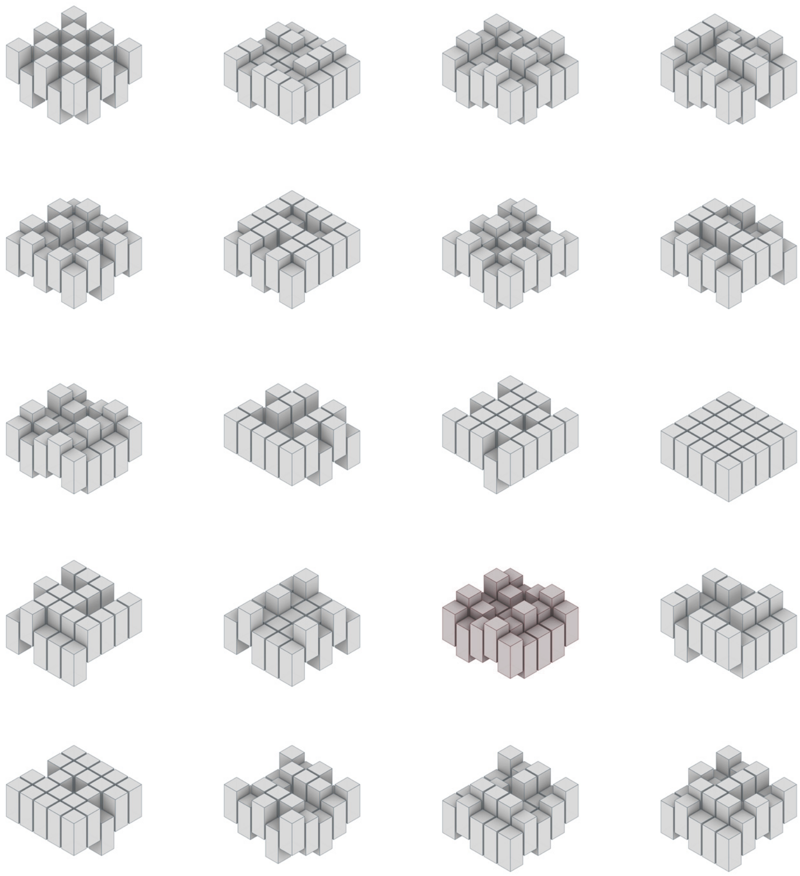

THE SOUND BENDING PROJECT

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THE SOUND BEND|||NG PROJECT

Sustainable Graduation Studio

30. 07. 2020

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" . . . If I do anything, it is to tune souls insetad of instruments, to harmonize people instead of notes. If there is anything in my philosophy, it is the law of harmony ; that one must put oneself in harmony with oneself and with others. "

Hazrat Inayat Khan

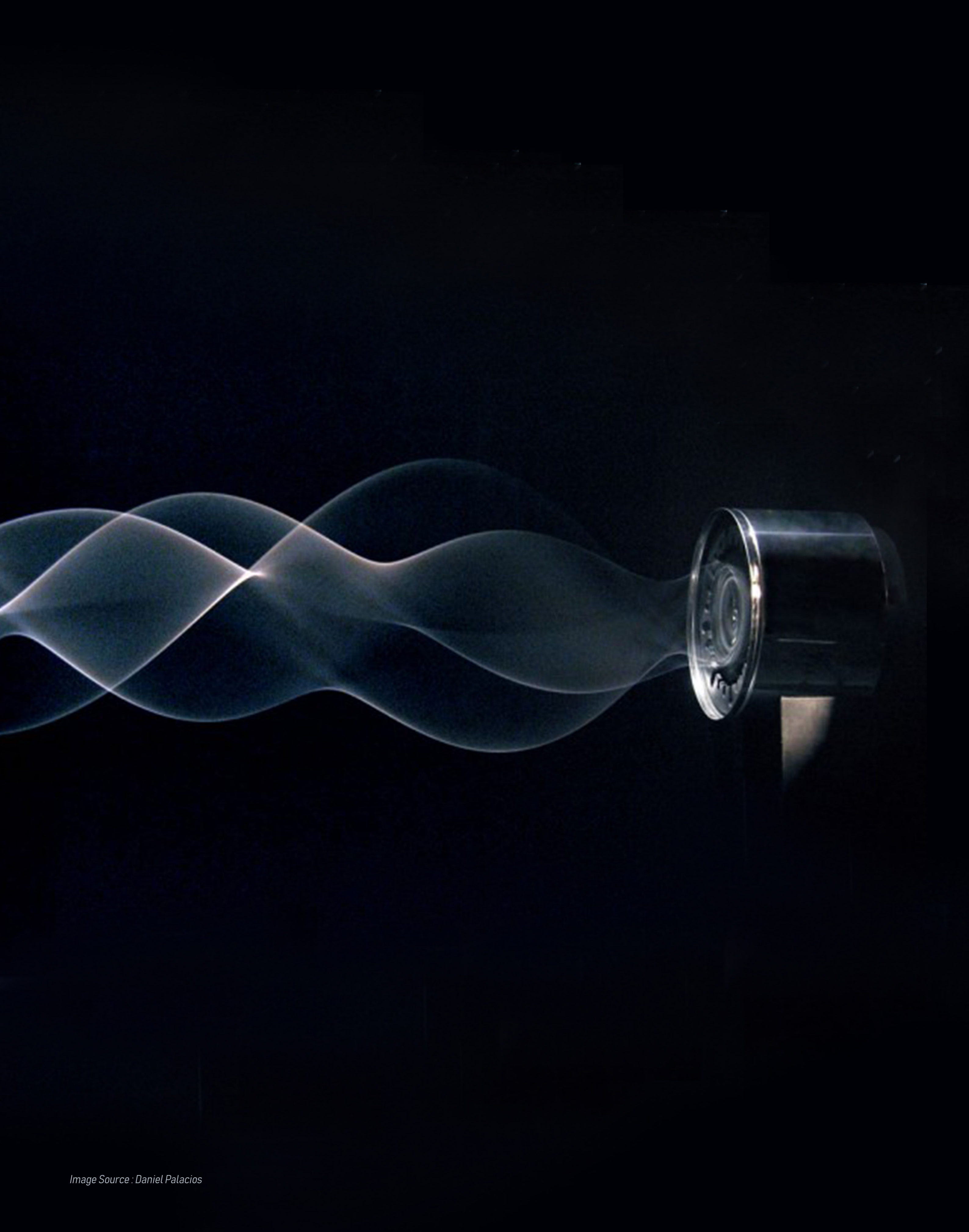

Image Source : Daniel Palacios

MANIFESTO

Sound with a power so immense, is visually depicted through a responsive surface which improves the acoustical experience of a user. Responsive architecture is an exciting field with a scope for fresh research. Creating responsive surfaces allows for research through design, which entails a combination of computational and mechanical tools. Pairing it with building physics, acoustics in this case, makes it relevant in improving the built environment. Design for interaction makes it even more interesting and adds to the overall sensory experience.

