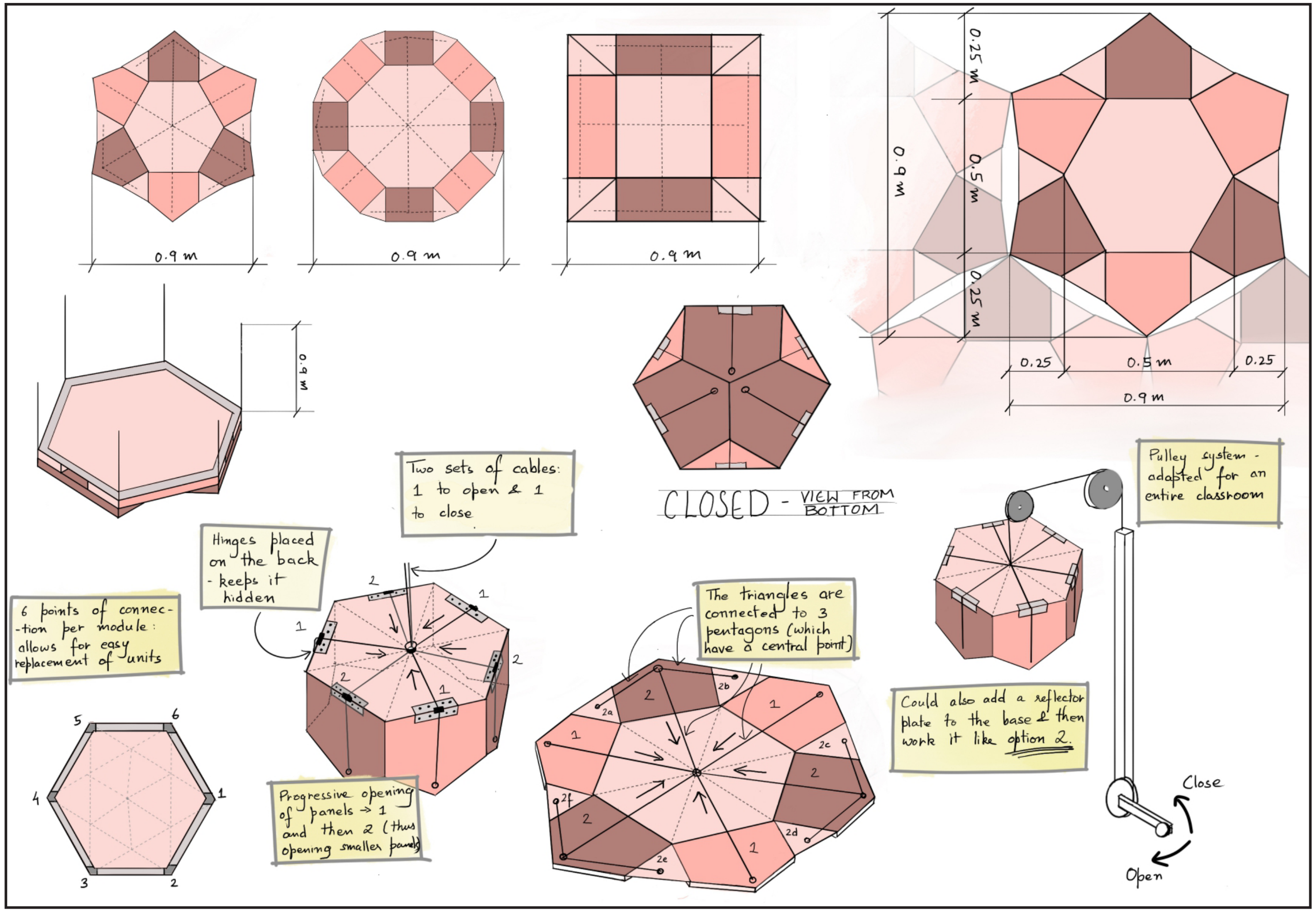
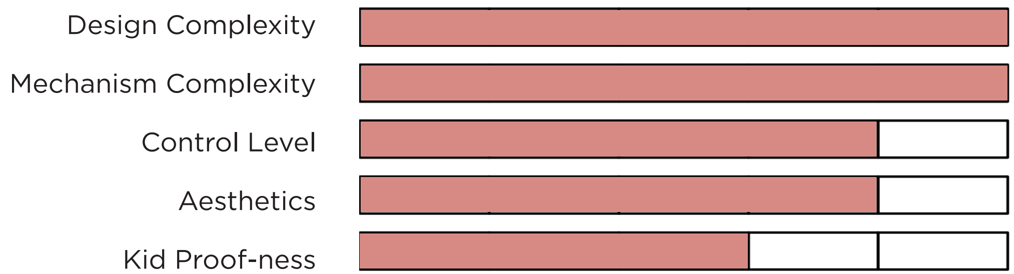


Image 5.12 [illustration]: Raghunathan, M. (2023). *Design Option #12*



Pre-Simulation																		
Options	General							Acoustic Factors				Scenario				Kid Proof-ness	Overall Score
	Mechanics	Control Level	Configuration	Aesthetics	Module Size	Design Complexity	Mechanism Complexity	No. of Materials	Absorption 1 (per module)	Absorption 2 (per module)	Reflector (per module)	1	2	3	4		
1	Hinge	3		1		1	4	2	1 sq. m.	n/a	1 sq. m.	4	1	4	4	3	2.86
2	Push/Pull	3		2		3	5	2	1 sq. m.	n/a	1 sq. m.	2	3	3	4	3	2.86
3	Push/Pull	3		3		4	4	2	1 sq. m.	n/a	0.5 - 0.8 sq. m.	2	3	3	4	4	3.14
4	Push/Pull	4		4		3	3	2 - 3	1 sq. m.	n/a	0.5 sq. m.	3	4	3	4	5	3.86
5	Push/Pull	4		3		2	3	2	0.5 - 1 sq. m.	0.5 sq. m.	0.5 sq. m.	3	2	3	3	3	3
6	Push/Pull	5	Modules	5	0.9 x 0.9 m	5	5	3+	1 sq. m.	1+ sq. m.	1+ sq. m.	4	4	4	5	5	4.57
7	Rotation	5		4		2	4	3	1 sq. m.	1 sq. m.	1 sq. m.	5	4	4	4	5	4.25
8	Sliding	2		2		1	4	1	n/a	n/a	n/a	2	1	1	1	4	1.86
9	Rotation	3		2		1	5	3	0.5 sq. m.	0.5 sq. m.	1 sq. m.	3	2	2	3	5	2.88
10	Push/Pull	4		4		4	5	2 - 3	n/a	n/a	n/a	4	3	4	5	2	3.71
11	Deployment	4		4		5	2	2	n/a	n/a	n/a	3	3	3	3	3	3.29

Table 5.1 [data table]: Raghunathan, M. (2023). *Design Option Comparison; On the right, the data legend*

1	2	3	4	5
Bad	Ok	Neutral	Good	Best

5.3 Design Selection

The designs are analysed based on both, quantitative and qualitative factors that fall under a variety of topics: system design, geometry requirements, acoustic factors, and implementability. It is important to note that this assessment is subjective and is merely a method of short-listing viable designs for this thesis.

The categories used for assessing are as follows:
1. Control level
2. Aesthetics
3. Design Complexity
4. Mechanism Complexity
5. Applicability in the different scenarios
6. Kid Proofness

The factors are assigned values from 1 to 5 with 1 being 'bad' and 5 being 'good'. In the case of the design and mechanism complexity, the values work in reverse. The closer the number is to 5, the more 'negative'it is.
The values are then averaged and compared in order to find the design options that are most viable for further development.

This process revealed that design options number 6 and number 7 are most likely to be viable for future development. It is at this point, that the values assigned to design and mechanism complexity come into play. Upon comparison, it is seen that the design option 6 might be too complex for the current requirements.

Why does the complexity matter?
If the design and mechanism are too complex, it causes problems in production, cost and affordability, maintenance. and replaceability. It is important, as a designer and engineer, to take into consideration the location of intervention and account for the same.
Thus, the option finalised for further development is option number 7.

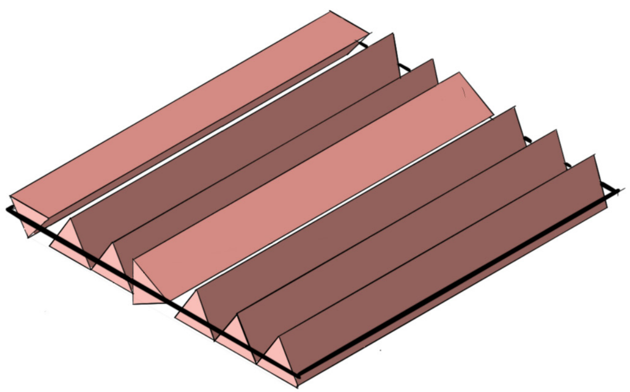


Image 5.13 [illustration]: Raghunathan, M. (2023). *Design Option #7 - Chosen design*

5.4 Design Development

The design has to take multiple factors into account at this stage.

The primary requirements for the design:

1. Have the different sides of the design interact with sound in a different way. For example, side 'A' of the triangle (on the right) could have absorption material 'A', side 'B' contain absorption material 'B', and have side 'C' act as a reflector.

2. This leads us to our next requirement. The design needs to be easily rotatable so that the different sides with the different materials can be 'exposed' (to the classroom) and utilised to its fullest extent.

3. Since there could be a requirement for acoustic intervention to cover the entire ceiling, the design also needs to be flexible enough to accommodate HVAC, lighting, and fire safety fixtures.

4. Easy production and installation. This design is intended for an education space. This means that the design cannot be complex to produce or install. Additionally, it is beneficial if popular mechanisms are utilised in the designing of the system.

The design also is sized keeping in mind the standard industry sizes *24" x 24", 24" x 48") for acoustic products to enable integration with existing systems.

Requirements of the Acoustic Behaviour of the Units:

1. One side 'A' should have peak absorption in the bass, speech frequencies of 125-500 Hz. This is to target excessively noisy classrooms during group sessions.

2. The other side, 'B', should be used as a default position of the unit. It should be used to bring the classroom down to the set acoustic standards (<0.8s RT, STI >0.75, Chapter 3).

3. The final side, 'C', the reflector is placed only in the required places. The placement of this is explored further in the next

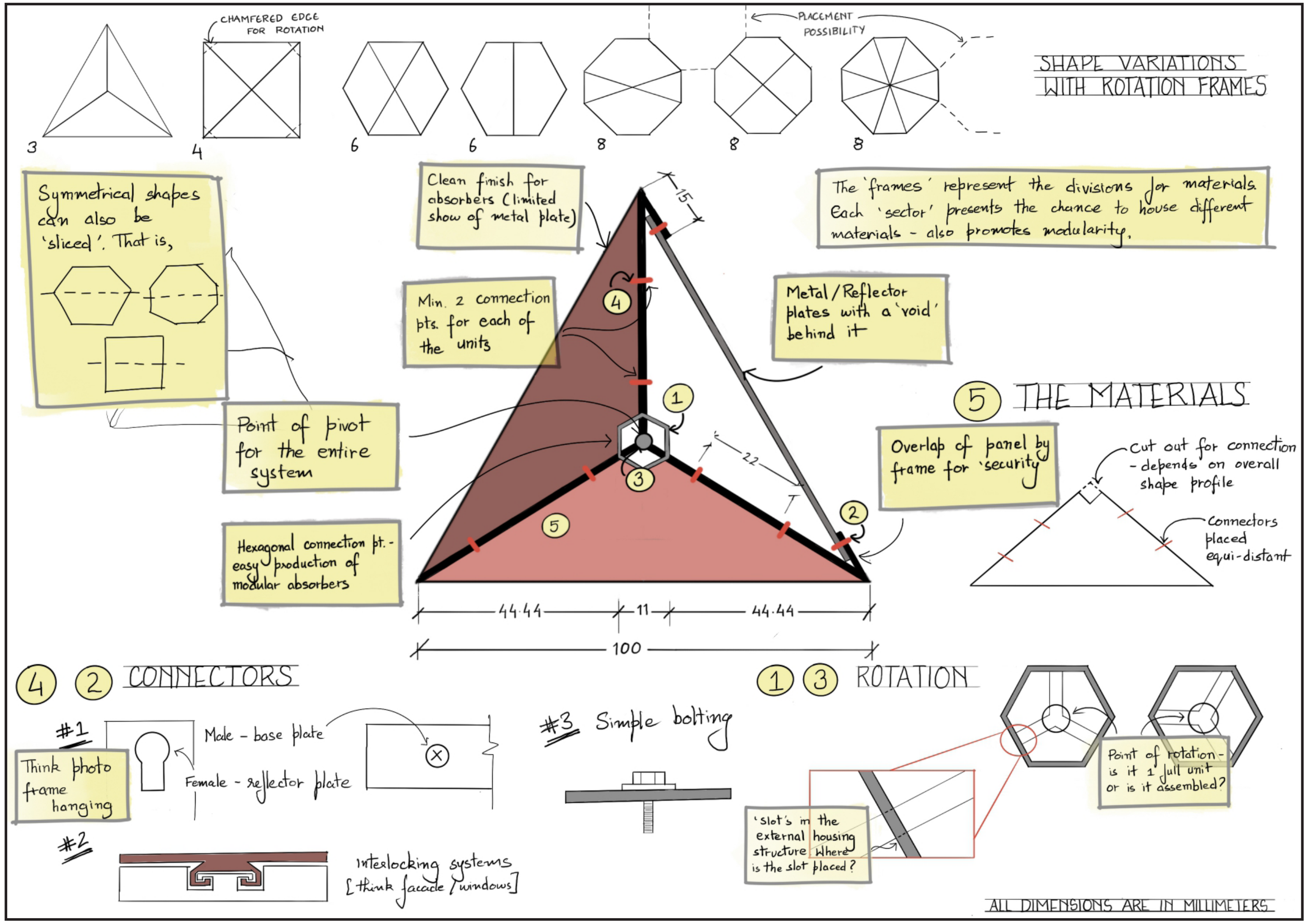


Image 5.14 [illustration/sketch]: Raghunathan, M. (2023). *Design Development stage 1, initial ideation and development of option 7.*

chapter (Chapter 06, The Impact of Ceiling on Room Acoustic Conditions, Section 6.6, part 6.6.3).

A concept seen previously in other designs (that is, a reflector plate in contact with an absorber, aids the behaviour of the absorber) makes its appearance once more. If there is an extruded metal triangle that can encompass and 'hold' the absorber in place within, it will aid in the stability of the unit overall. The metal extrusion can be perforated to different extents to manipulate the behaviour of the material within.

In order to estimate this, an excel made in accordance with information from Trevor Cox and Peter D'Antonio's book 'Acoustic Absorbers and Diffusers' is used, particularly the sheet regarding calculation of behaviour of perforated panels.

To determine the absorption behaviour of one triangular unit, the absorption of each 'section' of the triangle has to be individually accounted for and then compiled.

From this investigation (Table 5.2), it is evident that while it is possible to achieve optimal values for a peak absorption in the higher frequencies [1000 Hz and above], the values achieved for peak absorption in the bass frequencies are less than optimal. This means that the idea of perforations in the external housing structure must be revisited and refined for it to meet the requirements. The top three options are as listed in the table. The first option is chosen as the ideal combination of hole radius and repeat distance for one of the three sides of the design.

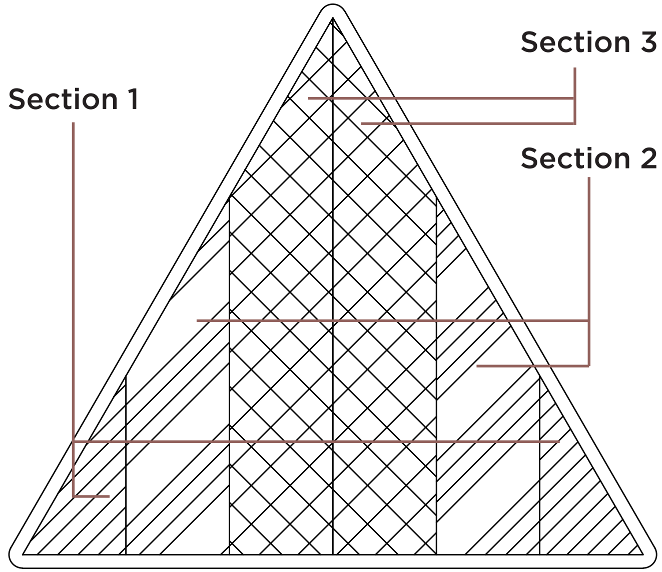


Image 5.15 [drawing]: Raghunathan, M. (2023). *The sections created in a unit of the proposed design to better estimate the acoustic performance of the unit as a whole.*

Table 5.2 [data table]: Raghunathan, M. (2023). *Various considerations for perforations of the external plate of the unit*

Section	Avg. Depth	Panel Properties				Absorber Flow Resistivity [rayls/m]	Frequencies						Avg. Absorption	Peak Absorption
		Thickness	Repeat Distance	Hole Radius	Open Area %		125	250	500	1000	2000	4000		
1	19.74	2	13	3	17%	22939	0	0	0.08	0.27	0.67	0.87	0.32	1000-4000 Hz
2	59.23						0.04	0.19	0.5	0.89	0.96	0.68	0.54	
3	98.71						0.17	0.41	0.76	0.95	0.95	0.68	0.65	
Avg. Absorption							0.07	0.2	0.45	0.7	0.86	0.74	0.5	
Section	Avg. Depth	Panel Properties				Absorber Flow Resistivity [rayls/m]	Frequencies						Avg. Absorption	Peak Absorption
		Thickness	Repeat Distance	Hole Radius	Open Area %		125	250	500	1000	2000	4000		
1	19.74	2	17.5	1	1%	22939	0	0	0.1	0.49	0.13	0.01	0.12	250-1000 Hz
2	59.23						0.04	0.23	0.76	0.26	0.06	0.02	0.23	
3	98.71						0.19	0.58	0.71	0.23	0.06	0	0.3	
Avg. Absorption							0.08	0.27	0.52	0.33	0.08	0.01	0.22	
Section	Avg. Depth	Panel Properties				Absorber Flow Resistivity [rayls/m]	Frequencies						Avg. Absorption	Peak Absorption
		Thickness	Repeat Distance	Hole Radius	Open Area %		125	250	500	1000	2000	4000		
1	19.74	2	20	1	1%	22939	0	0	0.11	0.46	0.08	0	0.11	500 Hz
2	59.23						0.04	0.25	0.7	0.17	0.04	0	0.2	
3	98.71						0.19	0.63	0.55	0.15	0.04	0	0.26	
Avg. Absorption							0.08	0.29	0.45	0.26	0.05	0	0.19	

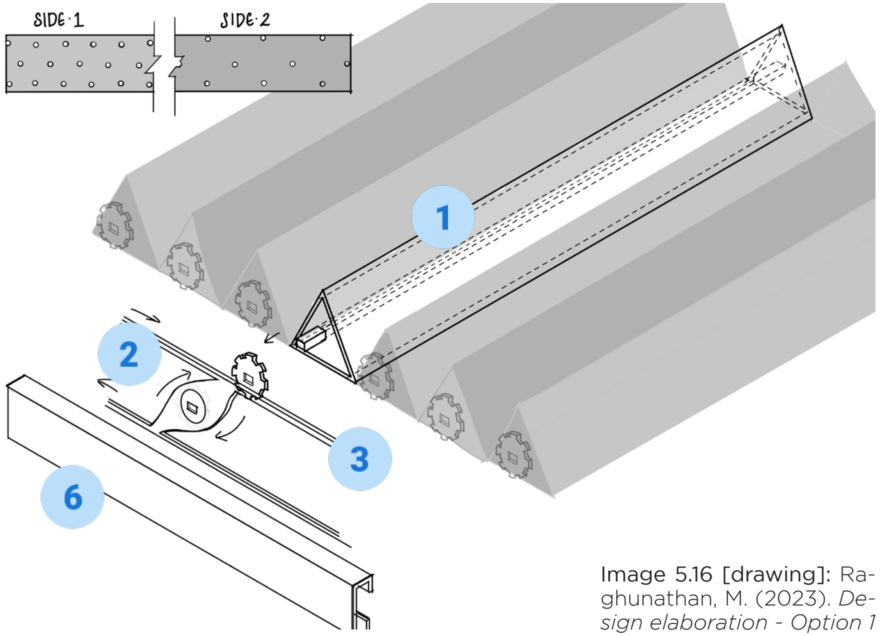


Image 5.16 [drawing]: Raghunathan, M. (2023). *Design elaboration - Option 1*

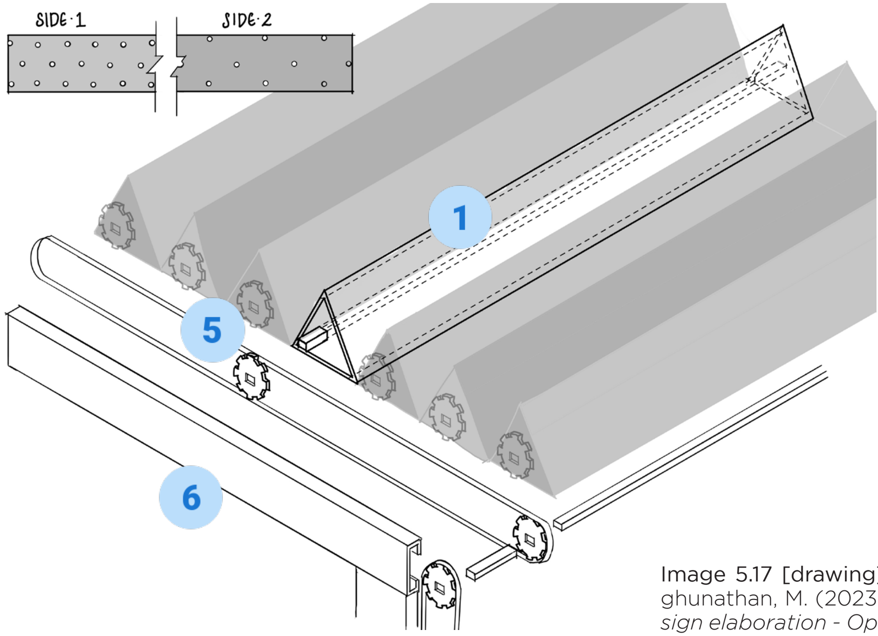
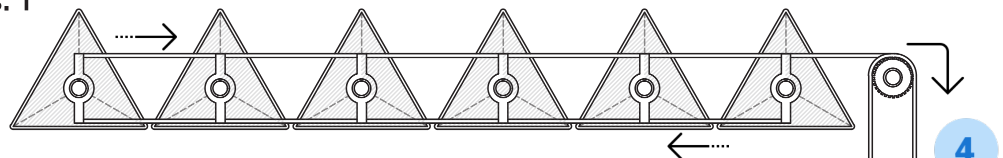
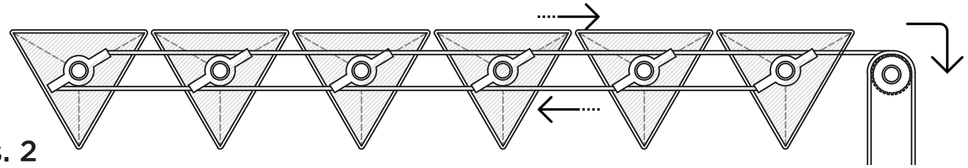


Image 5.17 [drawing]: Raghunathan, M. (2023). *Design elaboration - Option 2*

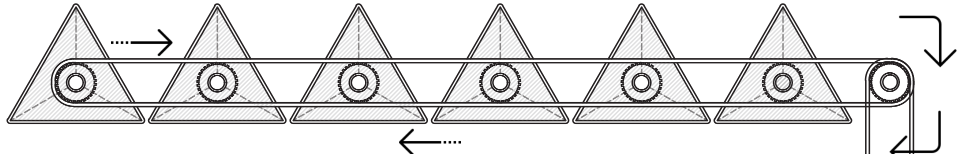
Pos. 1



The first option is to consider a 'pivot' system. Each unit (1) is connected to a rotational unit (2), which is in turn connected to 2 rods/belts (3). This is connected to a control gear with a belt in the vertical direction to allow for user control (much like drawing/shutting of blinds). The pulling of the rods causes the rotation unit to turn, thus turning the unit itself to expose a different surface. The degree of rotation determines the (amount of) surface revealed.



Pos. 2



The second option is to have the same central rod that runs through the units connect to a gear (5). A belt is then looped around all these gears. Much like the previous system, this then will loop around a control gear (4). This gear also connects to a vertical belt system where the user can control the movement of this system (like a curtain). Once again, the degree of rotation affects the extent of the surface revealed.

An external housing unit (6) covers the mechanism and acts as a point of connection for installation. At this stage, the housing unit is still quite bulky and would need to be further refined.

5.5 Finalised Design

The finalised design is as follows. An individual triangular unit has a rod running through the center of it. This rod is fed through a ball bearing joint, and then a gear. The ball bearing is encased in a frame that runs around the entire set of units. The frame also acts as a connector point to the ceiling. The gears are also connected to a central gear/rod. This gear has another belt running in the vertical plane that functions as the point of user control much like the drawstrings of a curtain.

The individual units are extruded, folded or assembled metals or reflector plates that encases an acoustic material within. The extent of material reveal on either side determines its acoustic performance. This is utilised by allowing the unit to rotate, allowing for the same product to create different acoustic conditions in the same room. The design is further elaborated on page 53.

The advantage of this design is that it can be easily adapted to the requirements of the space. The frame can be lengthened to accommodate lesser, more units or lengthier units. The central gear can also be used to control multiple modules at once. This makes it easy to install these units around other installations seen in a classroom (lighting, HVAC and fire safety), or around architectural/structural elements. Another advantage is that this system utilises existing as well as simple mechanisms to operate. This mechanism can also be easily motorised. Doing so would result in higher production costs as well as increasing the cost to users.

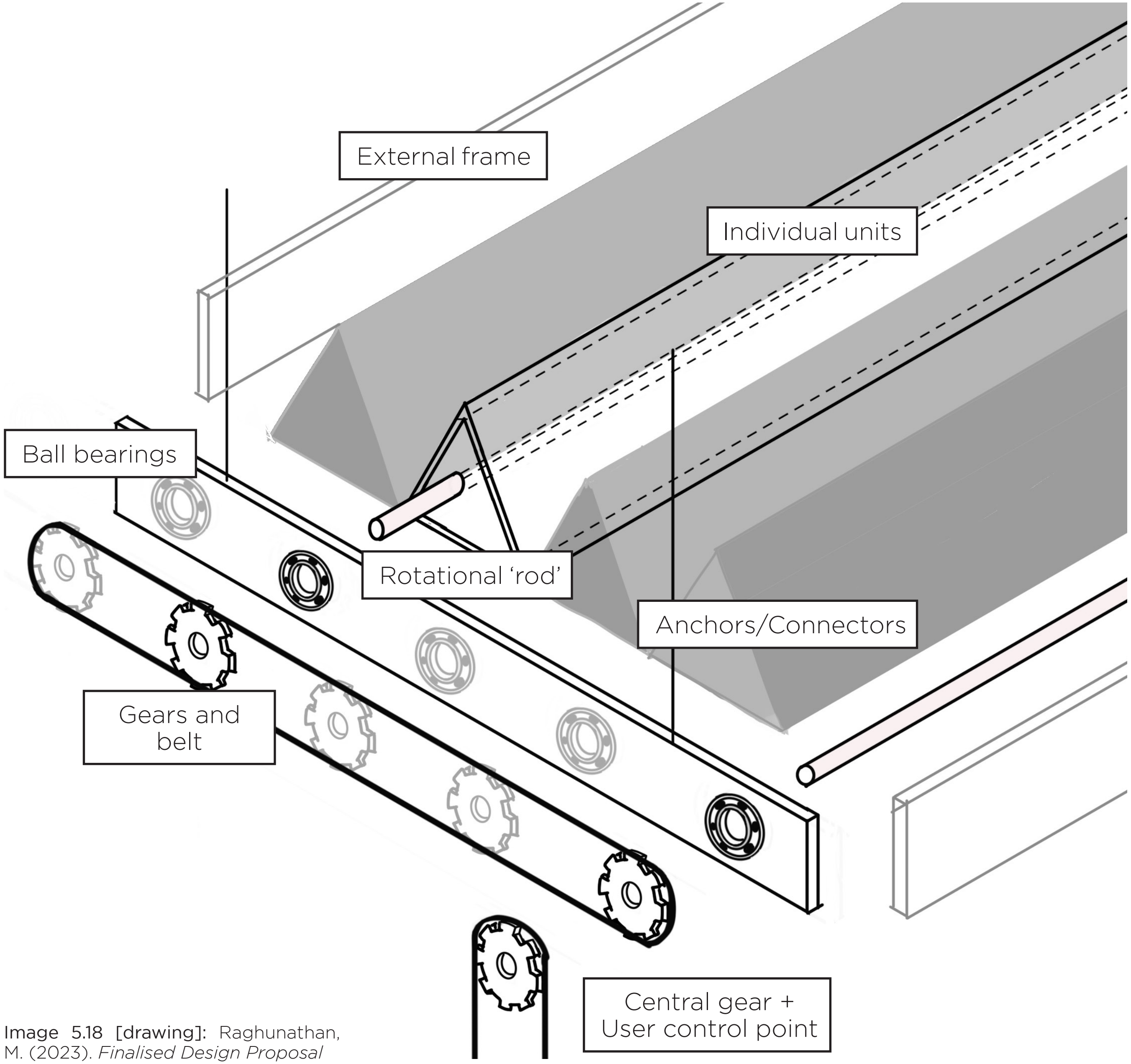
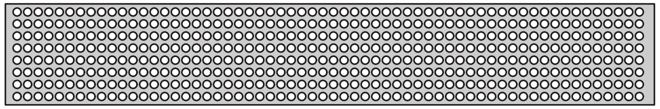


Image 5.18 [drawing]: Raghunathan, M. (2023). *Finalised Design Proposal*

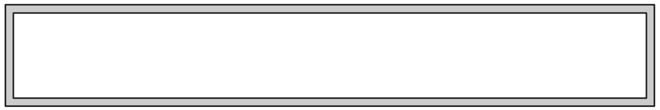
The Individual Units

Side ‘A’ is a reflector - that is, the surface enclosing the absorbing material is without perforations.

Side ‘B’ is an absorber with the peak absorption in the 500-1000 Hz frequency. This is brought about by perforating the exterior panel (hole radius - 3mm, repeat distance - 13 mm for an open area of 17%).



Side ‘C’ is an absorber that maximises the properties of the material itself. The extruded material is ‘cut out’ on this side, leaving enough to anchor the material to the system but not to cover the material in a way where it affects its acoustic properties (however, the material is covered by a thin mesh to prevent it from infiltrating the air in the classroom).



This approach to designing the units means that it can be additionally customised by varying the materials, the extent of perforations, and the combinations of absorbers, reflectors and diffusers. The design can also be changed by varying the base profile of the unit (the unit can be an octogon, hexagon, square, etc.).

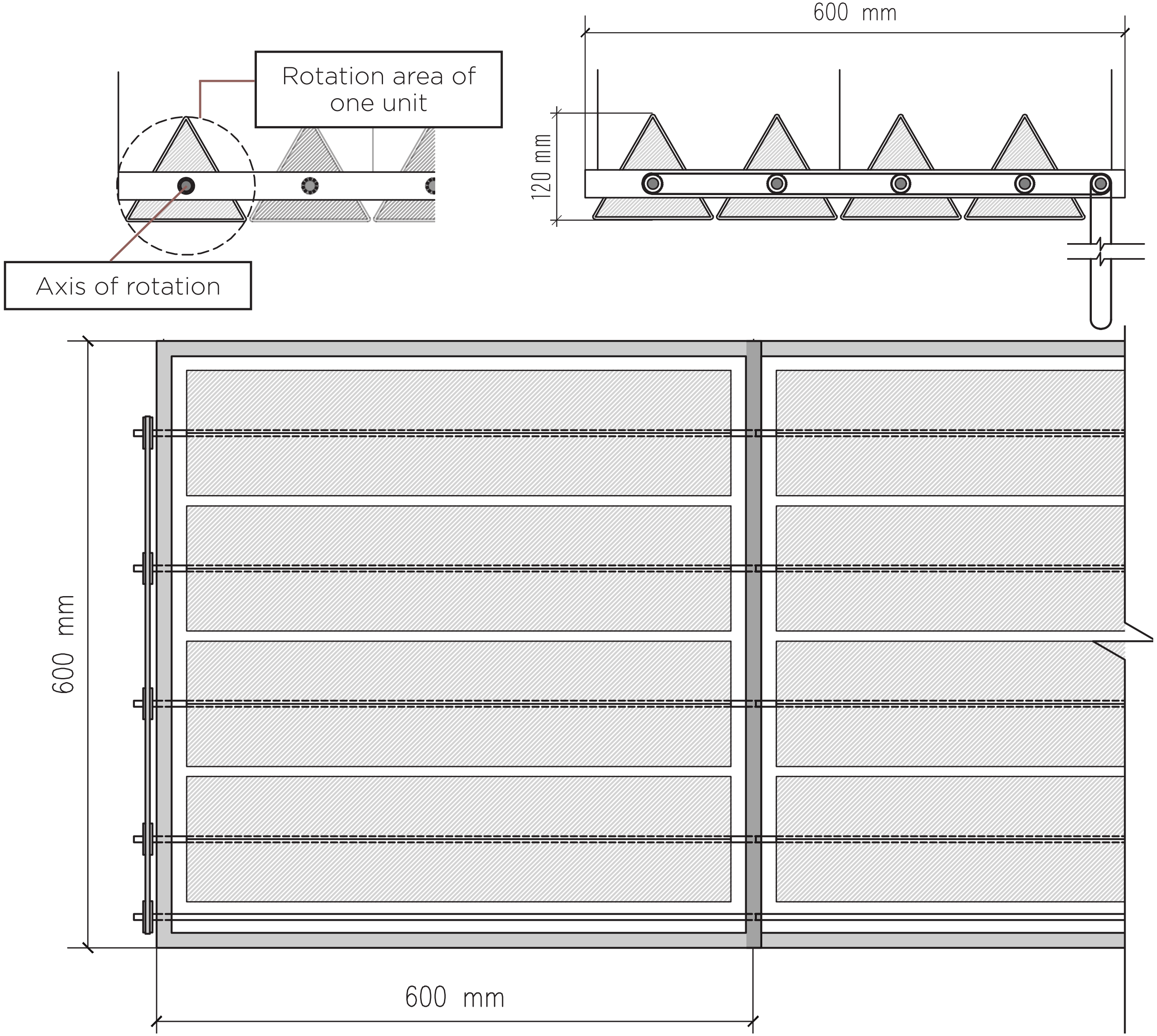


Image 5.19 [drawing]: Raghunathan, M. (2023). *AUTOCAD drawings showing the plan and side elevations of proposed design*

6.1 Introduction

A standard classroom consists of 6 planes: 4 walls, 1 ceiling, and 1 floor with the opposing planes being parallel. Acoustics is something that is dependant on both, geometry and materials. The latter has been maximised in offering acoustic solutions, so why hasn't the former?

Design option #6 brought up some interesting questions. The literature research has also established that the ceiling can make or break room acoustics. So why do we treat it as a static element and not a malleable architectural feature? Perhaps varying the placement and angle of acoustic panels could result in a better quality of sound. This chapter delves into the impact of ceiling profiles on room acoustic conditions and consequently impact of the placement of acoustic materials on the room conditions as well.

A small investigation was conducted into the impact of ceilings on room acoustics. Six ceilings were chosen based on the extent of their usage in the building industry. They are as follows:
- Flat
- Inverted
- Pitched
- Hip
- Convex
- Concave

This gives rise to the next question. Where do you place the pitch line? If ceilings have an impact on the room acoustics then surely the placement of the pitch line also matters. This resulted in subdivisions being created in order to arrive at reliable results. The pitch line or the radius (as applicable) were varied based on set criteria (as elaborated further on in the chapter).

The results are analysed based on the reverberation criterion T-30 and the speech quality factor C50. Each roof variation is also tested in the 4 distinct scenarios (Scenario 1,2,3 and 5; Refer to chapter 4, section 4.3). This allows the ceiling variations to be tested against and chosen based on the different situations a classroom hosts, giving us a better platform to choose the most optimal solution.

The variations considered are as follows (and as illustrated in image 6.1):
- Flat ceiling - no variations
- Inverted ceiling - 7
- Pitched ceiling - 7
- Hip ceiling - 4
- Convex ceiling - 2
- Concave ceiling - 2

6.1.1 Limitations
The effect of ceiling geometry on room acoustics and the optimisation of the same demands dedication akin to a thesis topic of its own. As this investigation is a part of a broader topic, certain limitations have to be placed on it to make it tackle-able.

1. The room height at the lowest point of the ceiling is restricted to 2.70 m.
2. As a follow up to the previous statement, the highest point of the room is limited to 3.00 m.
3. Popular roofs seen in architecture are analysed
4. Standard industry practices and approaches are given priority (such as ease of construction, installation).

The ceiling profiles are initially assessed using a surface receiver (set at 2.60 m) based on the reverberation time. The difference in results (at this stage) vary minimally between 2.60m and 1.20m. C50 is used as an additional filter or factor in choosing and understanding the quality of sound in the space.

The graphs seen later on in the chapter are better represented in Appendix 07.

AUTHOR'S NOTE 04

This is an interesting point of investigation. Since this forms a smaller part of the bigger picture in this thesis, certain assumptions had to be made to reduce the breadth of the study.
However, the conclusion simply establishes the better option of the current choices and is not indicative of the most optimal ceiling. Ceiling optimisation could result in further enhancement of room acoustics in a passive and yet effective manner.

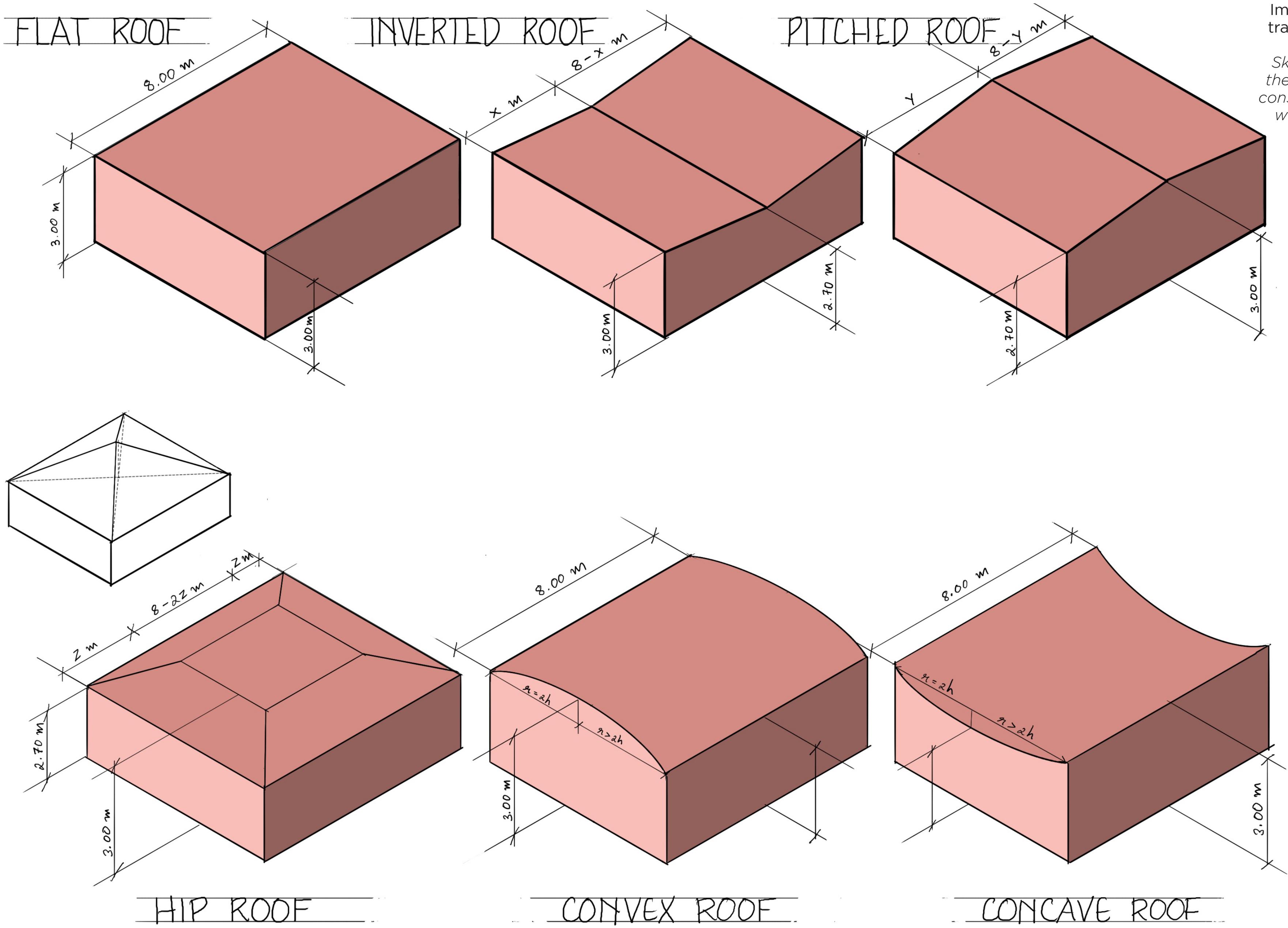


Image 6.1 [R, Illustration]: Raghunathan, M. (2023). *Sketches showing the ceiling types in consideration along with the variables considered*

6.2 Pitched Ceiling

6.2.1 Dimensions & Areas

Surface Area of

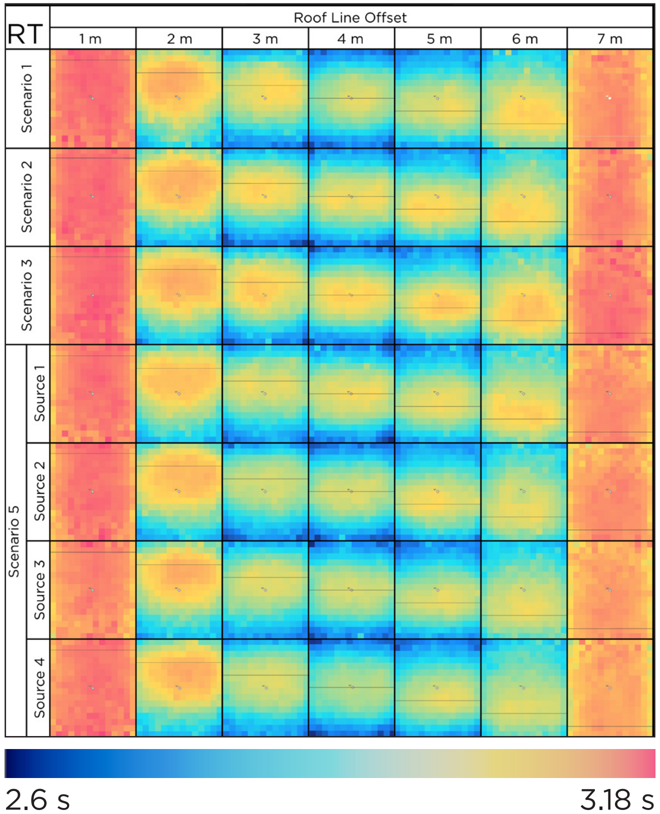
1. Long Walls = 22.8 m² each = 45.6 m²
2. Short Walls = 18.9 m² each = 37.8 m²
3. Floor = 56 m²
4. Ceiling = 56.4 m² (variants 1 & 7)
   56.2 m² (variants 2-6)

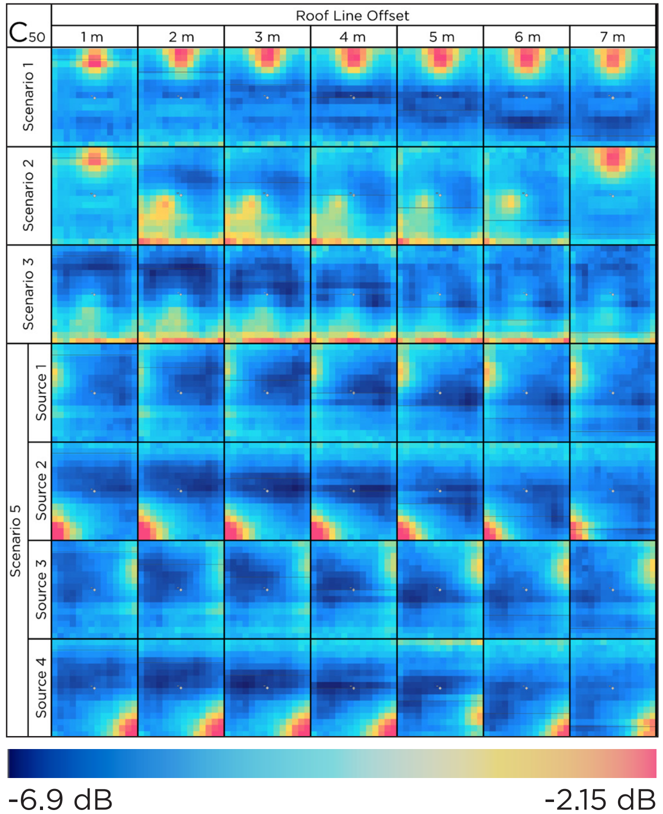
Total Surface Area = 195.8 m² (variants 1 & 7)
195.6 m² (variants 2-6)

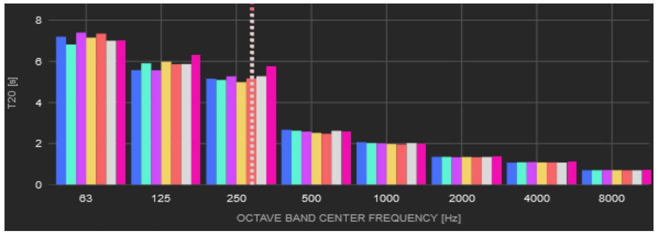
Total Volume = 159.6 m³

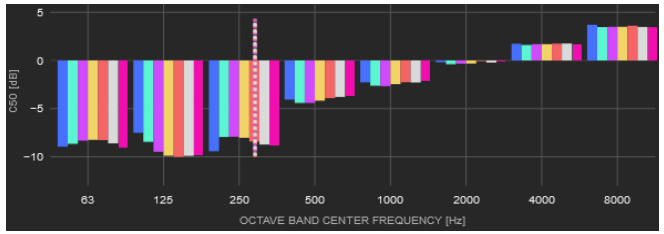
6.2.2 The Behaviour of Sound

The angled planes of the pitched roof result in a concentration of sound that in a sense 'follows' the pitch line. The intensity of which is also dependent on the proximity of the pitch line to other reflective planes which in this case would be the bounding walls of the classroom. Thus, the line offsets 1m and 7m result in a highly reverberant field. The closer the pitch line gets to the centre of the classroom, the lesser the reverberation time (even at the peak intensity spaces). Similarly, the C50 also peaks near the speaker and the speech clarity worsens near the pitch line.

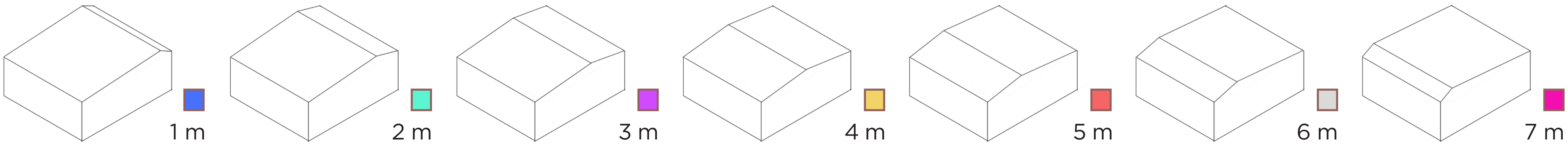








Images 6.2-6.12 [Clockwise, Illustration]: Raghunathan, M. (2024). *RT chart, C50 chart, C50 comparison graphs, Roof variations (1m to 7m), RT comparison graph*



6.3 Inverted Ceiling

6.3.1 Dimensions & Areas

Surface Area of

1. Long Walls = 22.8 m² each = 45.6 m²
2. Short Walls = 18.9 m² each = 37.8 m²
3. Floor = 56 m²
4. Ceiling = 56.4 m² (variants 1 & 7)
   56.2 m² (variants 2-6)

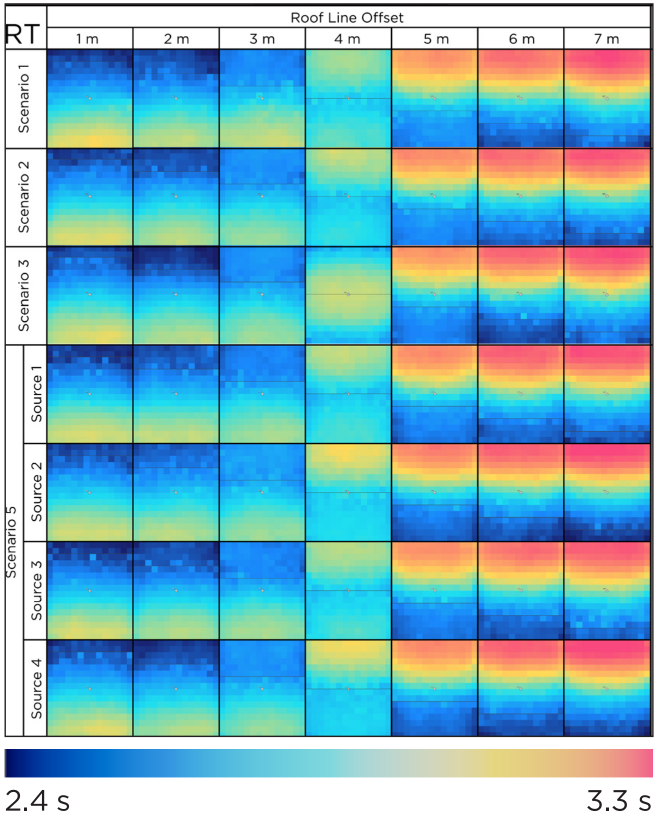
Total Surface Area = 195.8 m² (variants 1 & 7)
195.6 m² (variants 2-6)
Total Volume = 159.6 m³

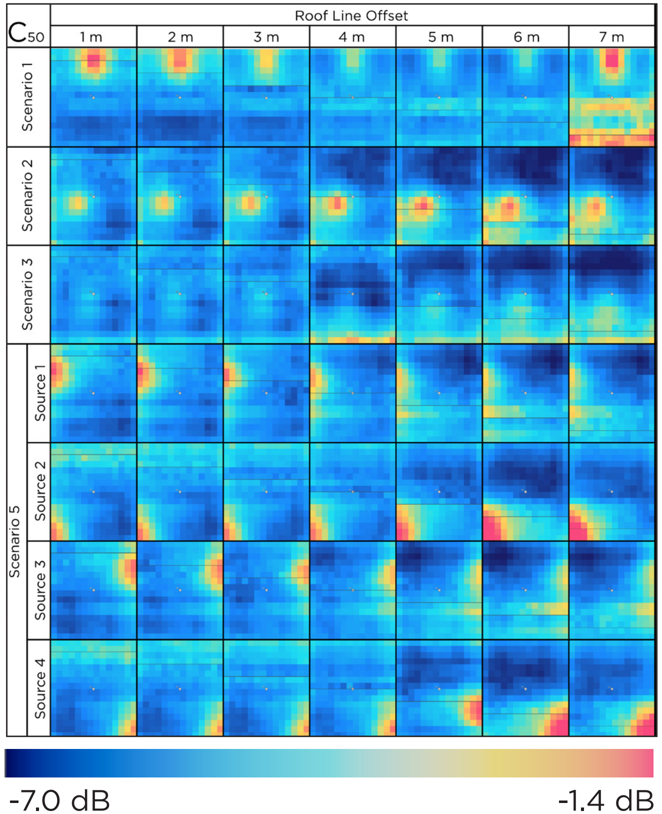
6.3.2 The Behaviour of Sound

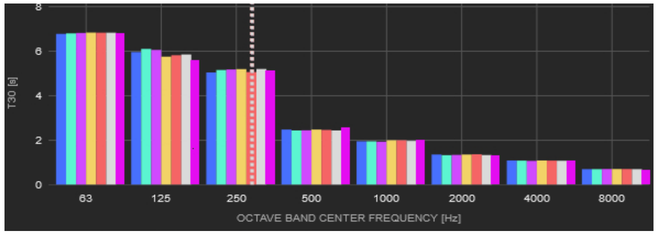
The inverted roof contrasts the behaviour of the pitched roof. The peak reverberation section 'follows' the direction of the plane with the larger area.

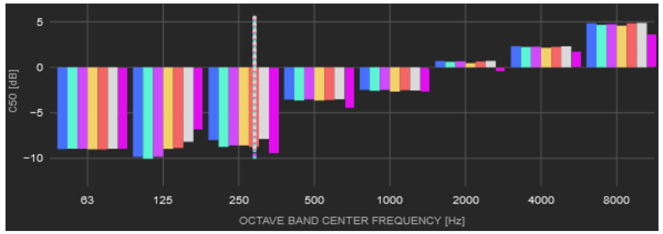
This means for the 1m, 2m, and 3m offset, the peak reverberation time is seen in the back of the classroom. For the 5m, 6m, and 7m offsets, the peak reverberation time is seen at the front of the classroom. The C50 also reflects this behaviour. The dark blue sections indicate the region with the 'poorest' C50 values. As mentioned earlier, it is seen on the side of the larger ceiling plane.

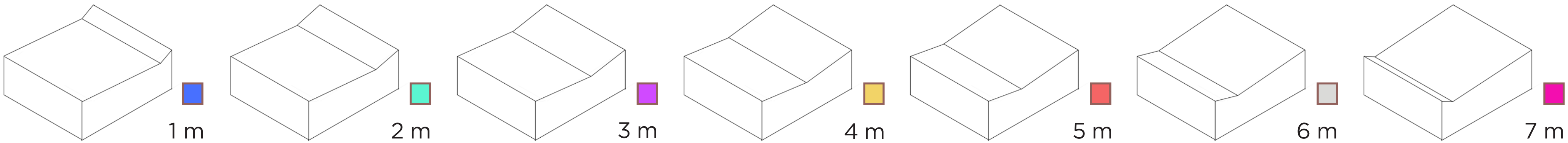
Images 6.13-6.23 [Clockwise, Illustration]: Raghunathan, M. (2024). *RT chart, C50 chart, C50 comparison graphs, Roof variations (1m to 7m), RT comparison graph*











6.4 Hip Ceiling

6.4.1 Dimensions & Areas

Surface Area of

1. Long Walls = 21.6 m^2 each = 43.2 m^2
2. Short Walls = 18.9 m^2 each = 37.8 m^2
3. Floor = 56 m^2
4. Ceiling = 56.4 m^2 (variants 1 & 7)
   56.2 m^2 (variants 2-6)

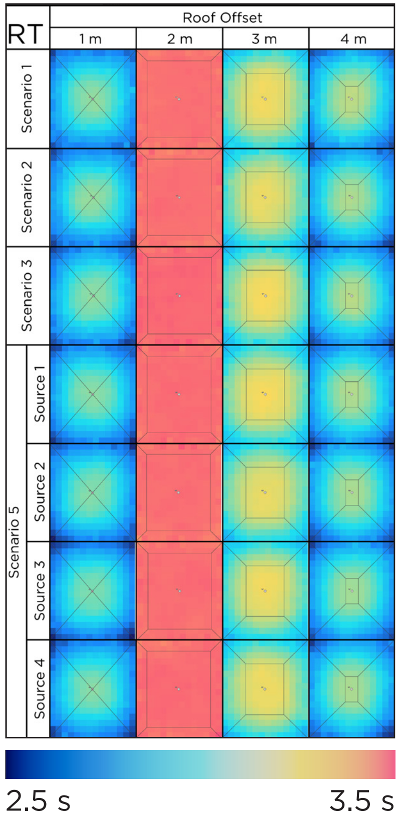
Total Surface Area = 198 m^2 (variant 1)
198.9 m^2 (variant 2)
198.3 m^2 (variant 3)
198.1 m^2 (variant 4)
Total Volume = 159.6 m^3

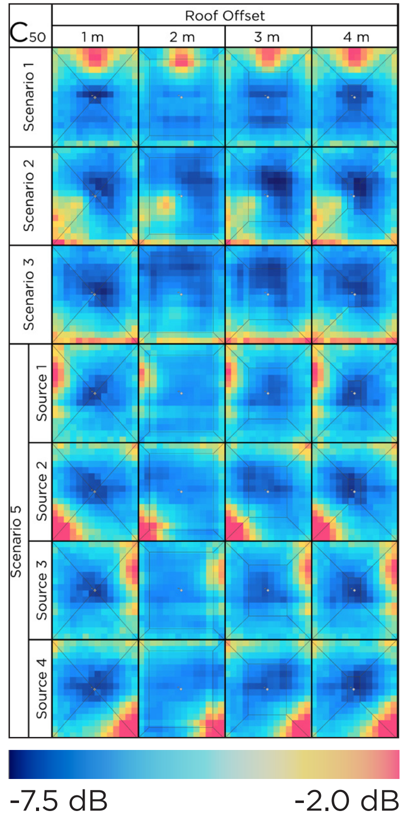
6.4.2 The Behaviour of Sound

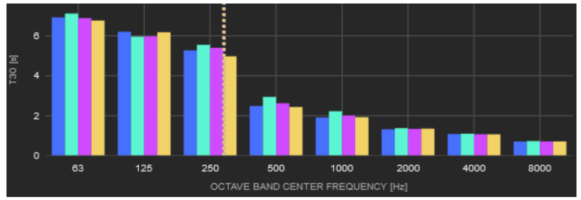
The behaviour of sound in this typology is similar to that seen in the pitched roof.

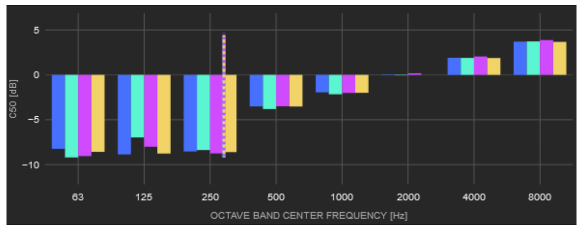
The '0m' offset shows the concentration of sound at location of the peak of the roof. With the introduction of a flat plane in the middle, the area of concentrated sound follows the area of the flat plane. This means that the larger the area of the flat plane, the more even the reverberation across the space. In the case of the 1m offset, the size of the angled planes on the side result in the reverberation time being relatively evenly spread across the entire classroom. This could be advantageous while treating a classroom.

The C50 also peaks at the center of the classroom, that is, the highest point of the ceiling experiences the worst speech clarity in comparison with the rest of the room. With the introduction of a plane, it follows the general area of the plane. The concentration of the poorest speech clarity is constantly seen at the centre of the classroom, regardless of speaker position.





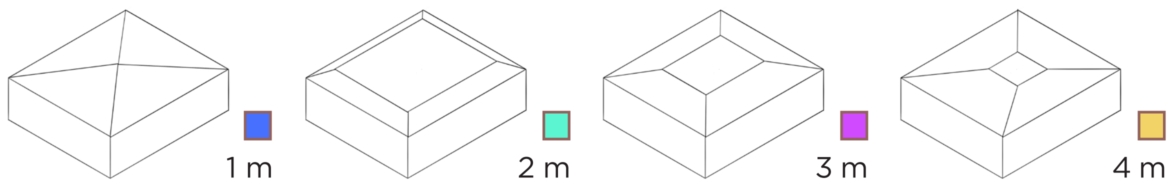




Images 6.24-6.25 [Top L to R, Map Graphs]: Raghunathan, M. (2024). *RT in different scenarios for different ceiling types, C50 in different scenarios for different ceiling types.*

Images 6.26-6.27 [R Top to Bottom, Graphs]: Raghunathan, M. (2024). *RT different ceiling types across frequency bands, C50 i different ceiling types across frequency bands*

Images 6.28-6.31 [Bottom L to R, Illustration]: Raghunathan, M. (2024). *Different ceiling variations considered*



6.5 Convex & Concave Ceilings

6.5.1 Dimensions & Areas

Surface Area of

1. Long Walls = 24 m^2 each = 48 m^2
2. Short Walls = 21 m^2 each = 42 m^2
3. Floor = 56 m^2
4. Ceiling = 56.03

Total Surface Area = 202.03 m^2
Total Volume = 159.6 m^3

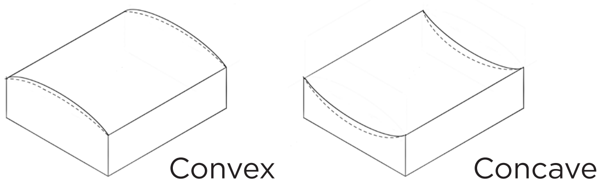
The radii of the ceilings are obtained from studies related to concert halls. There are two standard radii used; r = 2h and r > 2h. The values obtained are the following:

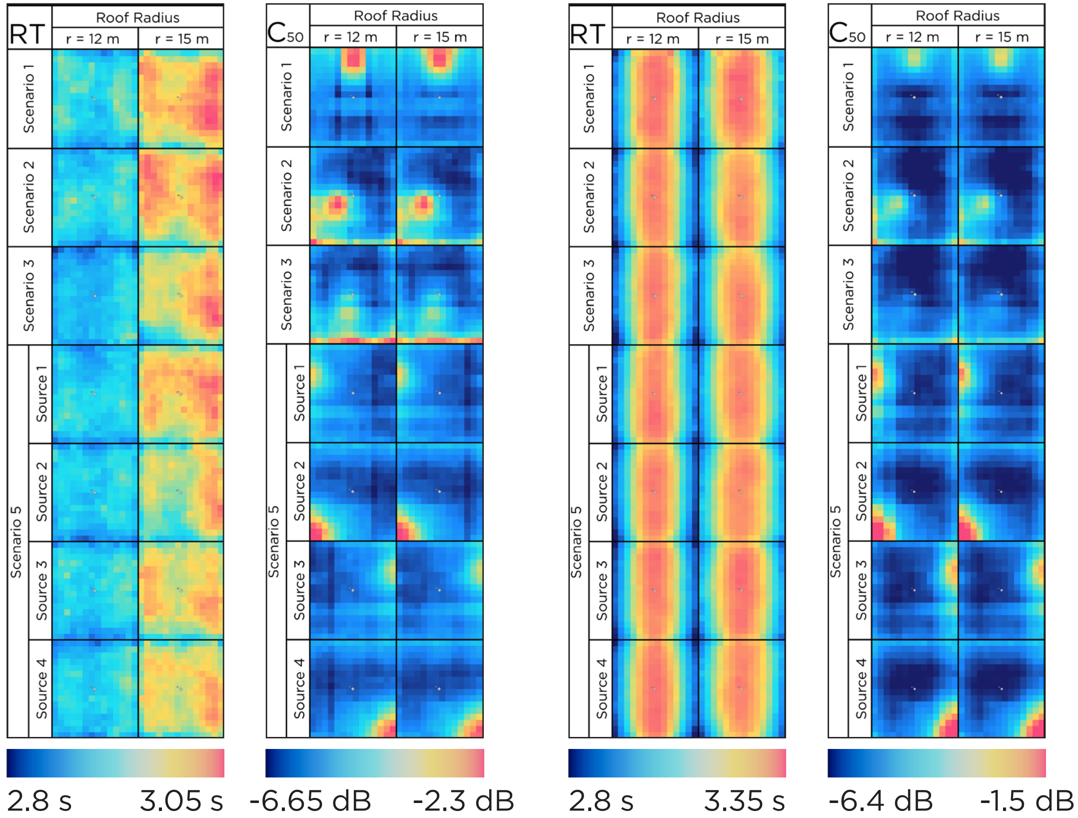
1. r = 2h = 2 x 3 => r = 6 m
2. r > 2h = r > 6 m => r = 7.5 m

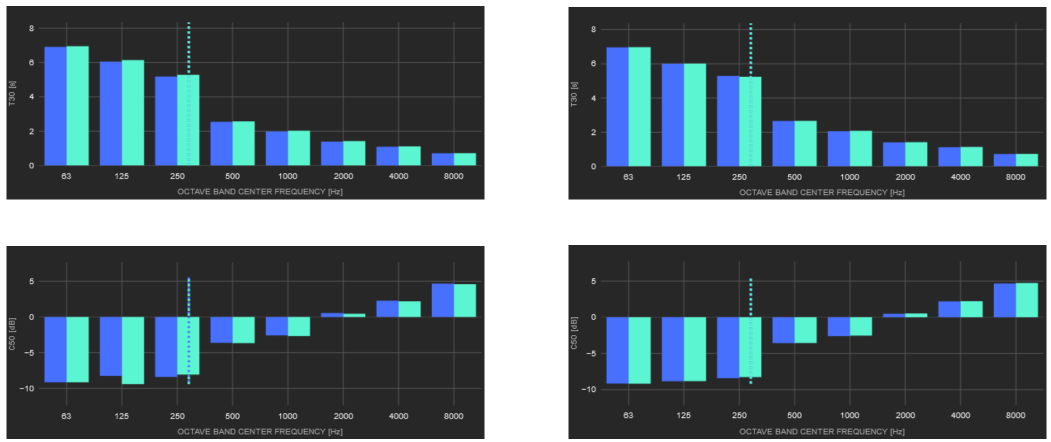
6.5.2 The Behaviour of Sound

The concave and convex roofs follow convention with the energy being focused in the center of the classroom in the case of the concave roof, and to the edges in the case of the convex roof.

In the concave roof, we see that the poorest C50 values are seen at the centre of the classroom whereas with the convex, it is spread almost evenly across the length and breadth of the classroom (the average student experiences poor speech clarity).







Images - Graphs 6.32-6.35 [L to R, Map Graphs]: Raghunathan, M. (2024). *RT & C50 comparison Convex, RT % C50 Comparison Concave*

Images 6.36-6.39 [R Clockwise, Graphs]: Raghunathan, M. (2024). *RT comparison Convex, RT Comparison Concave*

Images 6.40-6.41 [L, Illustration]: Raghunathan, M. (2024). *Ceiling variations (Convex and Concave)*

6.6 Evaluation & Analysis

6.6.1 Evaluative Process

The process of filtering down the 23 options (7 under inverted, 7 for pitched, 4 for the hip ceilings, 2 each for the convex and concave ceilings, and 1 standard flat ceiling) is quite simple. The variations in each category are evaluated against each other in terms of T-30, C50, G, and SPL, and the better performing variation is chosen to 'represent' the ceiling typology. This results in 6 options remaining (5 ceiling typologies + 1 standard flat ceiling).

Of these 6 options, the ones under convex and concave ceilings are eliminated due to the difficulty in installation, construction, and applications. This leaves 4 options remaining.

The ceilings in these 4 options are first compared against each other in each of the senarios outlined in Chapter 04, Section 4.3.

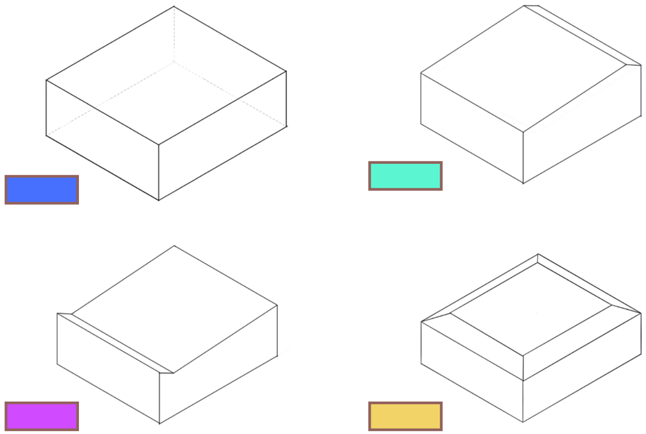
Then, the promising ceilings are treated with the similarly, with specific combinations of absorbers and reflectors (as seen in later in this section) and simulations are run again in the 4 scenarios. The best performing ceiling is then chosen and further investigations on the optimal placement of absorbers and reflectors are then carried out and the ideal placement for each scenario is determined.

6.6.2 Selection and Analysis

Since the goal of the thesis is to improve the quality of sound for students at every point of the classroom, ceilings that result in a relatively 'even' reverberation field are given a priority. In the case of the inverted roof, since no option meets this criteria, an exception is made for the ceiling type that reduces reverberation time at the back of the classroom.

As a result, the following ceilings are shortlisted and then compared against each other.

1. Flat Roof (For Comparison)
2. Pitched Roof - 1m Offset
3. Inverted Roof - 7m Offset
4. Hip Roof - 1m Offset



AUTHOR'S NOTE 05

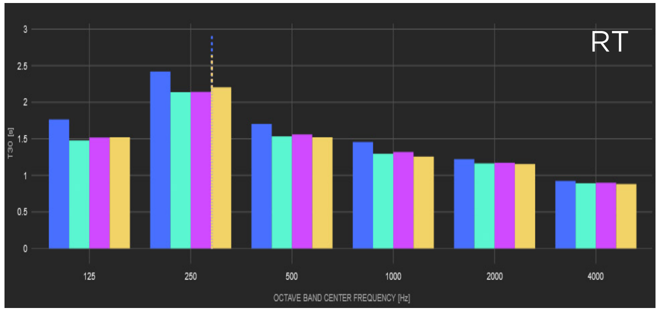
It is also important to note the impact of spatial volumes on the relevant acoustic factors. Since the ceiling profile in a sense 'eats' into the space, the volume enclosed by the different ceiling types will be lesser than the classroom with a flat ceiling. The entire table (encompassing values regarding the surface areas of each plane, the total volume and comparison of the same) can be found under Appendix 7.

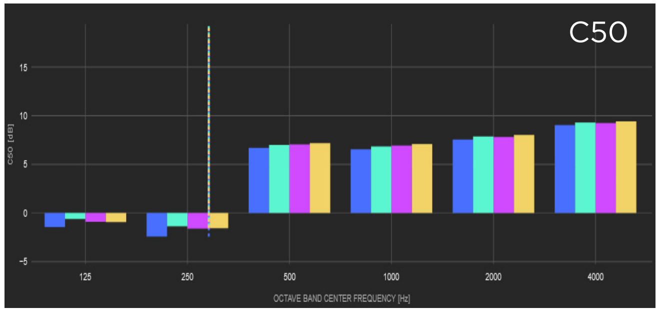
S.No.	Roof Type	Offset	Difference in Volume from room with Flat Roof (in m^2)
1	Pitched Roof	1 m	8.4
2		2 m	8.4
3		3 m	8.4
4		4 m	8.4
5		5 m	8.4
6		6 m	8.4
7		7 m	8.4
8	Inverted Roof	1 m	8.4
9		2 m	8.4
10		3 m	8.4
11		4 m	8.4
12		5 m	8.4
13		6 m	8.4
14		7 m	8.4
15	Hip Roof	0 m	11.2
16		1 m	4.1
17		2 m	7.4
18		3 m	9.9
19	Convex Roof	r = 2h (r=12 m)	1.8
20		r > 2h (r=15 m)	1.3
21	Concave Roof	r = 2h (r=12 m)	5.25
22		r > 2h (r=15 m)	2.43
23	Flat Roof	N/A	0

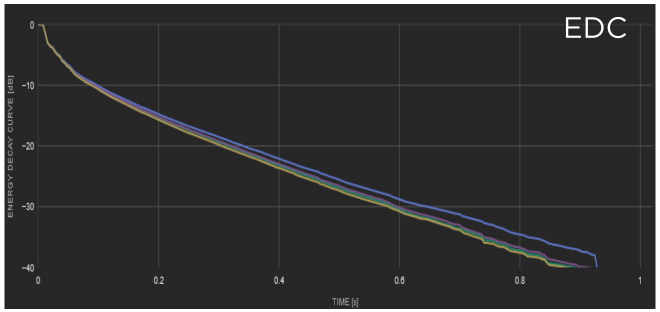
6.6.3 Comparison of Chosen Ceilings
The graphs (top to bottom) are T-30, C50, and the EDC graph (at position of student #15) for the 4 typologies of roof chosen.
The three chosen ceilings and the flat ceiling (for comparison) are assessed on the basis of reverberation time and C50 (speech clarity) in the 4 different scenarios outlined. The fifth scenario has 4 results for each of the speakers that the scenario entails.

The flat ceiling performs poorer in comparison to the other ceiling. The hip ceiling shows slightly higher values than the pitched and inverted ceilings but also shows higher (and preferable) values in terms of C50. The

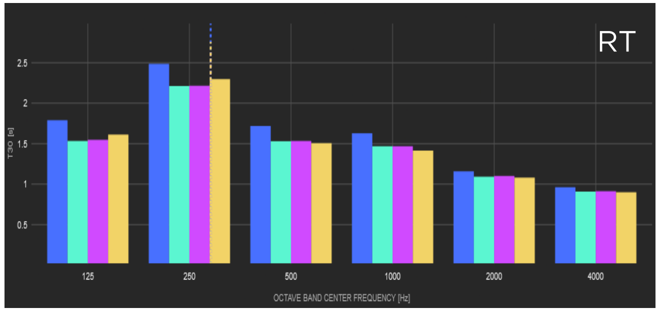
Scenario #1

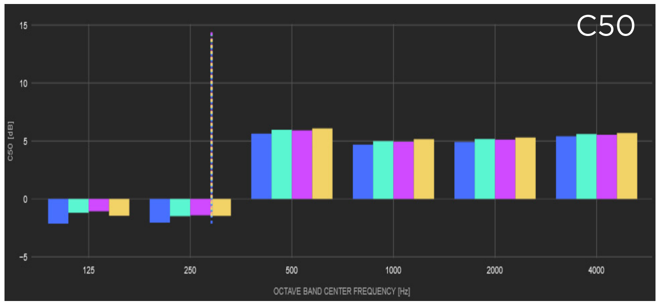


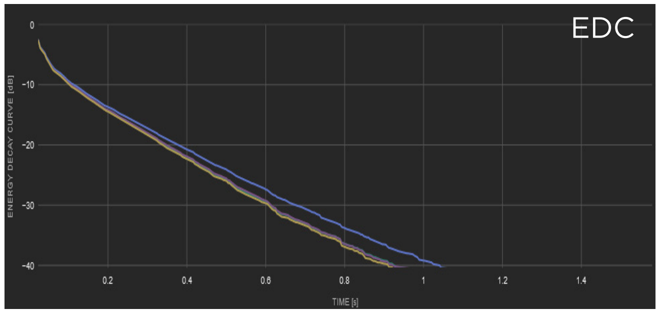




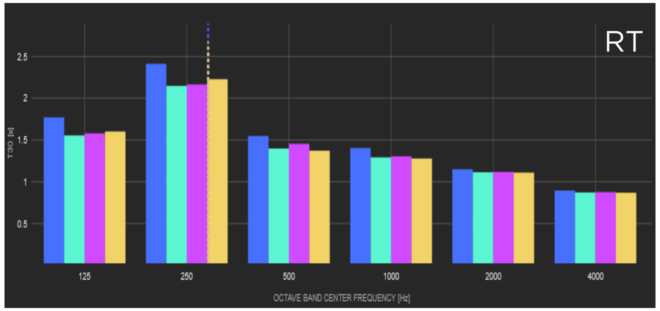
Scenario #2

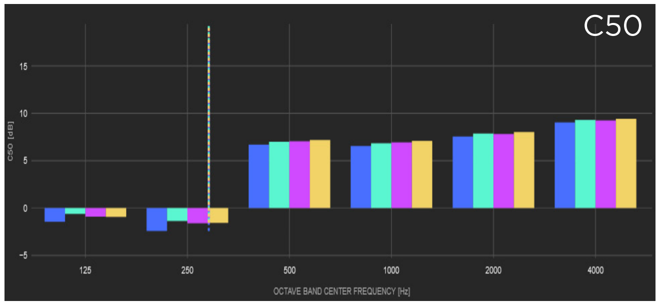


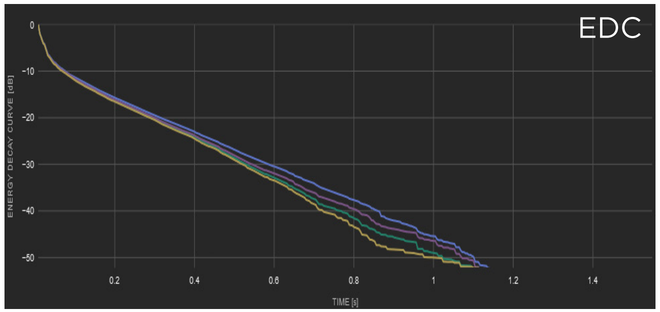




Scenario #3





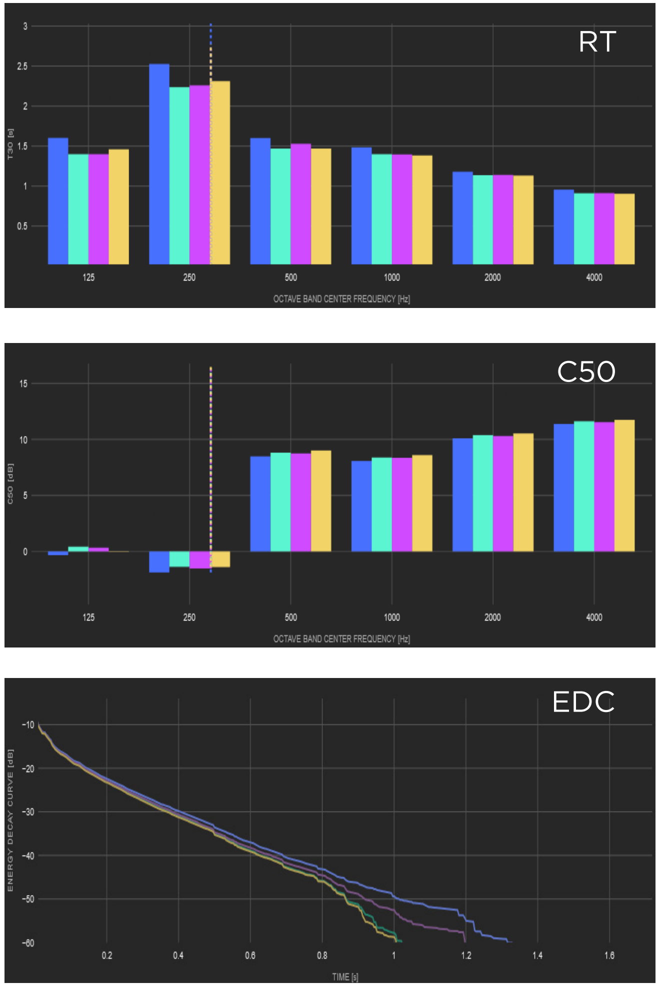


pitched ceiling results in lesser reverberation time and has comparable C50 values to the hip ceiling. However it is important to note that these results are from a surface receiver at height of 2.60 m and these values will vary when viewed in relation to a student's height. The hip roof also shows a faster decay rate in the EDC graphs. The next paragraphs show the RT and the C50 for the different ceilings per scenario [1-4].

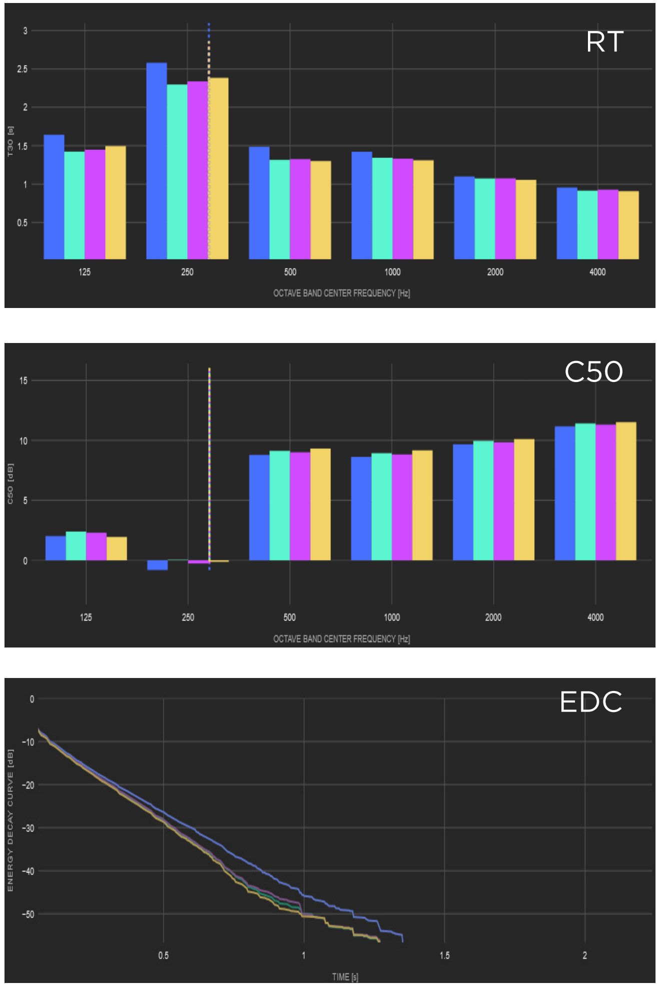
Avg. RT in seconds [250 - 2000 Hz]:

1. Flat Ceiling: 1.65, 1.69, 1.63, 1.7
2. Pitched Ceiling: 1.5, 1.53, 1.49, 1.56
3. Inverted Ceiling: 1.51, 1.54, 1.51, 1.58
4. Hip Ceiling: 1.5, 1.53, 1.5, 1.57

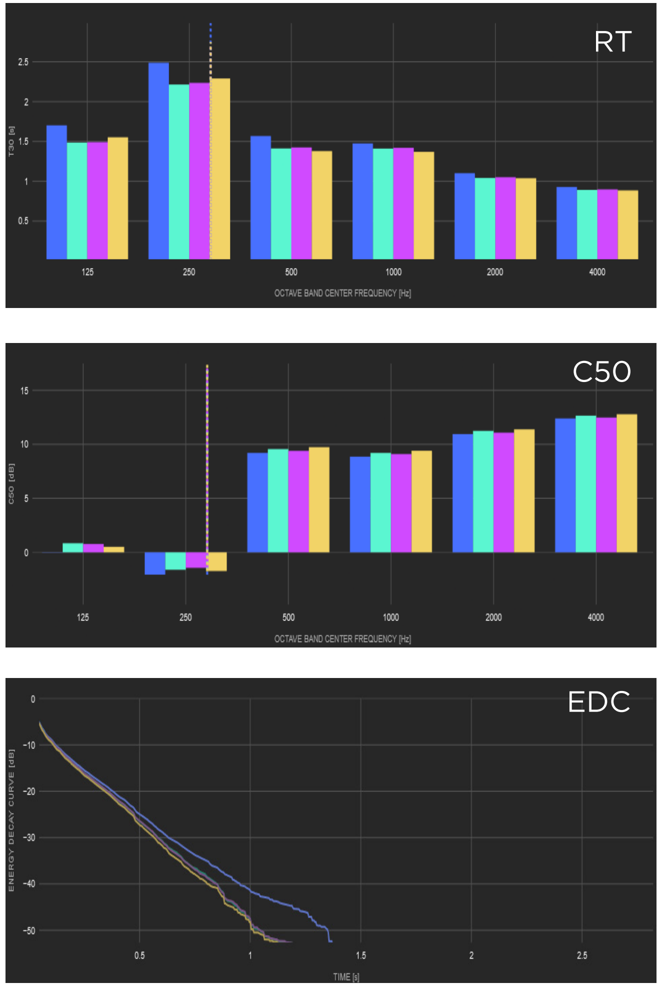
Scenario #5.1



Scenario #5.2

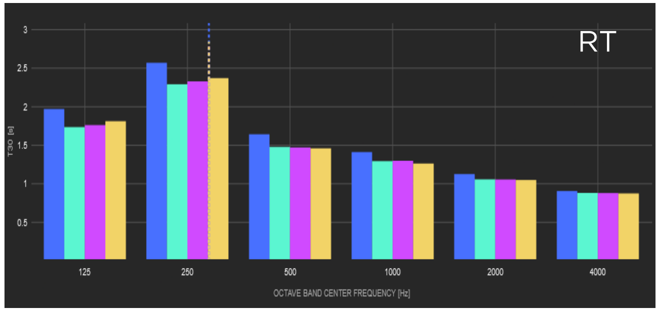


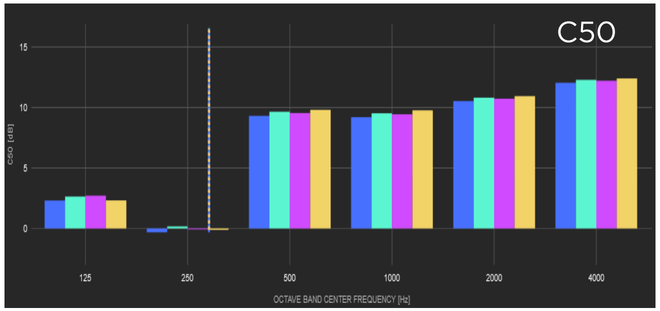
Scenario #5.3

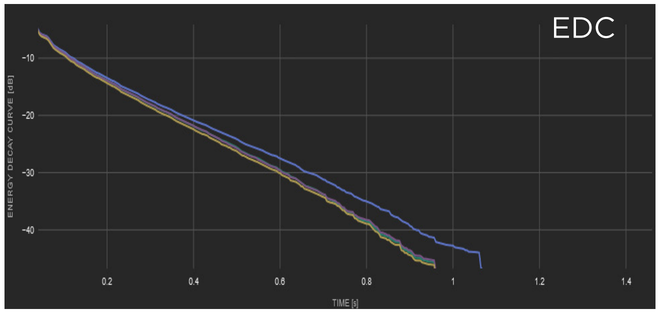


Avg. C50 in dB [250 - 2000 Hz]:
1. Flat Ceiling: 4.36, 4.99, 4.65, 4.86
2. Pitched Ceiling: 4.9, 5.5, 5.01, 5.2
3. Inverted Ceiling: 4.89, 5.4, 4.89, 5.11
4. Hip Ceiling: 4.93, 5.53, 5.17, 5.38

Scenario #5.4







Since the pitched ceiling and hip ceiling show comparable values to each other, and better values than the other ceilings, they are chosen for further investigation. The placement of absorbers and reflectors in the space is determined according to the literature research outlined in the Author's Note 06.

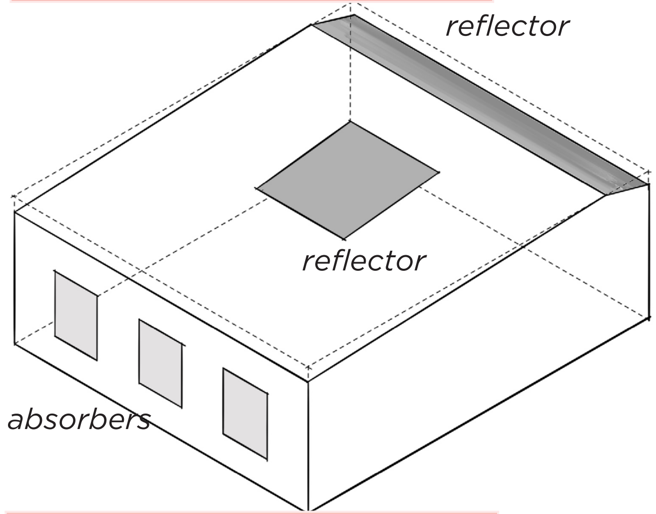
The two chosen ceilings (hip ceiling - 1m offset, and pitched ceiling - 1m offset) are compared and contrasted in the following scenarios:
1. Reflector placed on ceiling to maximise first order of reflections to receiver
2. Reflector placed behind the speaker
3. Reflectors placed in both locations

These scenarios are compared on terms of T-30 and C50. The average reverberation time and C50 values seen on the next pages are the averages from the frequency bands 250 to 2000 Hz.

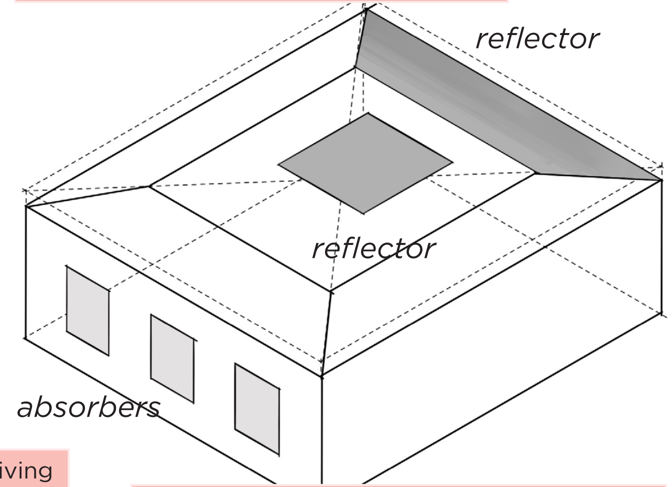
Interestingly, these roofs also follow certain standards/requirements that the literature research (Chapter 3) set out. They are as mentioned in the illustration on the right. This means that the benefits seen by the change in ceiling architecture is also (indirectly) validated by other pre-existing research.

For a teacher-centric class, late arriving sound needs to be dampened by means of sound absorbing panels on the rear wall.

"Additionally, J. Singer (2003) suggests placing angled panels behind the source to enhance speech clarity during lessons."



"J. Singer (2003) advices on the limitation of classroom height to 9 feet [2.7 m] in height."



"...also suggests limiting the room depth to 8.5m to reduce the late reflections from the rear wall. If in case this is exceeded, the rear wall would require acoustic interventions as well – either absorption or diffusion."

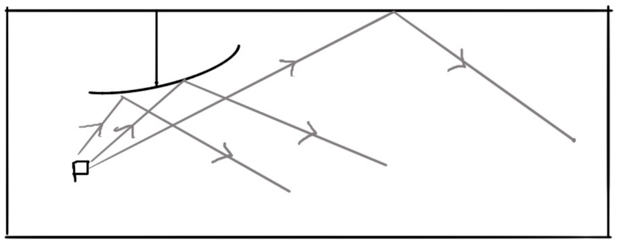
Images 6.42 [Illustration]: Raghunathan, M. (2024). *Pitched and Hip ceiling with interventions*

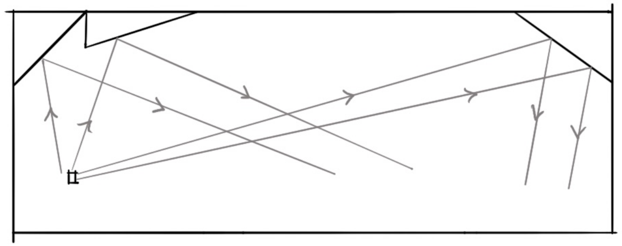
Author's Note 06: Placement of Absorbers and Reflectors

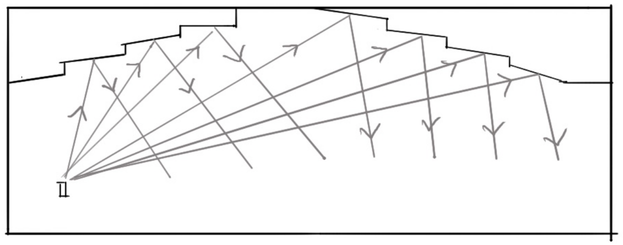
If we take a moment and consider spaces with a high demand of acoustic intervention, one typology immediately comes to mind; concerts and theatre halls.

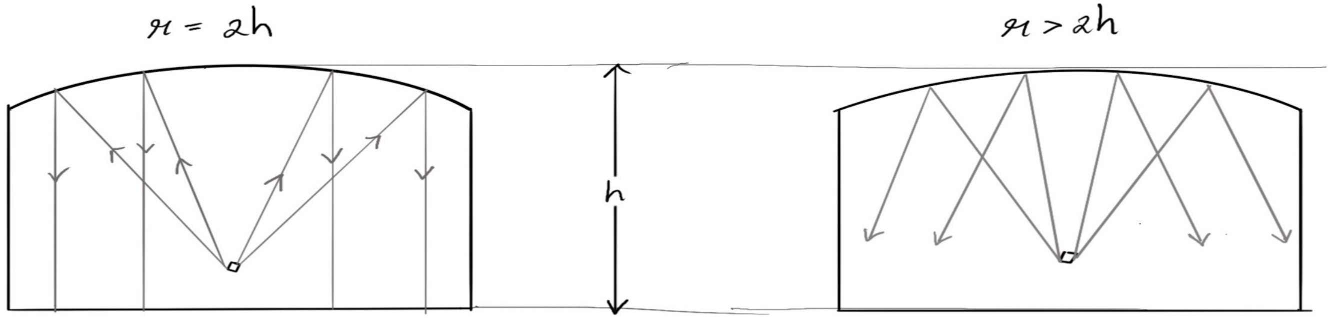
They require sound to be bounced to the back of the hall, and they also need to maintain a relatively even sound scape. In addition, they have varying demands depending on the type of performance taking place. This results in designs where the placement of reflectors and diffusers is dynamic.

Thus, a quick study was made into the more popular methods of reflecting sound to different and furthest parts of a room. Additionally, it also gives an insight into the impact of internal geometry on the behaviour of sound, thus supporting the claim made (and subsequently verified) that the ceiling architecture does in fact have a noticeable effect on the quality of sound and the behaviour of sound in a room.









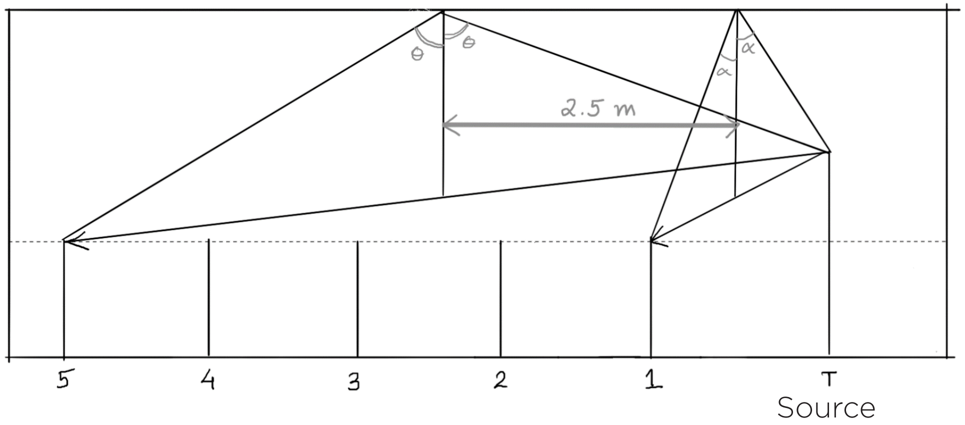
Another important intervention seen in these spaces is a higher priority given to the balance of absorber, diffuser, and reflector panels. The paper Chalfoun et al. (2015) uses the following method to estimate the placement of reflectors in a space.

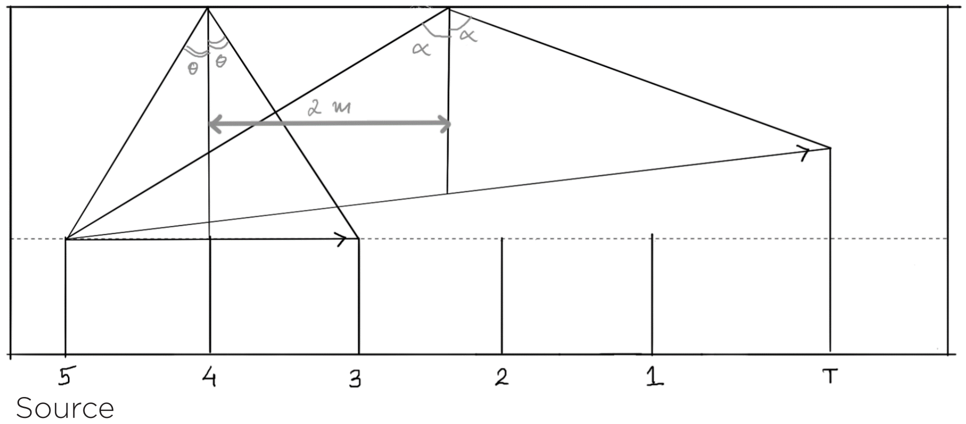
1. Note at least 3 points: 1 source, receiver 1 (closer to source), receiver 2 (further away from source)
2. Trace the direct path of sound from source 1 to receiver 1 *(Path 1)* and source 1 to receiver 2 *(Path 2)*.
3. Bisect these direct paths and draw a perpendicular line towards the ceiling *(Perpendicular lines 1 and 2).*
4. The distance between perpendicular lines 1 and 2 is the length and location of the required reflector.

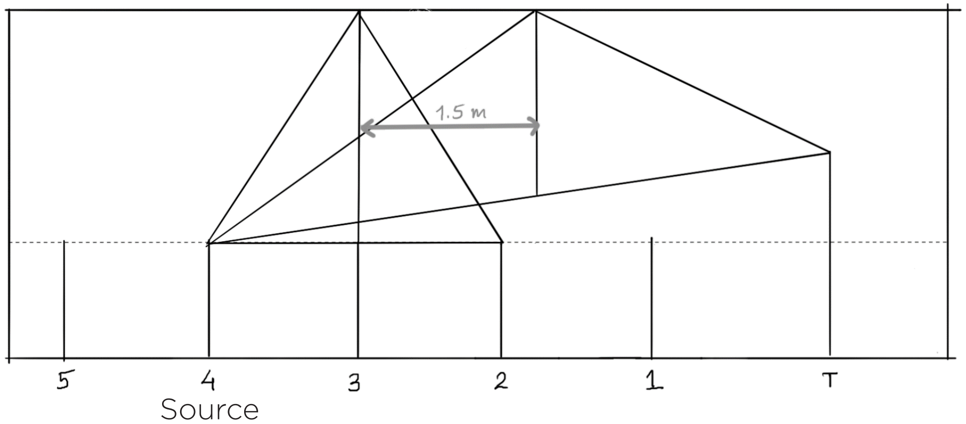
This approach uses the principle of equal angles of incidence and reflection of a sound wave (characterised by the alpha and theta signs in the diagrams).

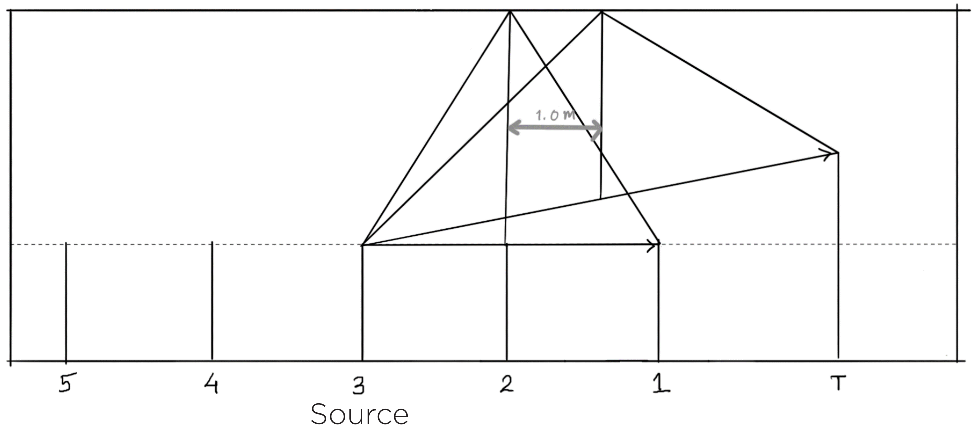
It is also important to note the following in order to understand the diagrams:

1. The numbers 1 through 5 are indicative of the rows in the classroom.
2. The letter T is indicative of the position of the teacher in the space.
3. The symbols alpha and theta are representative of the angle of incidence and reflection by the sound waves for the individual receivers.
4. The height of the student is taken to be 1.2 m (seated), and the height of the teacher is taken to be 1.7 m (standing).