'What cannot be easily reproduced is the perception or experience of the environment that is always transient, always unique.'

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INTRODUCTION

Power of Sound

The power of sound is immense. It provides an immersive experience for the user in many different forms, such as noise, melodies, voices or even a song. The sense of sound is the oldest and most primal mechanism in formulating a relation with a space. The acoustic character of a space feeds into our perception and sensory experience (Reinhardt, 2018). Acoustic performance depends on the quality and character of sound propagation as a function of both overall spatial volume and surface properties, which combine to affect the spoken word or sound: through the overall shape (or macro-geometry) of space, and the character of its surface finishes (or micro-geometry). Sound as a spatial/architectural element has dynamic transient qualities that our non-native mode of spatial representation that has left us ill-equipped to design for auditory perception (Mani, n.d.).

Varying sound in space

A space can have a wide spectrum of sounds that are generated either due to human intervention or through the spatial quality. It is very interesting to understand these sound sources and cull the less important ones for sensory pleasure. In spaces designed for temporal art or sports, such as concert halls, stadiums or theatres, the sound of the space needs to be precise to the performance type. An overall geometry of space impact the sound behaviour, but so can micro characteristics, patterns, and surface conditions. The scattering of sound, when reflected by a surface, can be a desirable characteristic in the acoustic treatment of spaces, and is achieved through patterns (Trevor J. Cox & DÁntonio, 2004). The acoustic surfaces provided to modify the sound should function as a mediator for transforming the generated noise into desired sound. These surfaces can be entrusted with multiple vital acoustical properties that dictate the sound performance and determine the overall sound quality (Krymsky, 2011). Traditionally the design of these surfaces is static, whereas the generated sound is constantly changing. As a result, these surfaces are not capable of adapting and responding to various changes they are exposed to.

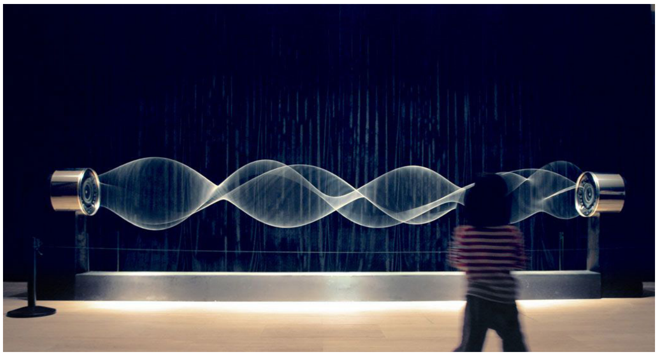


Figure 1.1 : Visual sound wave (Daniel Palacios)

Digital intervention

With the advent of acoustic technology and detailed analysis of sound, it is possible to design a space in ways to improve the acoustic experience of the space. By integrating the design and analysis of various fields around the digital technologies of modelling and simulation, the architect's and engineer's roles are increasingly being integrated from the earliest design stages (Kolarevic, 2005).

Environmentally responsive surfaces

Responsive facades are gaining popularity in the field of architecture. They actively adapt their behaviour over time in response to changing environmental conditions and performance requirements (Moloney, 2011). Initiation of responsive façade systems was to provide sustainable solutions in a building triggered by environmental stimuli. Studies have shown that such additions have 40-60% improvement rate in the efficiency of the building systems in comparison to static facades and surfaces (Mahmoud, Dewidar, Mohamed, & Ahmed, 2010). The focus was to provide visual and thermal comfort to the building occupants (Matin, Eydgahi, & Shyu, 2017). This research focuses on measuring the effect of responsive surfaces on auditory comfort of building users.

PROBLEM STATEMENT

There are different types of sounds prevalent in a space which require different acoustical treatments to provide a vivid acoustical experience. The acoustical systems are usually designed to tackle certain parameters that affect the acoustics of a space in a limited manner. These systems become obsolete if the functionality or usage of space changes. For instance, in theatre and performance spaces, the need for reflective surfaces is more as compared to libraries where absorptive surfaces play a dominant role. But in stadiums, it is important to keep the sound pressure levels in check while at the same time maintaining a vibrant acoustical environment for enhanced user experience. This multi-dimensional approach creates a need for a smart responsive surface that provides a right blend of reflection and absorption of sound. Thus, there is a need for an adaptable acoustic ecosystem that can respond to the sonic environment and improve the acoustic performance in a space.

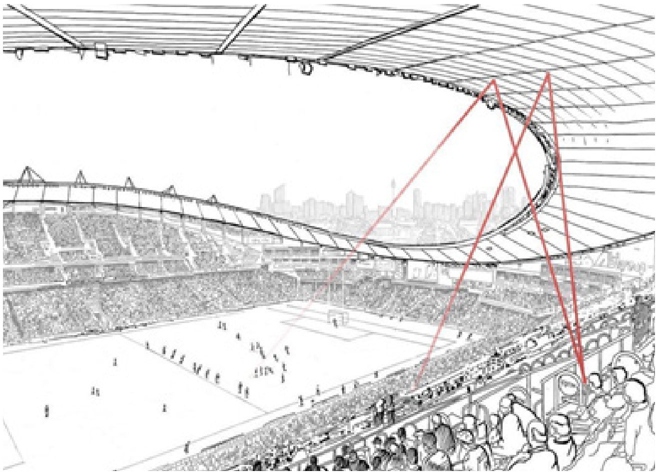


Figure 1.2 : Concept idea

Acoustics in stadiums

The atmosphere in a live game at a sports venue has a major impact on its surroundings, especially if the stadium is situated in a dense urban neighbourhood. This in turn can be used to have a positive impact on both players on the pitch and the spectators in the stands. Various techniques and approaches in the field of acoustic engineering are being applied to improve the game atmosphere. Even the design of the stadiums has an influence to improve the acoustics.

The design for new generation stadiums has an inclusive approach to acoustics wherein a lot of factors, starting from the size of the stadium to the materiality is taken into consideration. As the sound energy diminishes with travel distance, in a smaller size stadium it is easier to manipulate this noise to a great extent. This can also be achieved by having reflective surfaces in the stands for reflecting the noise back into the crowd or towards the players. It is also

Figure 1.3 : Sound waves in a stadium (Daftardar, 2016b)

known in stadium acoustics to increase the reverberations by using materials like wood and metal. This allows for sound to reverberate and travel through material enabling sound to be heard throughout the stadium. Another major design approach is to have an extended roof canopy over the spectators for better reflection of soundwaves (Daftardar, 2016a).