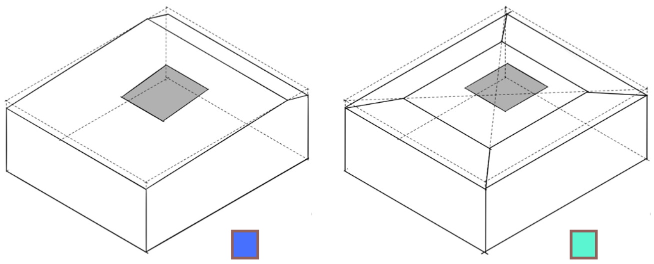
This also provides a solid conclusion that the position of the reflector is heavily dependent on speaker-receiver positions. This means that the position of the reflector cannot be fixed especially considering the varying combinations of source and receivers (as outlined until this point).

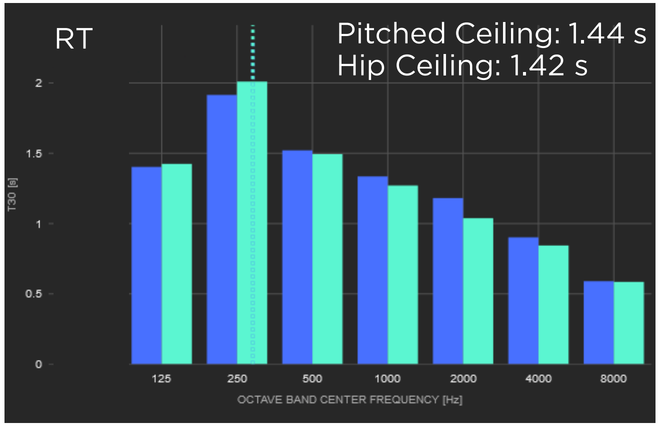
However, it is important to note that a reflector is not required in every scenario. In the case of a teacher addressing a classroom, the distance between the teacher and the student sitting in the last bench is too large. As such, a reflector might be able to enhance the quality of sound experienced by the student in this style of teaching.

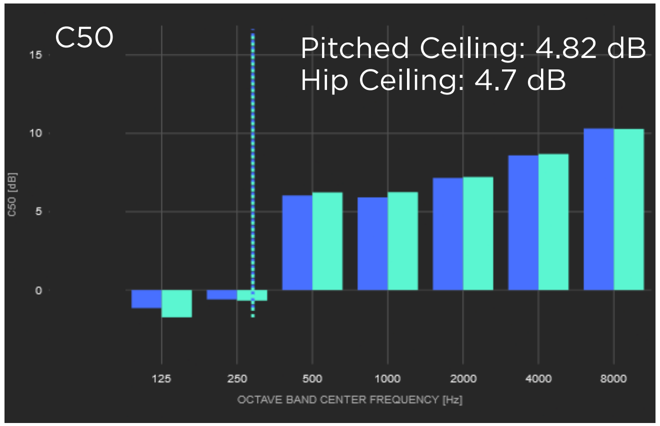
If the room is treated properly, then the reflectors may not be needed in the case of students talking to each other during down time and group projects.

6.6.4 Comparison of Pitched & Hip Ceilings in the Various Scenarios

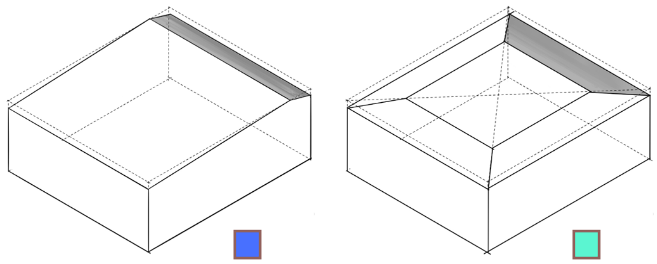
Comparison - Version #1.1

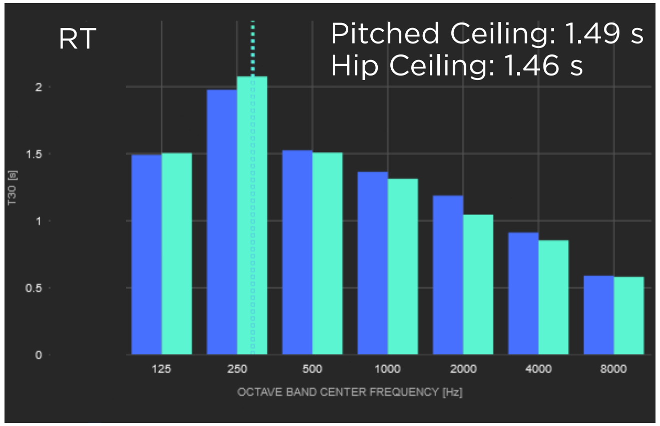


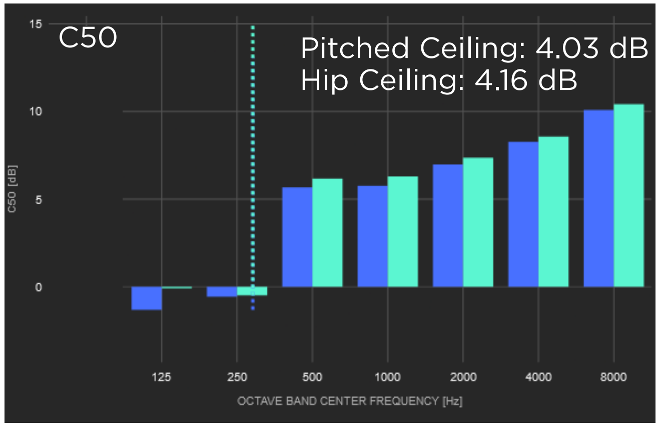




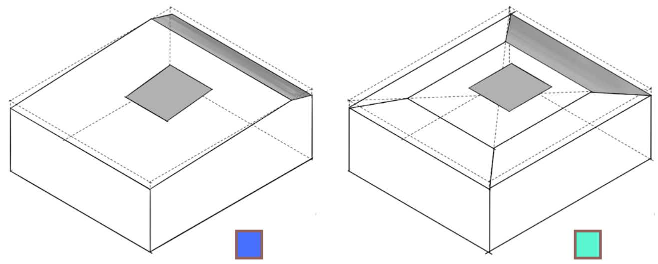
Comparison - Version #2.1

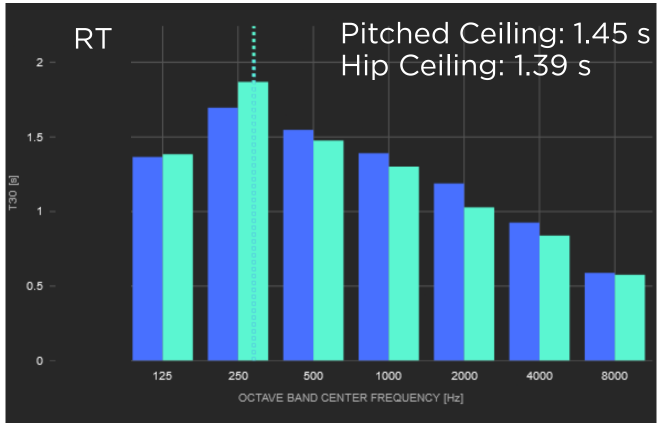


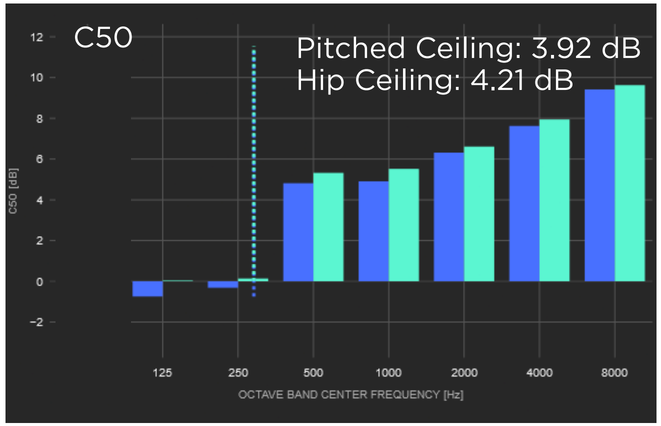




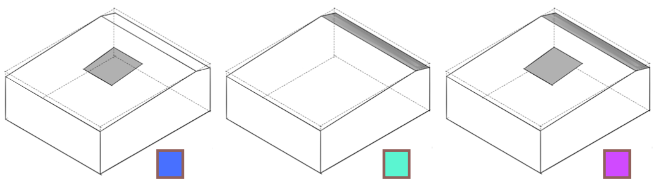
Comparison - Version #3.1

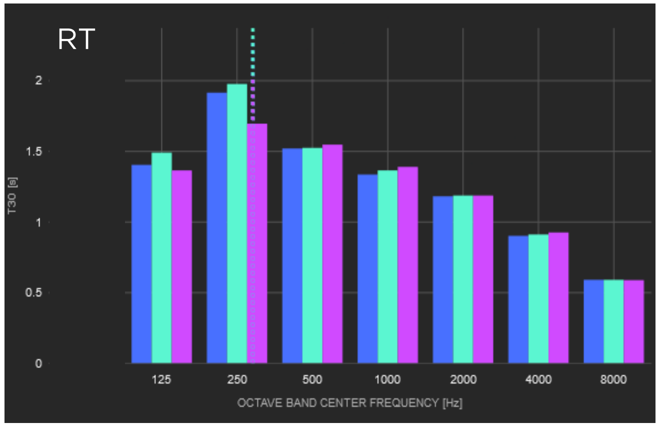


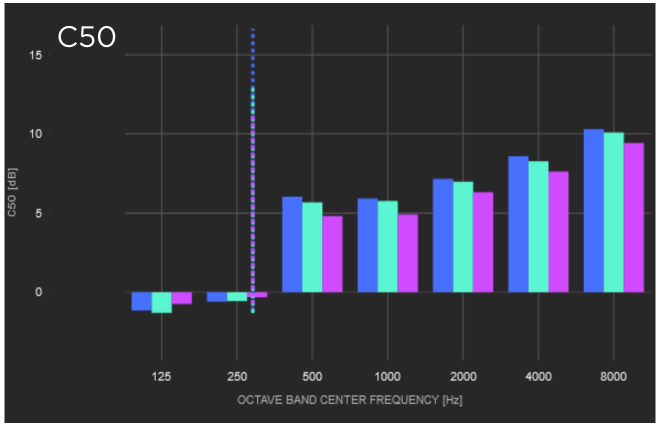




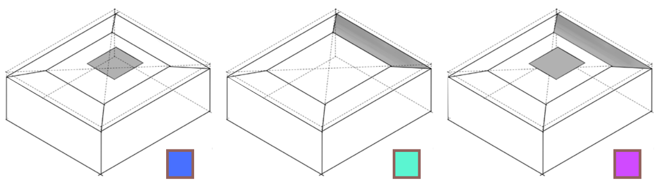
Comparison - Variations of the Pitched Ceiling

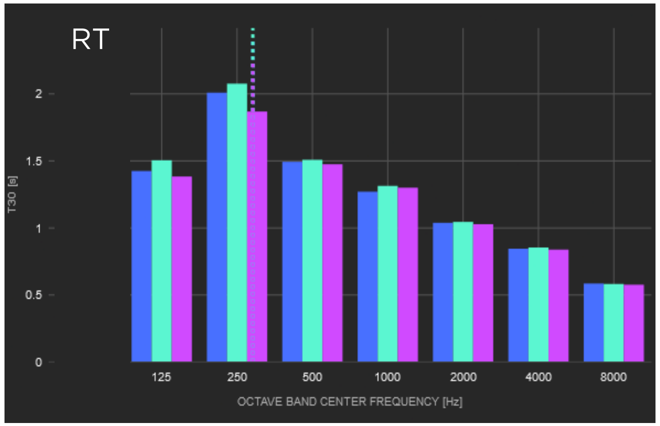


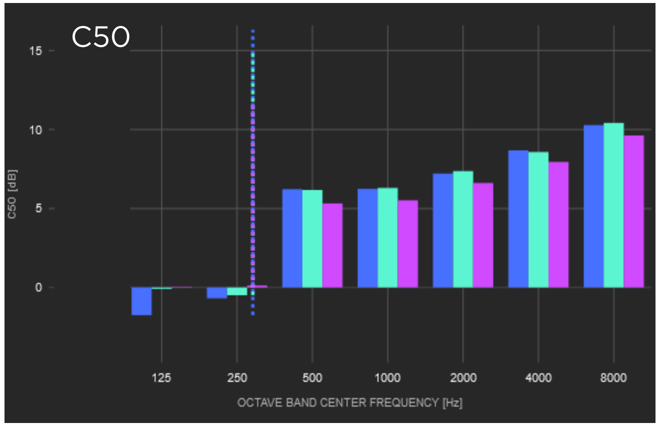




Comparison - Variations of the Hip Ceiling







Version #1
While there is a spike in RT in the 500 Hz for the hip ceiling, the C50 values of the ceiling remain similar to the pitched ceiling. The hip ceiling and the pitched ceiling see similar averaged performances in terms of both T-30 as well as C50.

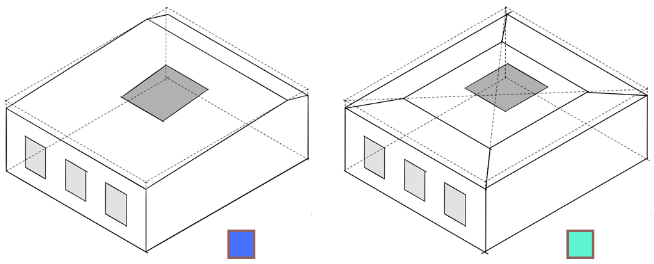
Version #2
The hip ceiling once again spikes in RT at the transition frequency but provides comparable C50 values to the pitched ceiling in the same frequency band. However, it also shows lower T-30 values (and thus higher C50 values) in the higher frequencies, enabling it to outperform the pitched ceiling, even if just by a little.

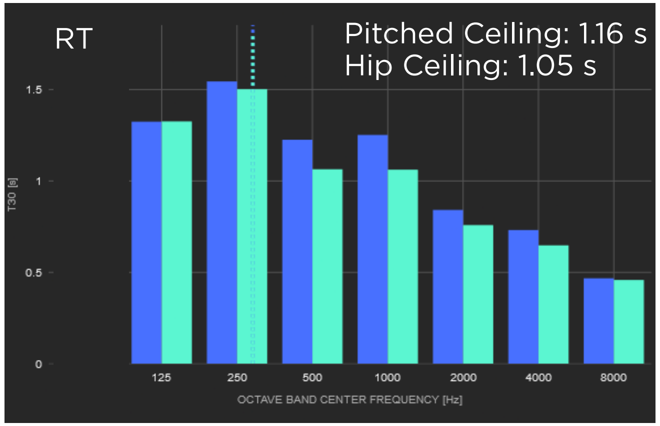
Version#3
This version sees the highest difference in performance of the two ceilings The hip ceiling (once again spiking at the transition frequency) shows lower reverberation time and better C50 values in all frequency bands excepting the 500Hz.

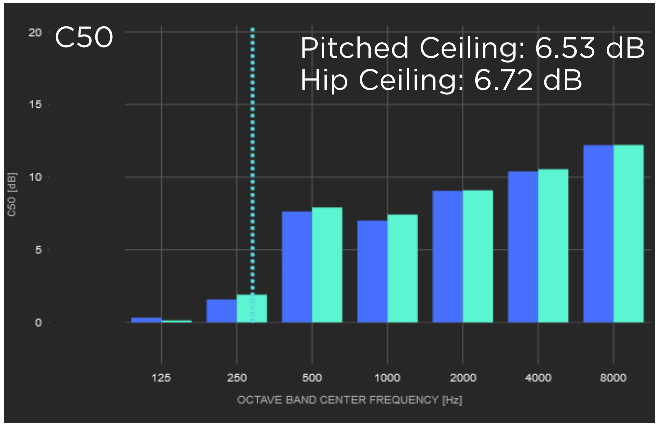
The hip ceiling with reflectors applied at both surfaces outperforms all the other variations with a reverberation time of 1.39 seconds. However, the hip ceiling with the reflector (version #2) only on the plane behind the speaker performs better in the speech frequencies.

The interventions are initially limited to the ceiling. Since this does not meet the standard acoustic requirements of a classroom, an additional intervention is applied in the form of sound absorbing panels on the rear wall.

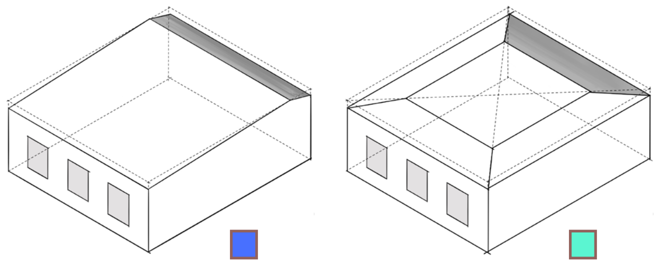
Comparison - Version #1.2

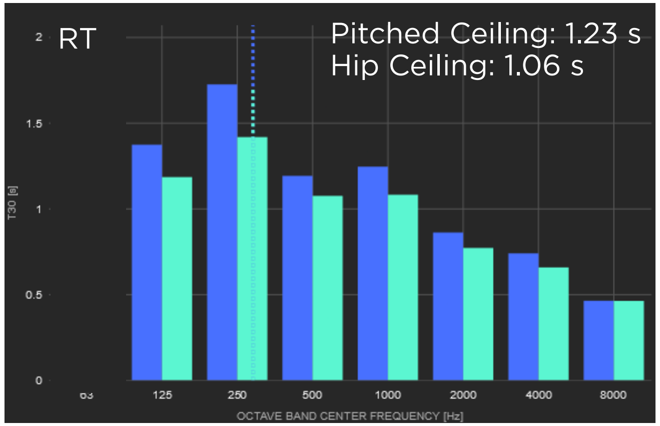


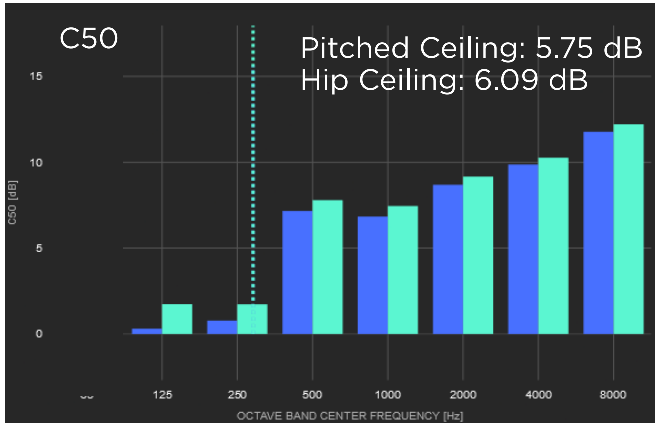




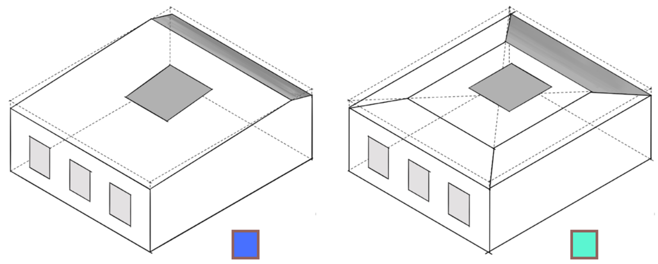
Comparison - Version #2.2

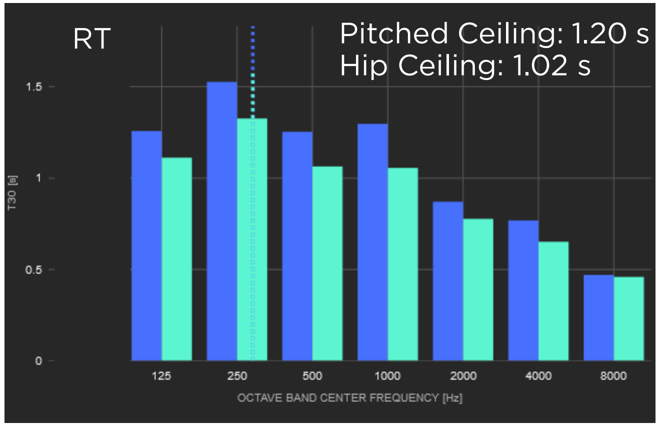


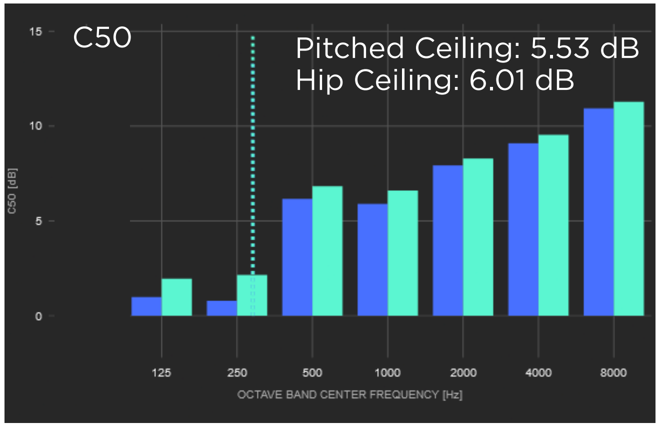




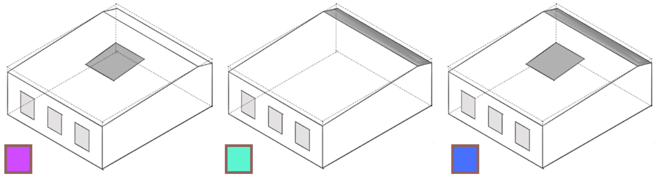
Comparison - Version #3.2

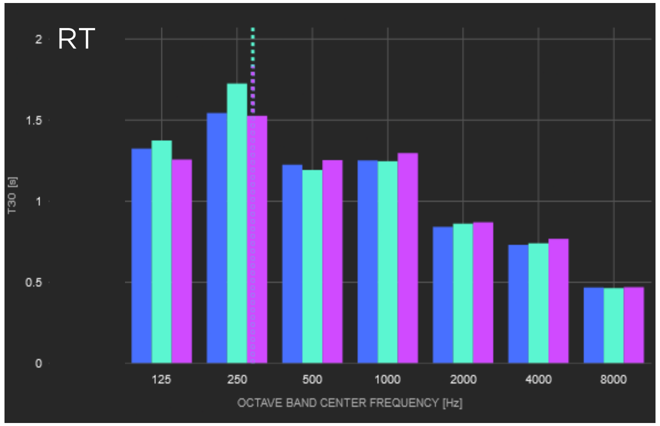


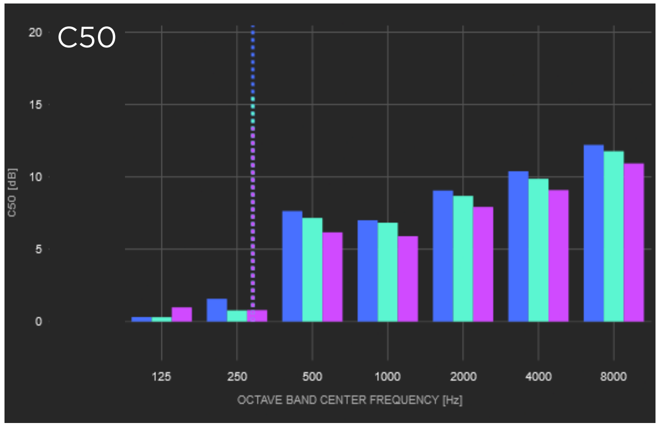




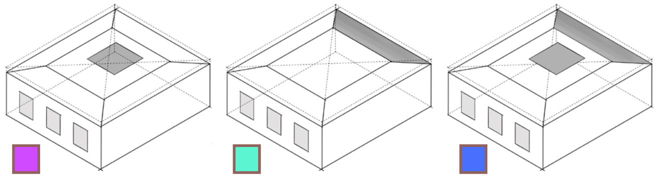
Comparison - Variations of the Pitched Ceiling

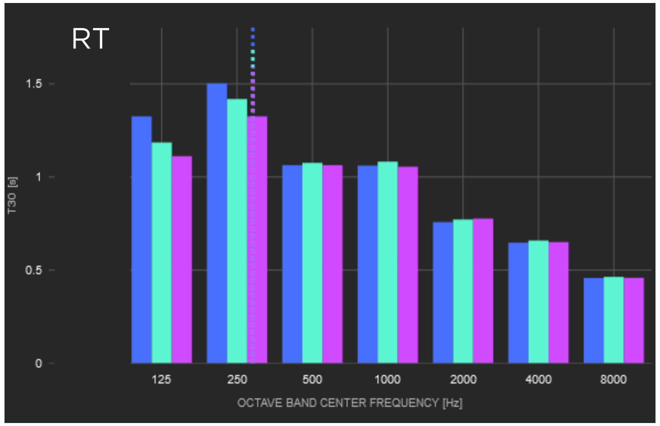


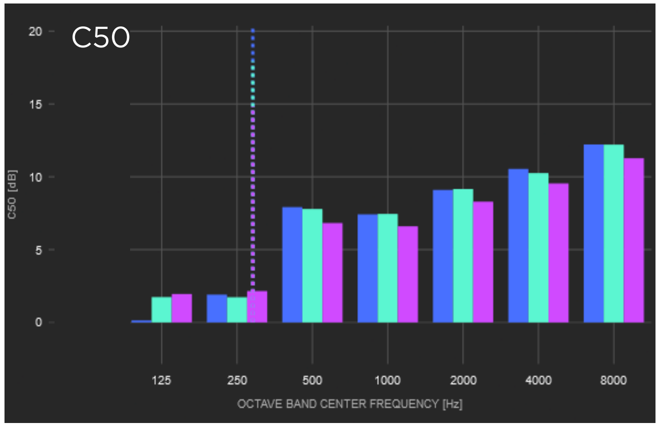




Comparison - Variations of the Hip Ceiling







Version #1
The values for RT and C50 are matched in the speech frequencies. As a result, the 250-2000 Hz averages for both are the primary deciding factor. The hip ceiling has an average RT of 1.06s as opposed to 1.23s of the pitched ceiling, and the former also has a higher C50 value of 6.09 dB by 0.19 dB.

Version #2
The hip ceiling once again outperforms the pitched ceiling but the average RT is comparable to the previous version with values of 1.06s and 1.05s. The C50 values however, while better than the pitched ceiling by 0.34 dB, is still lesser than the values shown by the version #1.

Version#3
This version also sees the similar trend of hip ceiling values being better than the pitched ceiling with the C50 values being outperformed by version #1.

When the three versions of the ceilings are compared against each other, the version #2 and #3 exhibit better RT values in the speech frequencies than version #1. The C50 values, however, are better in version #2 than version #3. As a result, the hip ceiling (version #2) is chosen for further investigation and to look at for integration with the developed design.

The placement of absorbers on the rear wall results in a predicted drop in ~0.4s (in reverberation time) for the hip ceiling and ~0.2s for the pitched ceiling. In terms of C50, the pitched ceiling sees a ~1.6 dB increase and the hip ceiling sees an increase of ~1.9 dB

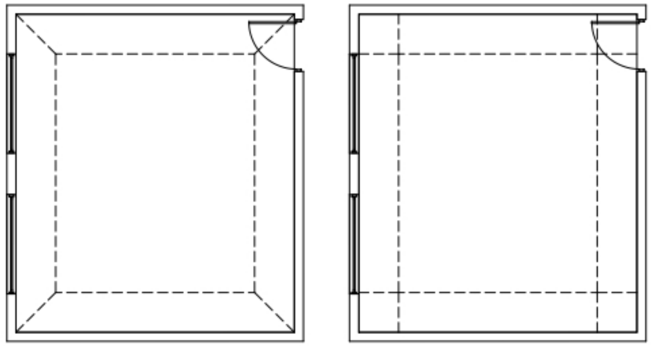
7.1 Introduction

The integration of the design with the ceiling comes with certain challenges: installation, placement, and integration with lighting and HVAC systems. Additionally, the space may have unexpected spatial obstacles such as columns, beams, furniture, or even irregular geometry. The design has to be adaptable and customisable to the situation.

7.1.1 Ceiling Plan

The ceiling of a space is an essential plane. It acts as a point of connection for much needed installations: lights, HVAC, fire safety, and acoustics. In fact, approximately 10-15% of the ceiling is utilised by the first three factors. This is an important point because an investigation done with 100% of the ceiling treated with acoustic material becomes unrealistic.

The first thing that needs to be taken care of is the profile of the ceiling. Currently the ceiling has angular corners. This is once again problematic when the practicality of installation is taken into consideration. In addition, it has also been shown that the 1m perimeter of the classroom is the least problematic area of the classroom. This (theoretically) allows for a minor change in the ceiling profile (dotted lines) without drastically affecting the sound performance of the intervention. From this chapter onwards, the hip ceiling profile is as illustrated (right image). The corner squares contain no acoustic material initially. If in case it is found that the initially designed ceiling layout for the product is insufficient, then additional material is placed on the squares.



A ceiling plan is then drawn up in order to understand the realistic placement of the various fixtures in a classroom.

Lighting Layout
According to European standards for classroom lighting design (UNE-EN 12464.1), 500 lux is the minimum requirement for spaces with reading and focus demands (rule-of-thumb). For this classroom, 28000 lumens are needed. Estimating the number and placement of lighting fixtures by this rule, we arrive at an average number of 6 (~5.4) fixtures (for a lighting unit with a value of 5200 luminous flux).

HVAC Systems
For a classroom of this size, an average of 2 supply systems and 2 return ducts are required. They are placed on the extremeties of the classroom (as indicated in the images 7.1-7.2).

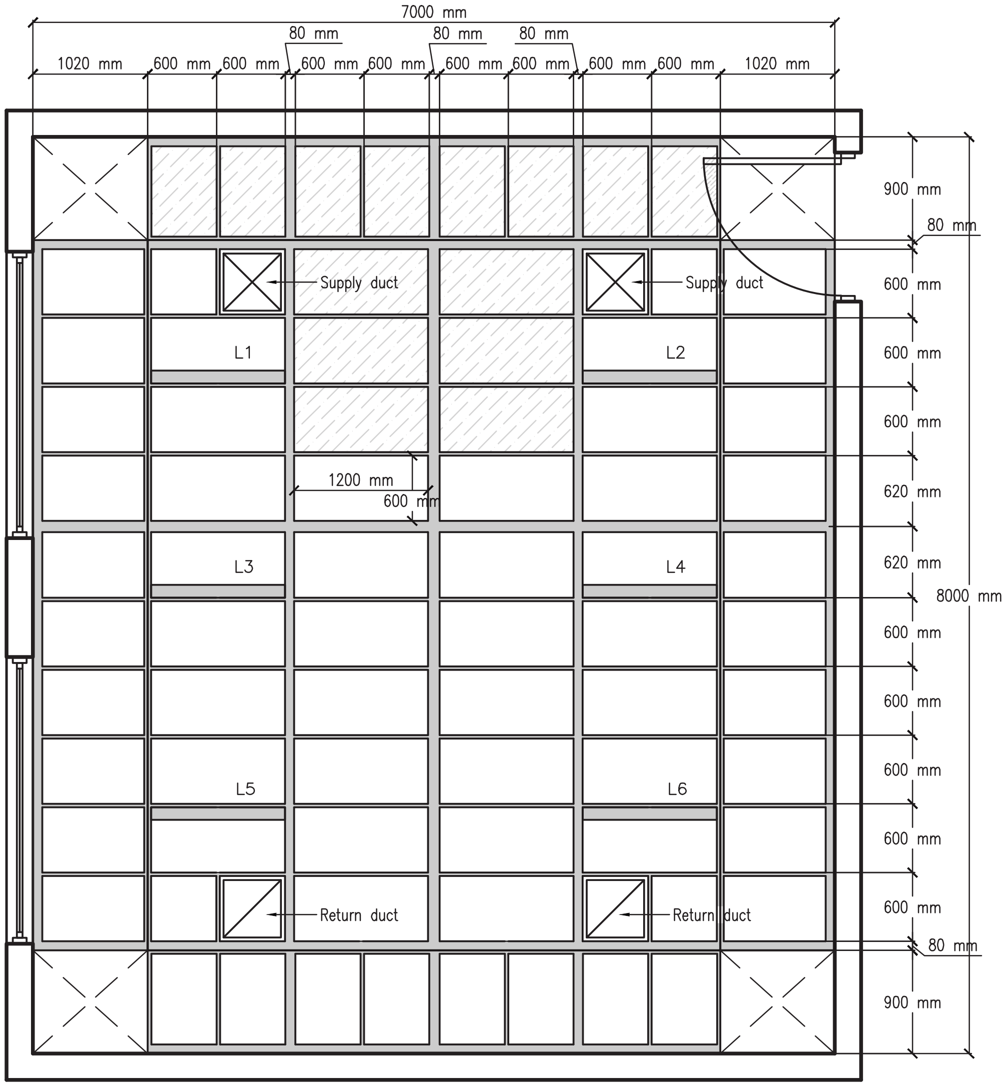
General Dimensions
The lowest allowable ceiling height in a space that is considered 'liveable' is 2.7m. If the flat plane of the hip ceiling is reduced to 2.7m, then the lowest part of the ceiling (the angled planes on the periphery) will be at a height of 2.4 m. This is not ideal. As a result, the acoustic product is placed at a height of 3.0m. However, this does not leave any space between the product and the ceiling for the HVAC ducts to run. For the above reasons, the clear height of the room will need to be increased to 3.3m.

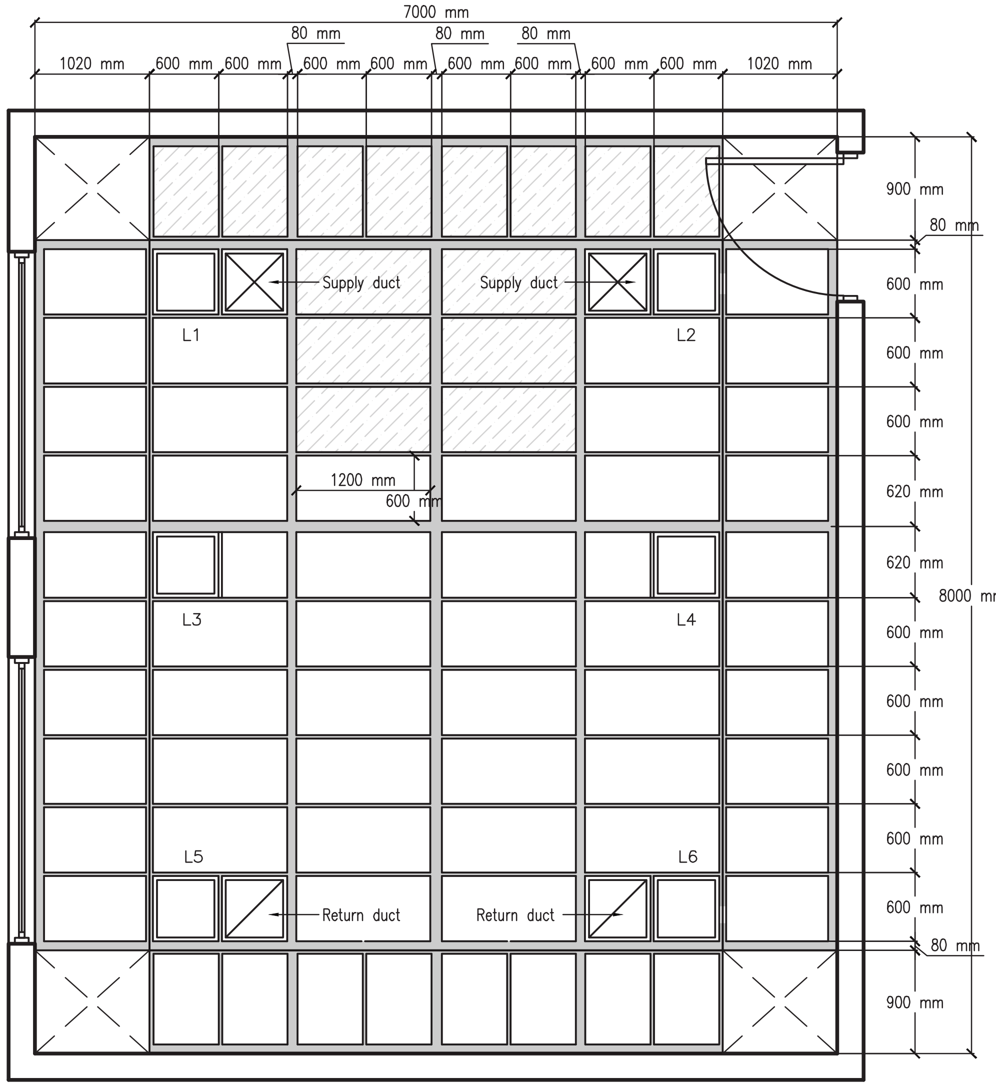
Integrating the Product with Installations
The biggest challenge is working around the dimensional differences between the various installations. For example, lighting units can be square, batons, or suspended, or HVAC systems can have square or rectangular supply/return vents. These variations cannot be predicted, and a design that has to be redesigned everytime there is a deviation from the expected can be inefficient. So, how is this resolved?

1. The modules are designed to fit standard dimensions of 600 x 600m or 600 x 1200m. Since this is the standard dimensioning used in the construction industry, it already resolves the big problems.

2. The module is adaptable to unusual sizes and can be integrated with linear elements easily.

These solutions are as illustrated on images 7.1-7.2.





Images 7.1, 7.2 [AUTOCAD drawing]: Raghunathan, M. (2024). *Ceiling plan options for the classroom*

7.1.2 Simulation & Scenario Set-up

For the sake of simplicity in simulation, only the layout with the square lights (Drawing 7.1, 7.2) is used since the linear luminaries result in small surface areas which could cause problems during the acoustic simulations.

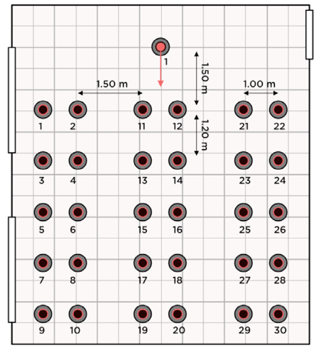
The integrated design is run in the following situations for all 3 scenarios (Images 7.3-7.5 on the right):

1. Side 'B' and 'C' (absorbers) - each independently used as the only absorber in the space
   Side 'A' (reflector/diffuser) - the plane behind the speaker in the scenarios where the teacher is talking (Scenario 1 & 2).
2. Side 'B' and 'C' seen at the same time (as a triangle) used as absorbers in the space simultaneously.
   Side 'A' (reflector/diffuser) - the plane behind the speaker in the scenarios where the teacher is talking (Scenario 1 & 2).

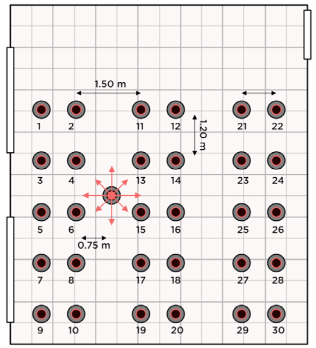
However, it is not necessary that the designed product covers the entire ceiling. It could meet the various requirements with lesser occupied area. In order to understand the ideal placement of the system, the following combinations are used (Images 7.6-7.10):

1. Version 1: Side 'A' or 'B' on the entire ceiling
2. Version 2: Side 'A' and 'B' exposed on the flat portion of the ceiling
3. Version 3: Side 'A' and 'B' exposed on the entire ceiling
4. Version 4: Side 'A' and 'B' exposed on the front half of the ceiling and on the sides. Side 'A' or 'B' on the other half.
5. Version 5: Side 'A' and 'B' exposed on the back half of the ceiling and on the sides. Side 'A' or 'B' on the other half.

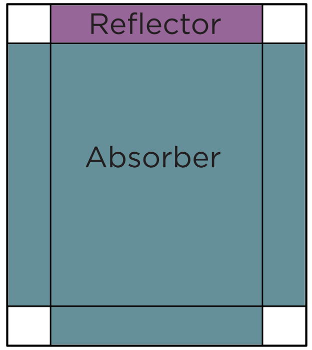
The panel behind the teacher is maintained as a reflector throughout. The corner panels are treated with a diffuser. The rectangles on the flat portion of the ceiling is indicative of installations in the ceiling as seen in drawing 7.2. Another set of simulations are run with the above combinations along with absorbtion on the rear wall.

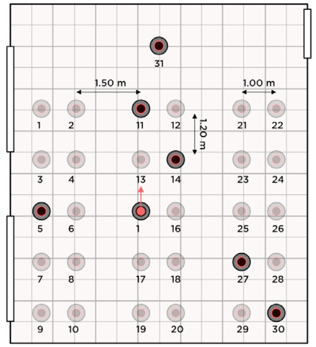


Scenario #1

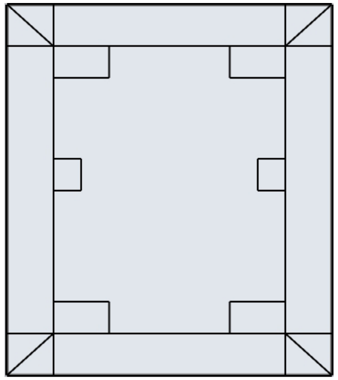


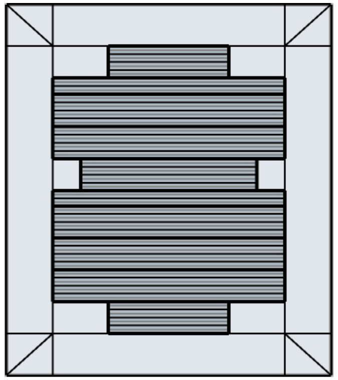
Scenario #2

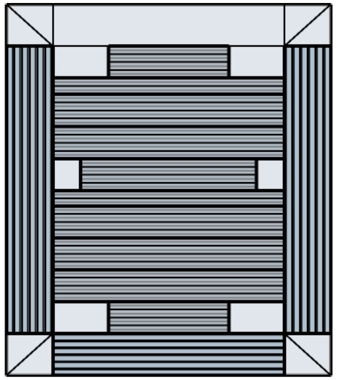


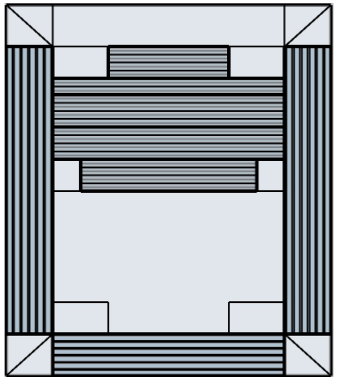


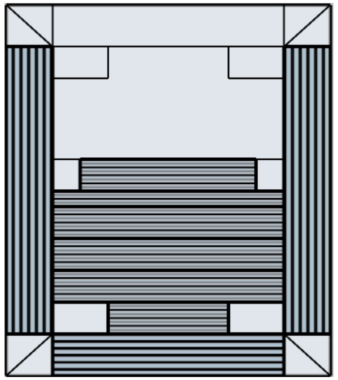
Scenario #3


Version 1


Version 2


Version 3


Version 4

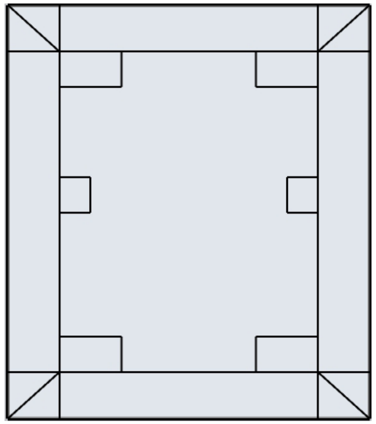

Version 5

Images 7.3-7.5 [Illustration, above]: Raghunathan, M. (2024). *Different scenarios used in analysis*

Images 7.6 [Illustration, above, bottom left]: Raghunathan, M. (2024). *Zoning of reflectors and absorbers*

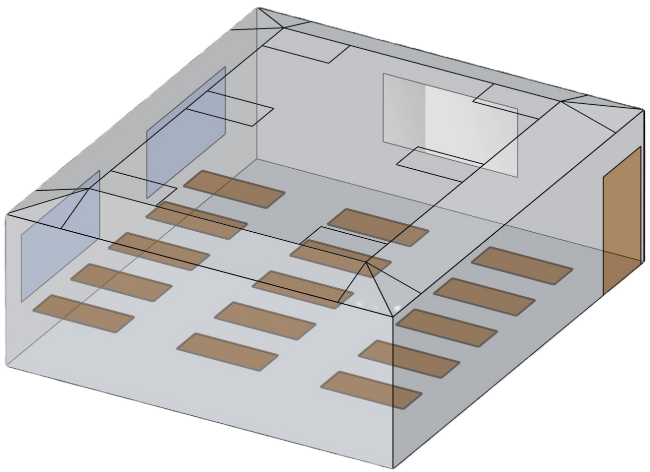
Images 7.6-7.10 [Illustration, left]: Raghunathan, M. (2024). *Ceiling plan for the variations in product placement*

7.1.3 Results - Version #1



The room is treated with a single absorbtive materials (Side 'A' or Side 'B' exposed) on the entire ceiling with the exception of the panel behind the teacher, which is treated as a reflector.

Total Absorbtive Surface Area: 43.7 m^2



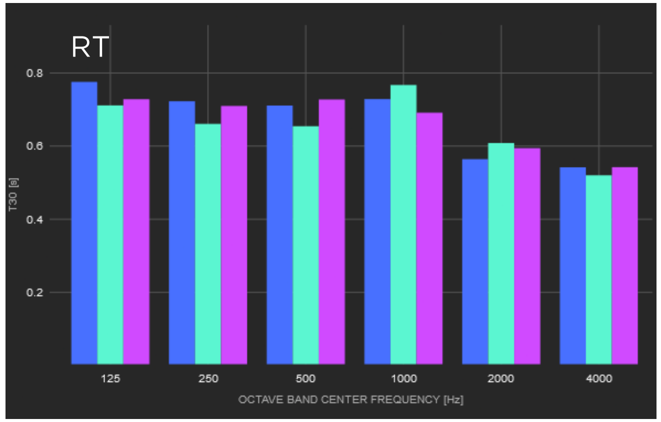
The results are as expected. The surface has a relatively even reverberation time across the frequency bands. This is advantageous since not only the average is within requirements, but each frequency band as well. This means that in addition to the entire average contributing to a good acoustic environment, the speech frequencies are additionally taken care of.

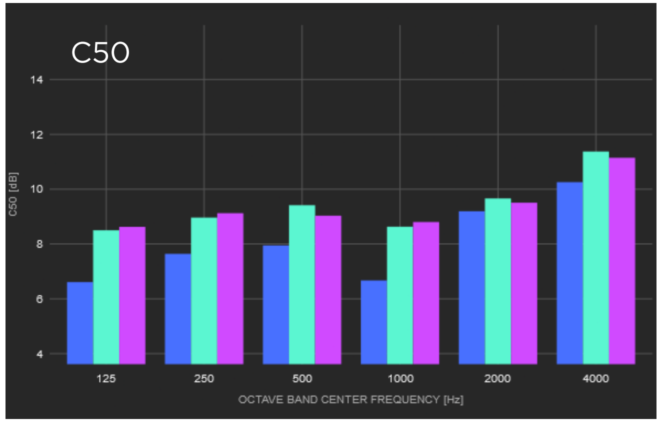
It is important to note the performance of the ceiling in the second scenario: the teacher talking while walking around the classroom. The C50 values for this scenario are high [8+ dB], implying that the quality of speech is not compromised by the movement of the speaker. This is validated by the results for scenario 3, where the student is talking, facing the front of the class. The SPL also boasts high values [~ 50+] in the bass speech frequencies in all three scenarios.

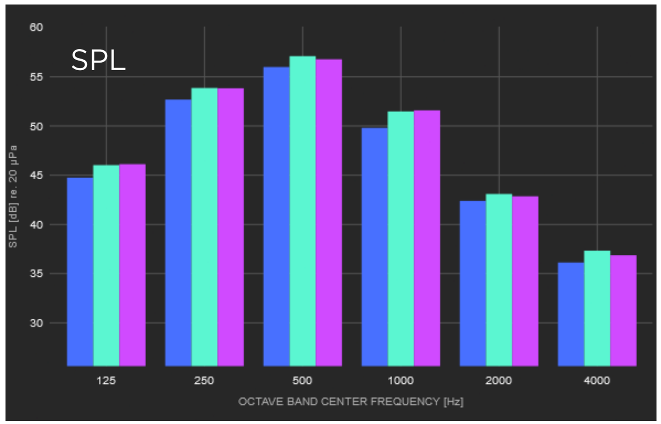
The entire data table is available in Appendix 10

Table 7.1: *RT, C50 and SPL values for version #1*

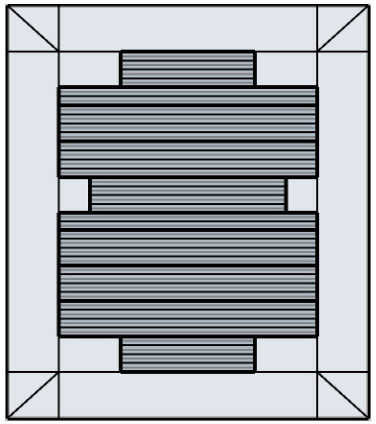
Acoustic Factor	Scenario	Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
RT	1	0.68	0.67
	2	0.67	0.65
	3	0.68	0.67
Average		0.68	0.66
C50	1	7.73	7.91
	2	8.72	8.93
	3	8.41	8.58
Average		8.29	8.47
SPL	1	49.99	46.72
	2	50.93	47.64
	3	50.56	47.22
Average		50.49	47.19





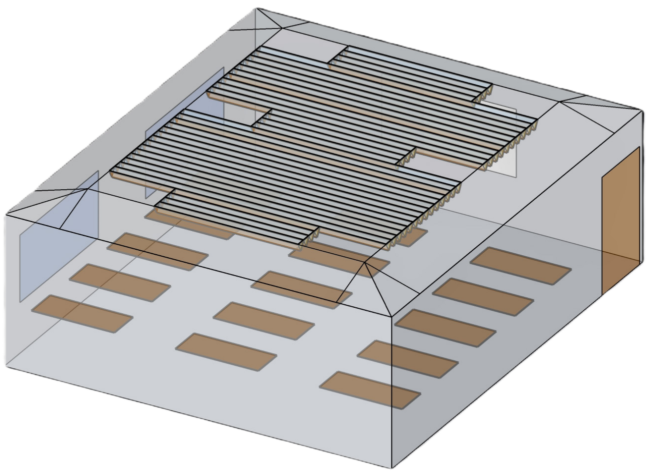


7.1.4 Results - Version #2



The room is treated with both absorbtive materials (Side ‘A’ and Side ‘B’ exposed) on the flat portion of the ceiling, one aborptive panel on the angled sides (Side ‘A’), and with the panel behind the teacher, treated as a reflector.

Total Absorbtive Surface Area: 69.80 m^2



While the average RT for all the scenarios are well under the requirements, there is a sudden spike in 250Hz for scenario #1 (0.79s) and 500Hz for scenario #2 (0.7s). These values are above the average and have to be carefully checked to make sure it does not affect the act of concentration/listening.

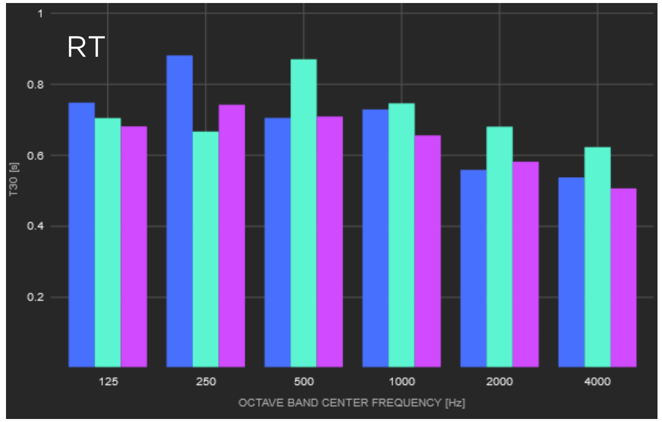
It is important to note the C50 performance of the ceiling. Scenario #1 sees a relatively even C50 value across the board. Scenario #2 sees a steady decrease across the frequency band whereas scenario #3 sees a steady increase.

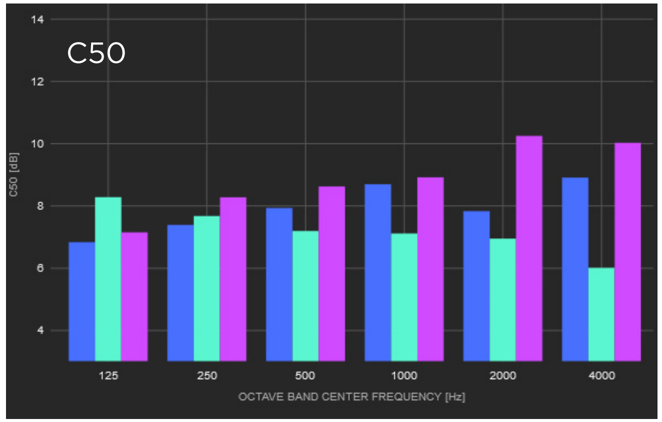
The SPL peaks at 250-500 Hz and decreases with an increase in frequency band. The values are similar enough in the different scenarios across the entire range of frequencies.

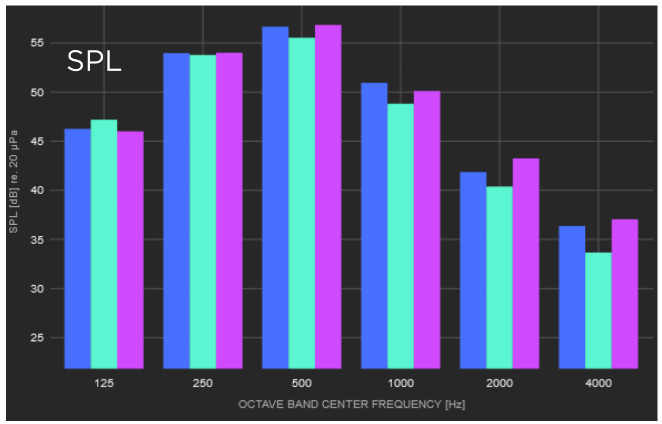
The entire data table is available in Appendix 10.

Table 7.2: *RT, C50 and SPL values for version #2*

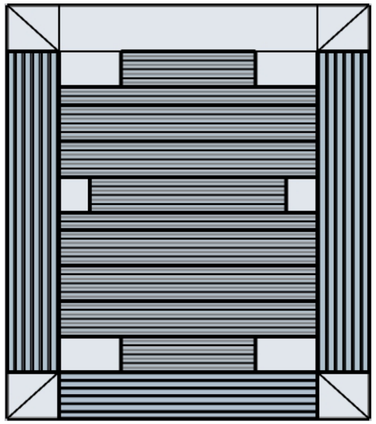
Acoustic Factor	Scenario	Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
RT	1	0.7	0.69
	2	0.68	0.66
	3	0.69	0.66
Average		0.69	0.67
C50	1	7.54	7.45
	2	8.83	8.69
	3	8.47	8.26
Average		8.28	8.13
SPL	1	49.72	46.61
	2	50.83	47.72
	3	50.45	47.32
Average		50.33	47.22





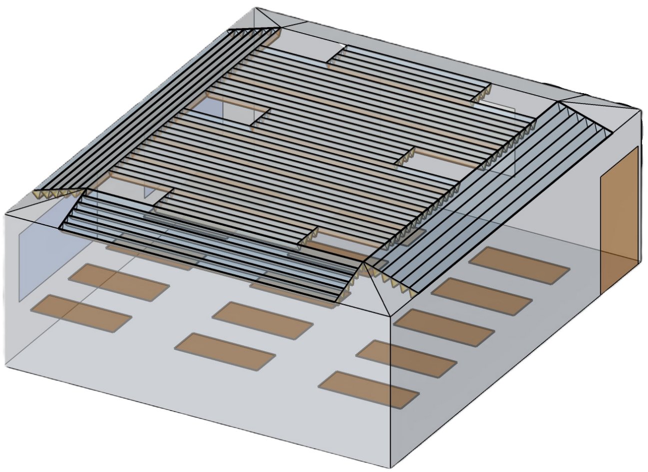


7.1.5 Results - Version #3



The room is treated with both absorbtive materials (Side 'A' and Side 'B' exposed) on the entire ceiling with the exception of the panel behind the teacher, which is treated as a reflector.

Total Absorbtive Surface Area: 87.50 m^2



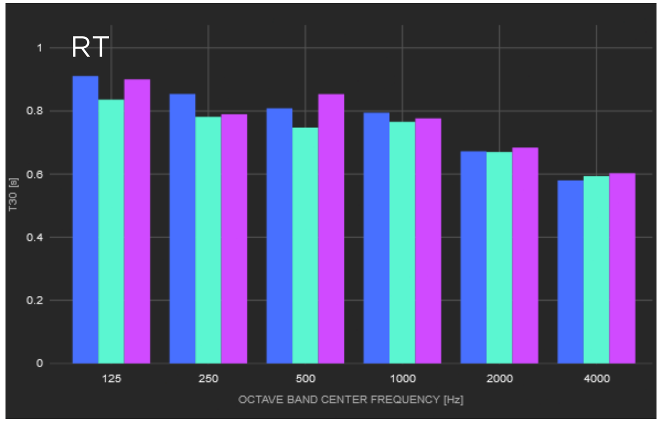
The results are quite unexpected. The combination has a relatively even reverberation time across the frequency bands. This is advantageous since not only the average is within requirements, but each frequency band as well. This means that in addition to the entire average contributing to a good acoustic environment, the speech frequencies are additionally taken care of. However, for a rooms with such extensive absorbtive treatment, it is expected that the reverberation time is much lower than shown by simulation. These results will need to be further validated by manual calculation/estimation.

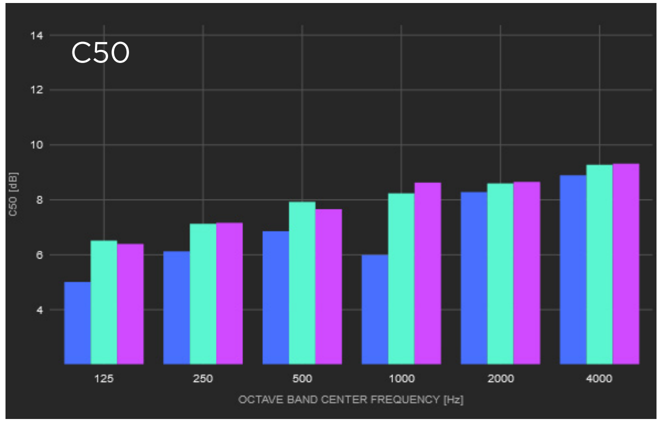
The C50 performance of the ceiling sees a steady decrease across the frequency band in all the scenarios, with the exception of a suddent dip in value at the 1000Hz (5.85 dB). The SPL peaks at 500 Hz and decreases steadily away from it. The values are similar enough in the different scenarios across the entire range of frequencies.

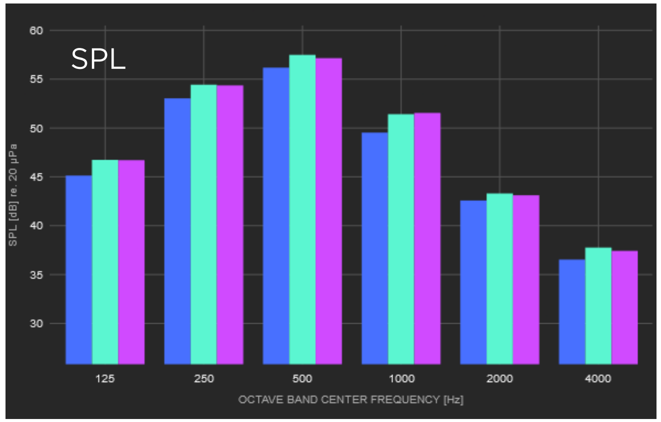
The entire data table is available in Appendix 10.

Table 7.3: *RT, C50 and SPL values for version #3*

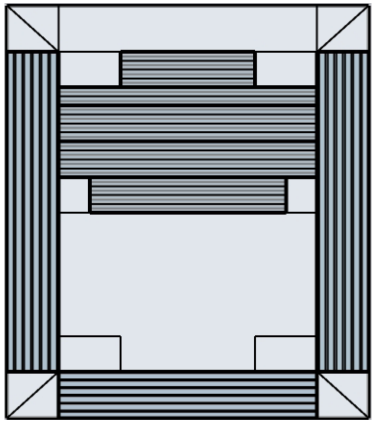
Acoustic Factor	Scenario	Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
RT	1	0.78	0.77
	2	0.74	0.73
	3	0.78	0.77
Average		0.77	0.76
C50	1	6.64	6.67
	2	7.53	7.48
	3	7.22	7.12
Average		7.13	7.09
SPL	1	50.14	46.98
	2	51.27	48.1
	3	50.93	47.74
Average		50.78	47.61





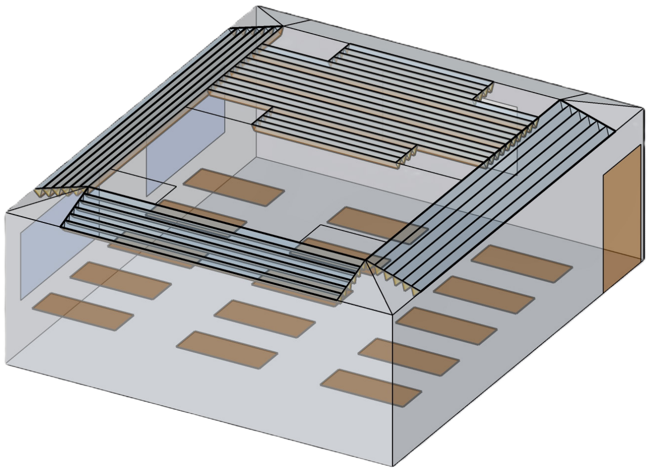


7.1.6 Results - Version #4



The room is treated with both absorbtive materials (Side ‘A’ and Side ‘B’ exposed) on the front half of the flat portion of the ceiling, and on the angled planes with the exception of the plane behind the teacher, which is treated as a reflector.

Total Absorbtive Surface Area: 74.45 m^2



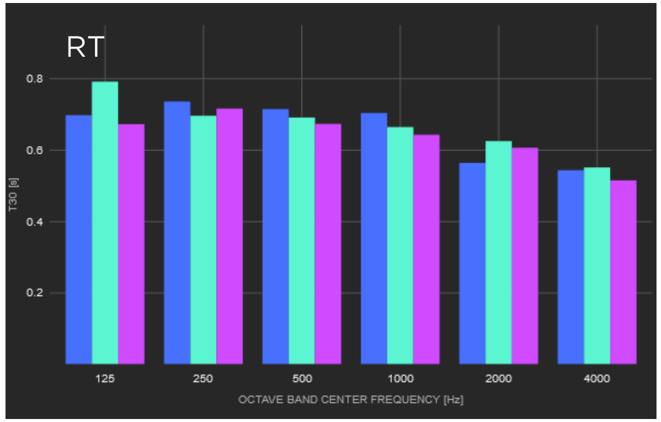
The results are as expected. The RT decreases with increase in the frequency band. However, the most variation is seen in the C50 values. The C50 in scenario 1 increases across the frequency bands, with good values in the speech frequencies. This could be due to the placement of the product. The other scenarios also show comparably good values in the speech frequencies, steadily increasing with increase in frequency.

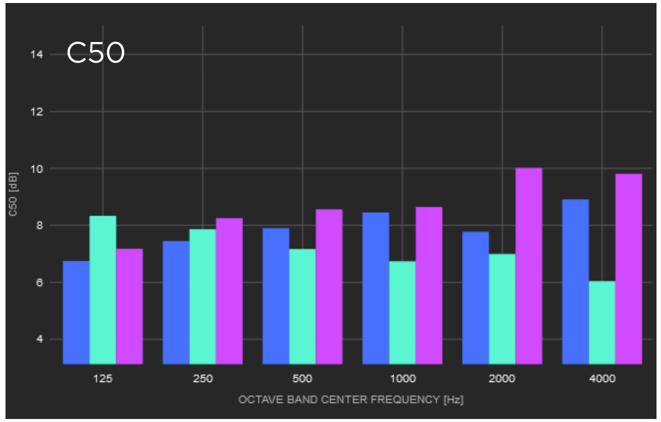
The SPL peaks at 250-500 Hz and decreases with an increase in frequency band. The values are similar enough in the different scenarios across the entire range of frequencies.

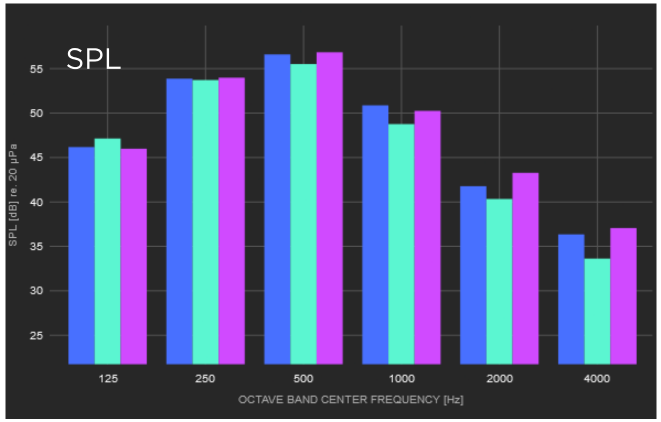
The entire data table is available in Appendix 10.

Table 7.4: *RT, C50 and SPL values for version #4*

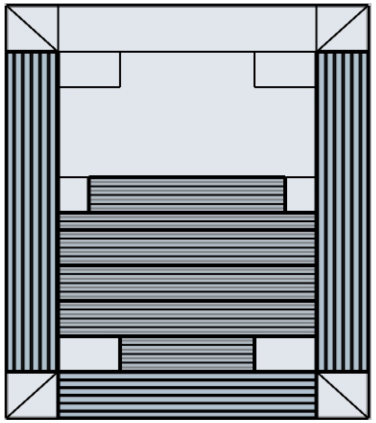
Acoustic Factor	Scenario	Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
RT	1	0.66	0.65
	2	0.67	0.67
	3	0.67	0.65
Average		0.67	0.66
C50	1	7.48	7.43
	2	8.72	8.64
	3	8.36	8.18
Average		8.19	8.08
SPL	1	49.79	46.66
	2	50.94	47.78
	3	50.6	47.42
Average		50.44	47.29





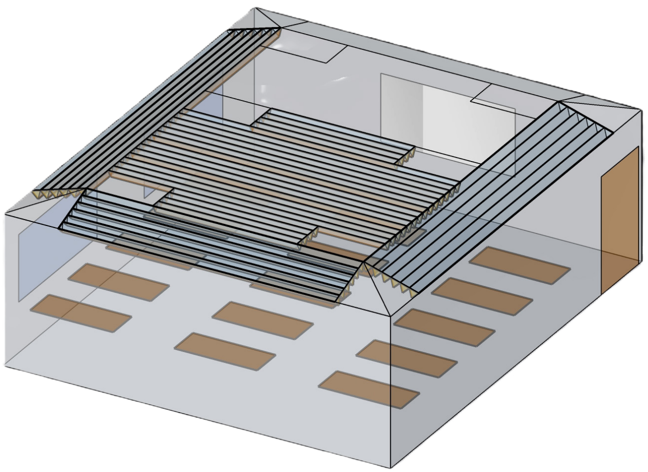


7.1.7 Results - Version #5



The room is treated with both absorbtive materials (Side 'A' and Side 'B' exposed) on the rear half of the flat portion of the ceiling, and on the angled planes with the exception of the plane behind the teacher, which is treated as a reflector.

Total Absorbtive Surface Area: 74.45 m^2



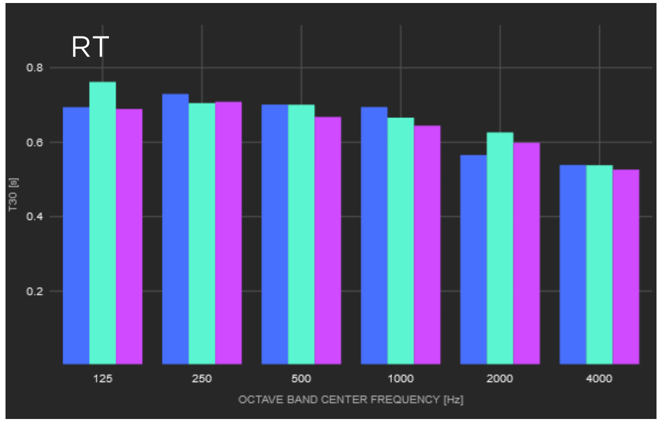
The results are as expected and are extremely similar to the previous version. This is an indication of a possible irregular interaction of the solver with the room geometry. The RT once again decreases with increase in the frequency band, and the most variation is seen in the C50 values. The C50 in the first scenario decreases across the frequency bands, with good values in the speech frequencies. The other scenarios also show comparably good values in the speech frequencies, steadily increasing with increase in frequency. The SPL once again peaks at 250-500 Hz and decreases with an increase in frequency band. The values are similar enough in the different scenarios across the entire range of frequencies.

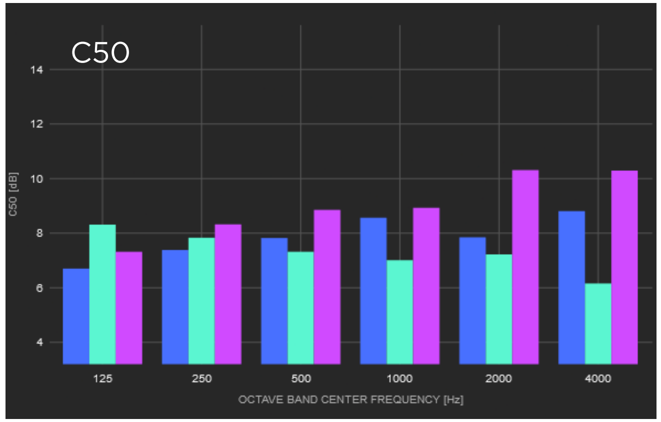
Since the results are extremely similar to the previous scenario, an additional study based on a map rendering would be beneficial in understanding the impact of the product placement.

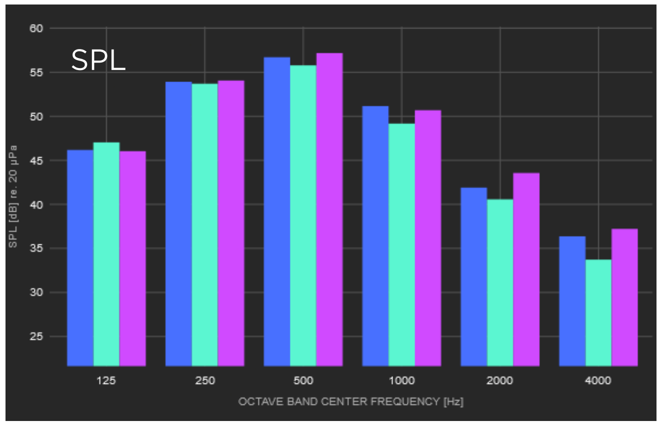
The entire data table is available in Appendix 10.

Table 7.5: *RT, C50 and SPL values for version #5*

Acoustic Factor	Scenario	Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
RT	1	0.66	0.65
	2	0.68	0.67
	3	0.67	0.65
Average		0.67	0.66
C50	1	7.55	7.48
	2	8.6	8.53
	3	8.2	8.05
Average		8.12	8.02
SPL	1	49.89	46.74
	2	50.79	47.63
	3	50.39	47.19
Average		50.36	47.19

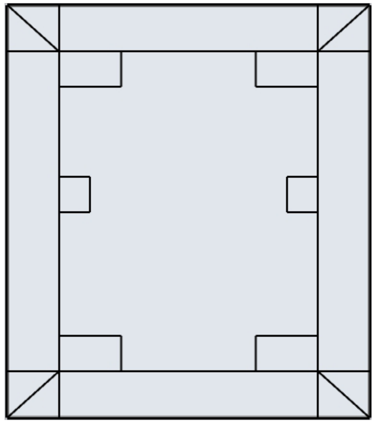




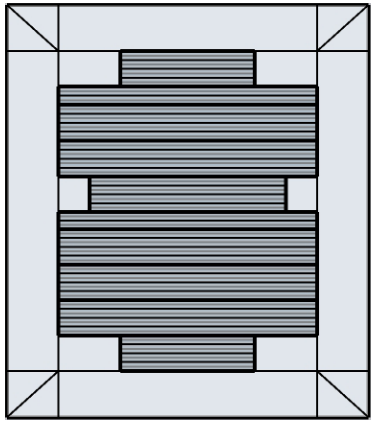


7.1.8. Hip Ceiling Results - Version Comparison - RT & C50

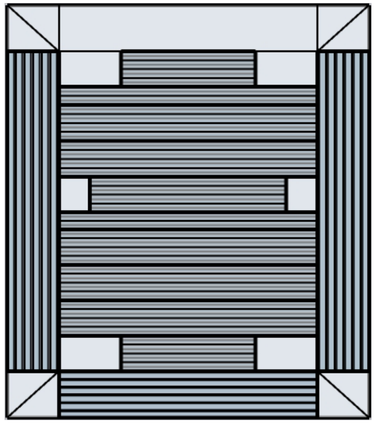
Version #1



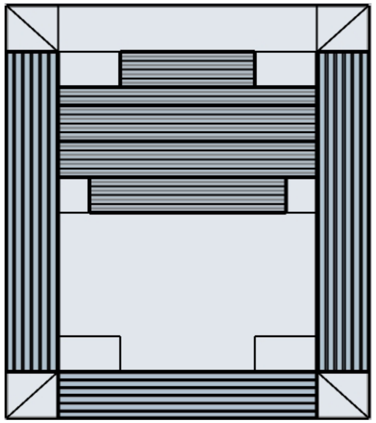
Version #2



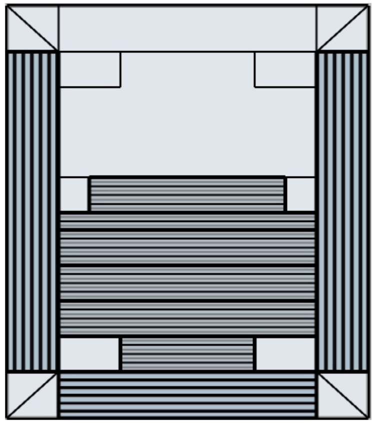
Version #3

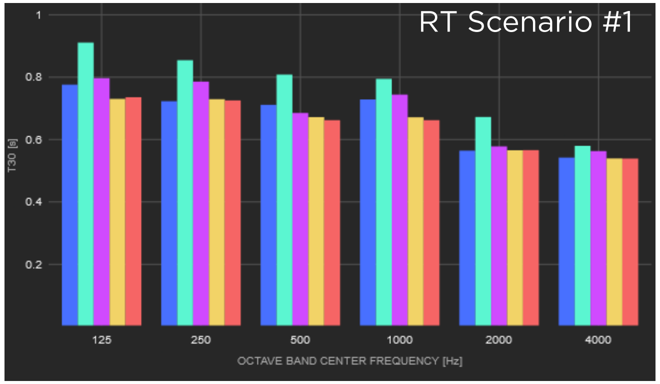


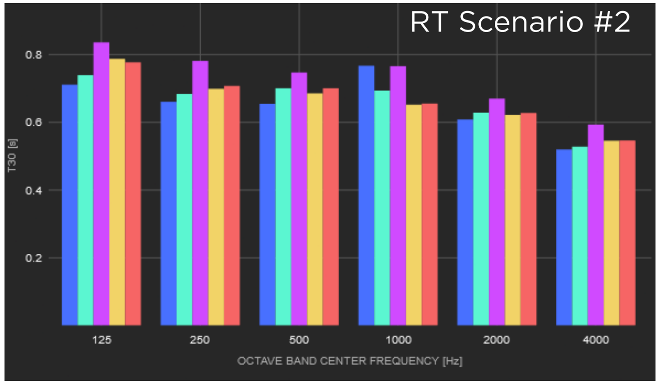
Version #4

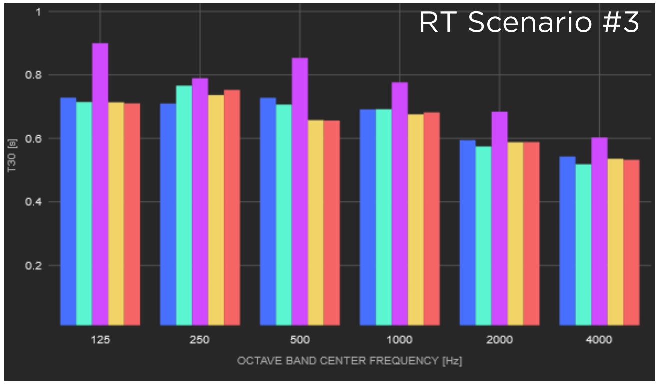


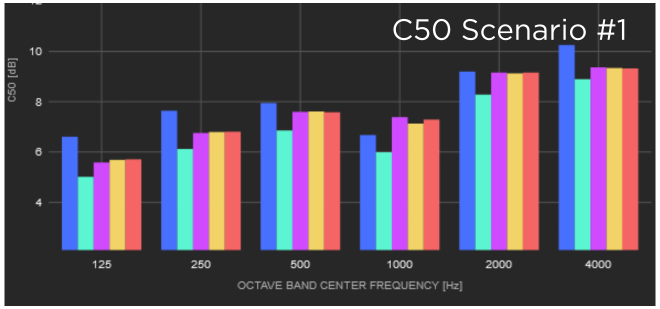
Version #5

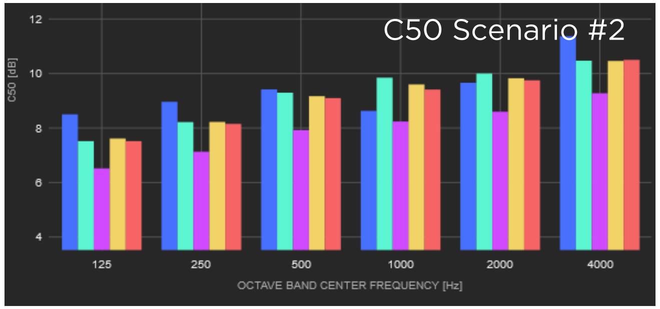


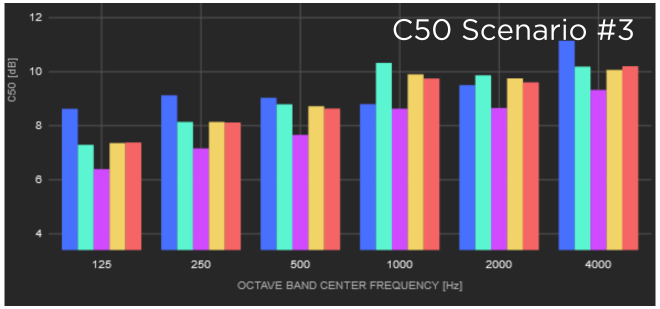






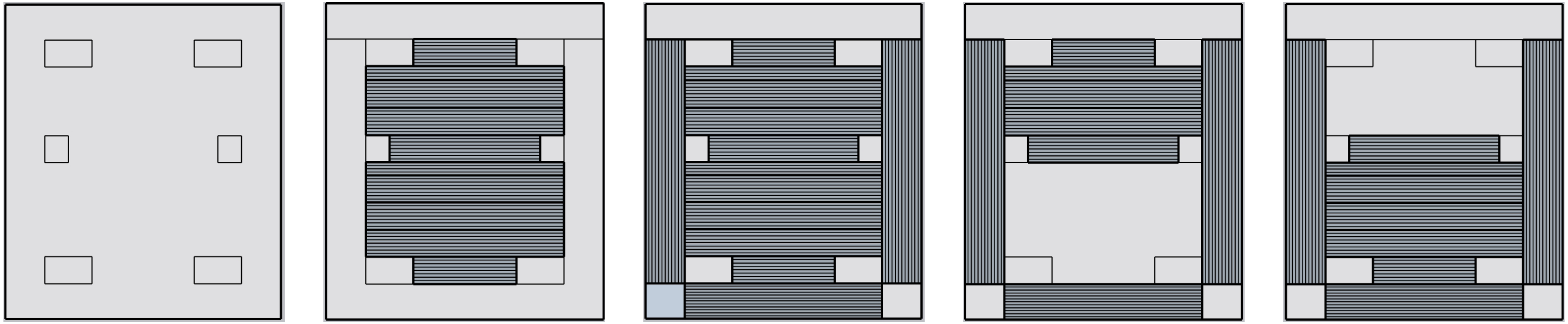


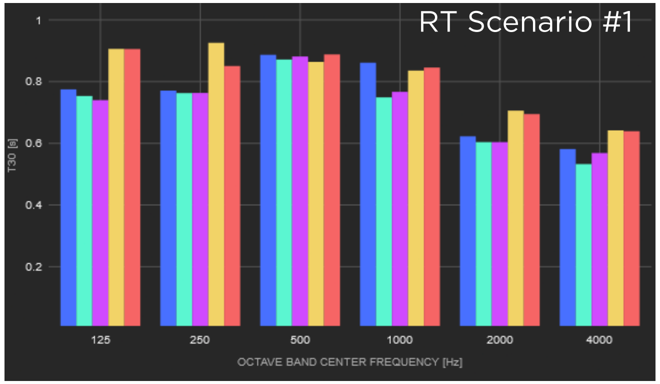


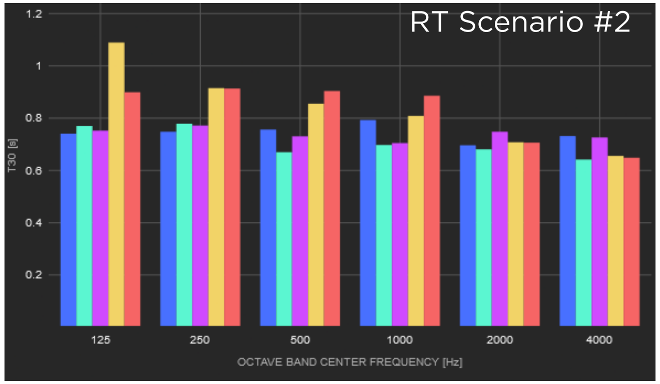


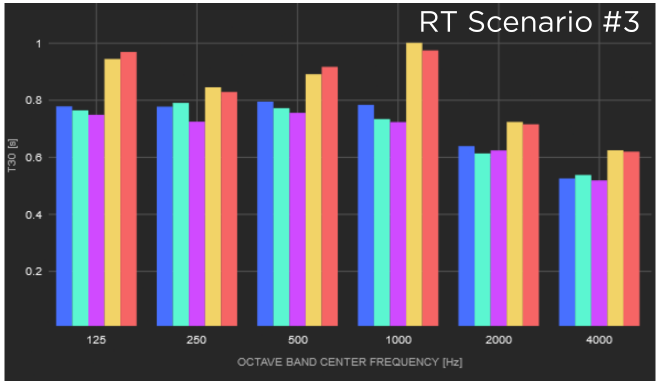
7.1.9. Flat Ceiling Results - Version Comparison - RT & C50

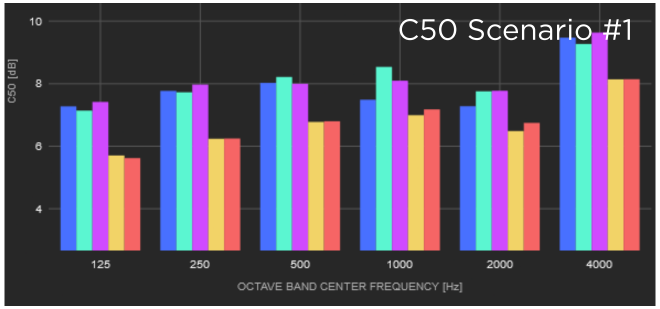
Version #1 | Version #2 | Version #3 | Version #4 | Version #5

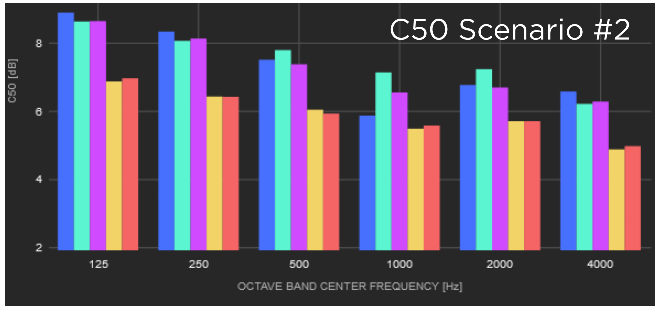


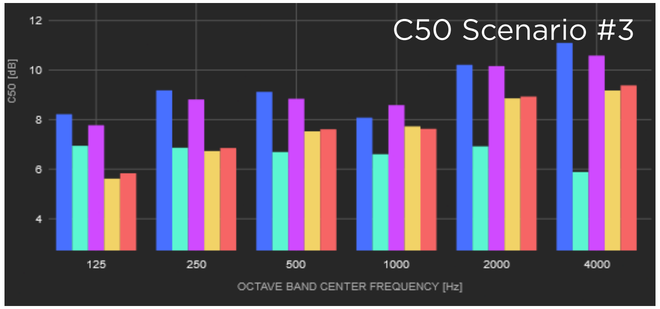












7.1.10 Comparison Against a Flat Ceiling

The variations seen and applied to the hip ceiling are replicated in the flat ceiling so that we can compare the effectiveness of the ceiling profile in the context of the design intervention. The table on the right offers an insight into the performance of the design across the ceiling types. From the RT average it is clear that the flat ceiling outperforms the hip ceiling only in version #3. However, these results should be further verified and clarified since the values themselves are quite uncharacteristic. The results indicate and reiterate earlier conclusions that the hip ceiling profile does improve the reverberation time in a room in most scenarios. The summary across variations and scenarios is as shown on the right.

Earlier results are limited to values produced by the geometric solver in Treble. The hybrid solution results in further anomalous values under the transition frequency, i.e. with the inclusion of values from the wave solver. The hypothesised causes of the anomaly are as follows:

1. The geometry is too detailed for a simulation software at this moment.
2. Related to the earlier point, the design's geometry could result in localised echoes between the triangles for frequencies under the transition frequency (possibly caused or seen by the wave approach to solution).
3. Treble's wave solver uses an omnidirectional speaker regardless of the source assigned. This results in the hybrid results

	Ceiling Type	Version	125	250	500	1000	2000	4000	Avg. 125 t/m 2000 Hz
S01	Hip Ceiling	1	0.776	0.723	0.711	0.729	0.564	0.542	0.7
		2	0.797	0.786	0.685	0.744	0.578	0.563	0.72
		3	0.911	0.854	0.808	0.794	0.672	0.58	0.81
		4	0.73	0.73	0.672	0.671	0.566	0.539	0.67
		5	0.735	0.726	0.662	0.662	0.566	0.539	0.67
	Flat Ceiling	1	0.745	0.77	0.788	0.816	0.62	0.582	0.75
		2	0.781	0.766	0.778	0.758	0.597	0.555	0.74
		3	0.753	0.776	0.78	0.766	0.609	0.565	0.74
		4	0.888	0.862	0.864	0.849	0.707	0.629	0.83
		5	0.896	0.905	0.875	0.843	0.69	0.632	0.84

	Ceiling Type	Version	125	250	500	1000	2000	4000	Avg. 125 t/m 2000 Hz
S02	Hip Ceiling	1	0.711	0.661	0.654	0.767	0.608	0.52	0.68
		2	0.739	0.684	0.701	0.694	0.628	0.528	0.69
		3	0.836	0.781	0.747	0.766	0.67	0.594	0.76
		4	0.787	0.699	0.686	0.652	0.622	0.546	0.69
		5	0.777	0.707	0.701	0.655	0.627	0.546	0.69
	Flat Ceiling	1	0.759	0.728	0.755	0.765	0.659	0.553	0.73
		2	0.787	0.747	0.693	0.707	0.638	0.544	0.71
		3	0.768	0.73	0.719	0.71	0.649	0.553	0.72
		4	0.945	0.906	0.818	0.831	0.714	0.626	0.84
		5	0.892	0.89	0.869	0.826	0.721	0.629	0.84

	Ceiling Type	Version	125	250	500	1000	2000	4000	Avg. 125 t/m 2000 Hz
S03	Hip Ceiling	1	0.683	0.669	0.664	0.648	0.575	0.509	0.65
		2	0.707	0.7	0.671	0.641	0.557	0.508	0.66
		3	0.836	0.777	0.784	0.753	0.653	0.576	0.76
		4	0.706	0.69	0.643	0.652	0.549	0.521	0.65
		5	0.71	0.7	0.646	0.657	0.553	0.525	0.65
	Flat Ceiling	1	0.838	0.826	0.848	0.77	0.642	0.566	0.78
		2	0.79	0.753	0.77	0.723	0.599	0.552	0.73
		3	0.792	0.781	0.822	0.734	0.627	0.539	0.75
		4	0.931	0.836	0.881	0.845	0.715	0.646	0.84
		5	0.941	0.85	0.91	0.803	0.724	0.636	0.85

Table 7.6: *Comparison of values across different scenarios between hip and flat ceiling types*

including results from an omnidirectional and speech source.

Thus, these results need further verification by means of manual calculations.

7.1.11. Targets & Goals
The acoustic factor goals shown in the table below. Different teaching styles have different targets to be achieved. Of course, the best performing option can be chosen as a one-size-fits-all but there are certain advantages to fine tuning it to the situation.

Teacher centred learning styles requires all attention to be directed to one speaker. Any other noise in the space would be detrimental to the task. Thus, it requires low reverberation time. Group projects involve multiple people talking at the same time. Extremely low reverberation time could result in everyone being able to hear each other too clearly, resulting in confusing listening demands. Higher reverberation time than the teacher centred style would result in more masking noise, allowing for students to ignore other speech in the room. Similarly, during individual work, there is no need to listen to other people talk. Higher reverberation time would let students ignore the noise better than they would be able to in an extremely quiet room.

The requirements are as indicated in Table 7.7 (with the full table and the sources for these values available in Appendix 11).

Once again, the different activities all have different requirements and one particular combination does not satisfy them all. Two arguments can be made here:

1. Either the best performing combination is chosen and that is placed as a static model. This would be the most cost efficient option and would be the ideal blanket solution.
2. Or, the entire ceiling is fitted with the dynamic module and the system can be placed in all 5 variations studied. This option would be expensive but would also address the niche needs of the varying learning activities.

A choice can be made at this stage based on the RT and C50 values if not for one necessary consideration. For children, the speech clarity should be assessed based on a threshold of 35 ms. For a valid conclusion to be derived, the C50 values must be recalculated to C35 (Author's Note 07: C35 Derivation).

7.2 Manual Calculation

The reverberation time of the classroom in the different versions of the design needs to be verified via manual calculation. There are multiple methods that can be used to manually calculate the reverberation time of a room subject to uneven absorbtion. They are as follows:

1. Fitzroy-Kuttruff equation
Sabine's or Eyring's formula for reverberation time assumes that the room has evenly distributed sound absorbtion. Kuttruff's correction (related to Eyring's formula) takes into account the uneven distribution of finishes. It also is appropriate for scenarios where the absorbtion is primarily on the horizontal

Type	**Acoustic Factors**			
	Reverberation Time (RT)	*Speech Transmission Index (STI)*	*Signal to Noise Ratio (SNR)*	*Equivalent Sound Pressure Level (L_{eq})*
Teacher Centered	< 0.4 - 0.6 s	> 0.75	+15 - +20 dB	35 dB
Group Projects	< 0.8 s	> 0.6	+15 - +20 dB	35 dB
Individual Work	< 0.8 s			
Additional Requirements	< 0.3 - 0.5 s	> 0.7	+20 dB (250 to 750 Hz), +15 dB (750 Hz to 4 kHz)	31 dB

Table 7.7: *Acoustic requirements in a classroom for different factors*

planes (i.e., the floor-ceiling planes) *(Reverberation Time Formulae, n.d.)*. As such, this method is utilised to further evaluate the performance of the integrated design.

2. Arau-Puchades equation
This equation is also a possibility since it addresses the delayed sound decay due to parallel opposed surfaces *(Reverberation Time Formulae, n.d.)*.

3. NEN-EN 12354-6, Appendix D [Estimation for irregular spaces and/or absorbtion distribution]
This is the more ideal approach to the problem. This standard takes into account the impact of object geometry, and the absorbtion coefficients and scattering coefficients of the different surfaces in the room. However, this method is time intensive and due to the current time limitations, it is not utilised in this thesis.

It would be interesting to re-evaluate and corroborate these results via the formula suggested in NEN-EN 12354-6 Appendix D alongside live measurements.

7.2.1 The Results
The integrated design's reverberation time in various product configurations is once again calculated using the Eyring-Kuttruff, Arau-Puchades, and the Fitzroy-Kuttruff formula to understand the theoretical impact of the product. The following surface areas are used:

1. Long walls: 48 m^2
2. Short walls: 37.8 m^2
3. Floor: 56 m^2
4. Ceiling:
    - Version #1: 43.70 m^2
    - Version #2: 69.80 m^2
    - Version #3: 87.50 m^2
    - Version #4/5: 74.45 m^2
    - Version #6: 56.75 m^2

An additional version (#6) is introduced to provide an intermediate configuration between versions #1 and #2. The appropriate materials are assigned keeping in mind the presence of doors, windows, and whiteboards (as outlined in Chapter 04).

As expected, the reverberation time decreases with increase in application of sound absorption in the room. This decrease in RT also starts to plateau with excessive sound absorption applied to the room (as seen in the table 7.8 - comparison of versions #2 with versions #4/5 and #3).

The increase in absorptive area of 26.10 m^2 from version #2 to version #3 results in only a decrease in 0.06s in reverberation time whereas the increase in absorptive area of 13.05 m^2 between versions #1 and #6 results in a decrease in reverberation time of roughly 0.12s. This already paints an understandable picture of the extent of impact of these different placement combinations.

7.2.2 Optimal Combinations
Although the calculated reverberation times vary with the methods used, the decrease in reverberation time with increase in absorption surface area is relatively steady. This difference is used to narrow down on the preferred versions for different classroom

Image 7.11: *The different scenarios analysed*

Eyring-Kuttruff										
Amount of Absorption	Version	125	250	500	1000	2000	4000	Avg.	Decrease in RT	Increase in absorptive area
43.7	1	0.61	0.47	0.54	0.59	0.45	0.41	0.53	-	-
56.75	6	0.48	0.37	0.42	0.48	0.36	0.33	0.42	0.11	13.05
69.8	2	0.39	0.3	0.34	0.39	0.29	0.27	0.34	0.08	13.05
74.45	4/5	0.37	0.28	0.32	0.37	0.28	0.26	0.32	0.02	4.65
87.5	3	0.32	0.24	0.27	0.32	0.24	0.22	0.28	0.04	13.05

Arau-Puchades										
Amount of Absorption	Version	125	250	500	1000	2000	4000	Avg.	Decrease in RT	Increase in absorptive area
43.7	1	1.07	0.99	1.34	0.98	0.75	0.55	1.03	-	-
56.75	6	0.94	0.86	1.15	0.86	0.66	0.49	0.89	0.14	13.05
69.8	2	0.84	0.75	1	0.77	0.58	0.44	0.79	0.1	13.05
74.45	4/5	0.81	0.72	0.96	0.74	0.56	0.43	0.76	0.03	4.65
87.5	3	0.72	0.64	0.85	0.67	0.51	0.39	0.68	0.08	13.05

Fitzroy-Kuttruff										
Amount of Absorption	Version	125	250	500	1000	2000	4000	Avg.	Decrease in RT	Increase in absorptive area
43.7	1	0.52	0.39	0.46	0.53	0.39	0.35	0.46	-	-
56.75	6	0.41	0.29	0.34	0.42	0.3	0.27	0.35	0.11	13.05
69.8	2	0.33	0.23	0.27	0.34	0.24	0.22	0.28	0.07	13.05
74.45	4/5	0.31	0.21	0.25	0.32	0.22	0.2	0.26	0.02	4.65
87.5	3	0.26	0.17	0.21	0.27	0.18	0.17	0.22	0.04	13.05

Table 7.8: *Reverberation time values based on different calculation methods*

activities.

Option #1
This option is relatively simple. It simply proposes that the only change in acoustic intervention be the ceiling profile itself. As proven earlier, this simple change in ceiling profile itself has a significant impact on reverberation time and consequently the speech clarity of the room.

Option #2

- Version #1
  Target: Group/Independent learning
- Version #6
  Target: Teacher Centred learning

This will result in a reduction of 0.11-0.14s in

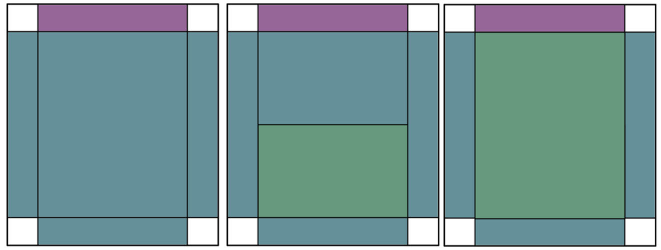
In table 7.8, the amount of absorption and increase in sound absorption area is in square metres, and the decrease in RT in seconds.

reverberation time across the versions. This can be considered to be a cost friendly version that affords the user (limited) control over their acoustic environment.

Option #3

- Version #1
  Target: Group/Independent learning
- Version #2
  Target: Teacher Centred learning

This will result in a reduction of 0.18-0.24s in reverberation time across the versions. This can be considered to be a combination that allows the user more control over the soundscape in the room but also becomes a more costly option.



Version #1 Version #6 Version #2

Placement of absorbers
Placement of reflectors
Placement of proposed design

Image 7.12: *The different combinations of absorbers and reflectors*

While the remaining versions do improve the reverberation time in the room, they require an excessive amount of material to reduce the value and even then, only by small amounts. This improvement is not nearly enough to justify the additional costs that come with applying this product to the entire ceiling.

Thus, the proposed options only offer combinations of the versions 1, 2 and 6. With further detailed calculations, these proposed combinations and solutions can be elaborated to include the more accurate expected improvement in reverberation times.

The formula has to be re-derived from the formula for the pressure/energy decay in a room with a diffused sound field:

$p^2_{eff}(t) = p^2_{eff}(0).e^{-(C0.A/4V)t}$

The limits for the formula in terms of sound energy (E in joules) are now 0 (o ms) to 0.035 (35 ms) for C35 instead of 0 (0 ms) to 0.05 (50 ms) for C50. With the relevant substitutions as illustrated on the right, it results in an early energy formula of:

$E_{0\text{-}35\,ms} = E_o.[1 - e^{(-0.48/T)}]$

In comparison, this formula for C50 is

$E_{0\text{-}35\,ms} = E_o.[1 - e^{(-0.69/T)}]$

The difference is seen in the factor 'e' - 0.48 in place of 0.69.