The new stadiums being designed are getting better in controlling the game atmosphere and thus improving the user experience for spectators inside the stadium and reducing the noise pollution for urban dwellers outside the stadiums. One such case study is of the Al Bayt stadium which is currently in construction for the 2022 FIFA world cup to be held in Qatar. The design takes inspiration from a tent like structure creating convex surfaces on the inside for better sound reflection and a fully controlled environment to prevent noise from escaping the stadium bounds. There is also a consideration on maintaining desired decibel levels during a game for ultimate user experience. In conclusion, factors such as the size and shape of the stadium and its roof canopy, plenty of reflective surfaces and optimum absorptive surface to control the decibel levels, need to be applied in the right balance to form a pleasant experience for the users.

Figure 1.4 : Al Bayt stadium, Qatar (AS+P architects)

RESEARCH OBJECTIVE

The aim of this research is to investigate whether responsive facades are feasible enough in improving the acoustics of a space. The intent is also to explore the strategies for designing kinetic facades which respond to sound though kinetic pattern and composition? The goal of this exploration is to establish early design processes, which are effective as alternative solutions to isolate design problems associated with kinetic façade design that respond to environmental factors, such as sound. It is also important to check the impact on the acoustic performance with testing the designed prototype in a controlled environment for validation of concept.

RESEARCH QUESTION

In reflection to the problems previously illustrated, there is a need in question for a dynamic acoustic surface that can adapt to the changing acoustic demands of a live stadium and add to the overall sound quality by improving the user experience. This hypothesis thus gives rise to the main research question that is:

> *" What is the design and operational feasibility of sound responsive surfaces? Can they have a noticeable impact on the acoustic performance in a space? "*

Sub Questions

The main question can be broken into sub questions for adressing the problem in detail. This can be only answered by first looking into the sub problems related to it.

ACOUSTICS & PROCESSING | How to read the sound source and which acoustic properties should affect the movement of panels?

PATTERN LANGUAGE | What are the different patterns and techniques to generate responsive surfaces?

DESIGN FOR INTERACTION | How to make the surface move effectively in response to the sound? The movement must be deliberate and controlled for optimum results.

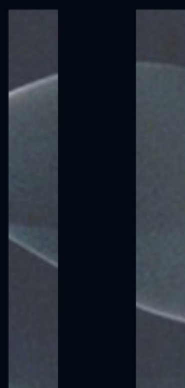
RESPONSE & FEEDBACK | Will the outcome of said design approach have a significant impact on the acoustic performance?

OUTCOME

The goal is to realize a physical working prototype which can be test for proof of concept and responsive alertness to real time sound data. So, the final output will be to enhance the user experience by developing a sound responsive skin triggered with real time sound and study its impact on the acoustic performance in an open space

THE 12TH MAN

Image source : Author



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RESEARCH METHOD

SOUND BENDIIING PROJECT

- **READ** | Receiving & measuring sound source
- **CONVERT** | Data extraction from sound
- **FEEDBACK** | Send sound information to panel
- **ACTUATE** | Change the pattern based on the info
- **TEST** | Testing the impcact on acoustic performance

LITERATURE REVIEW

The topics that will govern the research as listed below will be studied in detail and various existing literature relating to the subject will be reviewed for a better understanding and execution of this project.
Research topics:

- Acoustics in stadiums
- Theory of Acoustics
- Motion in acoustics | State of the art
- Pattern language
- Kinetic design & development
- Response and Actuation

RESEARCH FRAMEWORK

After undertaking investigation and research, the approach will be to produce a mock-up surface based on the thumb rules formulated according to the discussed acoustic principles. Using this as the focus, the whole simulation and test situation will be designed around it. The basic guidelines listed for acoustical surface development in stadiums are kept in consideration. This will formalize the process within a defined framework and further design developments and research will take place within the boundary conditions.

Reflection in action

One aspect of the research is focused on evaluating the performance of responsive surfaces through digital and analogue prototyping, which involves the notion of thing and doing. Research by design allows for a continuous feedback loop for both research and design. As described by Downton, "designing is an ability which requires and utilizes both doing and reflexive thought about that doing. Part of the process is constantly concerned with reflecting on the process of improving it" (Downton, 2003). By conducting this research with a project-based approach, specificities of the outcome can be achieved. The main investigation will comprise of three main process namely:

1. Identifying kinetic patterns for responsive surfaces
2. Evaluating kinetic patterns for acoustic conditions
3. Full-scale digital and physical prototyping of the responsive surface

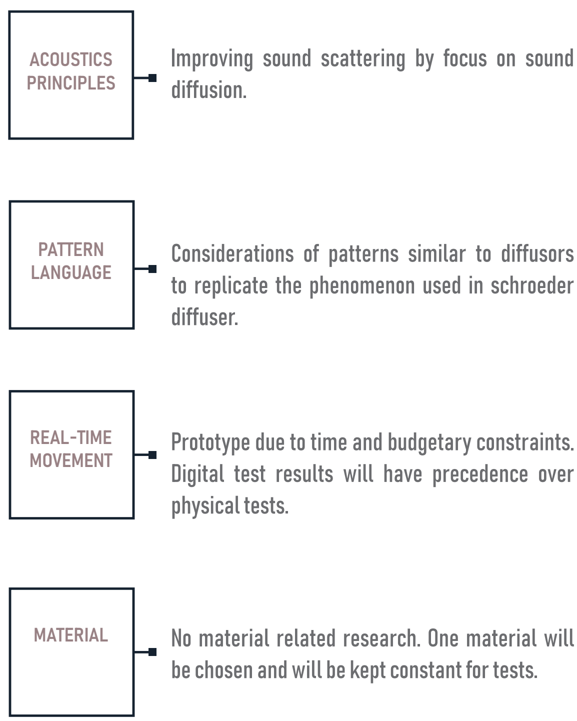
Boundary conditions

For a good research, it is vital to set some constraints to be able to focus on a given topic and provide enough reasoning relating to the main topic. The following boundaries are set to direct the research into the desired outcome.

ACOUSTICS | A basic knowledge in the field of acoustics is required to be aware of the terminology and principles that will be helpful in conducting the research. The focus will be on diffusion of sound and will be studied in detail with the various types of diffusers. No material related research will be conducted. The focus will remain on the pattern movement and its direct impact on the result without any material intervention.
PATTERN LANGUAGE | There is a wide possibility of dynamic and responsive patterns, but here the focus will be restricted to patterns that work in similarity to a Schroeder diffusor.

REAL TIME MOVEMENT & PROTOTYPING | As the idea is to test the impact of real time sound, due to budget and time restraints only a small part of the design will be prototyped to understand the working. The detailed design and effect of large-scale implementation will only be tested in digital simulation models.

MATERIALS | There wont be research for the material type. A particular material will be considered for the entire experiment.



Research Assessment

The validation of concept is necessary. This will be proved by testing the prototypes both in digital and physical setup. Both the responsive movement due to sound and their impact on acoustic quality will be tested separately as well. After analysing, a comparative inference will be presented. The conclusion of the research is critical for completing the project. It must entail all the ingenuities and shortcomings during the process and should be presented in a lucid manner for further referencing. For this, a closed setup is digitally modelled which will be used eventually.

DESIGN ASSIGNMENT

The project will undergo two separate streams. The first one that is the surface, will involve formulating a pattern and then configuring the movement system to the surface. The second one will deal about the sound from the source, as to how to read it and convert it into information that can help trigger the movement of the surface. Together, they will generate a response from the sound source on the surface. This response should have an impact on the acoustic performance as well. The same effect will be tested for validation of concept. The flow chart below explains it clearly.

RELEVANCE

Societal

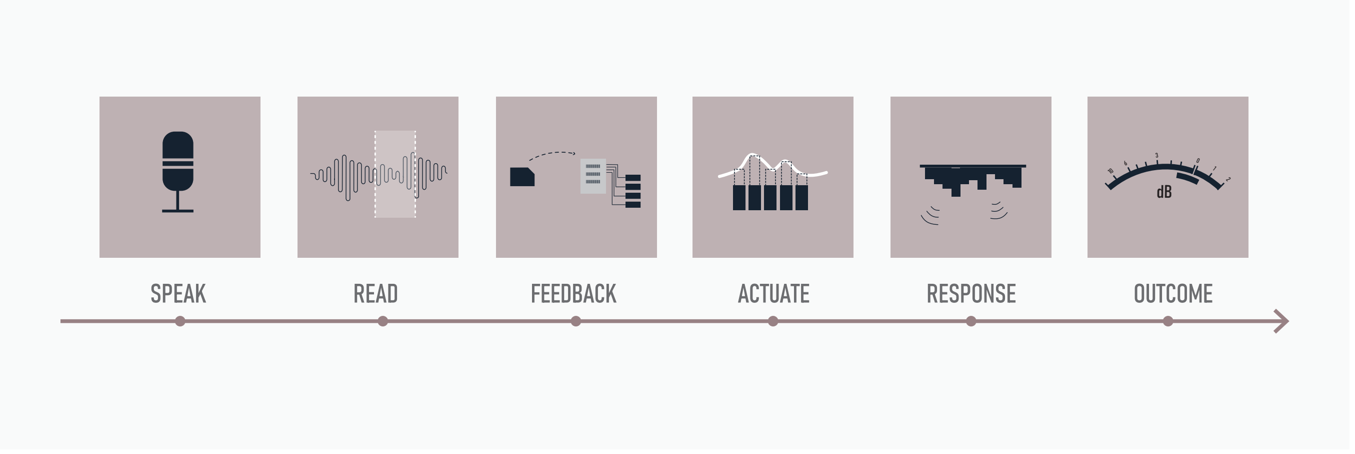
As hearing is one of the most critical senses for humans, it is important to find solutions to protect it from the loud noises inside a live stadium. Noise can have damaging effects that most individuals are unaware about. At the same time, the noise that escapes outside the stadium adds to the city's noise pollution. It is indeed a challenge to take up this problem where the stadium experience must be maintained while lowering the sound pressure level to the bearable levels. Responsive surfaces behave as a stimulus for interaction between individuals having a positive effect on their sociological behaviour.