This factor is then substituted in the formula for sound pressure level distribution in a room (according to Sato and Bradley - takes into account an empirical factor f_b) to arrive at the formulae for early and late components of SPL. The speech clarity, C35 is then given by the subtraction of the late frequency value from the early frequency value.

$$p^2_{eff}(t) = p^2_{eff}(0).\,e^{-\frac{c_0 A}{4V}t}$$

$$\Rightarrow W(t) = W(0).\,e^{-\frac{c_0}{24T}t}$$

$$\Rightarrow E_{t_1-t_2} = W(0).\int_{t_1}^{t_2} e^{-\frac{c_0}{24T}t}\,dt$$

Given $\frac{A}{V} = \frac{1}{6T}$

where W = Sound Power [W]

where E = Sound Energy [J]

For $t_1 = 0$ & $t_2 = 35\text{ ms} = 0.035\text{ s}$

$$E_{0\text{-}35ms} = W(0).\int_0^{0.035} e^{-\frac{c_0}{24T}t}.\,dt$$

$$= -W(0).\,\frac{24T}{c_0}.\,e^{-\frac{c_0}{24T}t}\Big|_0^{0.035}$$

But $W(0).\frac{24T}{c_0} = E_0$. So,

$$E_{0\text{-}35ms} = -E_0.\,e^{-\frac{c_0}{24T}t}\Big|_0^{0.035}$$

$$= -E_0.\left[e^{-\frac{c_0}{24T}0.035} - e^{-\frac{c_0}{24T}0}\right]$$

$$= -E_0.\left[e^{-\frac{331.4\times0.035}{24T}} - (1)\right]$$

c_0 @ 0°C = 331.4 m/s

$$= E_0\left[1 - e^{-\frac{0.48}{T}}\right]$$

Thus, Early Energy [0-35 ms], $E_{0-35ms} = E_0 \left[1 - e^{-\frac{0.48}{T}} \right]$

Late Energy [35 - ∞ ms], $E_{35-\infty ms} = E_0 \left[e^{-\frac{0.48}{T}} \right]$

$$L_{p\,early} = L_{w\,speech} + 10 \log \left[\frac{Q}{4\pi r^2} + \left[\frac{4(1-\bar{\alpha})}{\alpha S} \right]^{\frac{f_b r}{mfp}} \times \left[1 - \exp\left(\frac{-0.48}{T} \right) \right] \right] \longrightarrow (1)$$

$$L_{p\,late} = L_{w\,speech} + 10 \log \left[\frac{4(1-\bar{\alpha})}{\alpha S}^{\frac{f_b r}{mfp}} \times \left[\exp\left(\frac{-0.48}{T} \right) \right] \right] \longrightarrow (2)$$

$Q = 2$ (speaker)	S = surface area
$\pi = 3.14$	V = volume of room
$f_b = 2$ (classrooms)	
$mfp = \frac{4V}{S}$	

Reducing (1),

$$L_{p\,early} = L_{w\,speech} + 10 \log \left[\frac{2}{4 \times 3.14 \times r^2} + \left[\frac{4(1-\bar{\alpha})}{\alpha S} \right]^{\frac{2 \times r}{mfp}} \times \left[1 - e^{-\frac{0.48}{T}} \right] \right]$$

$$= L_{w\,speech} + 10 \log \left[\frac{1}{6.28 \times r^2} + \frac{4(1-\bar{\alpha})}{\alpha S}^{\frac{2r}{mfp}} - \frac{4(1-\bar{\alpha})}{\alpha S}^{\frac{2r}{mfp}} \times e^{-\frac{0.48}{T}} \right] \longrightarrow (3)$$

Reducing (2),

$$L_{p\,late} = L_{w\,speech} + 10 \log \left[\frac{4(1-\bar{\alpha})}{\alpha S}^{\frac{}{mfp}} \times e^{-\frac{0.48}{T}} \right] \longrightarrow (4)$$

$$C_{35} = L_{p\,early} - L_{p\,late}$$

$$= (3) - (4)$$

$$= \left[10 \log \left[\frac{1}{6.28 \times r^2} + \frac{4(1-\bar{\alpha})}{\alpha S}^{\frac{2r}{mfp}} - \frac{e^{-\frac{0.48}{T}} \, 4(1-\bar{\alpha})^{\frac{2r}{mfp}}}{\alpha S} \right] \right] - \left[10 \log \left[\frac{e^{-\frac{0.48}{T}} \, 4(1-\bar{\alpha})^{\frac{2r}{mfp}}}{\alpha S} \right] \right]$$

$$C_{35} = \left[10.\log\left(\frac{1}{6.28r^2} + \left(\left(\frac{4(1-\bar{\alpha})^{\frac{2r}{mfp}}}{\alpha S}\right) - \left(\frac{e^{-\frac{0.48}{T}}4(1-\bar{\alpha})^{\frac{2r}{mfp}}}{\alpha S}\right)\right)\right)\right] - \left[10.\log\left(\frac{e^{-\frac{0.48}{T}}4(1-\bar{\alpha})^{\frac{2r}{mfp}}}{\alpha S}\right)\right]$$

$$C_{50} = \left[10.\log\left(\frac{1}{6.28r^2} + \left(\left(\frac{4(1-\bar{\alpha})^{\frac{2r}{mfp}}}{\alpha S}\right) - \left(\frac{e^{-\frac{0.69}{T}}4(1-\bar{\alpha})^{\frac{2r}{mfp}}}{\alpha S}\right)\right)\right)\right] - \left[10.\log\left(\frac{e^{-\frac{0.69}{T}}4(1-\bar{\alpha})^{\frac{2r}{mfp}}}{\alpha S}\right)\right]$$

where,
C_{35} - speech clarity with a threshold of 35 ms
C_{50} - speech clarity with a threshold of 50 ms
r - distance to source [m]
S - total surface area of room enclosure [m^2]
mfp - mean free path of sound [m]
f_b - empirical factor = 2 for classrooms
T - reverberation time [s]
α - avg. absorption coefficient [m^2sabine]

The values assumed in the equation are as follows
C_0 @ 0°C= 331.4 m/s
Pi = 3.14
Q = 2
f_b = 2
mfp = 4V/S
where,
V - volume of the room
S - surface are of the room

7.3 C35 Calculation

The C35 is calculated with the following considerations:

1. The calculations are done for the reverberation times obtained via manual calculation.
2. The C35 factor is calculated for 9 student positions in the classroom (3 in the front row, 3 in the middle and 3 in the back row of the classroom - students 1, 5, 9, 11, 15, 19, 21, 25, and 29).
3. The RT value is assumed to be the same for each student position.
4. The surface areas and volume of the room varies with the variation in place and are as seen in the table below.
5. The table is arranged in increasing order of area of sound absorbtion in order to make the C35 values more understandable.

As expected, with an increase in applied sound absorbtion, the C35 value increases, eventually plateauing after version #2 (speaking strictly in terms of the order seen in this table). The options for product implementation (Section 7.2.2.) suggest the versions 1, 6, and 2, with option 1 being suggested for group learning and the latter two for teacher centered learning systems. The C35 values are shown to steadily increase with increase in absorbtion area, allowing for the variations used in situations requiring high focus to also boost speech clarity.

Table 7.9: *C35 calculation for the different versions of design integration.*

Eyring-Kuttruff					C35								
Amount of Absorption	Version	Surface Area	Volume of Space	Avg. RT	1	5	9	11	15	19	21	25	29
43.7	1	198.9	163.9	0.53	6.41	7.47	1.68	10.64	6.83	1.68	8.12	7.18	1.68
56.75	6	211.95	163	0.42	7.97	9.11	3.29	12.09	8.42	3.29	9.65	8.8	3.29
69.8	2	225	162.12	0.34	9.62	10.85	4.92	13.66	10.11	4.92	11.27	10.52	4.92
74.45	4/5	229.65	161.82	0.32	10.16	11.42	5.42	14.17	10.66	5.42	11.8	11.08	5.42
87.5	3	242.7	160.79	0.28	11.49	12.86	6.58	15.45	12.04	6.58	13.12	12.49	6.58

Arau-Puchades					C35								
Amount of Absorption	Version	Surface Area	Volume of Space	Avg. RT	1	5	9	11	15	19	21	25	29
43.7	1	198.9	163.9	1.03	3.91	5.11	-2.26	8.52	4.39	-2.26	5.83	4.79	-2.26
56.75	6	211.95	163	0.89	4.73	6.02	-1.46	9.24	5.25	-1.45	6.62	5.68	-1.45
69.8	2	225	162.12	0.79	5.5	6.89	-0.77	9.93	6.06	-0.77	7.36	6.52	-0.77
74.45	4/5	229.65	161.82	0.76	5.76	7.19	-0.55	10.16	6.34	-0.55	7.61	6.81	-0.55
87.5	3	242.7	160.79	0.68	6.54	8.07	0.11	10.85	7.16	0.11	8.36	7.66	0.11

Fitzroy-Kuttruff					C35								
Amount of Absorption	Version	Surface Area	Volume of Space	Avg. RT	1	5	9	11	15	19	21	25	29
43.7	1	198.9	163.9	0.46	7.12	8.16	2.65	11.29	7.56	2.65	8.81	7.89	2.65
56.75	6	211.95	163	0.35	9.1	10.21	4.68	13.14	9.54	4.68	10.74	9.91	4.68
69.8	2	225	162.12	0.28	11.06	12.26	6.58	15.02	11.54	6.58	12.67	11.93	6.58
74.45	4/5	229.65	161.82	0.26	11.78	13.01	7.27	15.72	12.27	7.27	13.39	12.68	7.27
87.5	3	242.7	160.79	0.22	13.63	14.97	8.96	17.53	14.17	8.96	15.23	14.61	8.96

Author's Note 08: Interesting Similarities & References

In the process of researching a multitude of topics for this thesis, I came across some that stood out for its work into similar topics. They are as listed below:

1. Caldwell, H. P. M. (2019). **An Investigation into Ceiling Geometries for Acoustic Control: Spatial Configurations for Absorption and Retroreflection**. https://ses.library.usyd.edu.au/bitstream/2123/20765/1/Caldwell_hc_thesis.pdf

Caldwell looks into the impact of varying geometrical configurations on the focal area of reflected sound energy and spatial decay rate and concludes that a cubic coffered ceiling performed better than the other options considered in the thesis. The author also states the importance in specific shapes of absorptive material in attenuating sound over a distance.

2. Barrett, P., Zhang, Y., Davies, F., & Barrett, L. (2015). **Clever Classrooms: Summary report of the HEAD Project**. *University of Salford.* http://apo.org.au/node/120746

The article mentions that soft texture absorbing surfaces can be utilised in a space to be able to change the sound characteristics of a space depending on the requirements.

Other Interesting Theoretical References

1. Snyder, S. D. (2000). Fundamentals of noise control. In Springer eBooks (pp. 36–45). https://doi.org/10.1007/978-1-4419-8560-6_3

2. Gracey, B. (n.d.). Acoustic Glossary Home page. https://www.acoustic-glossary.co.uk/index.htm

3. Mealings, K. (2021). The effect of classroom acoustic conditions on literacy outcomes for children in primary school: A review. Building Acoustics, 29(1), 135–156. https://doi.org/10.1177/1351010x211057331

4. Treasure, J. (n.d.). Why architects need to use their ears [Video]. TED Talks. https://www.ted.com/talks/julian_treasure_why_architects_need_to_use_their_ears?autoplay=true&muted=true&subtitle=en

5. Fitzroy, D., & Reid, J. L. (n.d.). Acoustical environment of school buildings. https://eric.ed.gov/?id=ED031070

6. Nelson, P. B., & Soli, S. (2000). Acoustical barriers to learning. Language, Speech & Hearing Services in Schools, 31(4), 356–361. https://doi.org/10.1044/0161-1461.3104.356

7. Liu, X., Liu, M., & Xin, F. (2023). Sound absorption of a perforated panel backed with perforated porous material: Energy dissipation of Helmholtz resonator cavity. Mechanical Systems and Signal Processing, 185, 109762. https://doi.org/10.1016/j.ymssp.2022.109762

8.1 Research Questions

"How do the various teaching styles, and the acoustic requirements of a middle school learning environment influence the implementation of acoustic control systems?"

The different teaching styles *result in a single space facing multiple acoustic demands. For example, a teacher teaching the class results in different listening demands than group work. Based on the type of activity taking place in the class, the (ideal) placement of acoustic interventions varies.*

The acoustic requirements of a middle school *depend on multiple factors such as the user in question (children have stricter acoustic targets than adults), the position of the listener and speaker, and the activity taking place. Additionally, the acoustic interventions cannot be expensive. They need to be an affordable for schools to be able to use them.*

As a consequence, the implementation of acoustic control *is then challenged to achieve satisfactory sound environments while keeping in mind, both, the varying demands from the same space, as well as the need to be easy to use and implement. This thesis, by design of a passive and dynamic acoustic product, has shown that room acoustic conditions can be adjusted without technological interventions. This makes it an equally viable method of affording a user control over their acoustic environment (in this case, in a classroom).*

8.1.1 Literature Research Questions

1. What are the different teaching/learning styles in a middle school?

The standard classroom sees three main types of teaching and learning styles; teacher led, group work, and technology infused. These styles (the last especially) also include some extent of personal work as a part of the teaching.

2. How often are the different teaching/learning styles employed?

The extent of usage of these teaching styles are extremely subjective, depending on factors such as learning curriculum, student ages, subjects, etc. Currently, the following order is reflective of the usage of these styles (ordered from most used to least used): teacher led, group work, personal work/technology driven. This can change with the years and is relevant only in the current scenario.

3. What is the influence of room acoustics on a student's/teacher's comfort and performance/productivity?

Poorly managed room acoustics has a lasting impact on the health of teachers (physical and mental). Mismanaged acoustics of classrooms also not only impacts students' health (once again, mental and physical), but also has a direct impact on their scholastic achievements. The smallest of variables like location of the student in the class, their age, or additional requirements have a significant impact on their education and interpersonal relationships.

4. To what extent can providing control over a student's/teacher's room acoustic environment improve their task performance?

Providing control over the acoustic conditions of the classroom can significantly impact the longevity of a teacher's career by reducing their vocal strain. It also helps in improving the scholastic achievements of the students as well. The extent of the improvements however, are rather subjective and can be measured with questionnaires when this thesis is validated with live measurements.

5. What type of acoustic measures exist to support users in their hybrid working systems?

Effective acoustic measures for hybrid systems are currently more in the sector of technology than product or design innovation. Apart from a person physically getting up and changing locations for a different acoustic condition, there are close to no passive measures that satisfy the needs created by hybrid environments. The active systems are limited to masking of background noise, and the more expensive options allow the user to create a 'personal sound bubble'.

8.1.2. Practical Research Questions

1. What are the key (acoustic) factors that play a vital role in evaluating acoustic comfort in (middle) schools?

Reverberation time is not the only factor that matters while designing an indoor acoustic environment. The speech clarity factor also is an important deciding factor (for children, *the speech factor should be assessed based on C35). A room could have a low reverberation time but also poor speech clarity if it is not accounted for. The acoustic factors G and SPL also play an important role in assessing the performance of the intervention. Lastly, it is important that one takes into account the SNR of the room. The higher the SNR of the room, the better the speech clarity/intelligibility.*

2. To what extent can users have control over their acoustic environment?

This thesis concludes with the idea that the passive interventions are effective in providing personalised control of acoustics at the room level. For there to be control given at the user level, there has to be some intervention using technology available at the time of the development.

3. To what extent does acoustic control affect the (perceived) acoustics in middle schools?

This question, unfortunately, cannot be answered without live testing. However, some thought has been given to the execution of the same. The integrated solution can be implemented in a controlled, model classroom. Lesson plans can be conducted with the different configurations of the design in place. Test subjects (ideally, middle school children but since this brings up ethical challenges and as a result can be difficult to set-up, adults can be substituted as test subjects). Questionnaires should be handed out to every participant containing a set list of questions to assess their perception of the acoustic environment in the classroom.

8.1.3. Evaluative Questions

1. How affordable/accessible/user-friendly is the proposed acoustic (control) measure?

The design has been formulated such that it can be adapted to more automated processes or simple user controlled processes. The system uses existing mechanisms and simplistically designed movement. This makes the proposed measure quite familiar (small learning curve for user). With further development of the system (introducing motorised and automated functions) could reduce the need for user intervention but could also very well drive up the price of the system.

2. How does the proposed solution affect other indoor environment quality factors?

The product is easily integrated with other IEQ factors. Modular units and for lack of a better word, modules, makes it easy to accommodate luminaries, ducts, and pipes of various sizes and placements/locations. It has a comparable performance with these elements as any other acoustic product.

8.2 Limitations

As mentioned previously in this chapter, the thesis has some limitations. The conclusions arrived at in this thesis are a result of simulations. Simulations help give an idea of the behaviour of sound in a room but vary from live measurements. They are not indicative of the true values. The results concluded in this research need to be verified by further testing.

The ceiling study done also is limited to analysis by RT and C50. It would benefit for the initial analysis and subsequent narrowing down of options to be done based on the factor C35 instead. SPL (and spatial decay rate) should also be included in the initial analysis. SNR needs to be present at every stage of selection. However, limited by time and manpower, certain restrictions had to be placed in order to make this achievable in the given time frame.

The design conclusions are made using reverberation time formulae that are relatively simple for the situation being analysed. This conclusion needs to be further verified with

1. Detailed calculations in accordance with NEN-EN 12354-6, Appendix D, and
2. Live measurements

8.3 Next Steps & Potential for Future Research

This thesis has explored many topics in its pursuit to understand and design personalised acoustic control in a space. Thus, it stands to reason that each topic is full to the brim with potential for future research and further development.

8.3.1. Further Elaboration & Testing

This thesis has delved into the personalised control of acoustics theoretically. It has utilised an acoustic simulation suite (Treble) as a part of its study. Treble, while powerful, lacks in one main regard; it is not live measurement and testing! It does not take into account the 'live' variables present in a space (geometry, materials, etc.). As much as we try, simulation can only take us part-way. This is seen in the later stages of the thesis where the simulation of the integrated design did not offer nearly enough data to shed light on the nuances of the variations considered. These results and the thesis as a whole could benefit by validation via live measurements.

8.3.2. Ceiling Optimisation

The ceiling profiles analysed in this research are merely the popular styles as seen in architectural construction. It would stand to reason that there is an optimal ceiling profile for the intended spatial application (in this case, middle school classrooms).

It would be advantageous to look towards parametric optimisation and modelling to develop the optimal ceiling for a space. It would also be beneficial to delve specifically into the impact of passive geometry on acoustic conditions of a space (not necessarily limited to ceilings).

8.3.3. Product Development

The current product design and development is more indicative of the potential it presents as an acoustic product. Design is a never ending process. With developing technology, system, and even parts, every design can stand to improve.

8.3.4. Personalised Control of Acoustics

This thesis is merely a scratch on the surface of this topic. It talks about the personalised control of acoustics relative to the typology and the space. However, it is my hope that this thesis helps in the pursuit of personalised acoustics; which would only improve the quality and experience of a space if every user was afforded control over their acoustic environment, redefining the way we approach user comfort in a space. Further research can focus more on the user end of the system.

8.4 Final Conclusions

There are many things that go into the design of personalised acoustic control systems. The passive interventions are heavily dependent on large scale elements such as room geometry. The smaller elements that dictate the quality of acoustics in a room are related to the acoustic panels/products themselves.

The ceiling profile has a significant impact on a room's acoustic environment and should not be neglected in the design of a classroom. Minor variations in construction can already improve the perception of sound, helping limit the extent of intervention needed later.

Furthermore, reverberation time should not be the only factor taken into account while designing a space. Speech clarity factors such as C50 (or C35 for children), and STI are integral in understanding the intelligibility of speech. SNR adds to this understanding. A space could have low reverberation time but if SNR is not high enough, the clarity of speech is muddled, and all in all will result in a less than satisfactory design. Sound strength, G and SPL also need to be taken into account. These factors tie in with the previous (SNR) to paint a complete picture of the acoustic environment of a room.

Finally, passive, dynamic acoustic products can be the intermediate stage (placed squarely between static and technological interventions). Further research and testing in this field can enable a user friendly and affordable solution to the control of room acoustics.

8.5 Personal Reflections

This thesis has challenged me every step of the way. It has taught me to slow down and look at all the possible paths to a solution... and then make sure I have back-up plans for them as well. It has cemented the idea that any research hinges on a good plan, and an understanding that things might not always go to according to it.

Conducting this thesis with a company and with a university also gave me a unique insight into the different approaches to a solution; one practical and technical, the other innovative and technological. It has also taught me a lot about the construction and building physics industry.

As an architect and an engineer, I was able to uniquely appreciate the challenges each role faces while interacting with the other. I was given the chance to build on my understanding of room acoustics, the challenges faced by different users and how to account for them, and the utilisation of software in analysing room conditions. It has impressed upon me the requirement for attention to detail in design.

The later stages of the thesis also impressed upon me the importance of including live measurements and testing alongside theoretical understandings. This is a note I will carry forward with me. Additionally, I have understood that any design does not exist in a vacuum and studying the interactions with its surroundings is essential to arrive at a good design.

Overall, I believe that I have had the chance to improve holistically with this thesis, growing as a person, a researcher, and as a professional.

X

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This section covers terms that are addressed or spoken about over the course of the research.

1. Phenomena
1.1. Lombard Effect
The involuntary tendency of speakers to increase their vocal effort when speaking in loud environments to enhance the audibility of their voice. E.g.: trying to talk to your friend in a pub with live music.

1.2. Lombard Coefficient
The rise in voice level per decibel of background noise level *(Whitlock & Dodd, 2008).*

1.3. Flutter Effect
A phenomenon where in a given acoustic space, two parallel surfaces reflecting sound between one another are far enough apart that a listener hears the reflections between them as distinct echoes.

1.4. Echo
A sound or sounds caused by the reflection of sound waved from a surface back to the listener.

2. Speech Conditions
2.1. Speech Intelligibility Index (SII)
It represents the intelligibility of speech under a variety of adverse listening conditions such as noise masking, filtering, and reverberation.

2.2. Articulation Index (AI)
A sound metric that was developed to indicate how much background sound levels can interfere with human speech.

2.3. Privacy Index (PI)
It indicates the level of speech privacy between spaces and takes into account the acoustical performance of everything in the space.

2.4. Integration Time of Speech
It is the point in time after which reflections of a speech signal do not have the required usefulness in contributing to the direct signal *(Whitlock & Dodd, 2008)*.

3. Room Conditions
3.1. Equivalent Sound Pressure Level (L_{eq})
The sound level in decibels, having the same total sound energy as the fluctuating level measured.

3.2. Working Noise
The amount of acoustic energy received by a person's auditory system while working in a given environment.

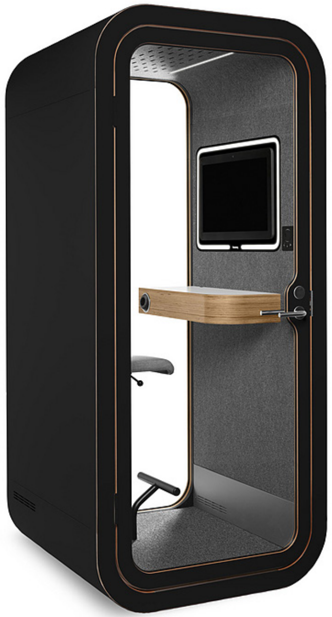
3.3. Oral-Binaural Room Impulse Response (OBRIR)
Impulse response measured at a microphone located at the end of the ear canal of a dummy head when a loudspeaker inside its mouth acts as a source *(Garcia et al., 2014)*.

3.4. Spatial Decay (D_2S)
This factor talks about the influence of the design of the room on the extent of sound decay rate (in relation to distance). The sound level is inversely proportional to the logarithmic distance from the sound.

1. Personal Control Systems

Noise cancelling headphones

Video Call Booths



Personal Radio Aids

Soundfield Systems

Hardwired Auditory Trainers

2. Active Control Systems

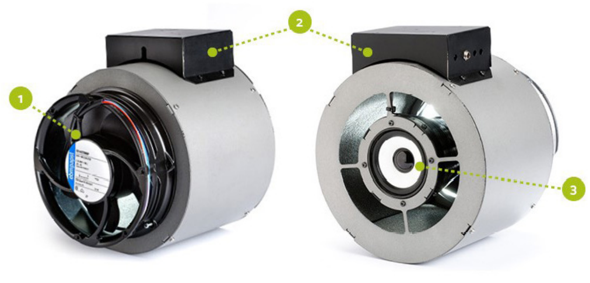
White Noise Machines

Personal Audio Chair Systems

3. Products in the Market

Silentium - Zonal Bubble

Silentium - At Source

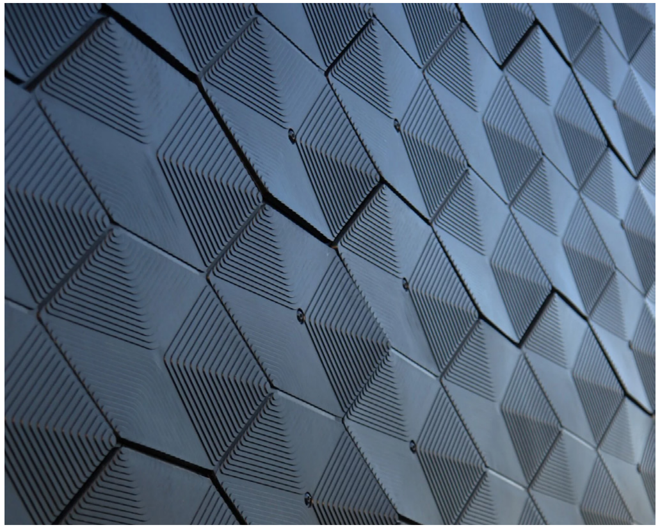


1. The microphone receives the noise to be cancelled (unwanted noise) and forwards it to the controller
2. The Speaker physically produces the anti-noise
The Controller generates the correct signal to send to the speaker, which will produce the anti-noise to cancel out the unwanted noise

Modio

ADAM

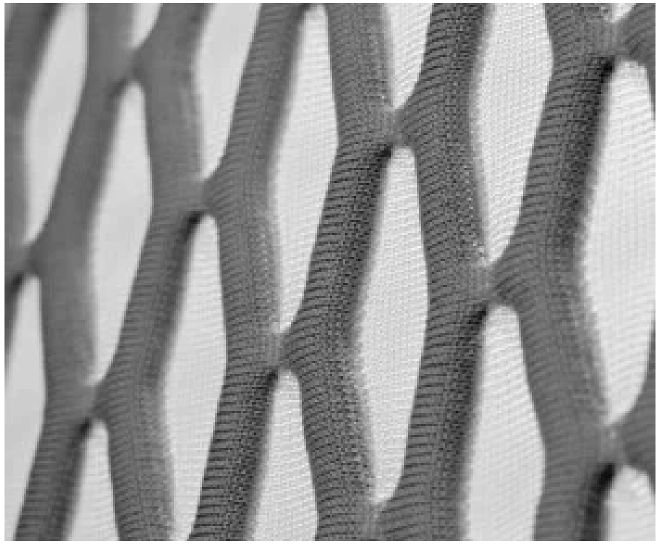
Made of Air



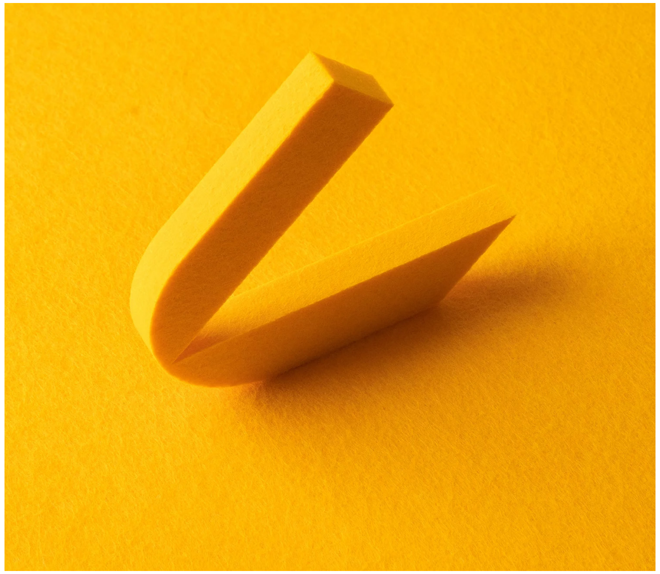
CircuLUM™

NOWN

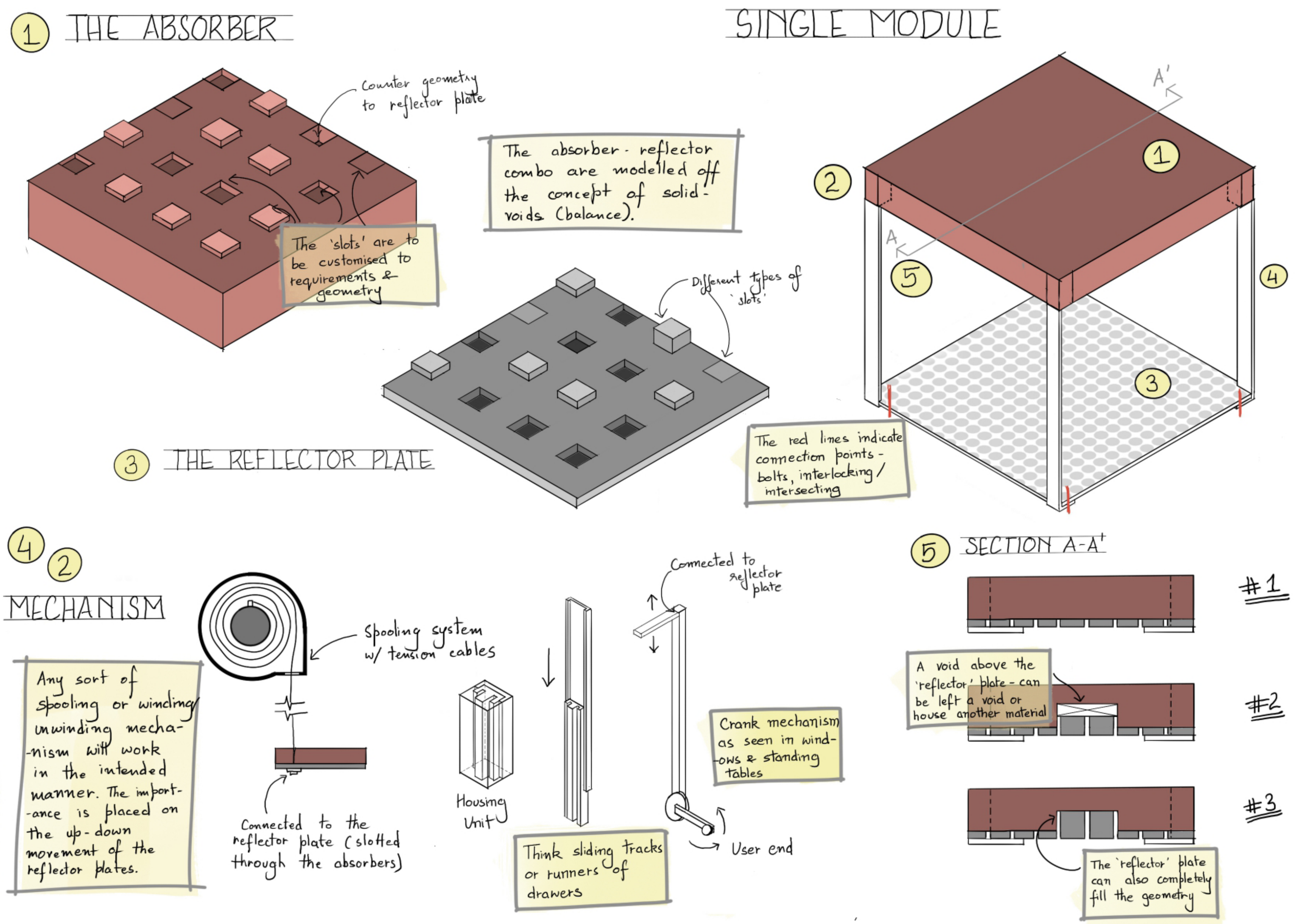
INFIKNIT™



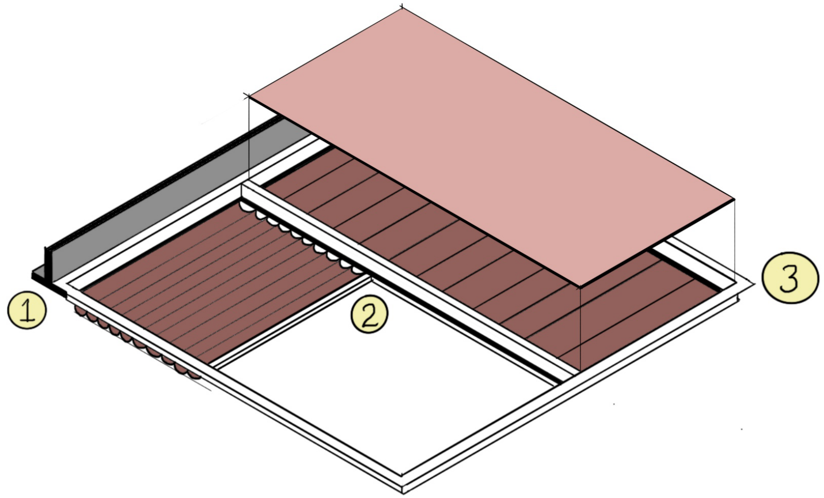
Soft Sound®



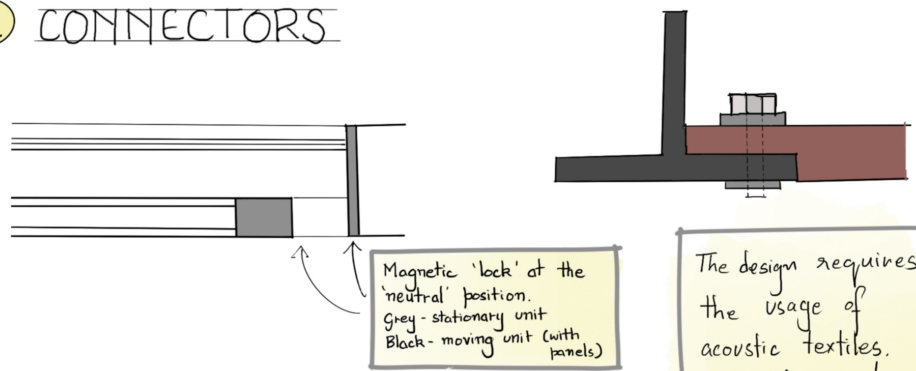
Option #2


1 THE ABSORBER
Counter geometry to reflector plate
The 'slots' are to be customised to requirements & geometry
The absorber - reflector combo are modelled off the concept of solid - voids (balance).
SINGLE MODULE
A'
A
1
2
3
4
5
Different types of 'slots'
The red lines indicate connection points - bolts, interlocking / intersecting
3 THE REFLECTOR PLATE
4 2 MECHANISM
Any sort of spooling or winding/ unwinding mechanism will work in the intended manner. The importance is placed on the up-down movement of the reflector plates.
Spooling system w/ tension cables
Connected to the reflector plate (slotted through the absorbers)
Housing Unit
Think sliding tracks or runners of drawers
Connected to reflector plate
Crank mechanism as seen in windows & standing tables
User end
5 SECTION A-A'
#1
#2
#3
A void above the 'reflector' plate - can be left a void or house another material
The 'reflector' plate can also completely fill the geometry

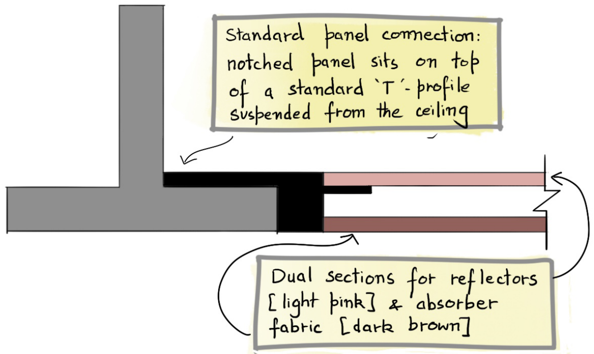
Option #5



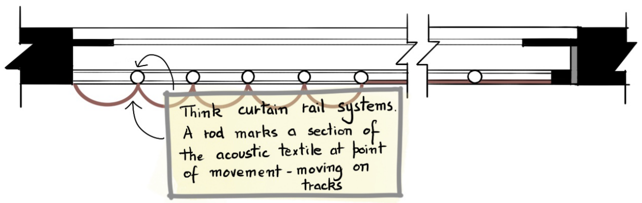
2 CONNECTORS



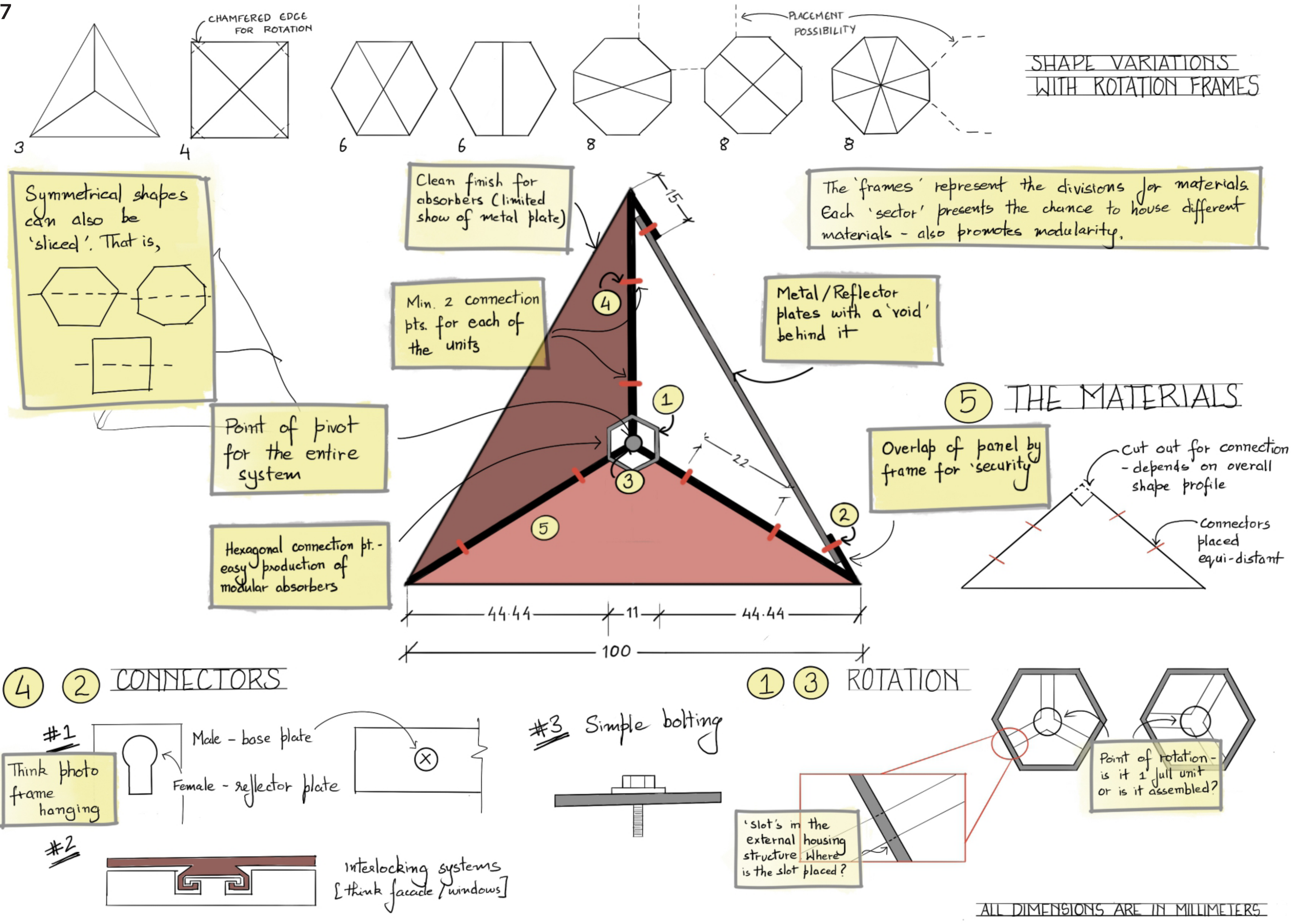
1 SUSPENSION SYSTEM



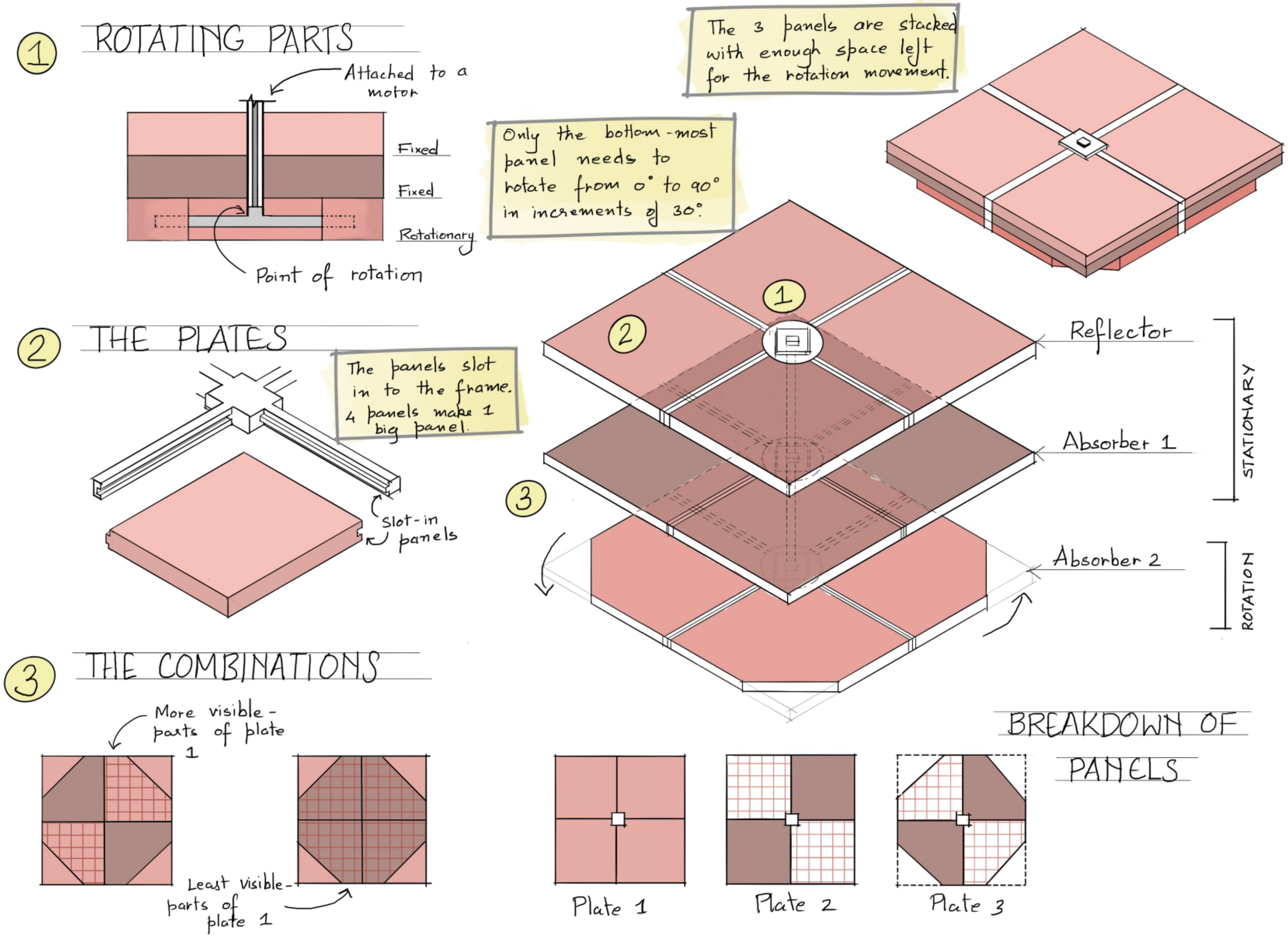
3 TRACKS & RUNNER



Option #7


CHAMFERED EDGE FOR ROTATION
PLACEMENT POSSIBILITY
3
4
6
6
8
8
8
SHAPE VARIATIONS WITH ROTATION FRAMES
Symmetrical shapes can also be 'sliced'. That is,
Clean finish for absorbers (Limited show of metal plate)
15
The 'frames' represent the divisions for materials. Each 'sector' presents the chance to house different materials - also promotes modularity.
Min. 2 connection pts. for each of the units
Metal / Reflector plates with a 'void' behind it
4
1
5 THE MATERIALS
Point of pivot for the entire system
3
22
Overlap of panel by frame for 'security'
Cut out for connection - depends on overall shape profile
2
5
Connectors placed equi-distant
Hexagonal connection pt. - easy production of modular absorbers
44.44
11
44.44
100
4 2 CONNECTORS
1 3 ROTATION
#1
Think photo frame hanging
Male - base plate
Female - reflector plate
#3 Simple bolting
Point of rotation - is it 1 full unit or is it assembled?
'Slot's in the external housing structure. Where is the slot placed?
#2
interlocking systems [think facade / windows]
ALL DIMENSIONS ARE IN MILLIMETERS

Option #9


1
ROTATING PARTS
Attached to a motor
Fixed
Fixed
Rotationary
Point of rotation
2
THE PLATES
The panels slot in to the frame. 4 panels make 1 big panel.
Slot-in panels
3
THE COMBINATIONS
More visible parts of plate 1
Least visible parts of plate 1
Only the bottom-most panel needs to rotate from 0° to 90° in increments of 30°.
The 3 panels are stacked with enough space left for the rotation movement.
1
2
3
Reflector
Absorber 1
Absorber 2
STATIONARY
ROTATION
BREAKDOWN OF PANELS
Plate 1
Plate 2
Plate 3

Appendix 06 | Chosen Design - Elaboration

Table 5.2: Various considerations for the perforations of the external plate of the unit

Side 1

Section	Avg. Depth	Panel Properties				Absorber Flow Resistivity [rayls/m]	Frequencies						Avg. Absorption	Peak Absorption
		Thickness	Repeat Distance	Hole Radius	Open Area %		125	250	500	1000	2000	4000		
1	19.74	2	16	3	11%	22939	0.04	0.19	0.52	0.94	0.82	0.4	0.49	1000 Hz
2	59.23						0.17	0.42	0.79	0.96	0.81	0.4	0.59	
3	98.71						0	0.08	0.28	0.74	0.58	0.13	0.3	
Avg. Absorption							0.07	0.23	0.53	0.88	0.74	0.31	0.46	

Section	Avg. Depth	Panel Properties				Absorber Flow Resistivity [rayls/m]	Frequencies						Avg. Absorption	Peak Absorption
		Thickness	Repeat Distance	Hole Radius	Open Area %		125	250	500	1000	2000	4000		
1	19.74	2	13	3	17%	22939	0	0	0.08	0.27	0.67	0.87	0.32	1000-4000 Hz
2	59.23						0.04	0.19	0.5	0.89	0.96	0.68	0.54	
3	98.71						0.17	0.41	0.76	0.95	0.95	0.68	0.65	
Avg. Absorption							0.07	0.2	0.45	0.7	0.86	0.74	0.5	

Section	Avg. Depth	Panel Properties				Absorber Flow Resistivity [rayls/m]	Frequencies						Avg. Absorption	Peak Absorption
		Thickness	Repeat Distance	Hole Radius	Open Area %		125	250	500	1000	2000	4000		
1	19.74	2	13	7	113%	22939	0	0	0.08	0.25	0.56	0.82	0.29	1000 Hz
2	59.23						0.04	0.18	0.47	0.8	0.95	0.99	0.57	
3	98.71						0.17	0.4	0.71	0.89	0.96	0.99	0.69	
Avg. Absorption							0.07	0.19	0.42	0.65	0.82	0.93	0.51	

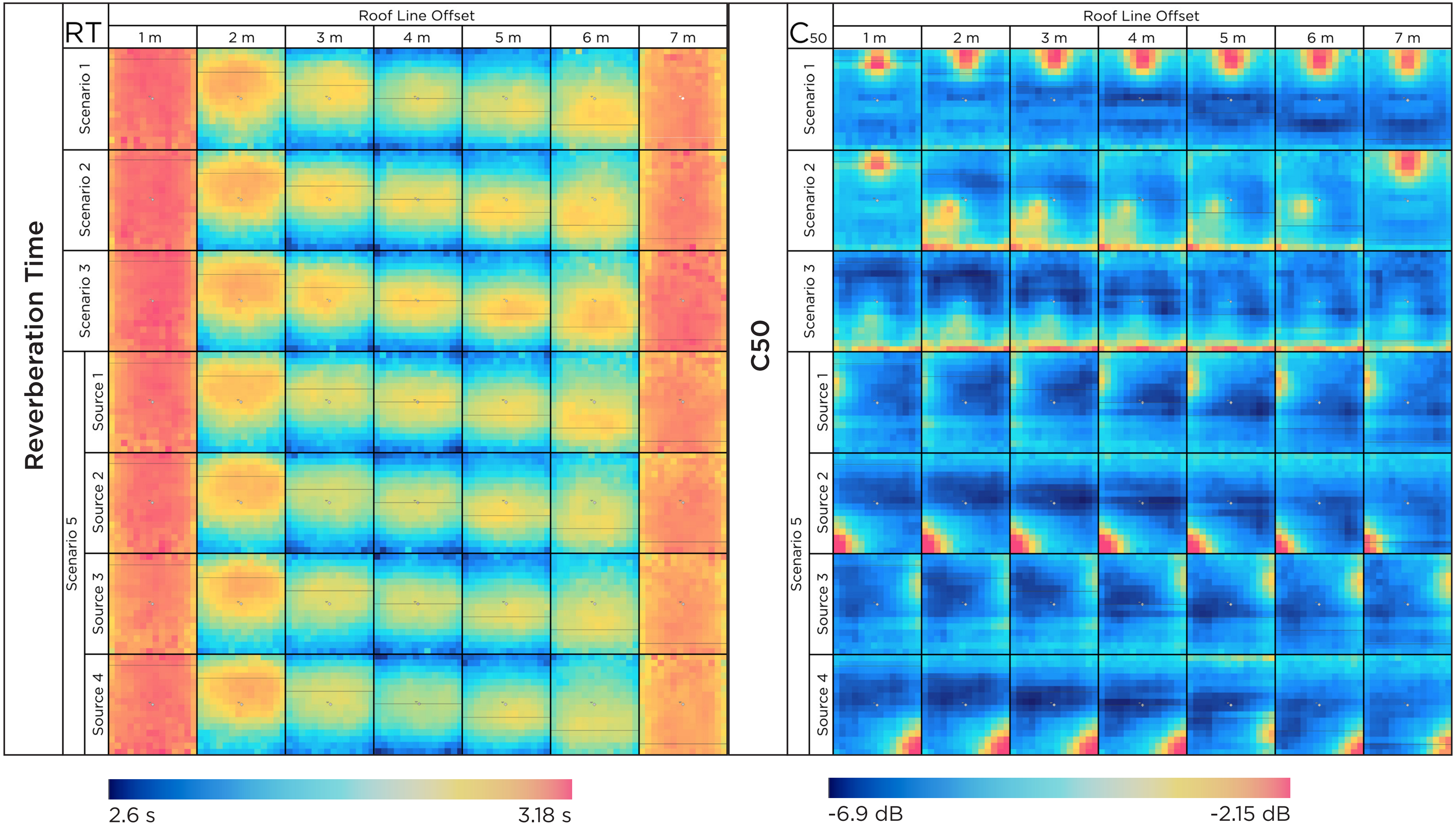
Side 2

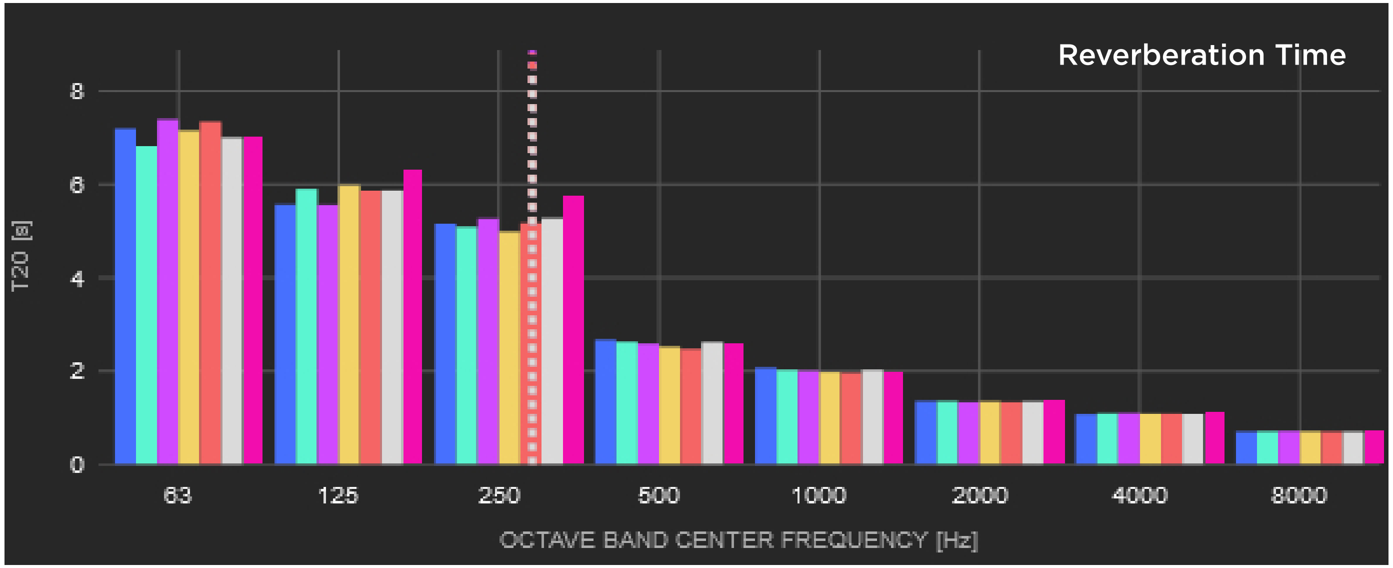
Section	Avg. Depth	Panel Properties				Absorber Flow Resistivity [rayls/m]	Frequencies						Avg. Absorption	Peak Absorption
		Thickness	Repeat Distance	Hole Radius	Open Area %		125	250	500	1000	2000	4000		
1	19.74	2	17.5	1	1%	22939	0	0	0.1	0.49	0.13	0.01	0.12	250-1000 Hz
2	59.23						0.04	0.23	0.76	0.26	0.06	0.02	0.23	
3	98.71						0.19	0.58	0.71	0.23	0.06	0	0.3	
Avg. Absorption							0.08	0.27	0.52	0.33	0.08	0.01	0.22	

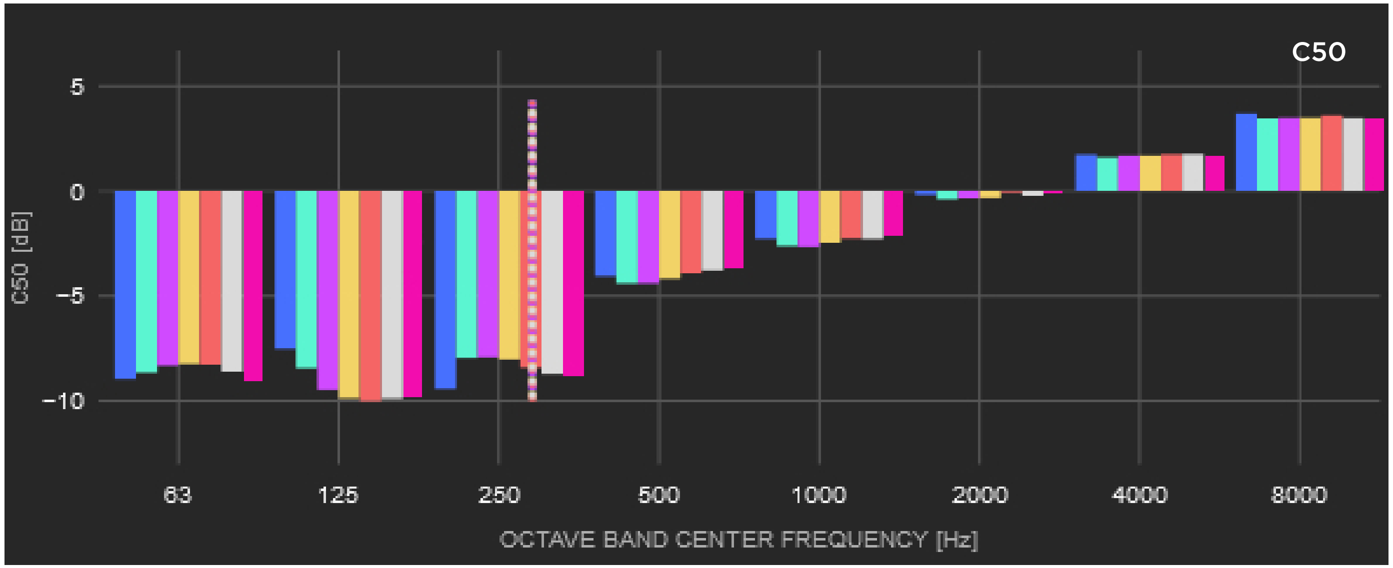
Section	Avg. Depth	Panel Properties				Absorber Flow Resistivity [rayls/m]	Frequencies						Avg. Absorption	Peak Absorption
		Thickness	Repeat Distance	Hole Radius	Open Area %		125	250	500	1000	2000	4000		
1	19.74	2	25	1	1%	22939	0	0	0.14	0.29	0.02	0	0.08	250-500 Hz
2	59.23						0.05	0.3	0.45	0.08	0	0	0.15	
3	98.71						0.21	0.69	0.3	0.08	0	0	0.21	
Avg. Absorption							0.09	0.33	0.3	0.15	0.01	0	0.15	

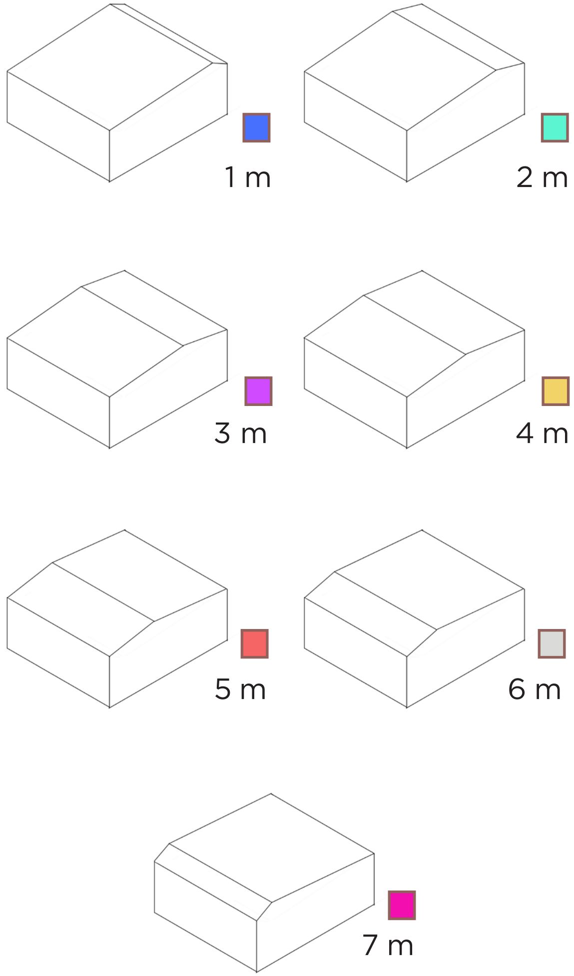
Section	Avg. Depth	Panel Properties				Absorber Flow Resistivity [rayls/m]	Frequencies						Avg. Absorption	Peak Absorption
		Thickness	Repeat Distance	Hole Radius	Open Area %		125	250	500	1000	2000	4000		
1	19.74	2	20	1	1%	22939	0	0	0.11	0.46	0.08	0	0.11	500 Hz
2	59.23						0.04	0.25	0.7	0.17	0.04	0	0.2	
3	98.71						0.19	0.63	0.55	0.15	0.04	0	0.26	
Avg. Absorption							0.08	0.29	0.45	0.26	0.05	0	0.19	

Pitched Ceiling

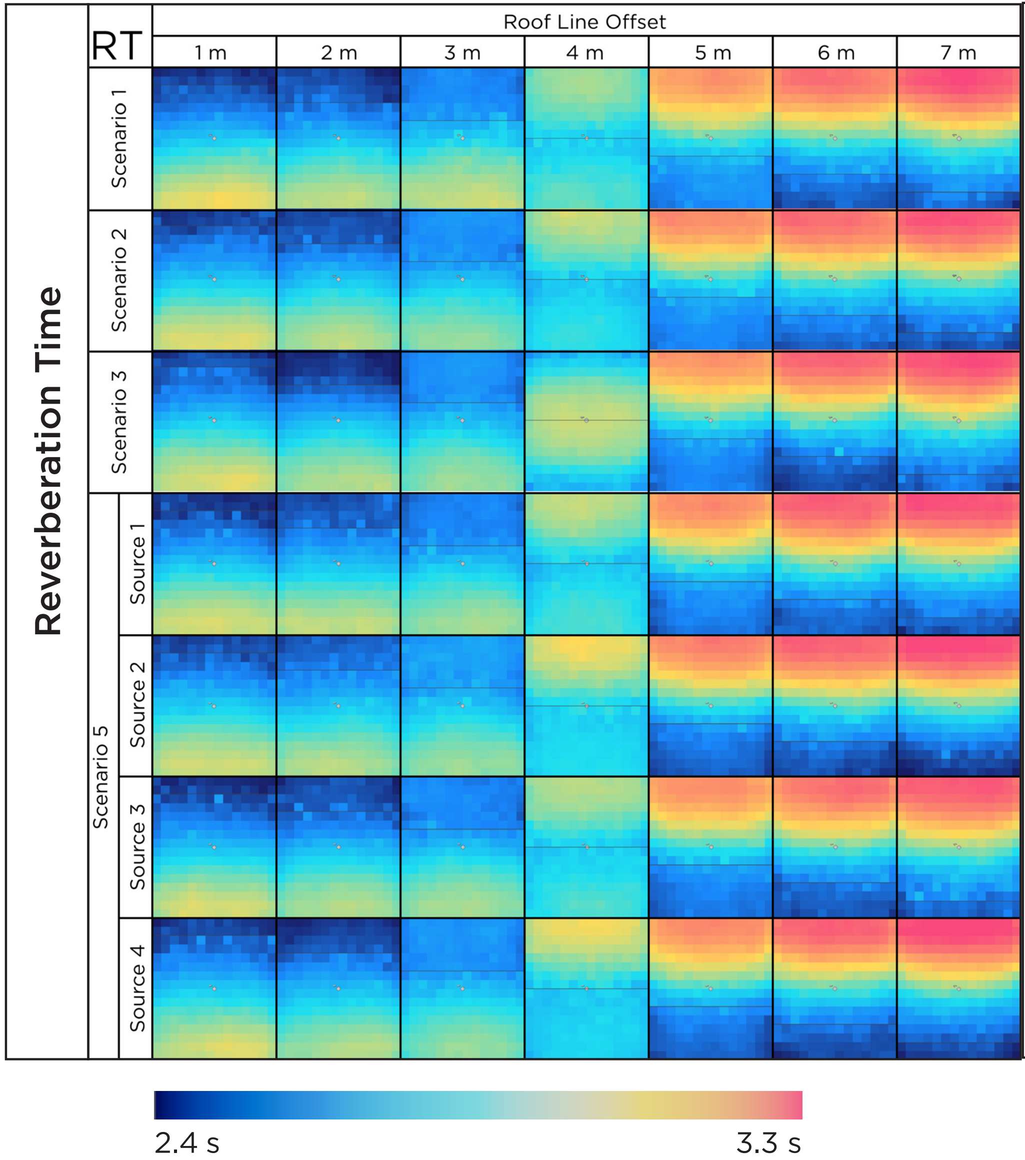


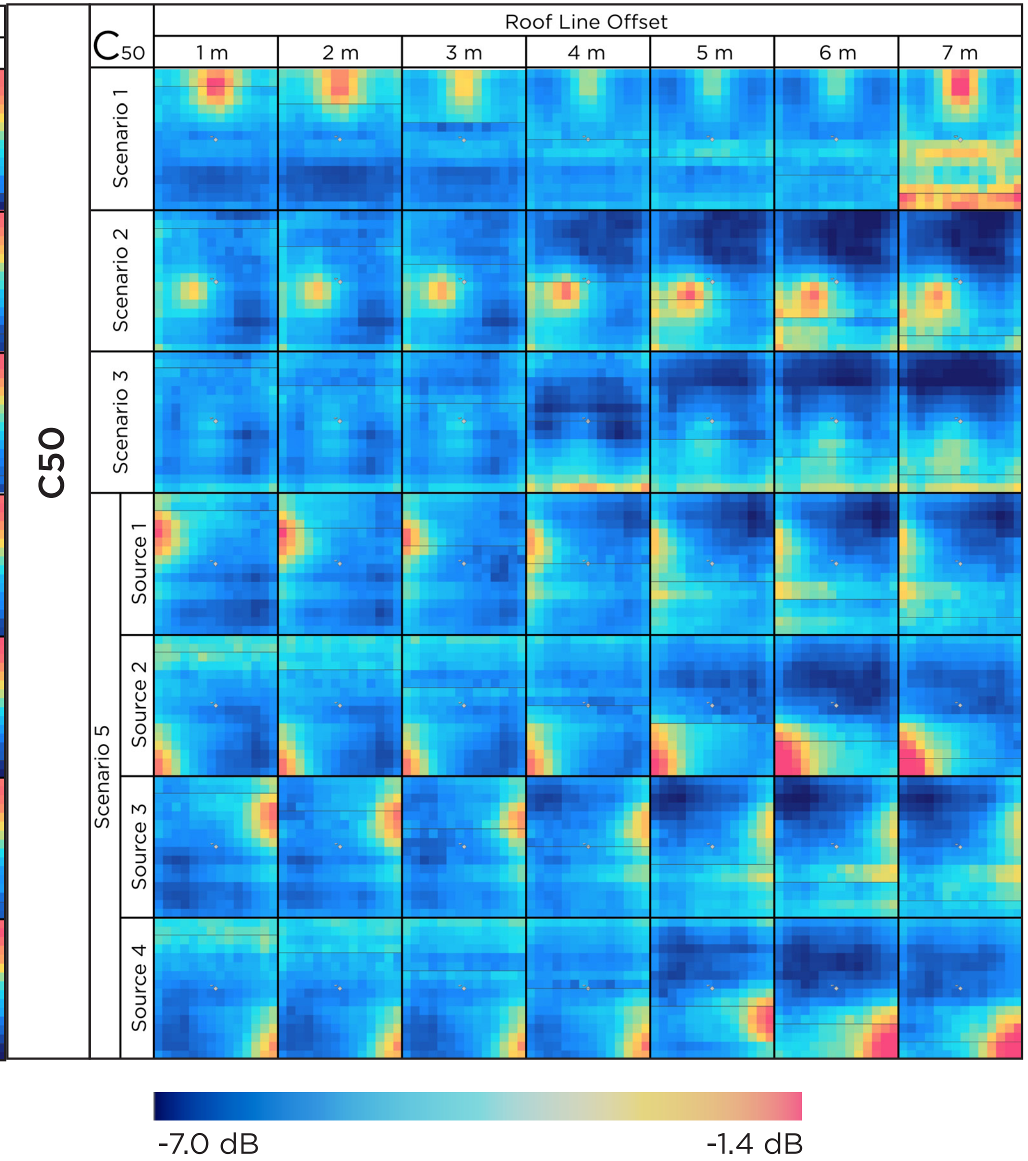

Reverberation Time
T20 [s]
8
6
4
2
0
63
125
250
500
1000
2000
4000
8000
OCTAVE BAND CENTER FREQUENCY [Hz]

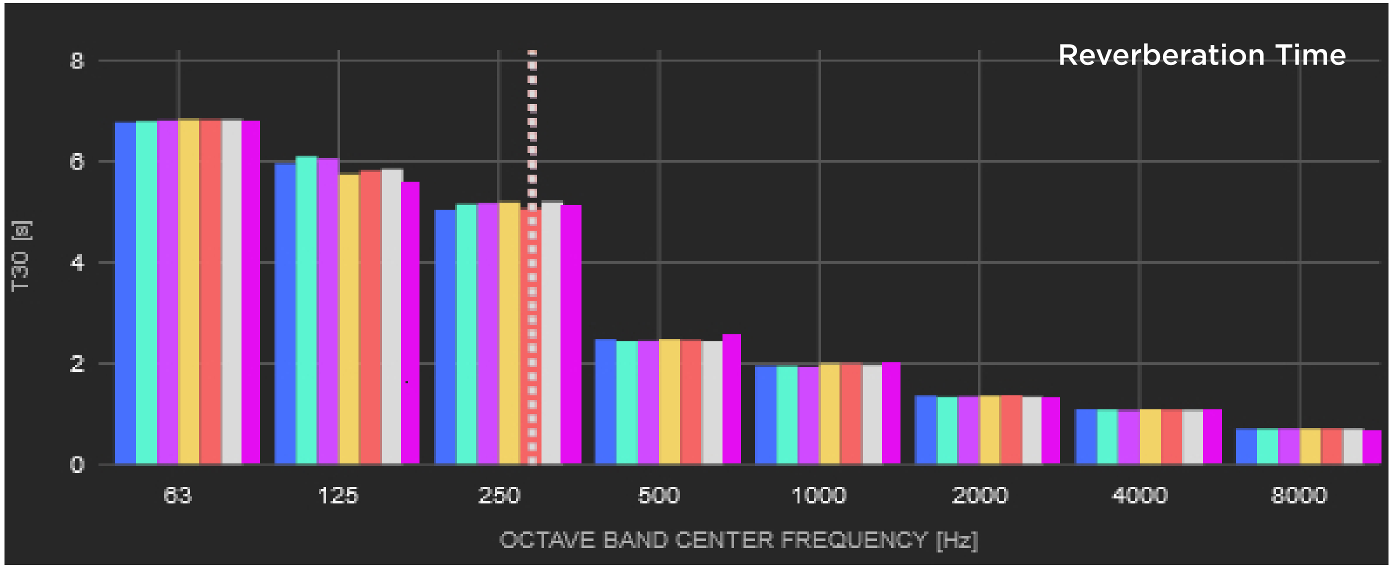

C50
C50 [dB]
5
0
−5
−10
63
125
250
500
1000
2000
4000
8000
OCTAVE BAND CENTER FREQUENCY [Hz]

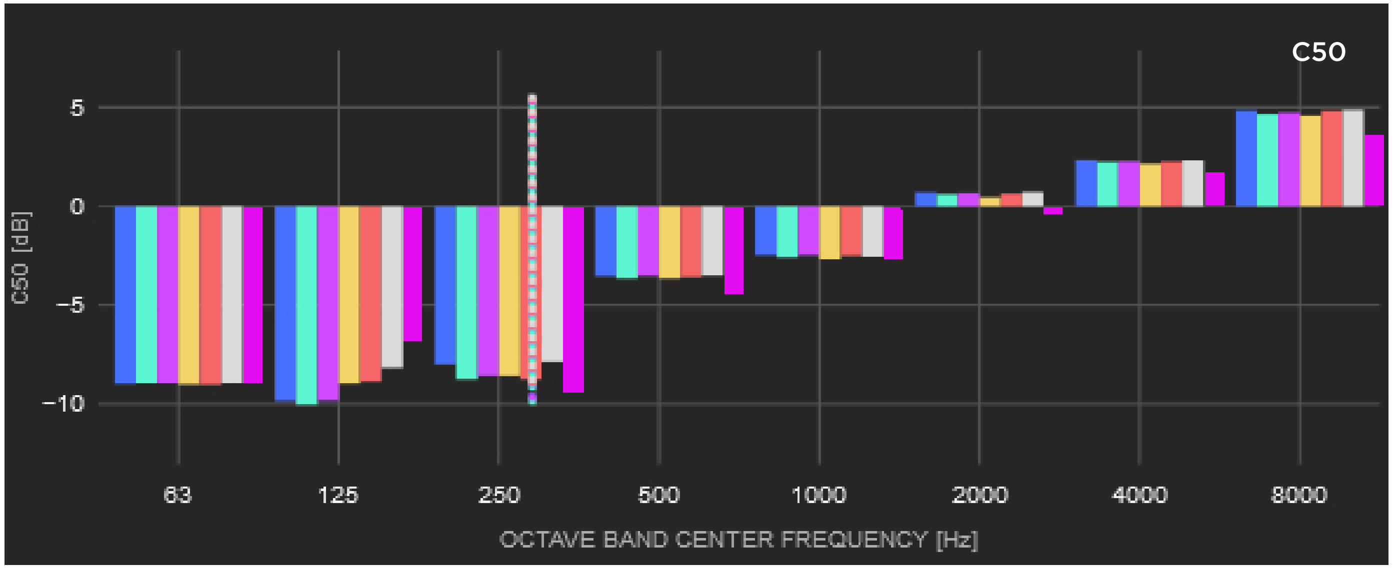

1 m
2 m
3 m
4 m
5 m
6 m
7 m

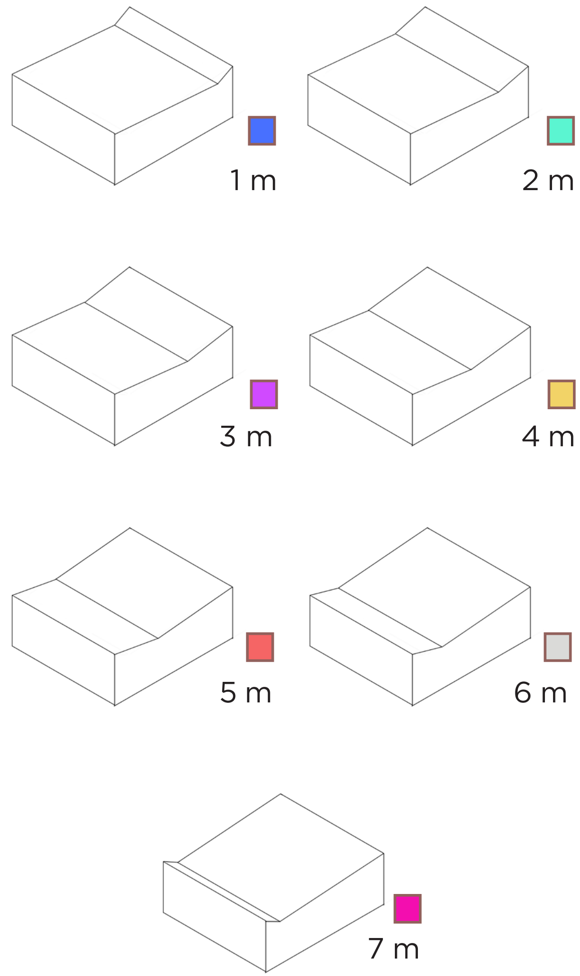
Inverted Ceiling



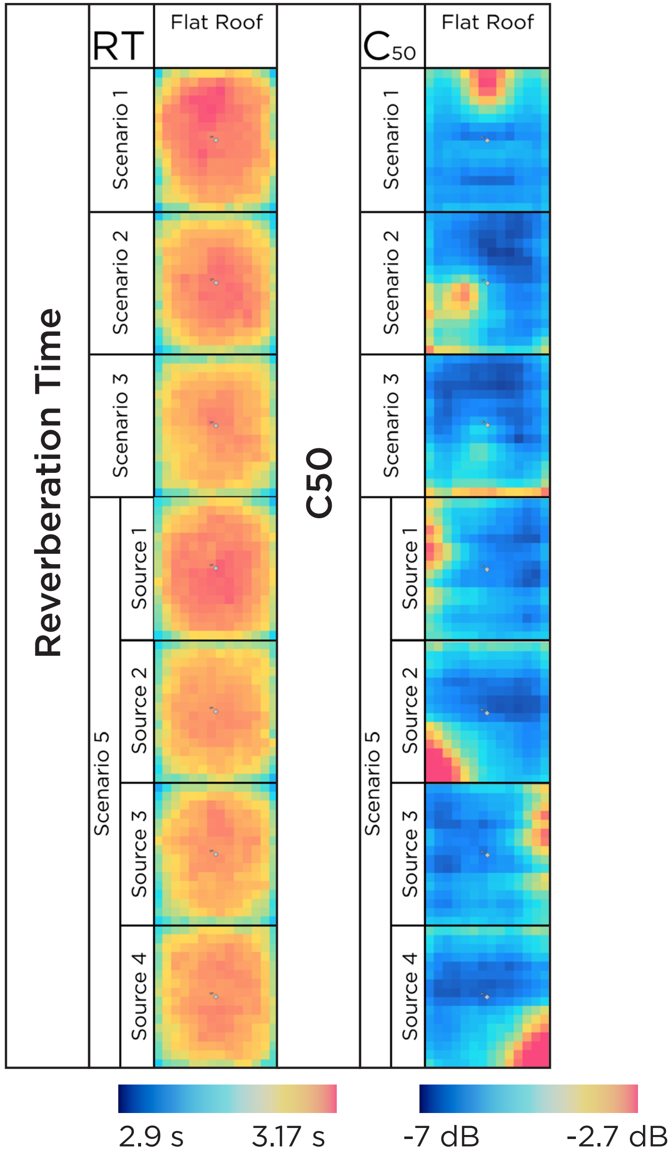



Reverberation Time
T30 [s]
8
6
4
2
0
63
125
250
500
1000
2000
4000
8000
OCTAVE BAND CENTER FREQUENCY [Hz]

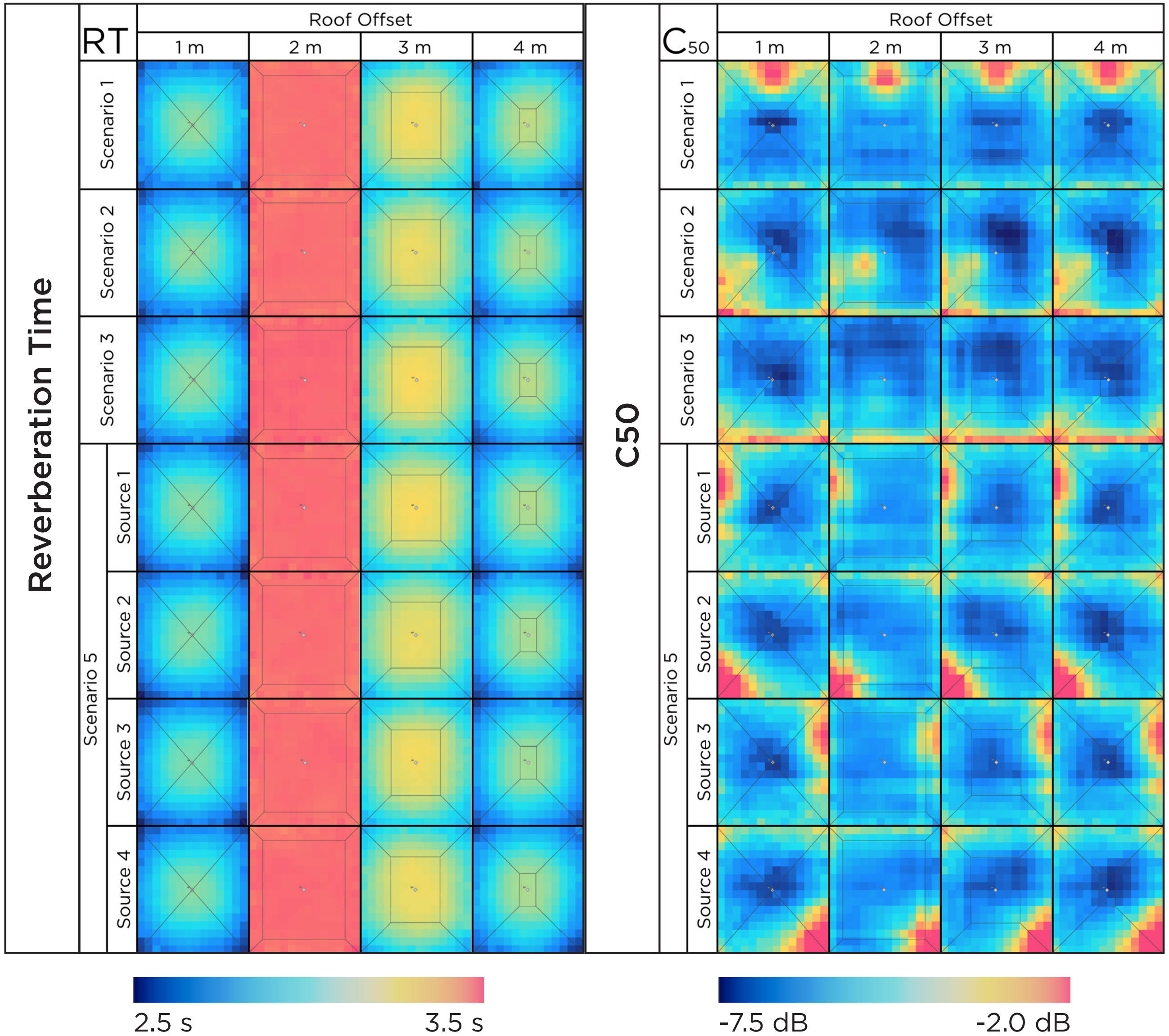

C50
C50 [dB]
5
0
−5
−10
63
125
250
500
1000
2000
4000
8000
OCTAVE BAND CENTER FREQUENCY [Hz]

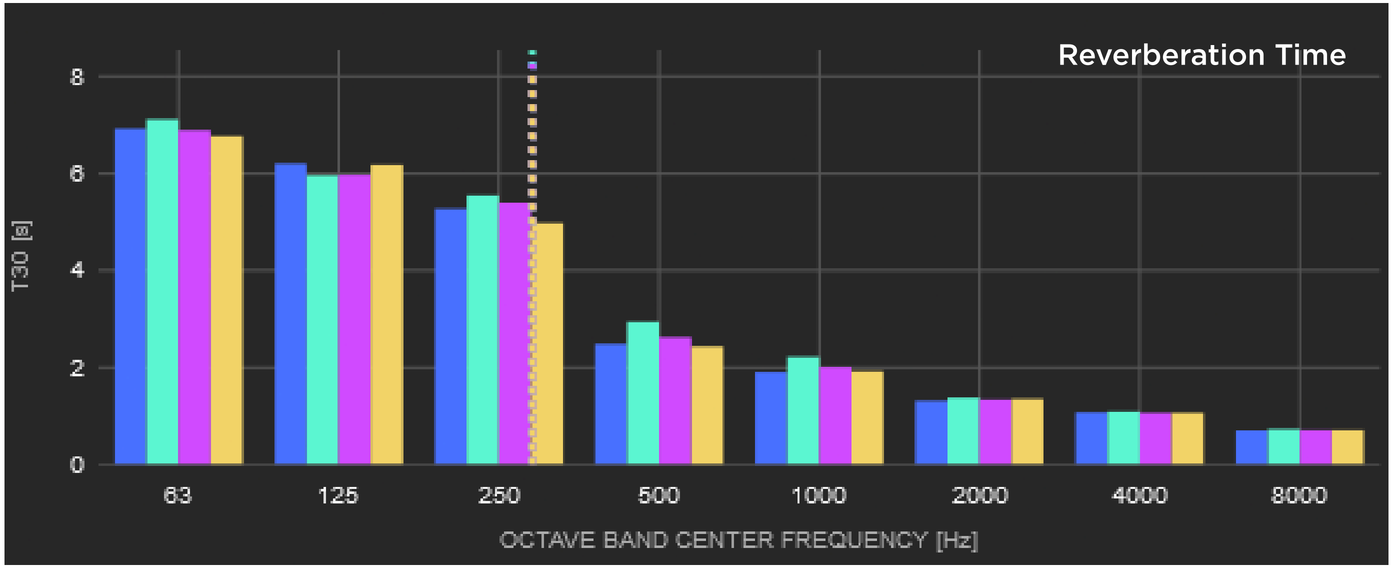

1 m
2 m
3 m
4 m
5 m
6 m
7 m

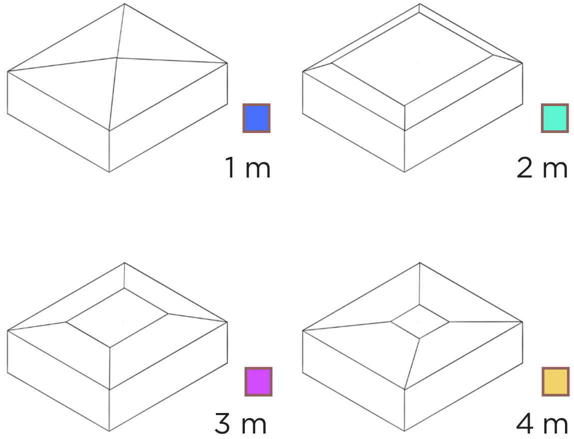
Flat Ceiling

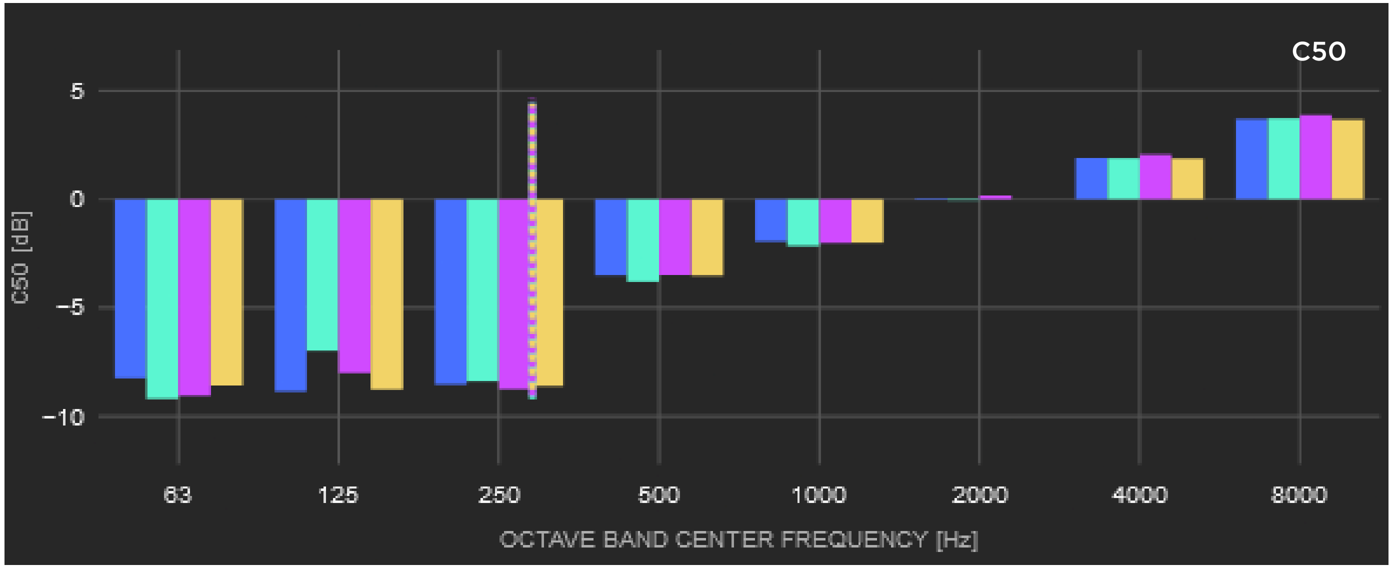


Hip Ceiling

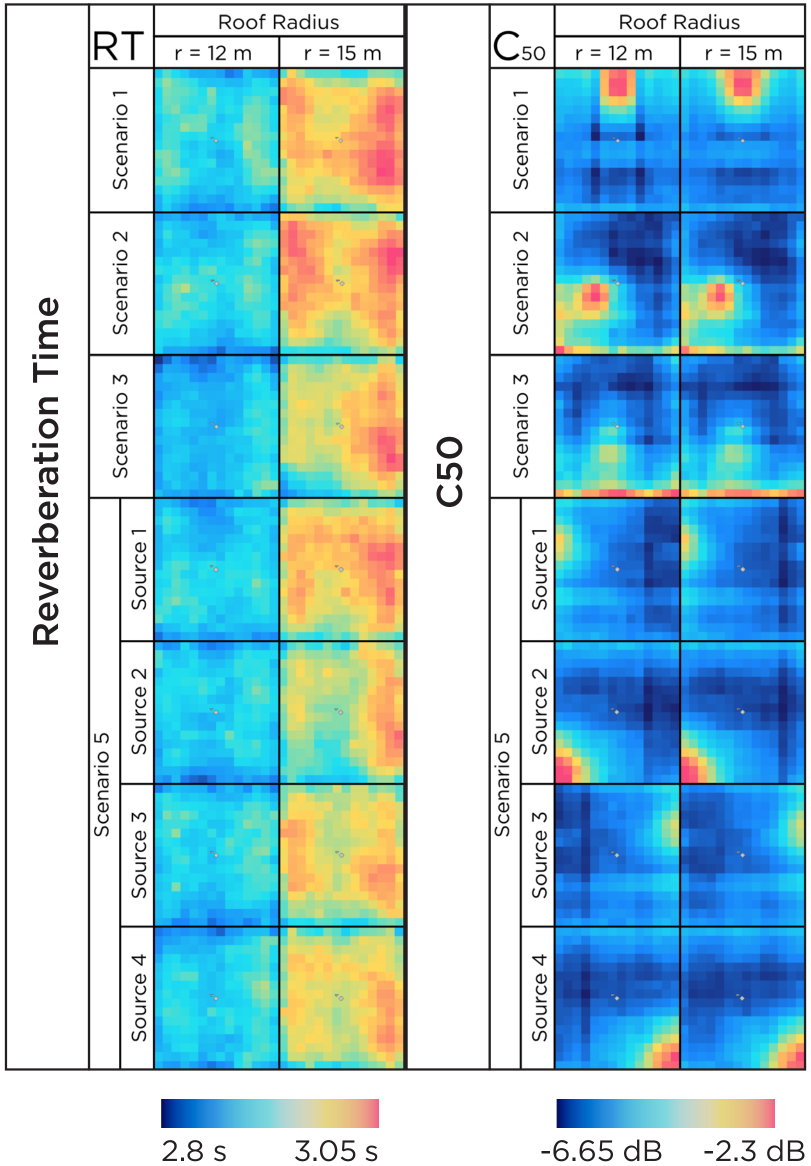


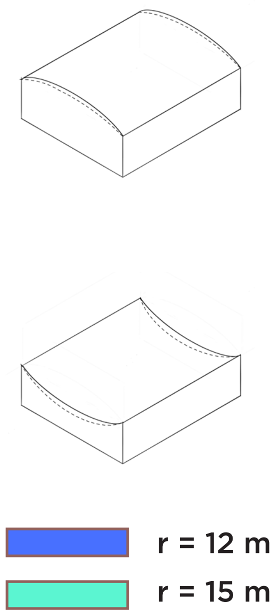

Reverberation Time
T30 [s]
8
6
4
2
0
63
125
250
500
1000
2000
4000
8000
OCTAVE BAND CENTER FREQUENCY [Hz]


1 m
2 m
3 m
4 m

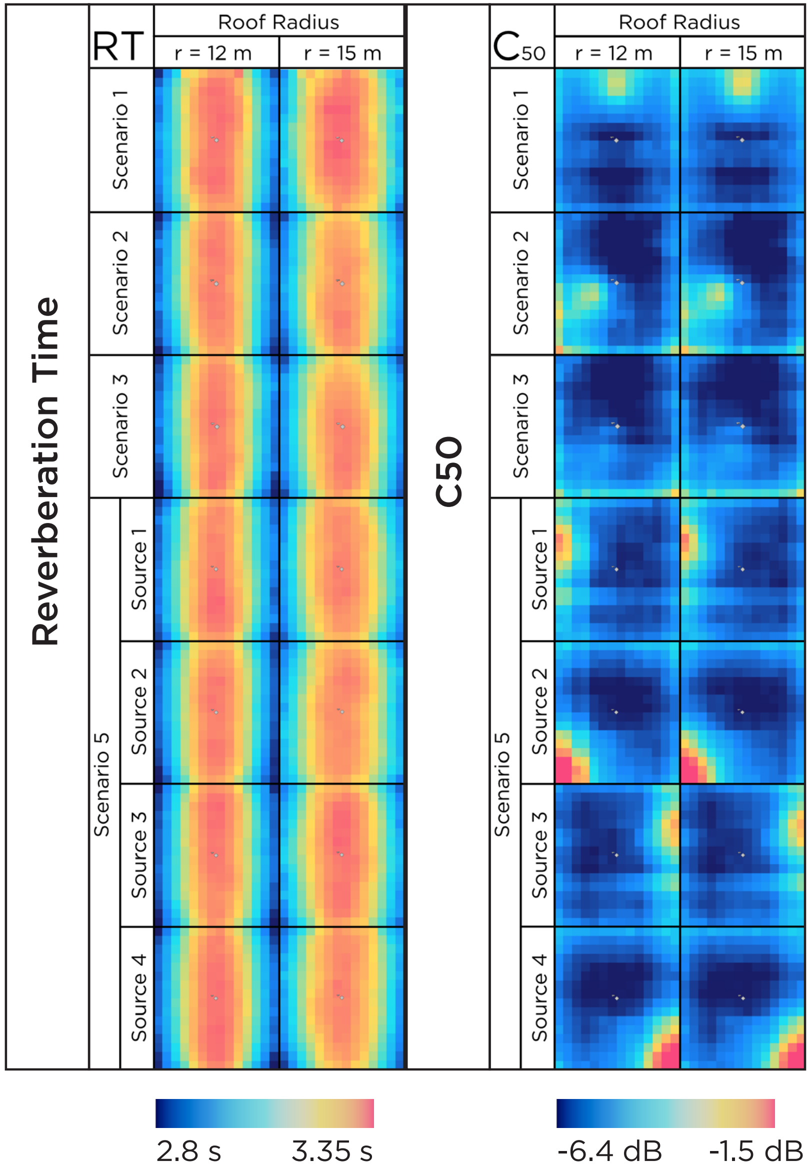

C50
C50 [dB]
5
0
−5
−10
63
125
250
500
1000
2000
4000
8000
OCTAVE BAND CENTER FREQUENCY [Hz]