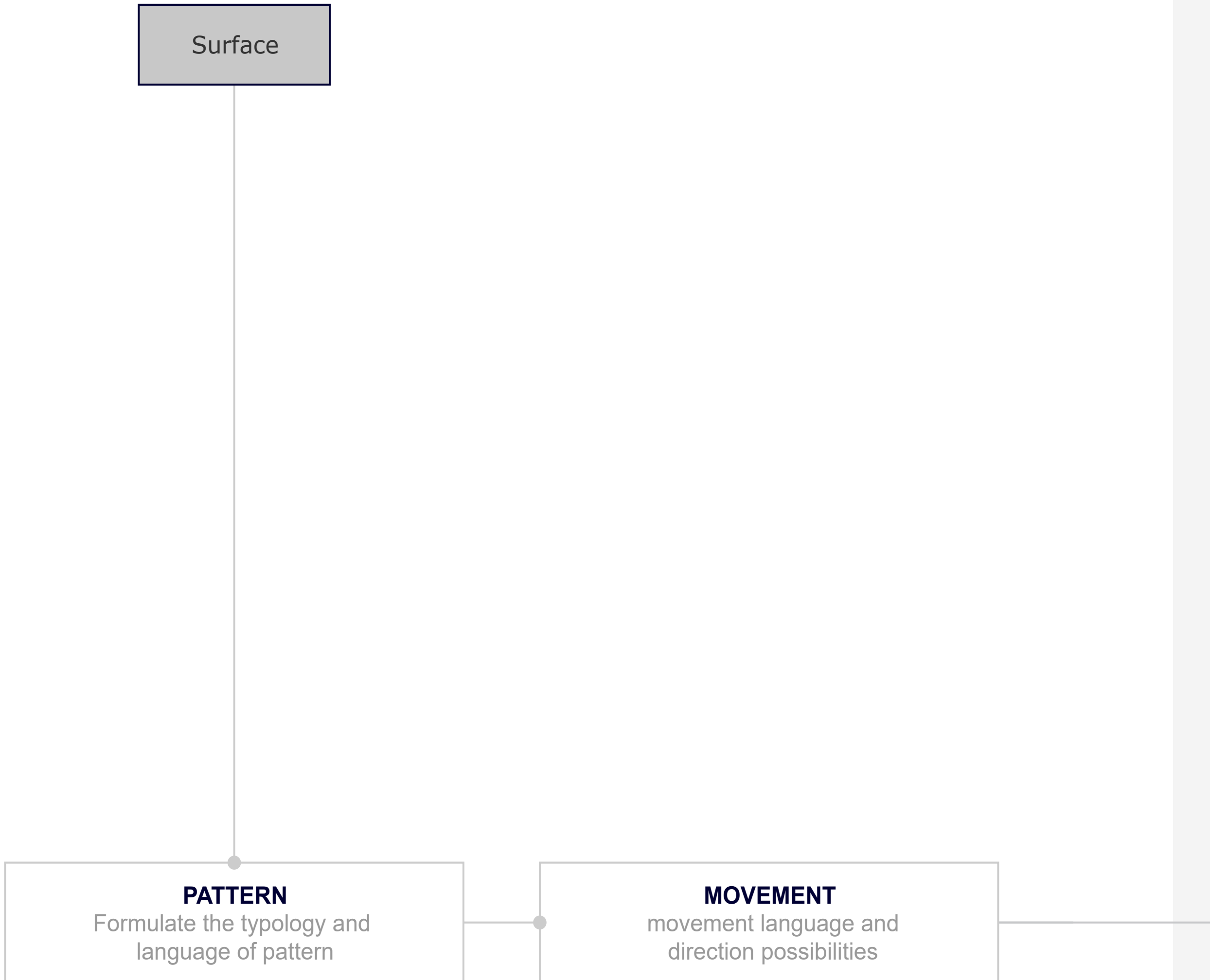
Scientific

Acoustics are rarely considered while designing a space. The state of research in sound responsive kinetic surfaces is still in its nascent stage but holds a huge potential in improving the acoustic performance in a space. Movement of surface in response to sound can be imagined but there is a need to have a controlled responsive movement, to be able to have quantifiable effect on the acoustic performance as well in addition to the positive sensory effects it can have on human beings. With some research already happening, there is a possibility of further exploration to improve the idea in terms of simplicity of design and ease of operations. Responsive panels can be used in various spaces to attain the required acoustic experience. This research might serve as a reference for the state of research in the domain of sound responsive surfaces.

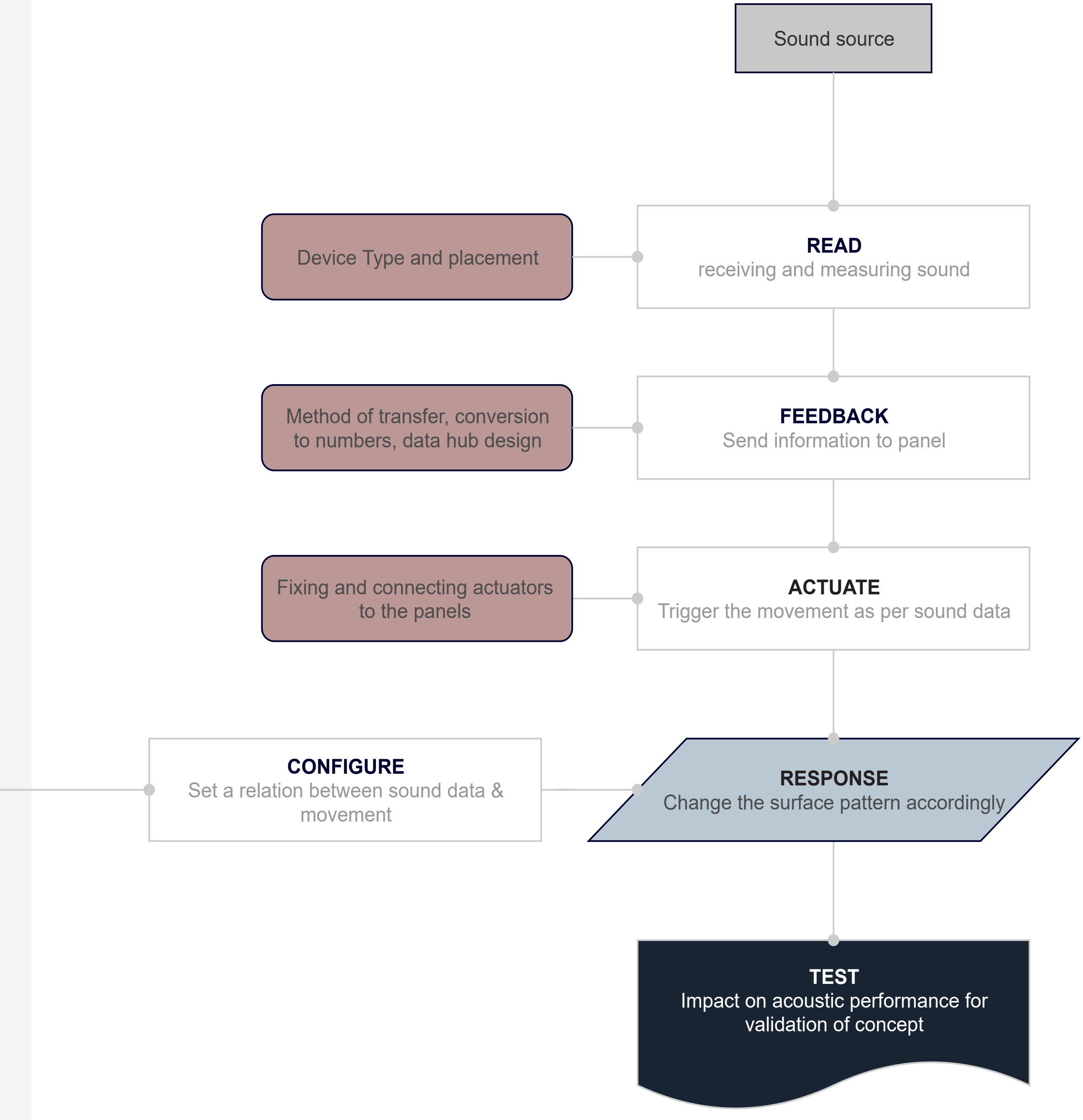
TU Delft programme

Responsive architecture is a growing field and the architectural engineering department incorporates a large part of it in their study curriculum for building technology. Design informatics chair bridges the gap between buildings and computational methods. The course Bucky lab also encourages the idea of responsive design to improve building condition. With research already happening for improving acoustics using computational tools, this research can contribute to it. Merging interactive design with acoustics gives a possibility for improving architecture and the way it is perceived.