Convex Ceiling

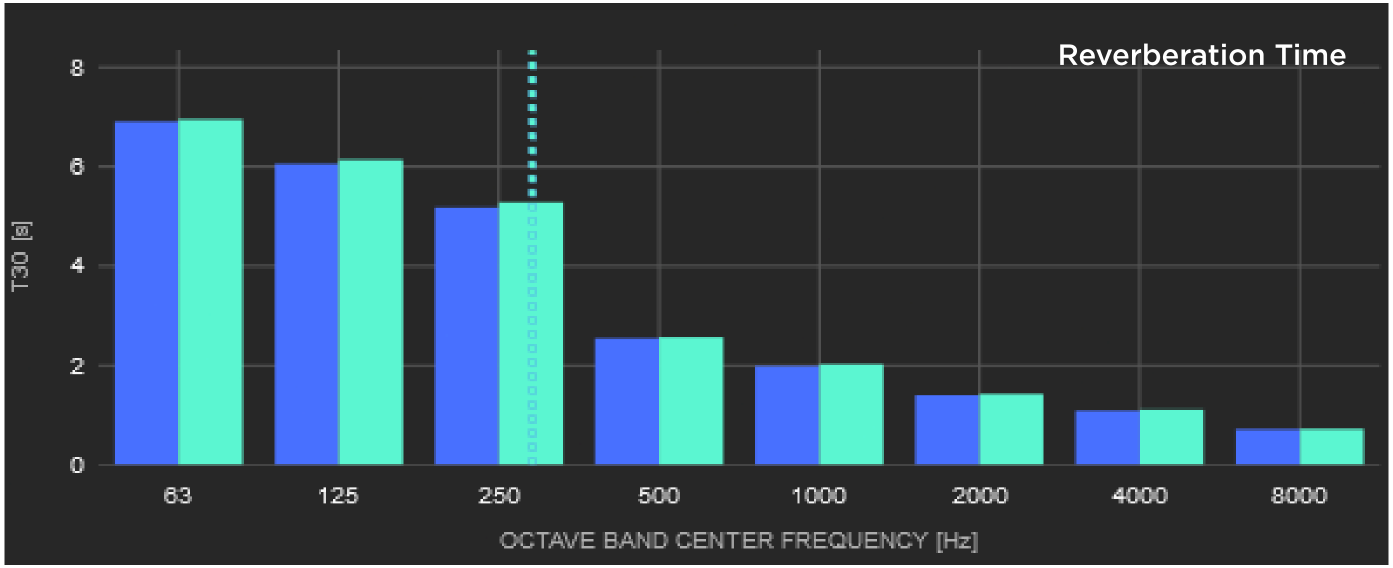


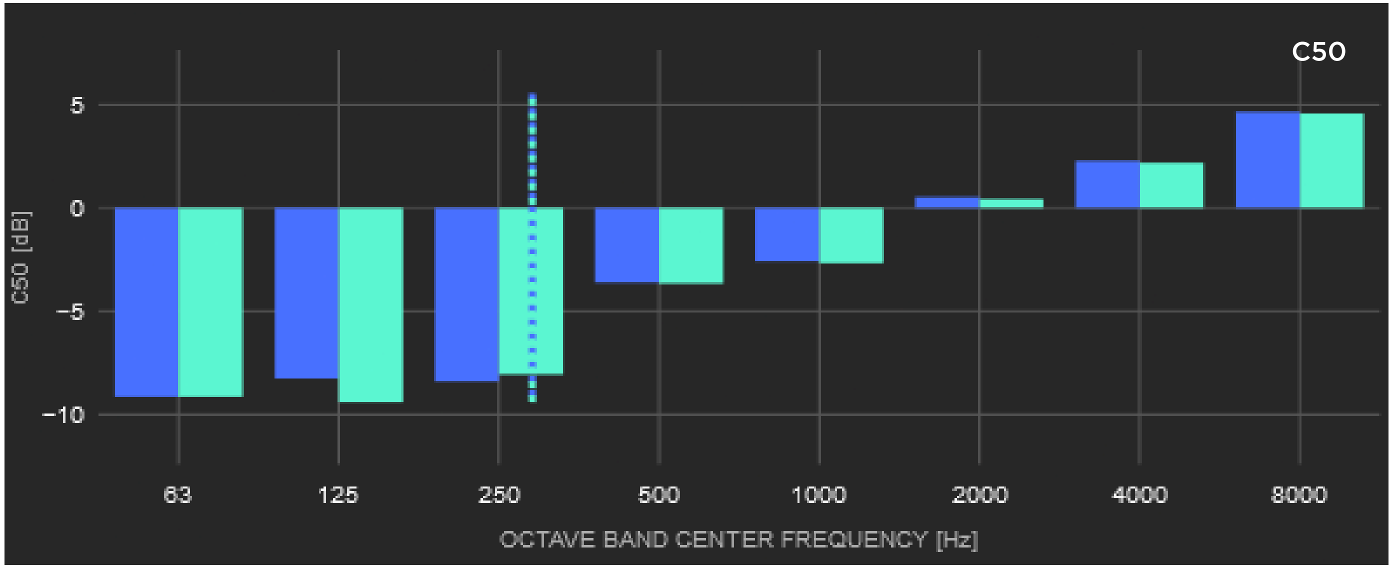


Concave Ceiling

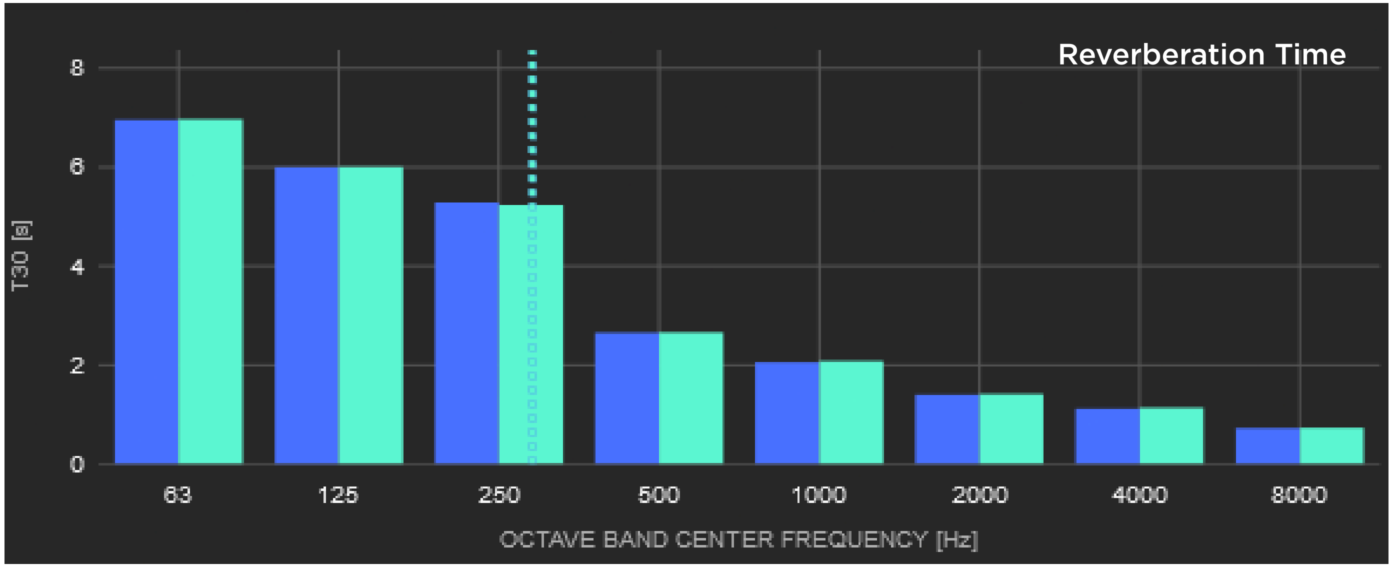


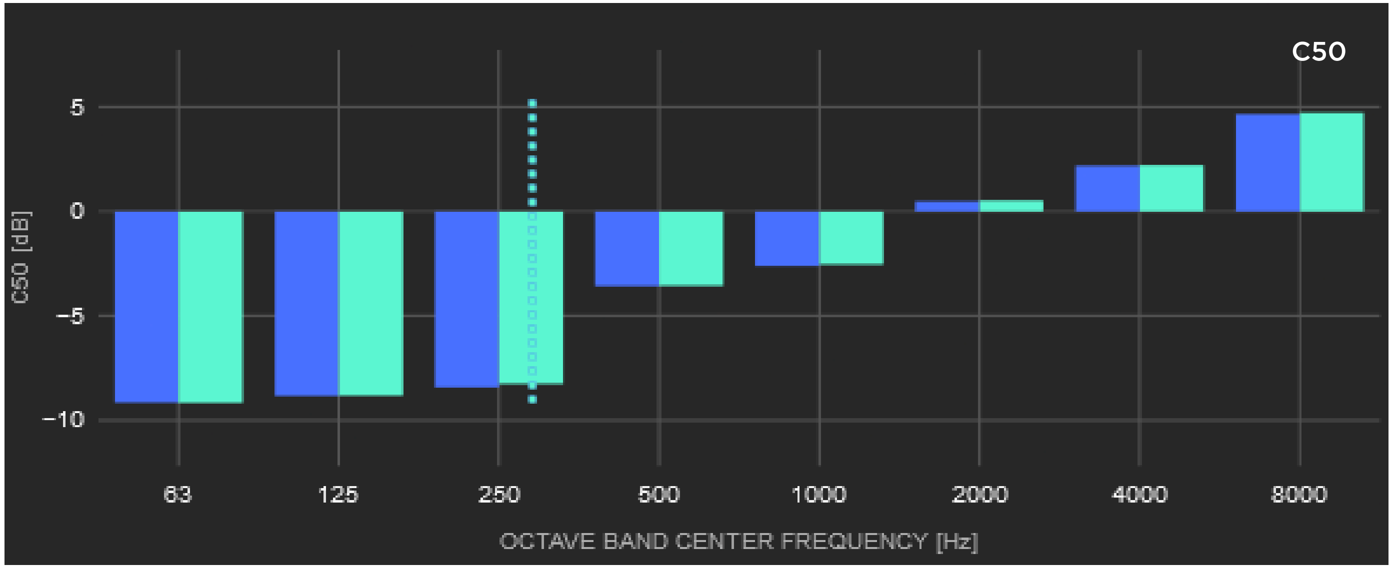
Convex Ceiling





Concave Ceiling

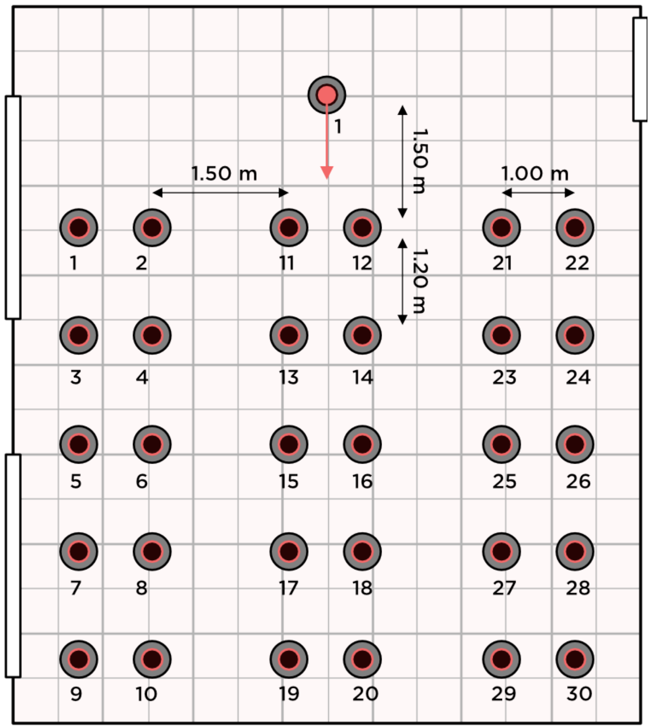


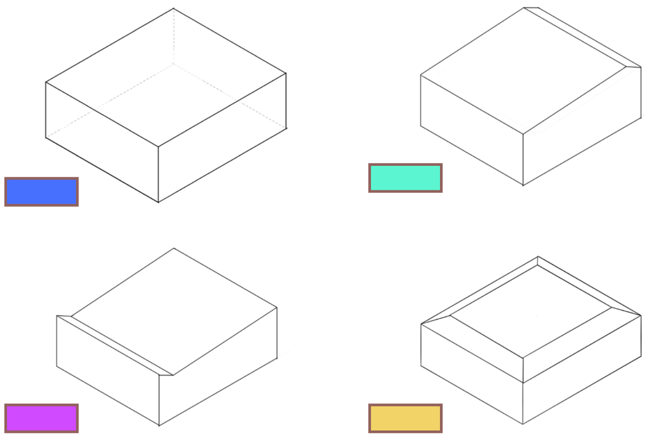


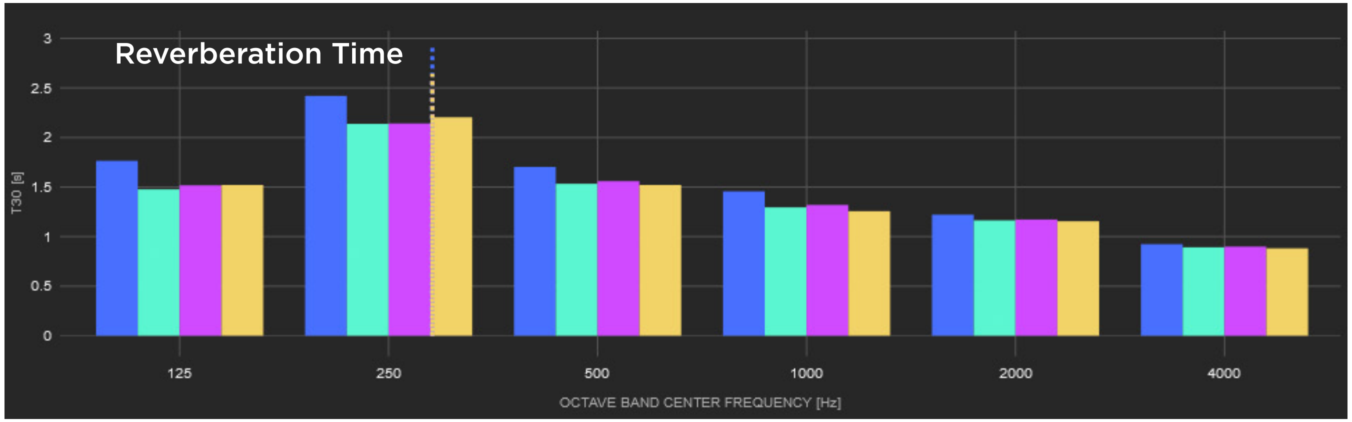
Ceiling Types & Relevant Data

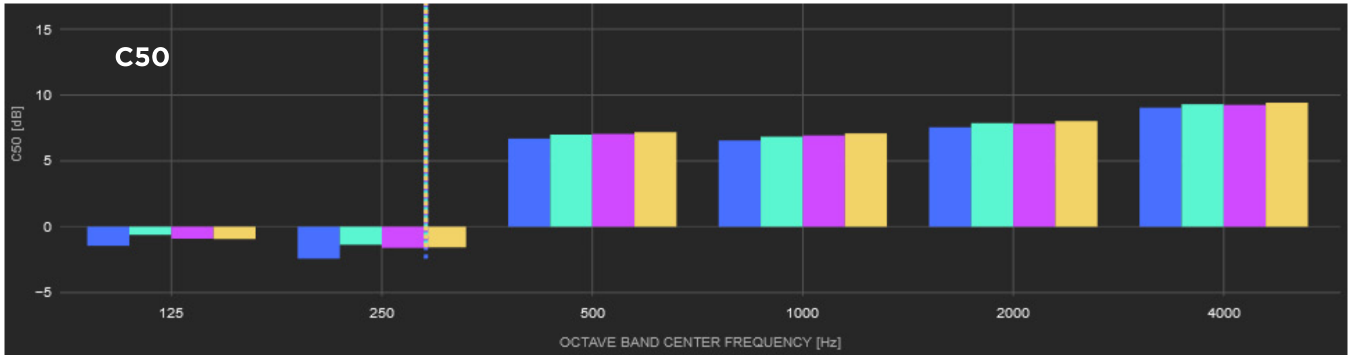
S.No.	Roof Type	Offset	Room Volume (in m^2)	Surface Area (in m^2)					Difference in Volume from room with Flat Roof (in m^2)
				Wall (Long)	Wall (Short)	Ceiling	Floor	Total	
1	Pitched Roof	1 m	159.6	45.6	37.8	56.4	56	195.8	8.4
2		2 m	159.6	45.6	37.8	56.2	56	195.6	8.4
3		3 m	159.6	45.6	37.8	56.2	56	195.6	8.4
4		4 m	159.6	45.6	37.8	56.2	56	195.6	8.4
5		5 m	159.6	45.6	37.8	56.2	56	195.6	8.4
6		6 m	159.6	45.6	37.8	56.2	56	195.6	8.4
7		7 m	159.6	45.6	37.8	56.4	56	195.8	8.4
8	Inverted Roof	1 m	159.6	45.6	37.8	56.4	56	195.8	8.4
9		2 m	159.6	45.6	37.8	56.2	56	195.6	8.4
10		3 m	159.6	45.6	37.8	56.2	56	195.6	8.4
11		4 m	159.6	45.6	37.8	56.2	56	195.6	8.4
12		5 m	159.6	45.6	37.8	56.2	56	195.6	8.4
13		6 m	159.6	45.6	37.8	56.2	56	195.6	8.4
14		7 m	159.6	45.6	37.8	56.4	56	195.8	8.4
15	Hip Roof	0 m	156.8	48	37.8	56.2	56	198	11.2
16		1 m	163.9	48	37.8	57.1	56	198.9	4.1
17		2 m	160.6	48	37.8	56.5	56	198.3	7.4
18		3 m	158.1	48	37.8	56.3	56	198.1	9.9
19	Convex Roof	r = 2h (r=12 m)	166.2	48	42	56.03	56	202.03	1.8
20		r > 2h (r=15 m)	166.7	48	42	56.03	56	202.03	1.3
21	Concave Roof	r = 2h (r=12 m)	162.75	48	42	56.03	56	202.03	5.25
22		r > 2h (r=15 m)	165.57	48	42	56.03	56	202.03	2.43
23	Flat Roof	N/A	168	48	42	56	56	202	0

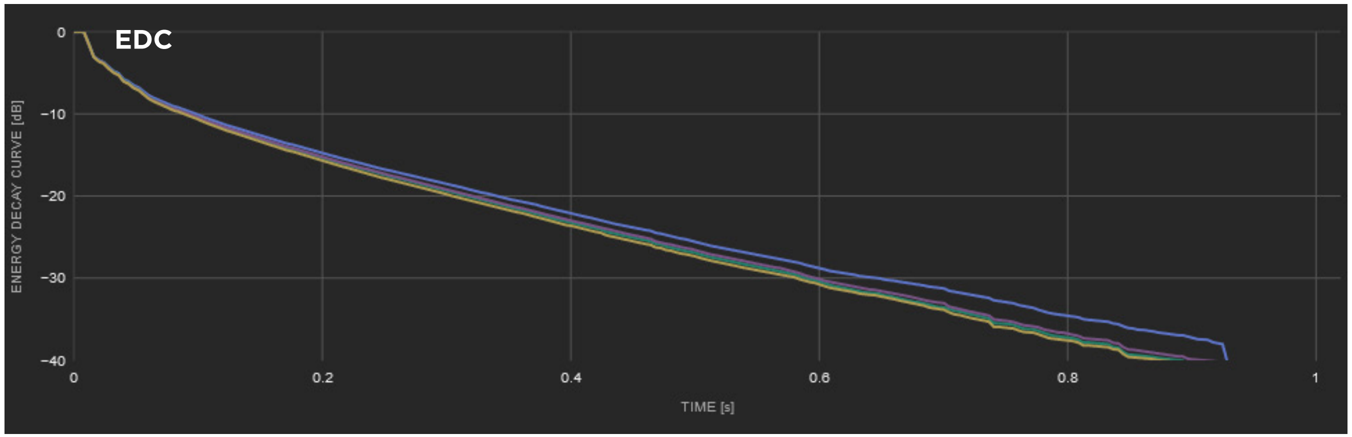
Scenario #1


1
1.50 m
1.50 m
1.00 m
1.20 m
1
2
11
12
21
22
3
4
13
14
23
24
5
6
15
16
25
26
7
8
17
18
27
28
9
10
19
20
29
30

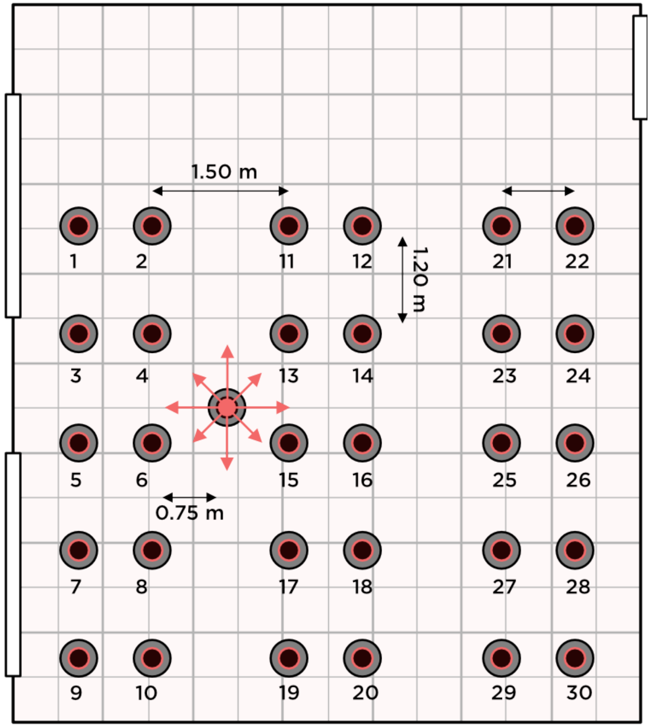


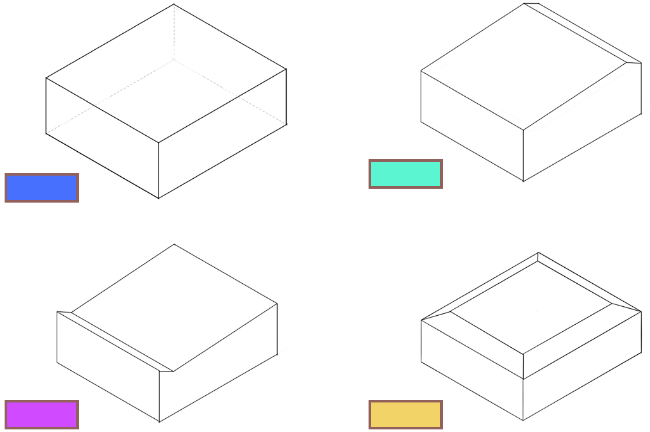

Reverberation Time
T30 [s]
3
2.5
2
1.5
1
0.5
0
125
250
500
1000
2000
4000
OCTAVE BAND CENTER FREQUENCY [Hz]

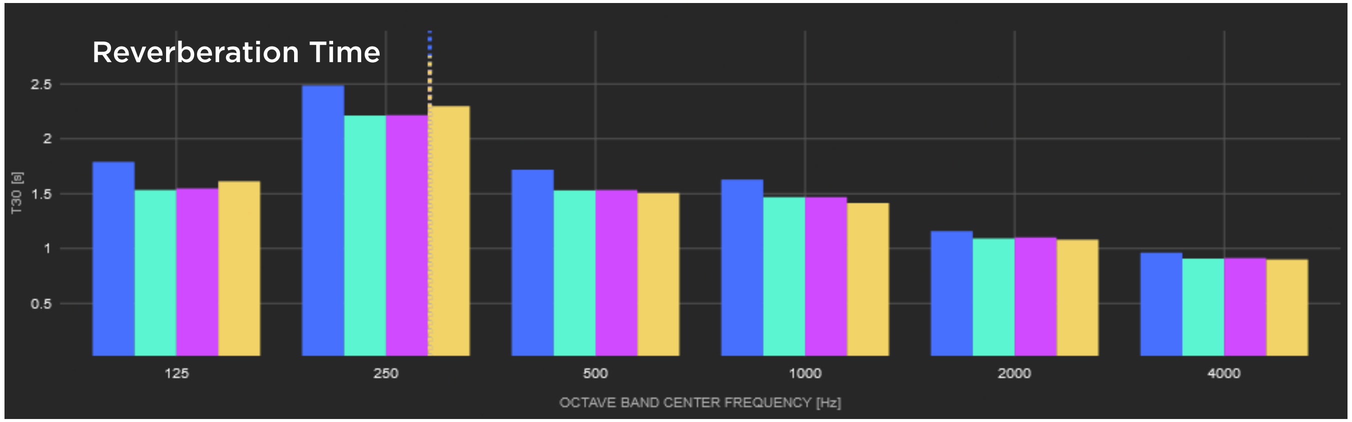

C50
C50 [dB]
15
10
5
0
−5
125
250
500
1000
2000
4000
OCTAVE BAND CENTER FREQUENCY [Hz]

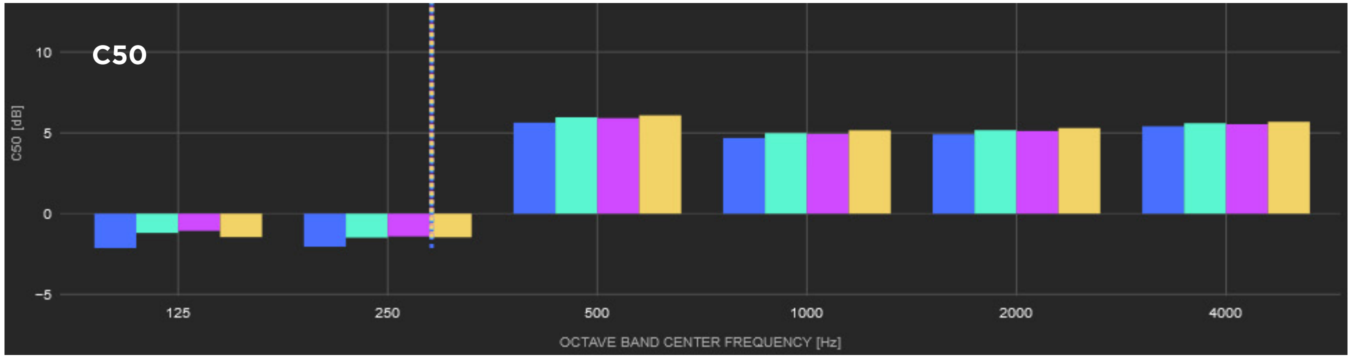

EDC
ENERGY DECAY CURVE [dB]
0
−10
−20
−30
−40
0
0.2
0.4
0.6
0.8
1
TIME [s]

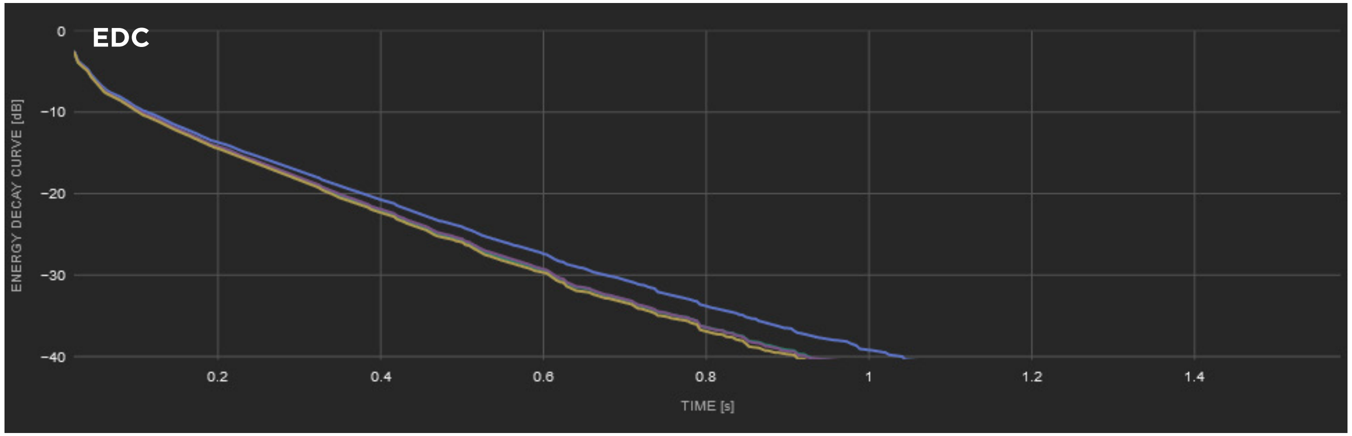
Scenario #2


1.50 m
1.20 m
0.75 m
1
2
11
12
21
22
3
4
13
14
23
24
5
6
15
16
25
26
7
8
17
18
27
28
9
10
19
20
29
30

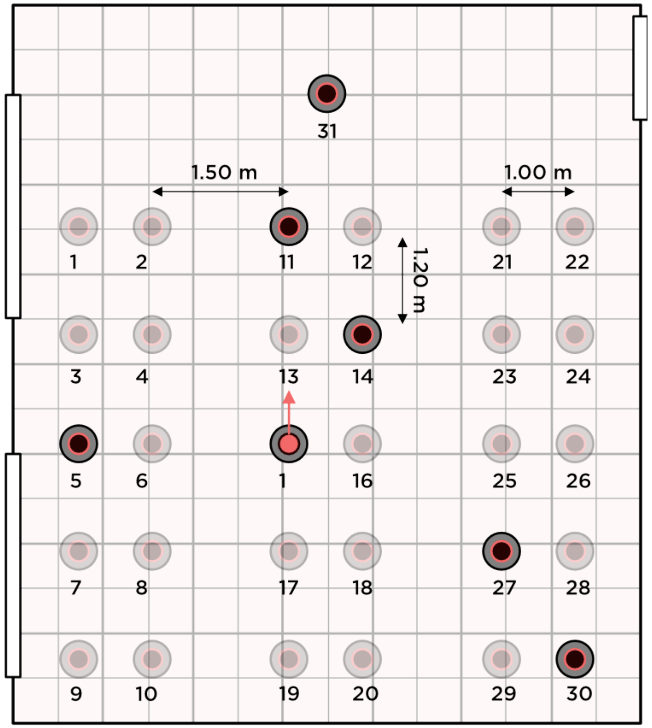


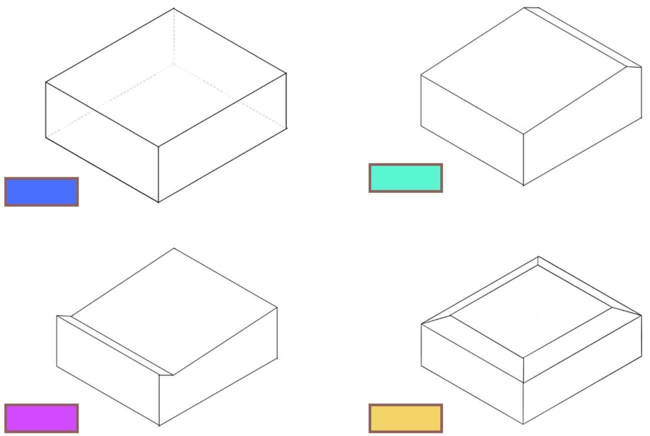

Reverberation Time
T30 [s]
2.5
2
1.5
1
0.5
125
250
500
1000
2000
4000
OCTAVE BAND CENTER FREQUENCY [Hz]

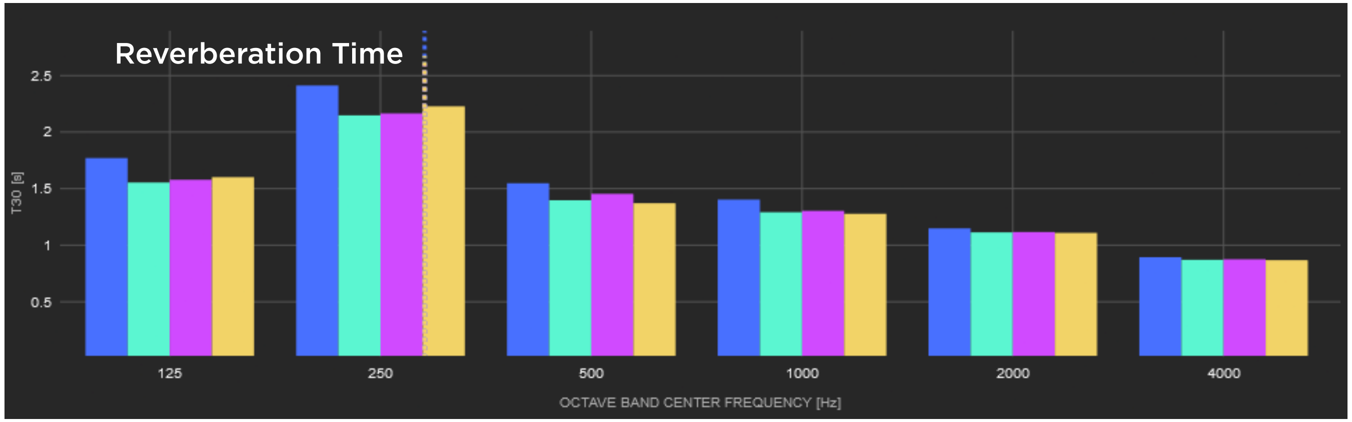

C50
C50 [dB]
10
5
0
−5
125
250
500
1000
2000
4000
OCTAVE BAND CENTER FREQUENCY [Hz]

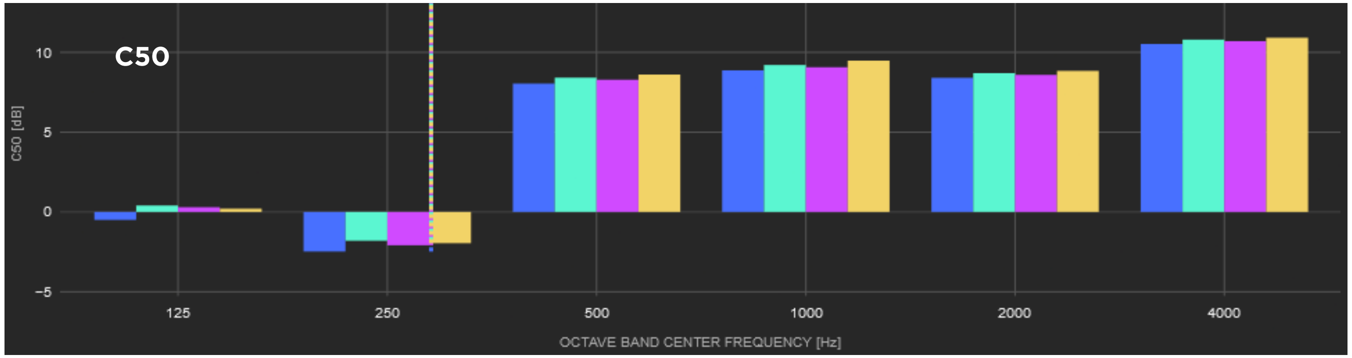

EDC
ENERGY DECAY CURVE [dB]
0
−10
−20
−30
−40
0.2
0.4
0.6
0.8
1
1.2
1.4
TIME [s]

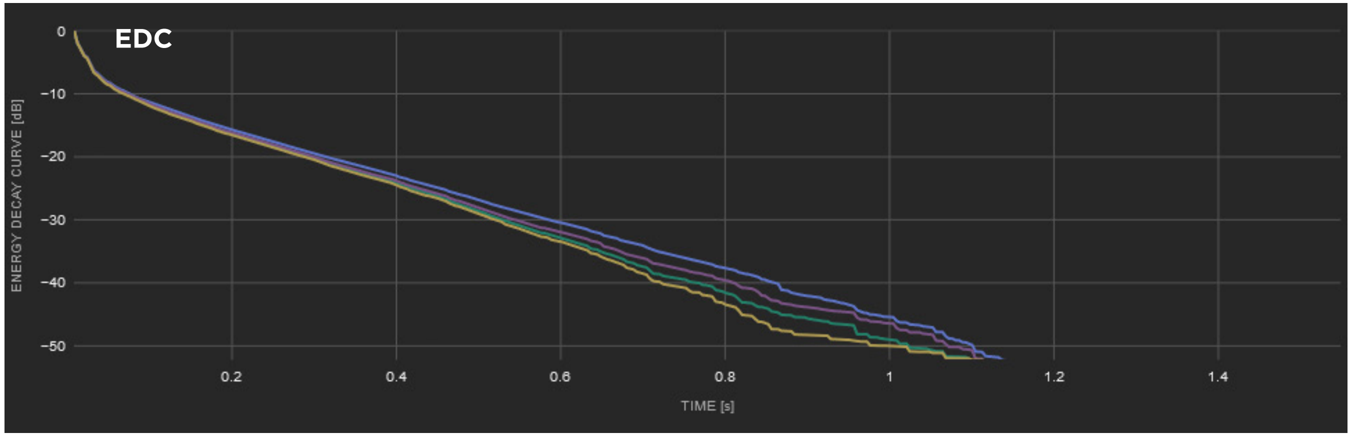
Scenario #3


31
1.50 m
1.00 m
1
2
11
12
21
22
1.20 m
3
4
13
14
23
24
5
6
1
16
25
26
7
8
17
18
27
28
9
10
19
20
29
30

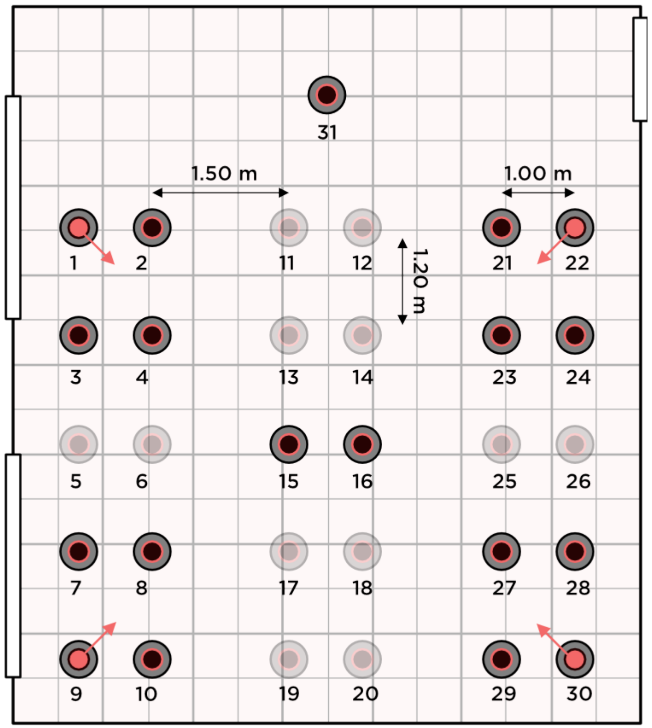


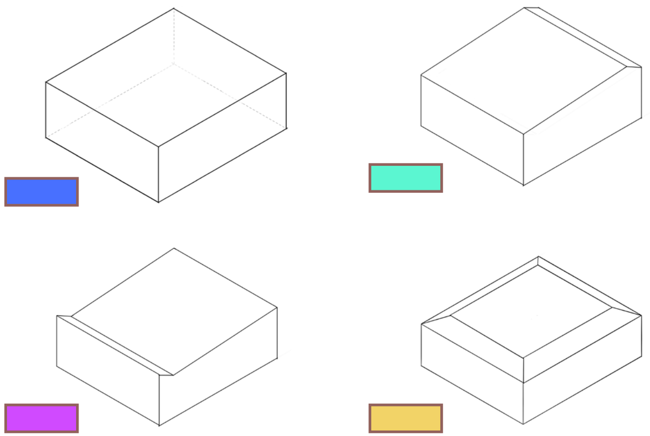

Reverberation Time
2.5
2
1.5
1
0.5
T30 [s]
125
250
500
1000
2000
4000
OCTAVE BAND CENTER FREQUENCY [Hz]

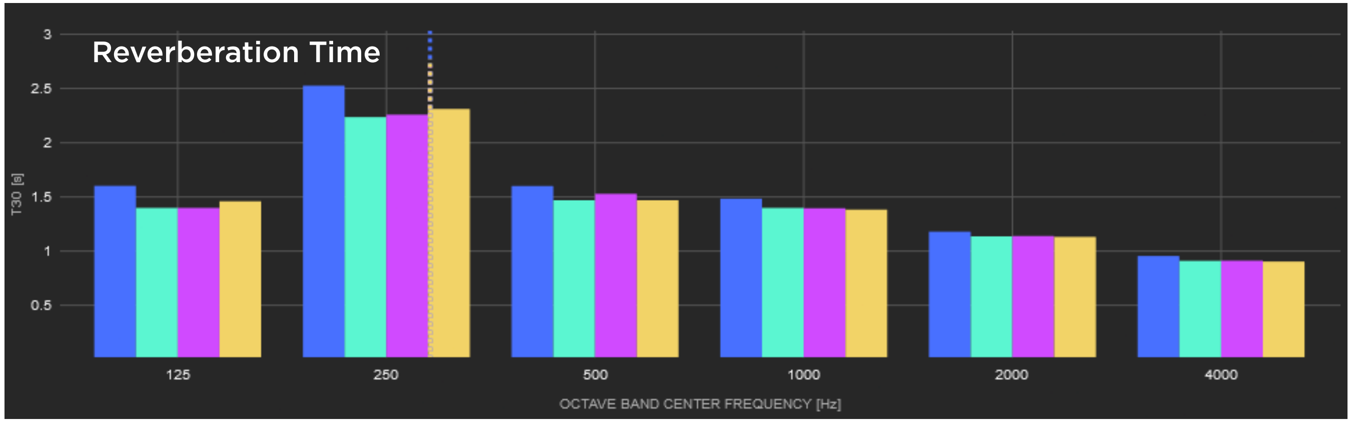

C50
10
5
0
−5
C50 [dB]
125
250
500
1000
2000
4000
OCTAVE BAND CENTER FREQUENCY [Hz]

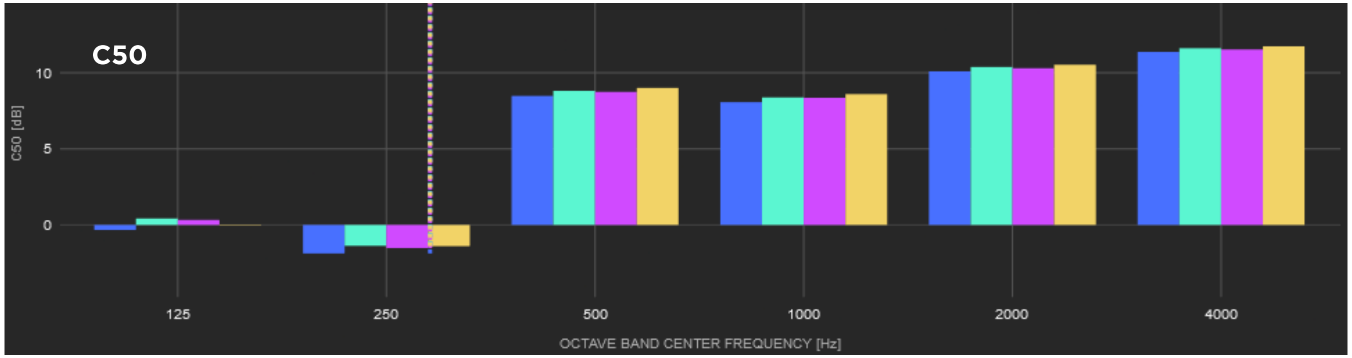

EDC
0
−10
−20
−30
−40
−50
ENERGY DECAY CURVE [dB]
0.2
0.4
0.6
0.8
1
1.2
1.4
TIME [s]

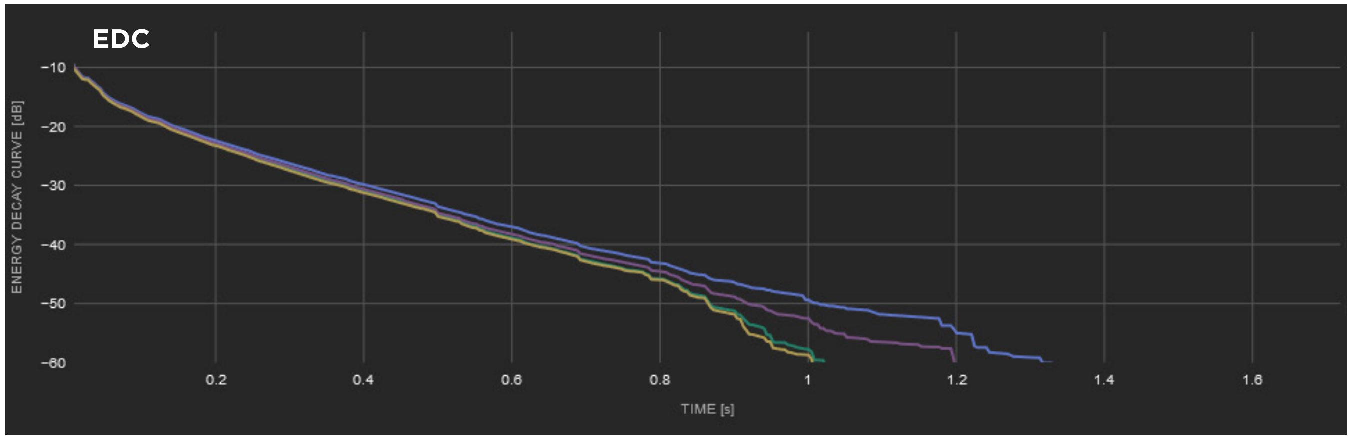
Scenario #5, Speaker 1



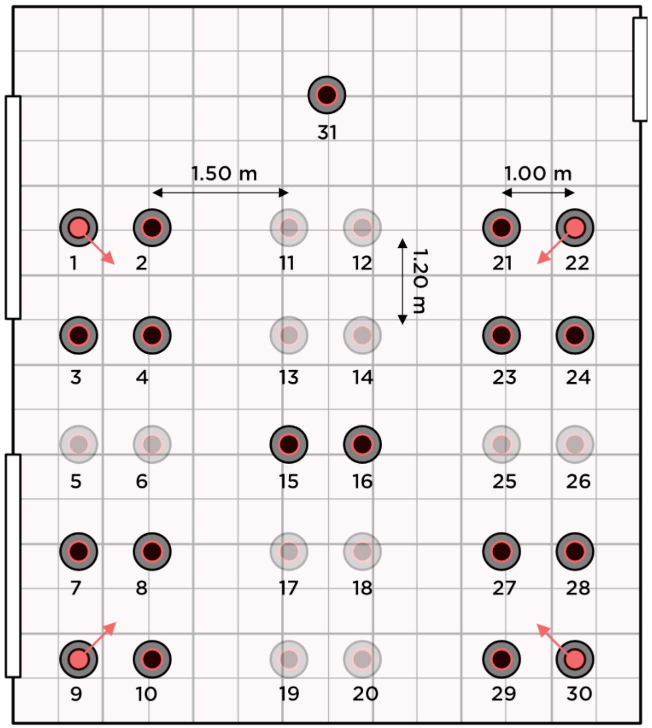


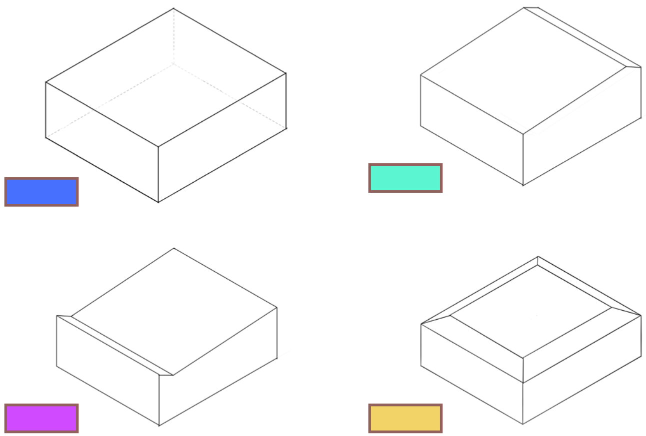


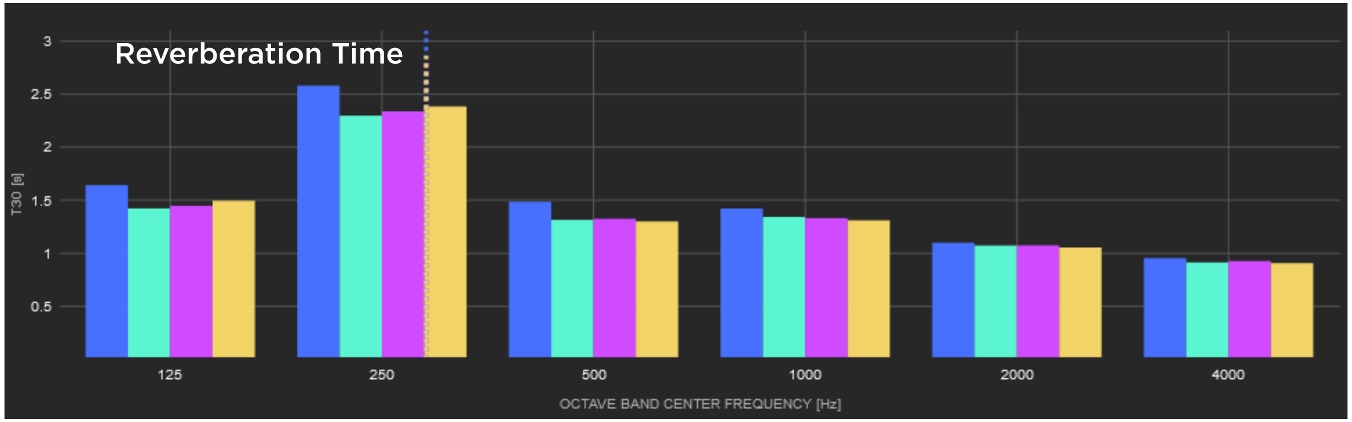


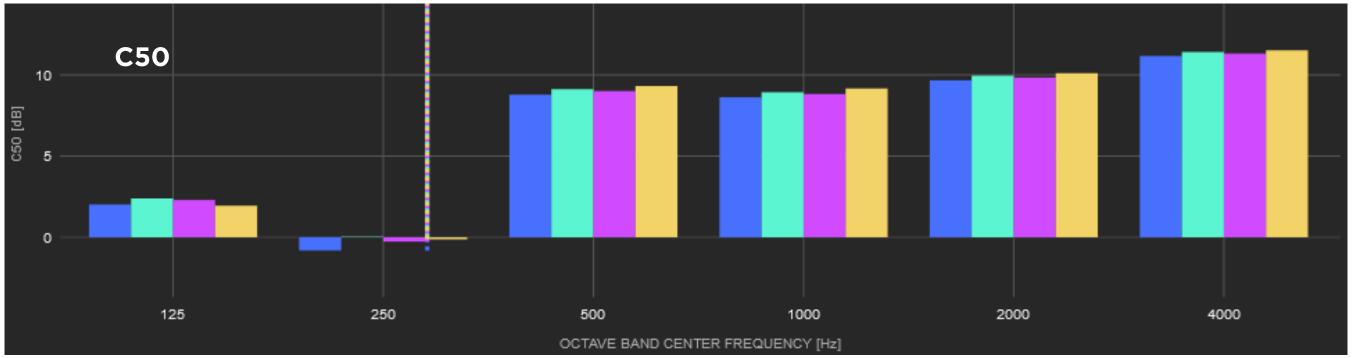


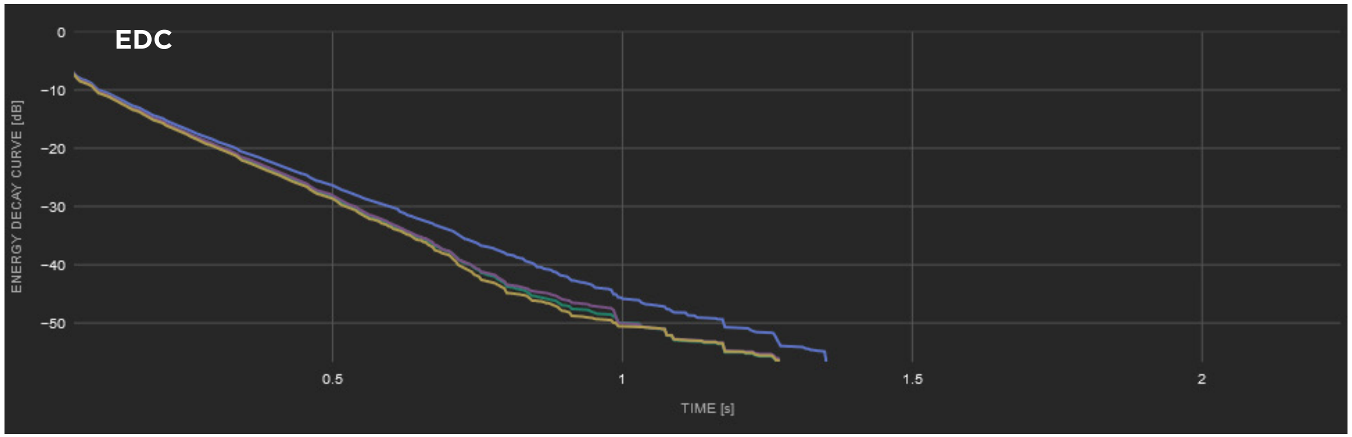
Scenario #5, Speaker 2



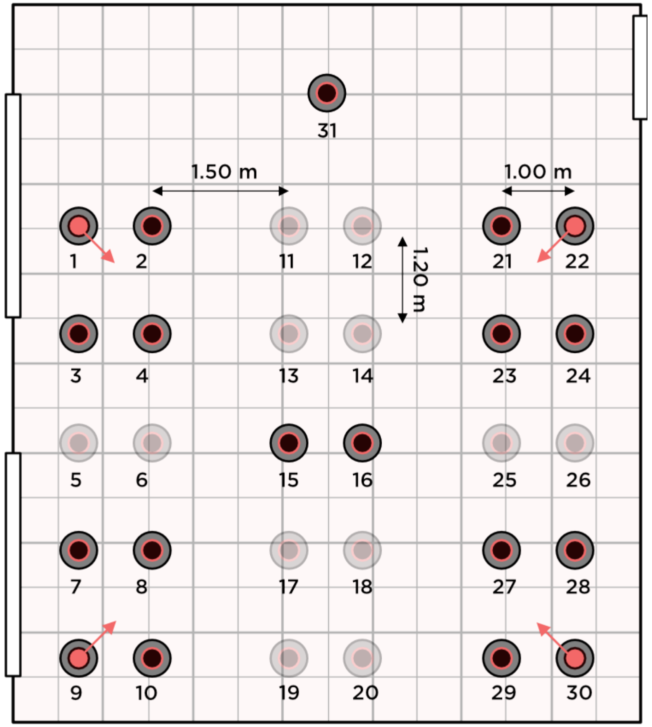


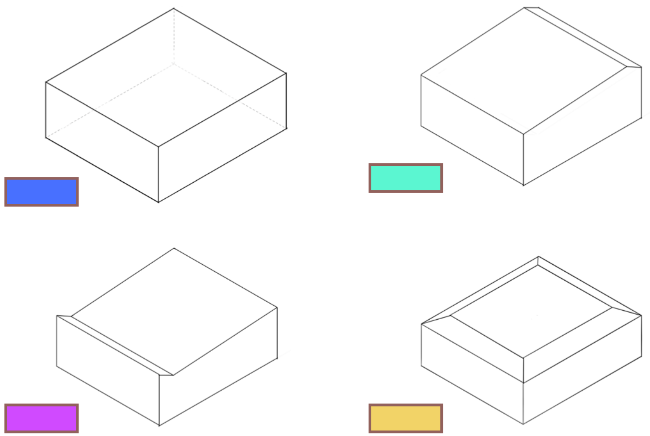


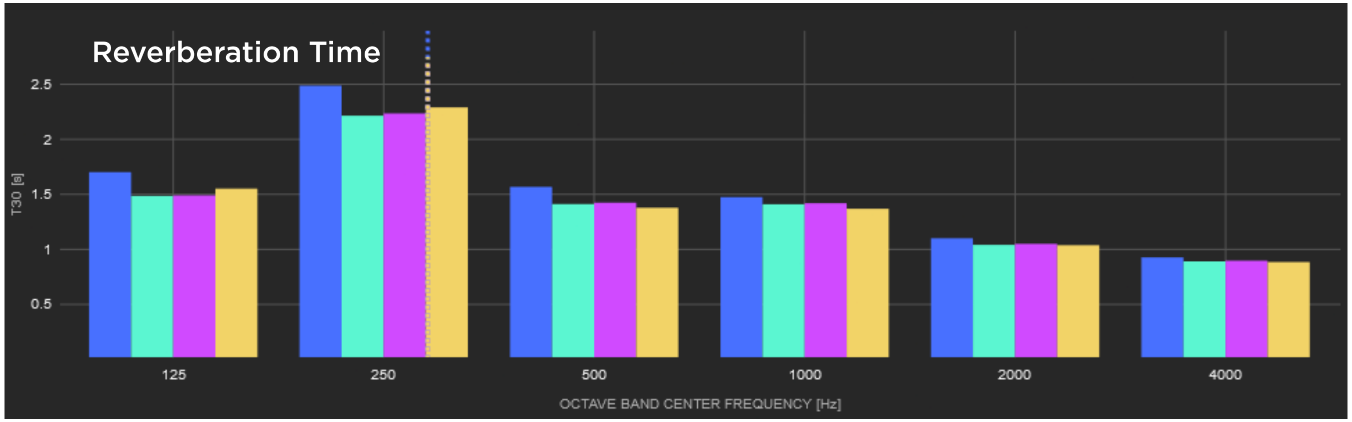


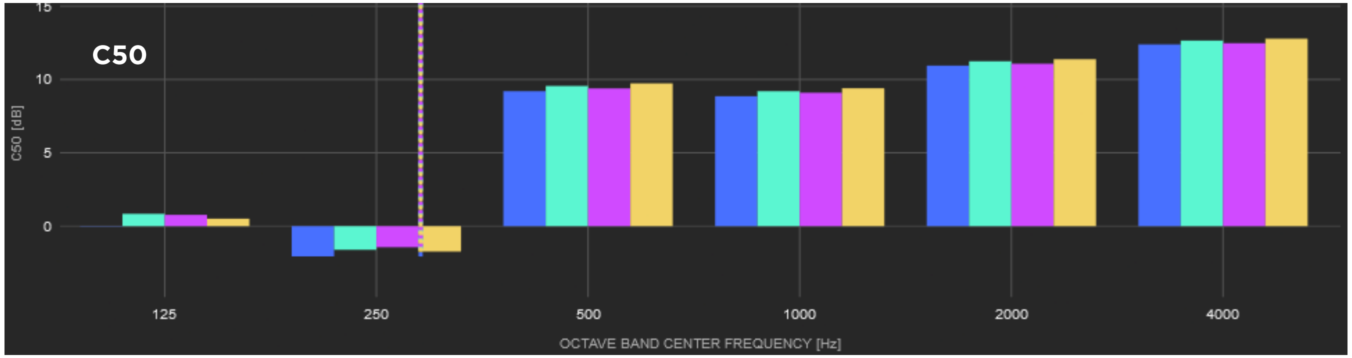


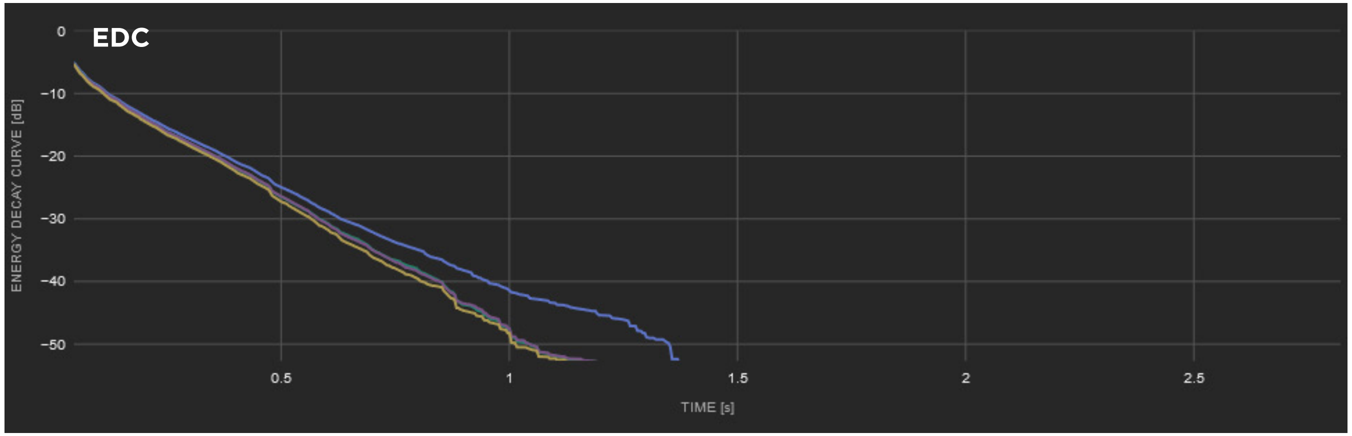
Scenario #5, Speaker 3



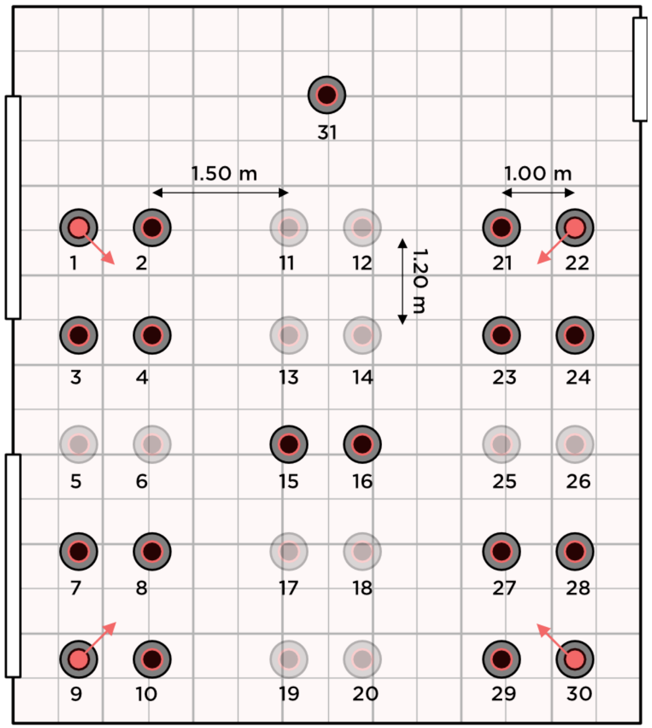


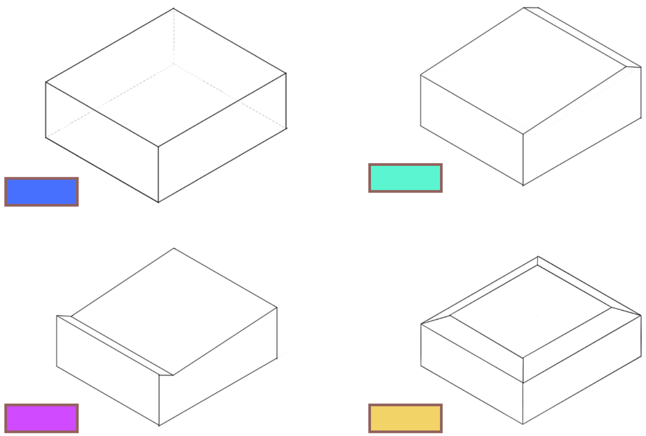


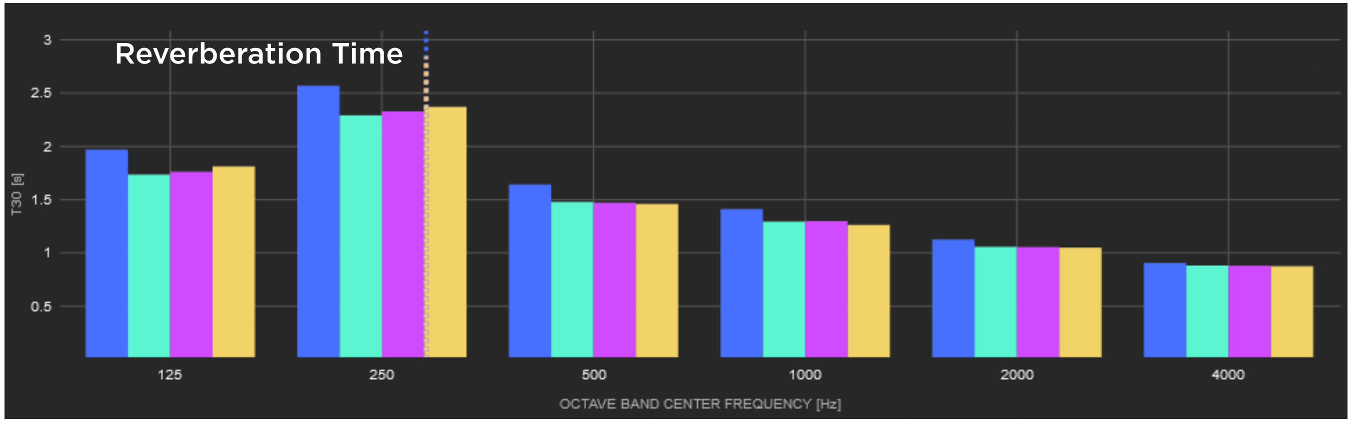


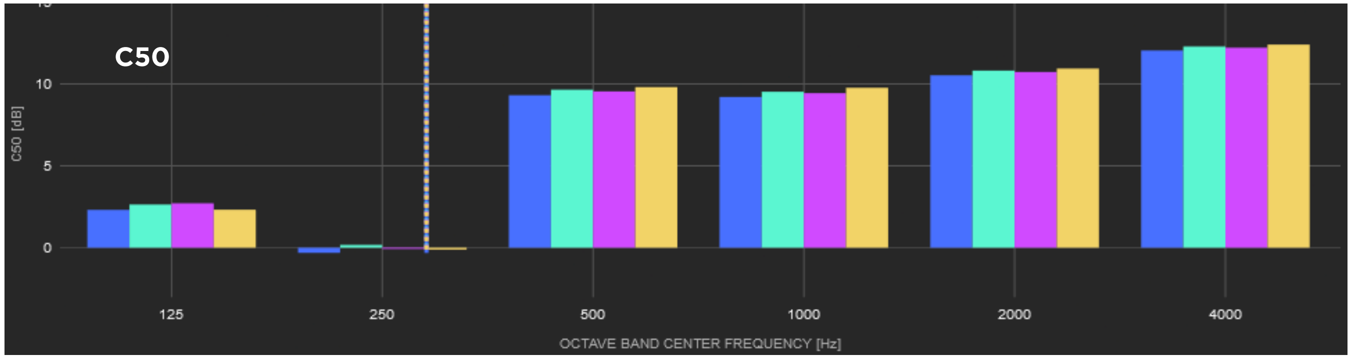


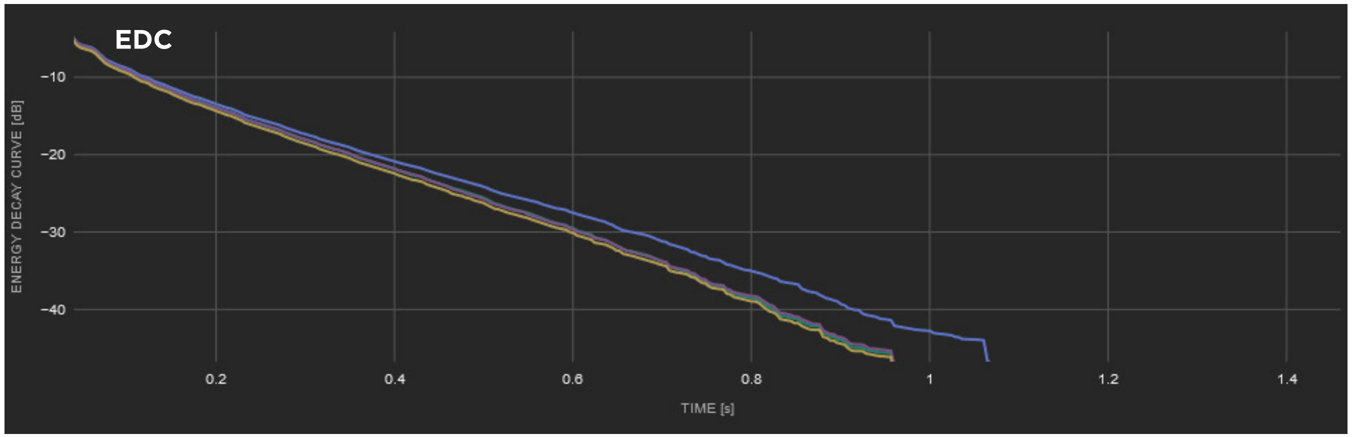
Scenario #5, Speaker 4





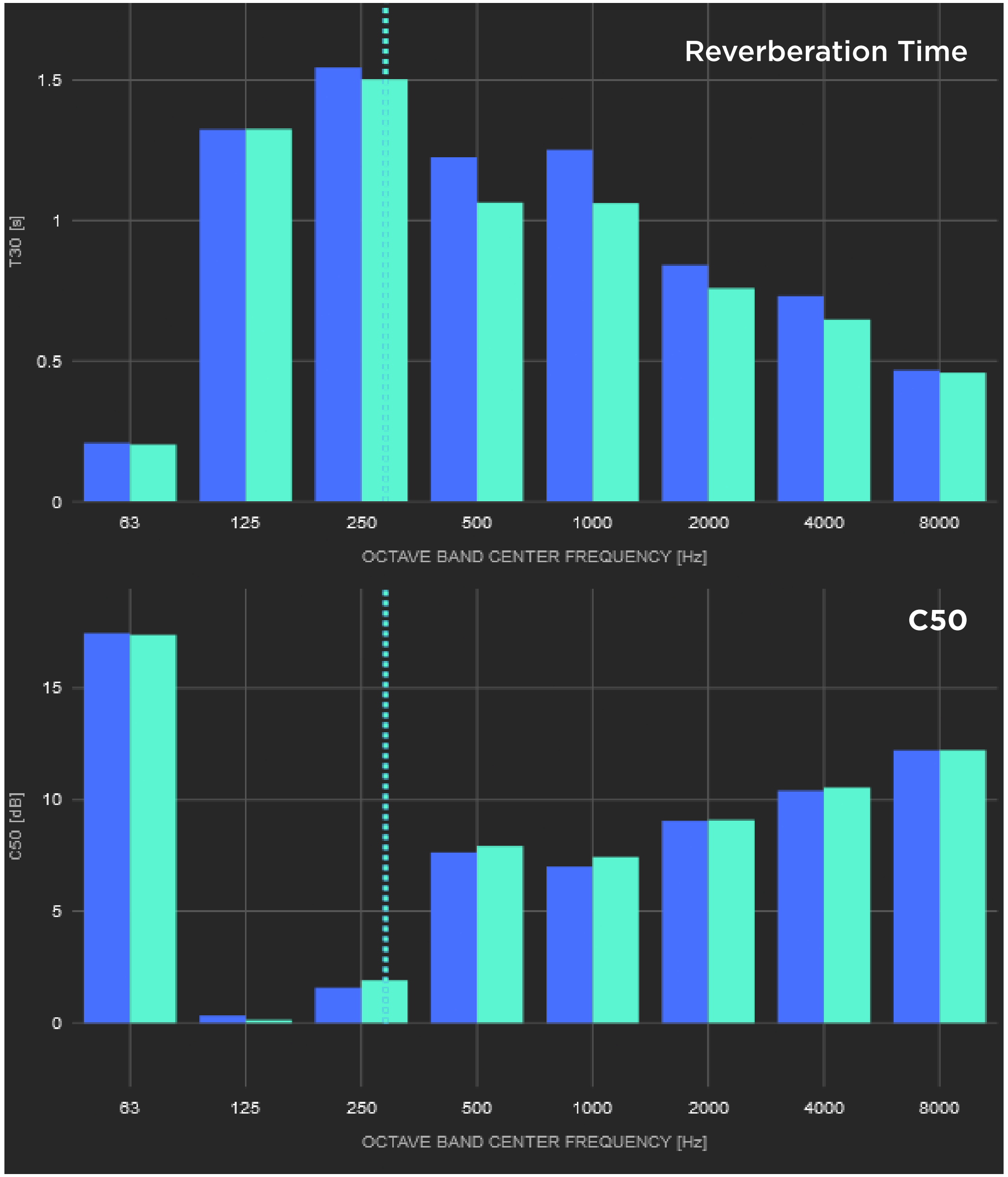


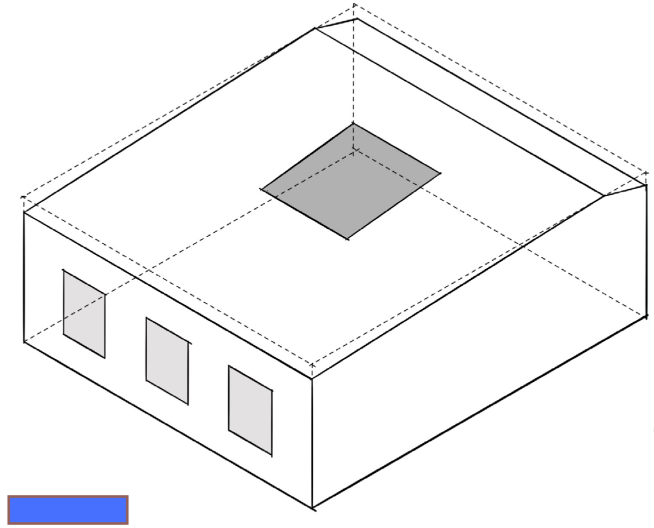


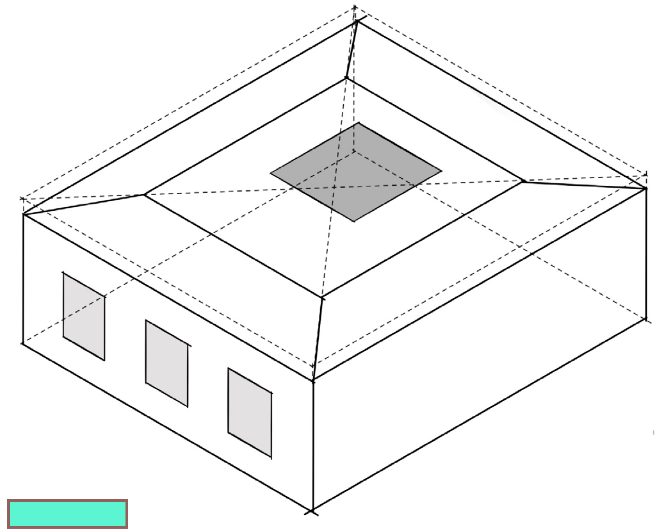


Appendix 9 | Comparison of Hip & Pitched Ceiling - with interventions

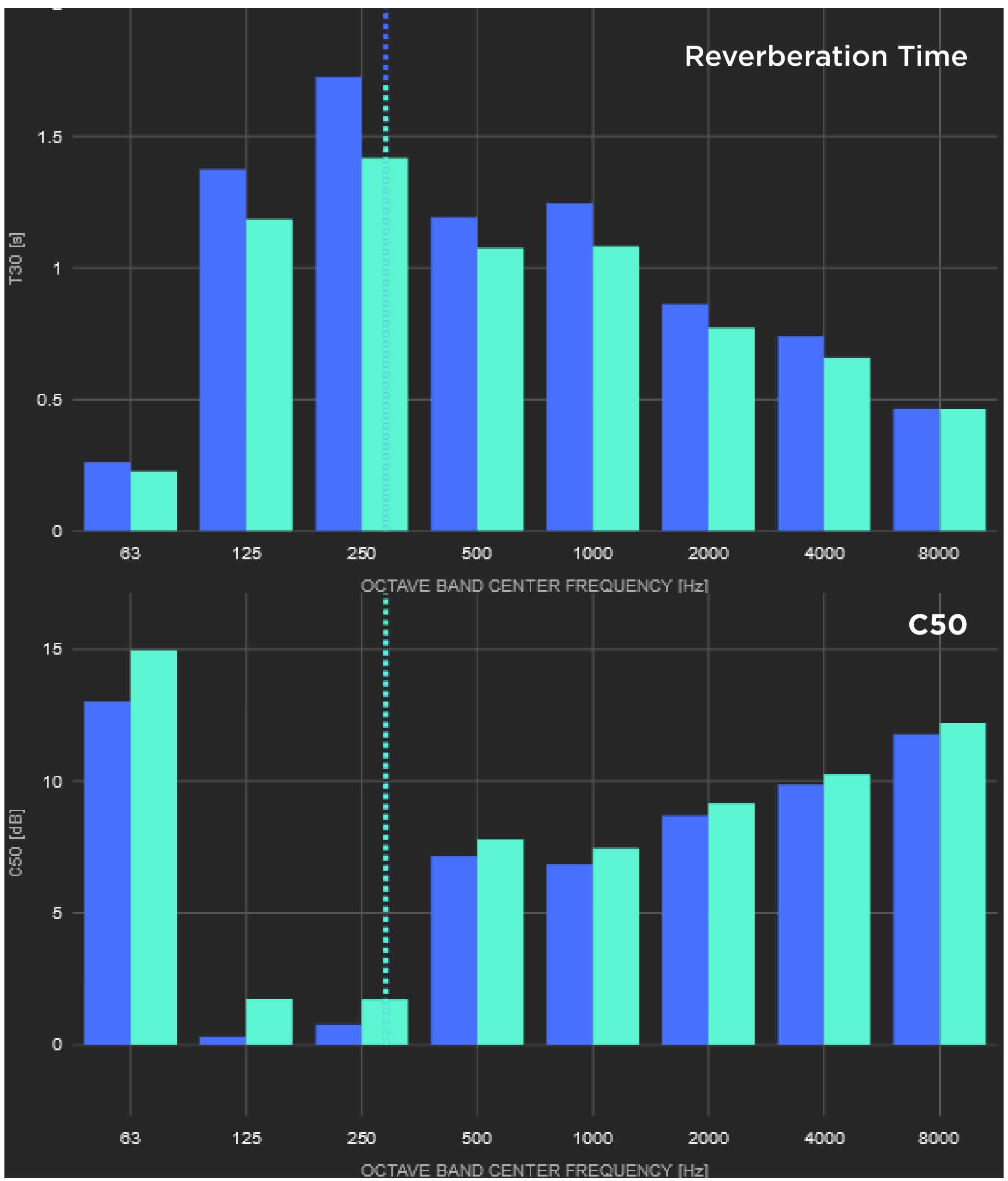
Version #1

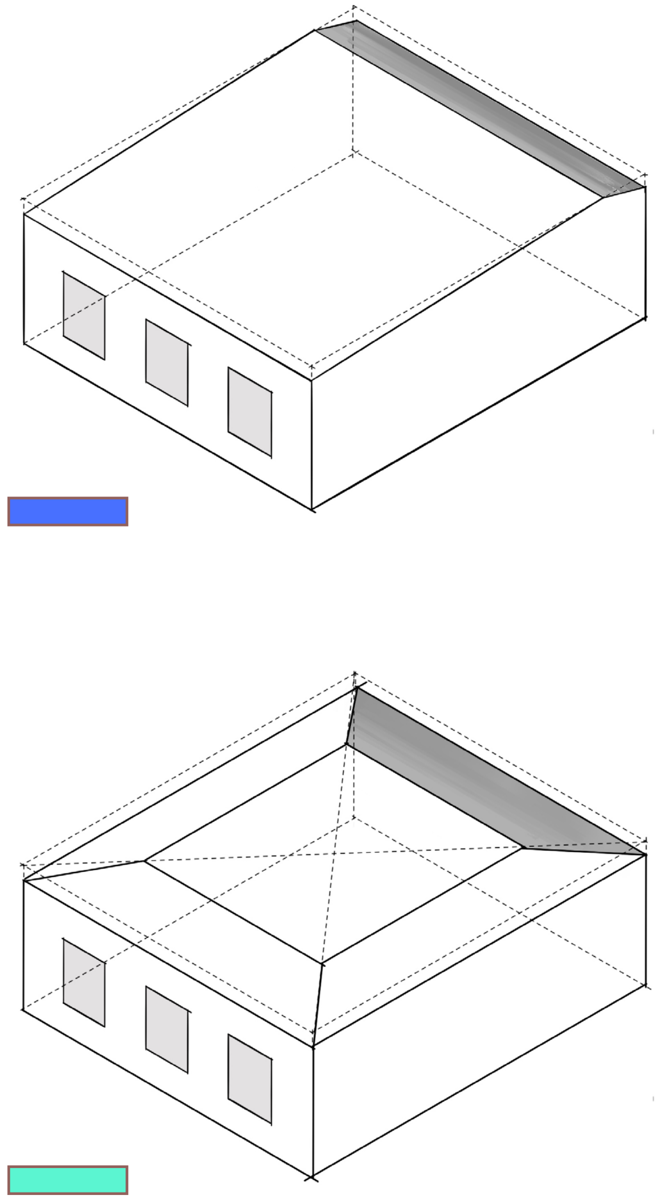




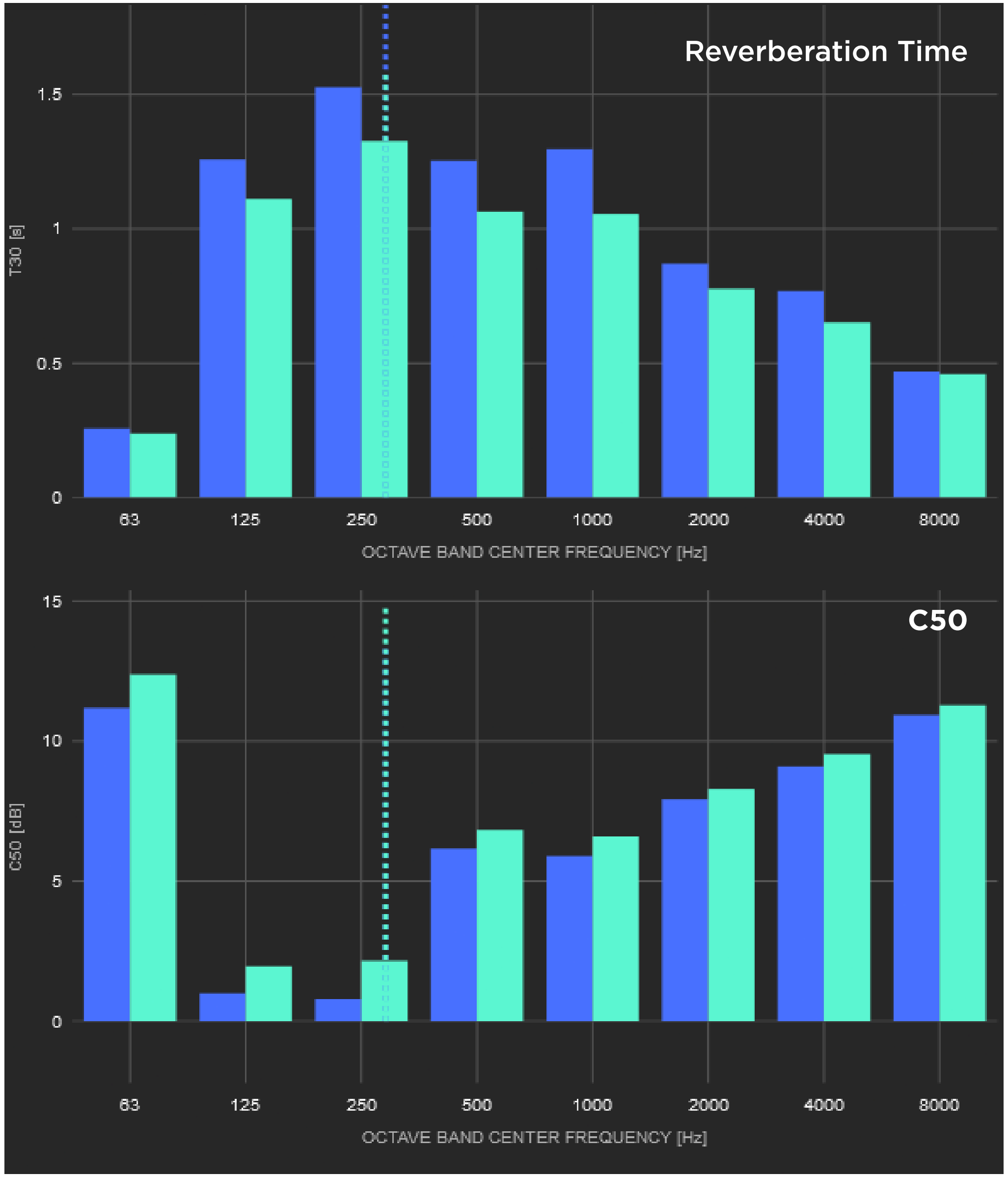


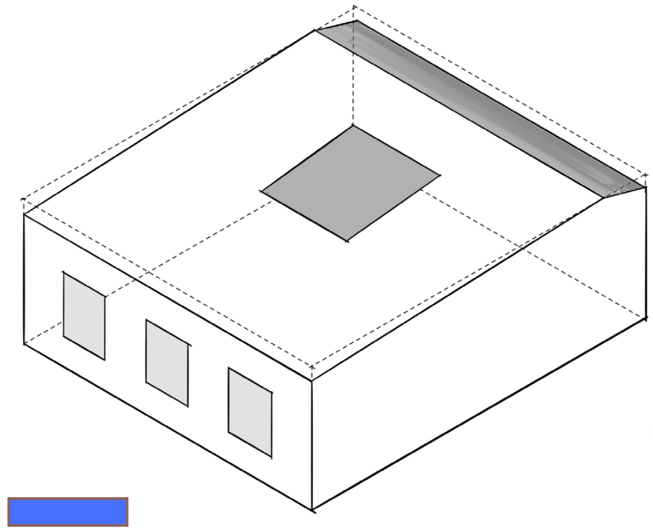
Version #2

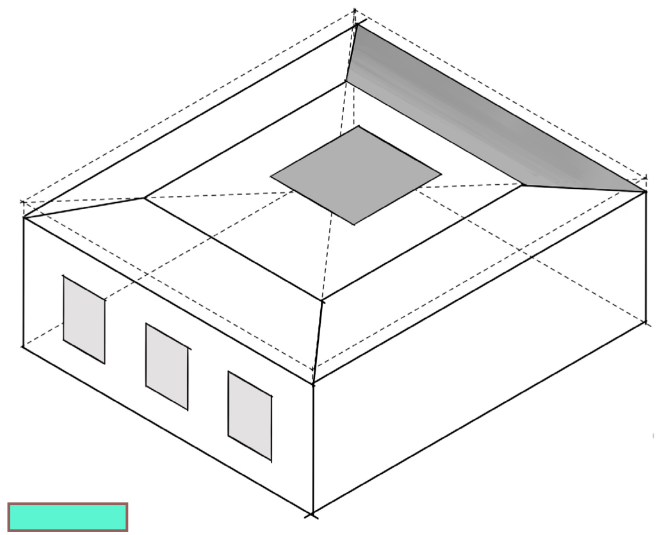

Reverberation Time
T30 [s]
1.5
1
0.5
0
63
125
250
500
1000
2000
4000
8000
OCTAVE BAND CENTER FREQUENCY [Hz]
C50
C50 [dB]
15
10
5
0
63
125
250
500
1000
2000
4000
8000
OCTAVE BAND CENTER FREQUENCY [Hz]



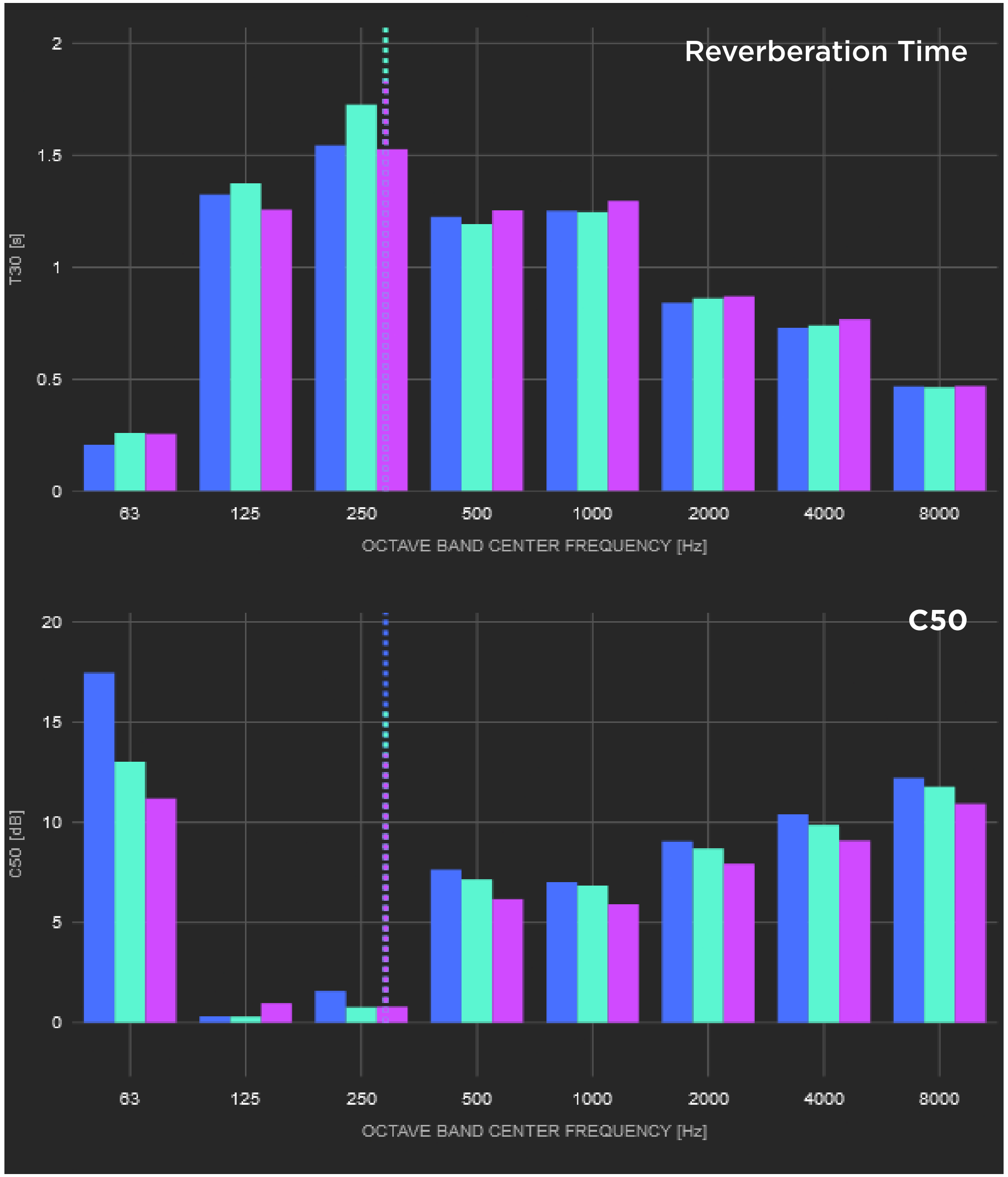
Version #3

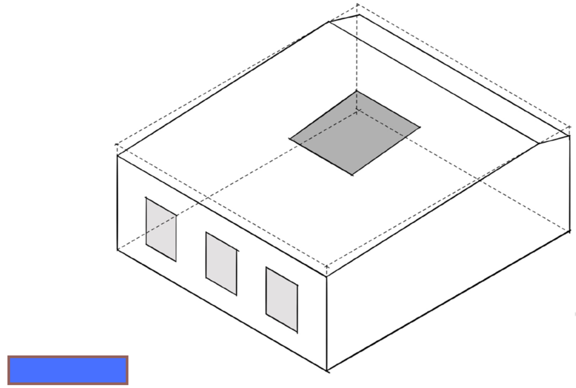

Reverberation Time
T30 [s]
1.5
1
0.5
0
63
125
250
500
1000
2000
4000
8000
OCTAVE BAND CENTER FREQUENCY [Hz]
C50
C50 [dB]
15
10
5
0
63
125
250
500
1000
2000
4000
8000
OCTAVE BAND CENTER FREQUENCY [Hz]

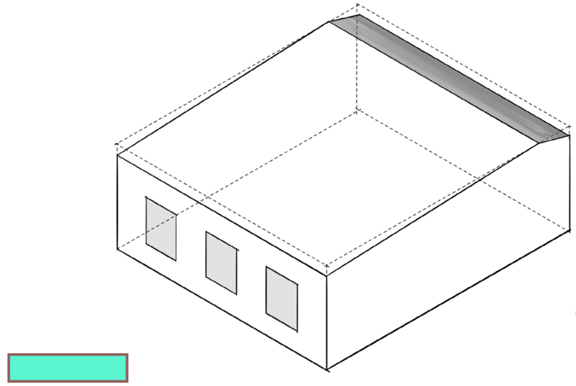


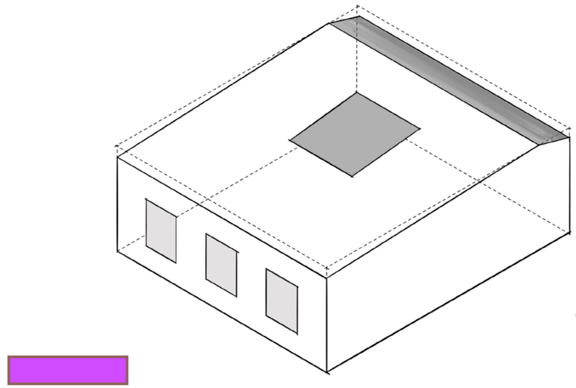


Comparison - Pitched Ceiling

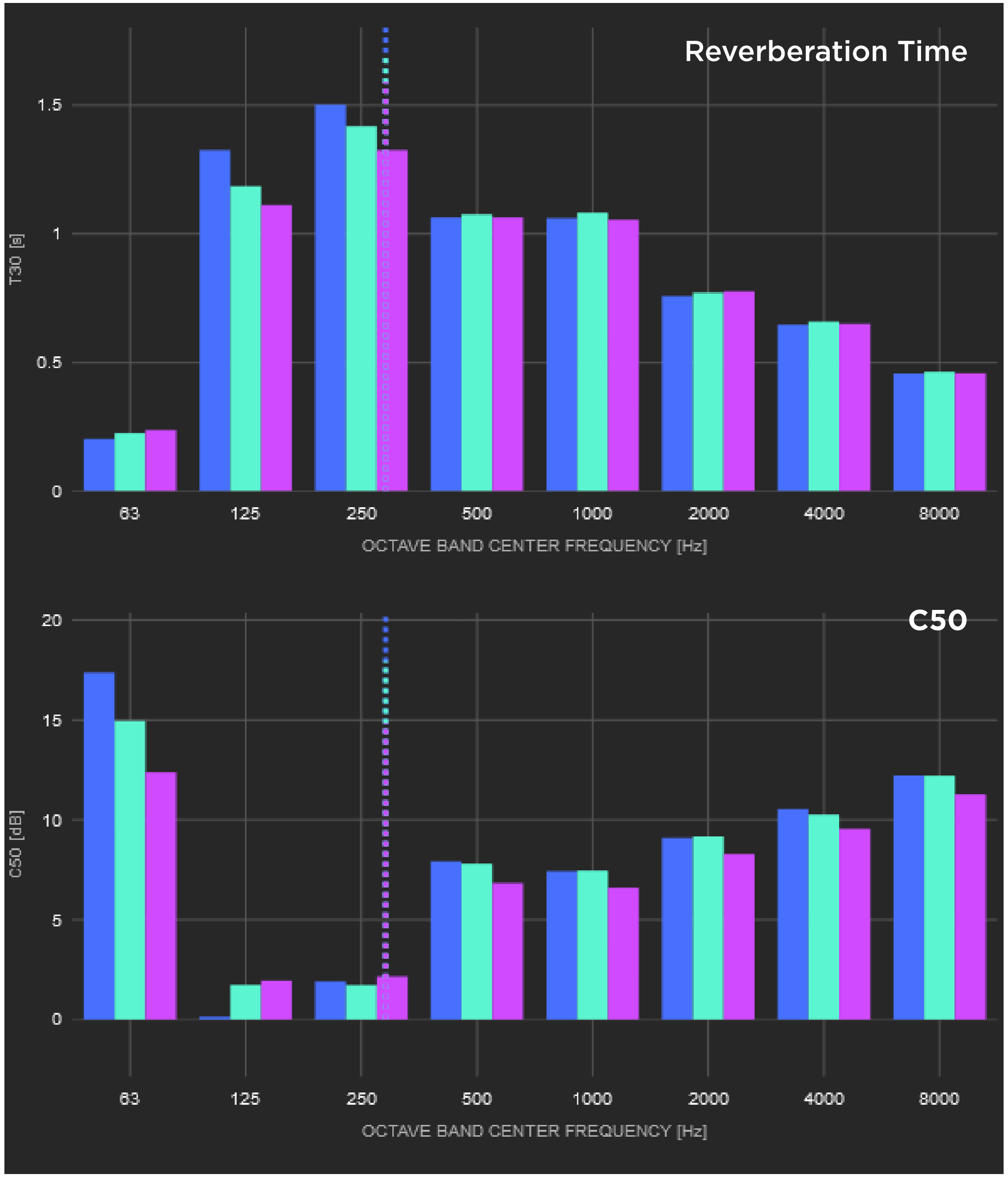


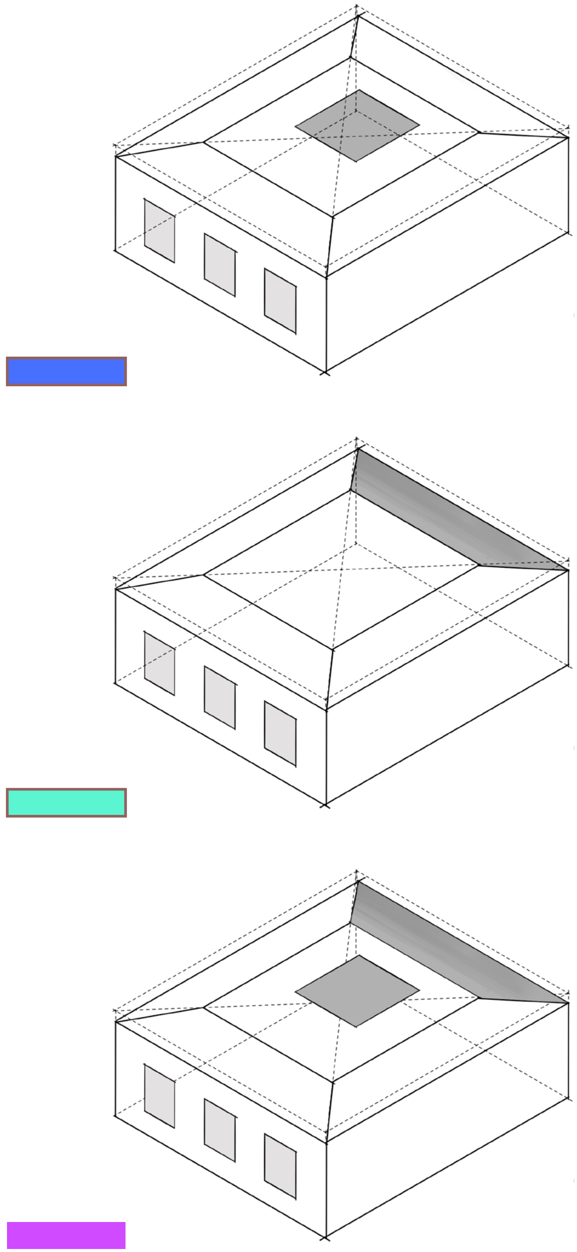






Comparison - Hip Ceiling





Results - RT

Version	Scenario	Frequency						Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
		125	250	500	1000	2000	4000		
1	1	0.78	0.72	0.71	0.73	0.56	0.54	0.68	0.67
	2	0.71	0.66	0.65	0.77	0.61	0.52	0.67	0.65
	3	0.73	0.71	0.73	0.69	0.59	0.54	0.68	0.67
Average		0.74	0.7	0.7	0.73	0.59	0.53	0.68	0.66

Version	Scenario	Frequency						Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
		125	250	500	1000	2000	4000		
2	1	0.8	0.79	0.69	0.74	0.58	0.56	0.7	0.69
	2	0.74	0.68	0.7	0.69	0.63	0.53	0.68	0.66
	3	0.71	0.77	0.71	0.69	0.57	0.52	0.69	0.66
Average		0.75	0.75	0.7	0.71	0.59	0.54	0.69	0.67

Version	Scenario	Frequency						Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
		125	250	500	1000	2000	4000		
3	1	0.91	0.85	0.81	0.79	0.67	0.58	0.78	0.77
	2	0.84	0.78	0.75	0.77	0.67	0.59	0.74	0.73
	3	0.9	0.79	0.85	0.78	0.68	0.6	0.78	0.77
Average		0.88	0.81	0.8	0.78	0.67	0.59	0.77	0.76

Version	Scenario	Frequency						Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
		125	250	500	1000	2000	4000		
4	1	0.73	0.73	0.67	0.67	0.57	0.54	0.66	0.65
	2	0.79	0.7	0.69	0.65	0.62	0.55	0.67	0.67
	3	0.71	0.74	0.66	0.68	0.59	0.54	0.67	0.65
Average		0.74	0.72	0.67	0.67	0.59	0.54	0.67	0.66

Version	Scenario	Frequency						Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
		125	250	500	1000	2000	4000		
5	1	0.74	0.73	0.66	0.66	0.57	0.54	0.66	0.65
	2	0.78	0.71	0.7	0.66	0.63	0.55	0.68	0.67
	3	0.71	0.75	0.66	0.68	0.59	0.53	0.67	0.65
Average		0.74	0.73	0.67	0.67	0.6	0.54	0.67	0.66

Results - C50

Version	Scenario	Frequency						Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
		125	250	500	1000	2000	4000		
1	1	6.55	7.54	7.79	6.59	9.01	10	7.73	7.91
	2	8.22	8.61	8.86	8.22	9.17	10.47	8.72	8.93
	3	8.22	8.55	8.46	8.07	8.55	9.62	8.41	8.58
Average		7.66	8.23	8.37	7.63	8.91	10.03	8.29	8.47

Version	Scenario	Frequency						Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
		125	250	500	1000	2000	4000		
2	1	5.48	6.63	7.38	7.22	8.93	9.07	7.54	7.45
	2	7.26	7.88	8.69	9.31	9.42	9.58	8.83	8.69
	3	6.9	7.58	8.16	9.32	8.83	8.79	8.47	8.26
Average		6.55	7.36	8.08	8.62	9.06	9.15	8.28	8.13

Version	Scenario	Frequency						Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
		125	250	500	1000	2000	4000		
3	1	4.88	5.97	6.65	5.85	8.07	8.62	6.64	6.67
	2	6.25	6.82	7.41	7.77	8.13	8.49	7.53	7.48
	3	5.99	6.56	7	7.67	7.65	7.87	7.22	7.12
Average		5.71	6.45	7.02	7.1	7.95	8.33	7.13	7.09

Version	Scenario	Frequency						Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
		125	250	500	1000	2000	4000		
4	1	5.6	6.67	7.4	6.97	8.89	9.06	7.48	7.43
	2	7.36	7.89	8.6	9.11	9.29	9.57	8.72	8.64
	3	6.96	7.57	8.11	8.98	8.78	8.69	8.36	8.18
Average		6.64	7.38	8.04	8.35	8.99	9.11	8.19	8.08

Version	Scenario	Frequency						Average [250 - 2000 Hz]	Average [125 - 4000 Hz]
		125	250	500	1000	2000	4000		
5	1	5.63	6.69	7.4	7.16	8.93	9.04	7.55	7.48
	2	7.21	7.79	8.49	8.89	9.22	9.59	8.6	8.53
	3	6.94	7.48	7.96	8.79	8.55	8.6	8.2	8.05
Average		6.59	7.32	7.95	8.28	8.9	9.08	8.12	8.02

Appendix 11 | Acoustic Requirements of Spaces in Relation with Teaching Styles

Type	**Specifics**	*Reverberation Time (RT)*	*Speech Transmission Index (STI)*	*Signal to Noise Ratio (SNR)*	*Equivalent Sound Pressure Level (L_{eq})*
Teacher Centered	Standard	< 0.6 s	> 0.6		35-40 dB
	Suggested	< 0.4 - 0.6 s [31,34]	> 0.75 [40]	+15 [39,40] - +20 dB [30]	35 dB
Technology Based	Standard				
	Suggested				
Group Projects	Standard				
	Suggested	< 0.8 s	> 0.6	+15 [39] - +20 dB [30]	35 dB
Individual Work	Standard				
	Suggested				
Hybrid	Standard				
	Suggested	< 0.6 s [34]			
Hearing Impairment Accomodations	Standard	< 0.4 s	> 0.6	+20 dB (250 to 750 Hz), +15 dB (750 Hz to 4 kHz)	30 dB
	Suggested	< 0.3 s [32], < 0.4 - 0.5 s [34]			

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