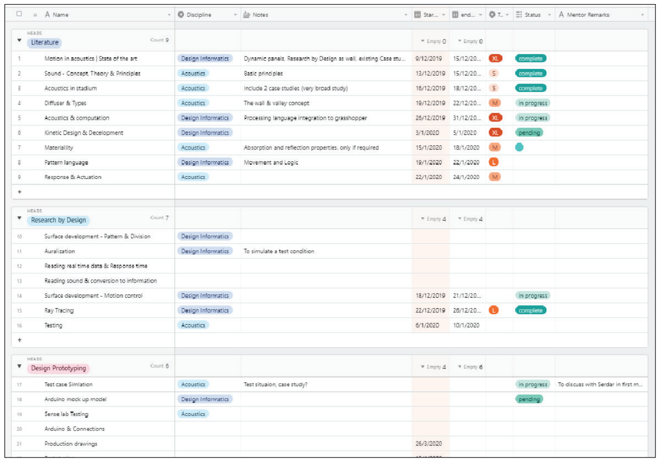


RESEARCH FLOW

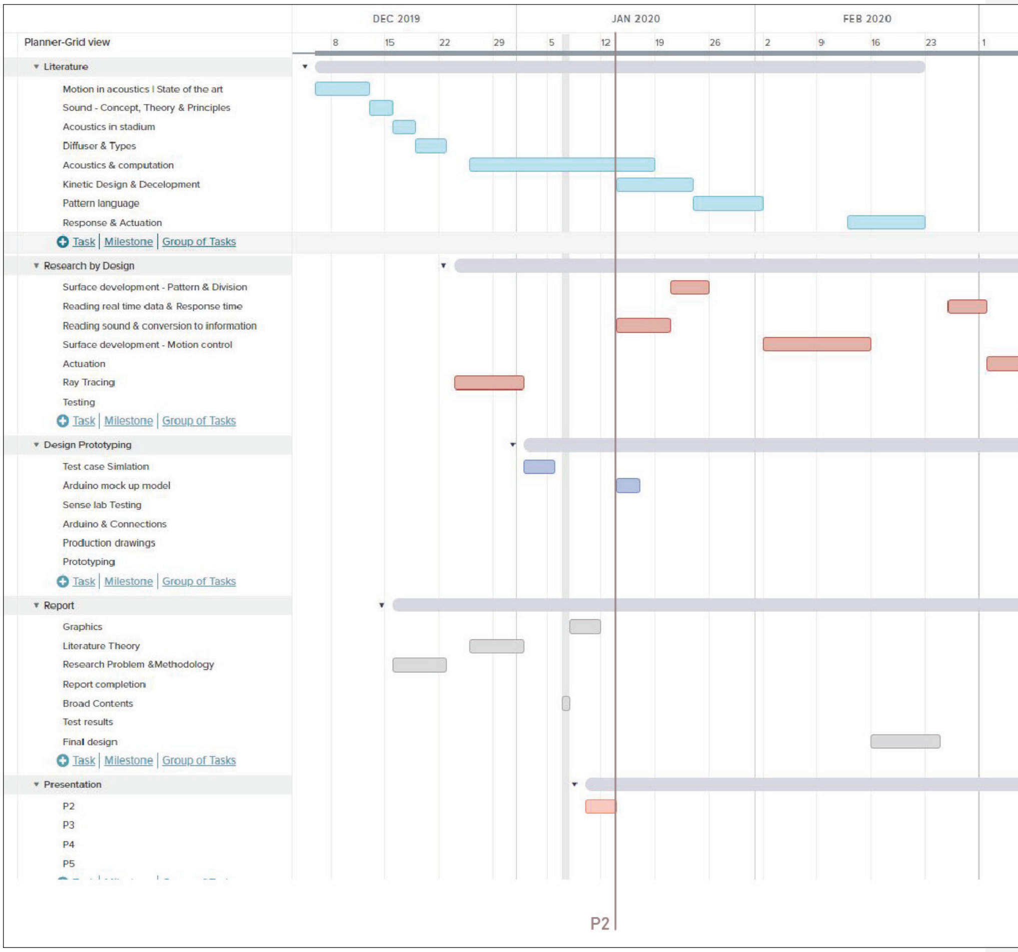

Sound source
READ
receiving and measuring sound
Device Type and placement
FEEDBACK
Send information to panel
Method of transfer, conversion to numbers, data hub design
ACTUATE
Trigger the movement as per sound data
Fixing and connecting actuators to the panels
CONFIGURE
Set a relation between sound data & movement
RESPONSE
Change the surface pattern accordingly
TEST
Impact on acoustic performance for validation of concept

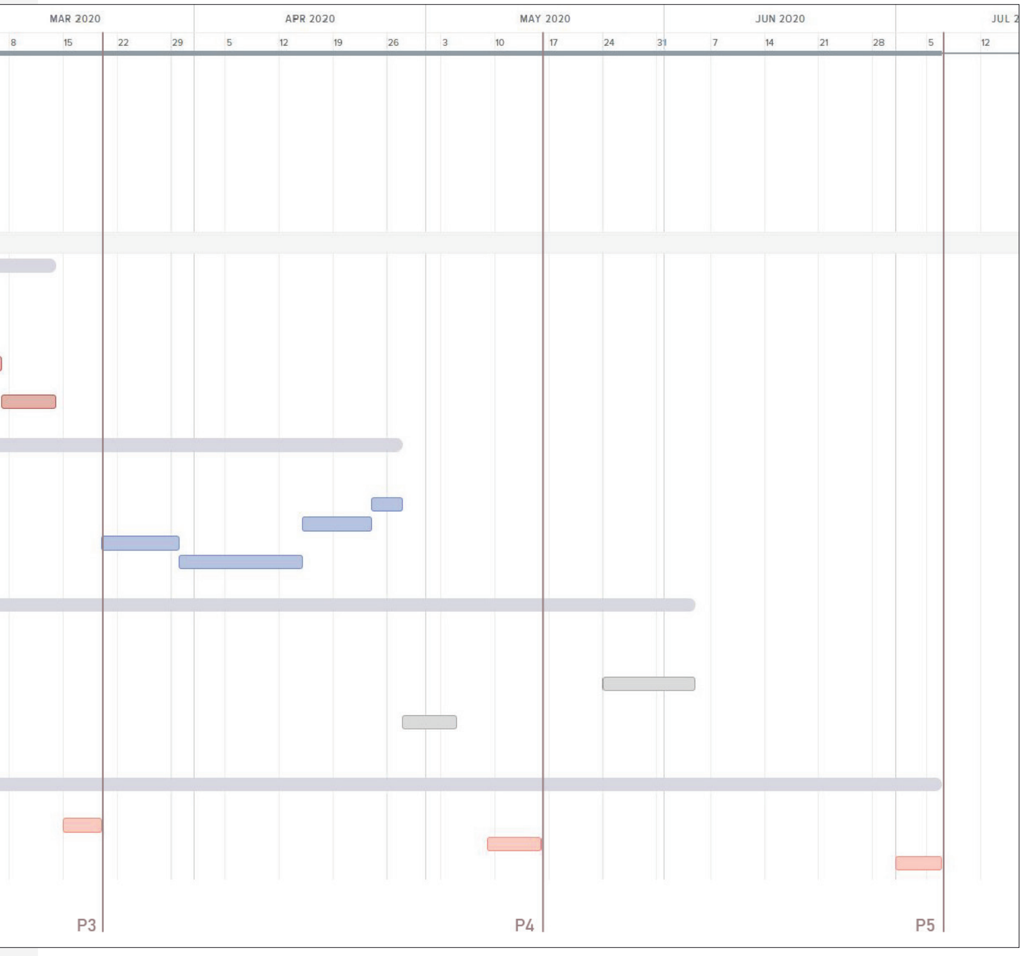
TIME PLANNING

The research as categorized into broader heads must be planned to ensure right workflow and time management. For this, an online task management tool is used, called Airtable. This tool helps in segregating the tasks while assigning them into subject categories, time required, target date, status and so on. It is constantly updated with tasks done and new tasks required to get an idea of progress. A Gantt chart is prepared to check the workflow in timeline and stay up to date for the thesis project.



	Name	Discipline	Notes	Star...	end...	T..	Status	Mentor Remarks
	HEADS Literature Count 9			Empty 0	Empty 0			
1	Motion in acoustics | State of the art	Design Informatics	Dynamic panels, Research by Design as well, existing Case stu...	9/12/2019	15/12/20...	XL	complete	
2	Sound - Concept, Theory & Principles	Acoustics	Basic principles	13/12/2019	15/12/20...	S	complete	
3	Acoustics in stadium	Acoustics	Include 2 case studies (very broad study)	16/12/2019	18/12/20...	S	complete	
4	Diffuser & Types	Acoustics	The wall & valley concept	19/12/2019	22/12/20...	M	in progress	
5	Acoustics & computation	Design Informatics	Processing language integration to grasshopper	26/12/2019	31/12/20...	XL	in progress	
6	Kinetic Design & Decelopment	Design Informatics		3/1/2020	5/1/2020	XL	pending	
7	Materialilty	Acoustics	Absorption and reflection properties, only if required	15/1/2020	18/1/2020	M		
8	Pattern language	Design Informatics	Movement and Logic	19/1/2020	22/1/2020	L		
9	Response & Actuation	Acoustics		22/1/2020	24/1/2020	M		
	HEADS Research by Design Count 7			Empty 4	Empty 4			
10	Surface development - Pattern & Division	Design Informatics						
11	Auralization	Design Informatics	To simulate a test condition					
12	Reading real time data & Response time							
13	Reading sound & conversion to information							
14	Surface development - Motion control	Design Informatics		18/12/2019	21/12/20...		in progress	
15	Ray Tracing	Design Informatics		22/12/2019	26/12/20...	L	complete	
16	Testing	Acoustics		6/1/2020	10/1/2020			
	HEADS Design Prototyping Count 6			Empty 4	Empty 6			
17	Test case Simlation	Acoustics	Test situaion, case study?				in progress	To discuss with Serdar in first m...
18	Arduino mock up model	Design Informatics					pending	
19	Sense lab Testing	Acoustics						
20	Arduino & Connections							
21	Production drawings			26/3/2020				

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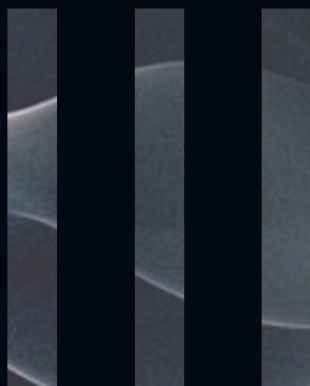

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THEORY OF ACOUSTICS

Sound is a phenomenon of motion due to the vibration of air molecules and other materials that are perceptible to the human ear (Bruel & Kjaer, 1984). It comprises waves generated from a source and their indirect reflections happening due to the environment around the source and receiver. In a closed space, direct and reflected soundwaves are essential in evaluating the quality of sound, also termed as the acoustics of a space. The primary objective is to manipulate the reflections to alter the sound propagation in a space and the way it is perceived (Trevor J. Cox & DÁntonio, 2004). To be able to alter the way sound propagates in a space, an understanding of the basic principles of acoustics is important. This will bring light to the factors responsible for specific acoustic qualities and their respective treatment methods.

Acoustics can be broadly understood by looking into its nature or form, how it is measured and how it propagates in a space. The intangible nature of sound has to be understood by representing the movement of sound by waves and rays directed in a particular direction. The sound when reaches the person is percieved in a different way than to what it received at an electronic receiver device. Thus, its is necessary to be clear as to what properties of sound will effect the the user experience and the corrections have to be made accordingly.

PRINCIPLES OF ACOUSTICS

SOUND WAVES | The longitudinal pressure vibrations generated in air, water or other materials are known as the sound waves. The number of complete vibrations occurring in a second are termed as the frequency of sound. Frequency is subdivided into power spectrums and is measured in Hertz (Hz). The audible range for human beings extends from 20Hz to 20,000 Hz (20 kHz). As an example, a bass drum has a low frequency while a whistle comes in the range of high frequency. Frequencies above or below the mentioned threshold are inaudible to human ears. The sound wave propagates in air from the source to the receiver and is described by its wavelength and amplitude, which correlates to perceived pitch and loudness, respectively. Knowing the speed of sound and a given frequency, the wavelength can be calculated using this formula.

$$f = \frac{c}{\lambda}$$

f = frequency [Hz]
λ = wavelength [m]
c = propogation speed of sound = 343 m s $^{-1}$

A standardized system of octave bands internationally applicable is used for measuring the sound, every band spectrum is represented by their middle frequency: in order 63 Hz, 125 Hz, 250 Hz, 500 Hz, and so on. Measurements of sound can thus be precisely categorised into different frequency spectrums (Linden & Zeegers, 2006). The image below shows the corresponding wavelength to the frequency of sound.

SOUND PRESSURE LEVEL | The sound is measured for its size or amplitude of the pressure fluctuations. The small pressure variations relative to the atmospheric air pressure is known as the sound pressure. Human ears can perceive an enormously wide range of pressure variations starting from as low as an amplitude of 20 millionths of a Pascal (20mPa) to a million times higher (Bruel & Kjaer, 1984). To avoid managing such a high range of numbers, another logarithmic scale i.e., the sound pressure level is used. The following expression is used to determine the sound pressure level.

$$L_p = 10 \log \left(\frac{p^2_{eff}}{p^2_o} \right)$$

L_p = sound pressure level [dB]
p_{eff} = effective sound pressure [Pa]
p_o = reference sound pressure = 2 · 10-5 Pa

Decibel (dB) is the unit of sound pressure level as sound power and intensity is rather expressed logarithmically. Decibel value is not additive. Hence, the SPL values need to be converted to actual pressure before addition.

$$L_{p;tot} = 10 \log \left(10 \quad + 10^{\frac{p2}{10}} + \dots \right)$$

$L_{p;tot}$ = resulting sound pressure level [dB]
L_1 = SPL of source 1 [dB]
L_{p2} = SPL of source 2 [dB]

Two same sound pressure levels result in an increase of 3 dB. The image below illustrates the typical sound pressure level in dB and Pa for numerous recognisable sounds existing in environment.

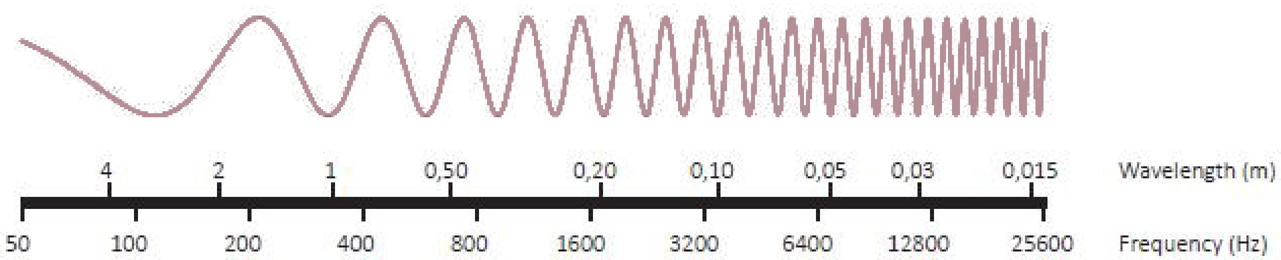


Figure 3.1 : Wavelength vs. frequency (Bruel & Kjaer, 1984)

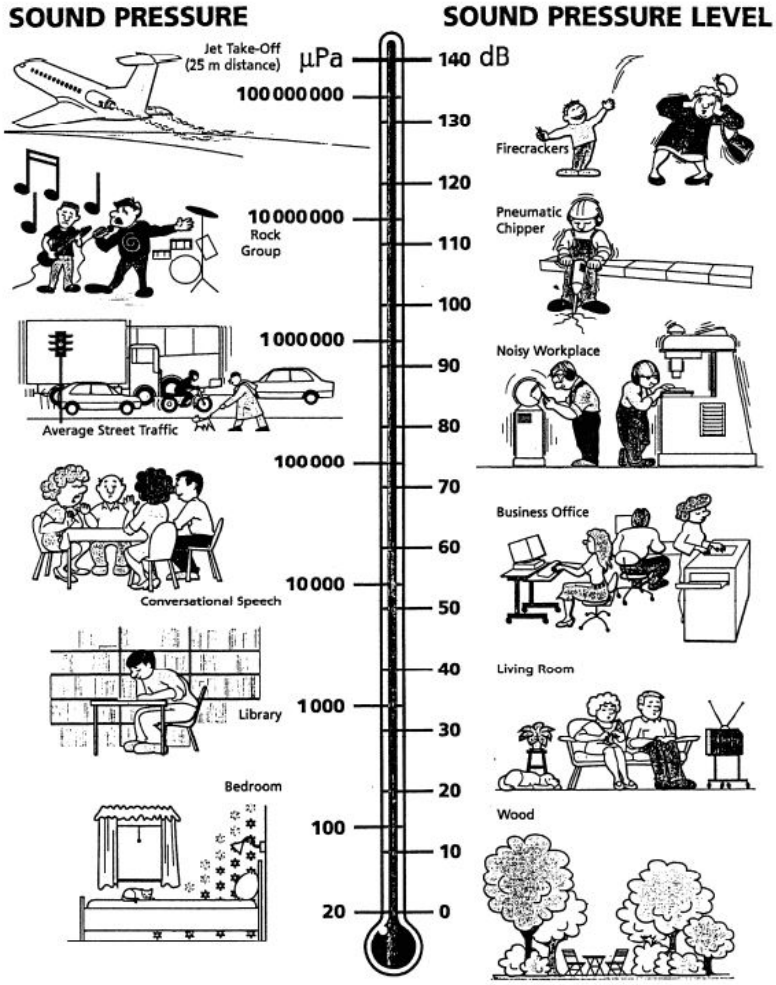


Figure 3.2 : Typical sound pressure levels (Bruel & Kjaer, 1984)

REVERBERATION TIME | The time taken by sound pressure level to decay by 60 dB after the source is silenced, is known as the reverberation time (RT_{60}). It is a measure of sound absorption level present in a space (Linden & Zeegers, 2006). Reverberation time is considered as one of the well-known aspects for measuring the sound quality of a space. However, as reverberation is a function of frequency, to get a more detailed result, sound with varying frequencies is required.

Sabine's equation :

$$T = \frac{55{,}3\,V}{c_o\,A} \approx \frac{1}{6} \cdot \frac{V}{A}$$

T = reverberation time [s]
V = volume of the room [m^3]
c = propogation speed of sound = 343 m s^{-1}
A = total amount of absorption [m² sabin]

Eyring's definition (Image source model):

$$T = -\frac{55{,}3\,V}{c_o\,S_{tot}\,\ln(1-\bar{\alpha})} \approx -\frac{1}{6} \cdot \frac{V}{S_{tot}\,\ln(1-\bar{\alpha})}$$

$\bar{\alpha}$ = average absorption coefficient [-]
S_{tot} = total surface area in room [m^2]

SOUND PROPAGATION

Once triggered from the source, sound moves in all directions but with different intensity depending on the directional field. When it strikes a surface obstructing its path, it is either transmitted, absorbed, or reflected in turn affecting the sound energy. This purely depends on the surface's acoustic properties. The shape of the surface also affects the reflection where a flat surface gives a specular reflection while a diffused surface scatters the reflected sound.

Distortion in acoustics can be controlled with diffusers and absorberws depending on the type and functionality of a space. It is very difficult to judge the better treatment out of the two as it is situation based and the other acoustic factors desired. Both absorbers and diffusers have a role to play in good acoustic design. They have complementary functions, which means that when used appropriately, better acoustics can be achieved.

Absorption

Absorption occurs when sound waves strike an absorptive material or surface resulting in reduction of sound energy. This energy absorbed is transmitted through the material where some of it gets converted into heat. Different materials have different absorption capacity represented by absorption coefficients, for example hard solid surfaces like concrete, have a low absorption coefficient compared to thick fibrous surfaces like glass wool. A room with a lot of background noise and reverberation can be treated using absorptive surfaces. The right amount of reverberation has a major impact on the quality of design for most rooms, whether the aim is to make the room sound vibrant for music, to make speech intelligibility reduce the noise levels to simply make the room sound pleasant (Jacobsen, Poulsen, & Rindel, 2018).

Diffusion

It is defined as the movement of a sound wave from an area of high concentration to a low concentration area. It is the scattering of energy and reducing the sense of localization. A good diffusor not only reflects the sound waves but evenly distributes them in all directions. Reflecting a sound wave in one or two directions is not enough, so the diffusors help in splitting the sound waves into multiple random even paths. A proper diffuser also impacts the time domain. If a sound wave is reflected into multiple directions evenly, the length of time these various waves require, will also get affected and change for each of one of them differently. In the realm of sound, as distance is proportional to time, by scattering the sound the reflected waves take different paths which will have varying intensities. These waves are less intense than the sound waves initially coming from the source, thus with diffusion it is possible to change three domains of a sound that is direction, time, and intensity.

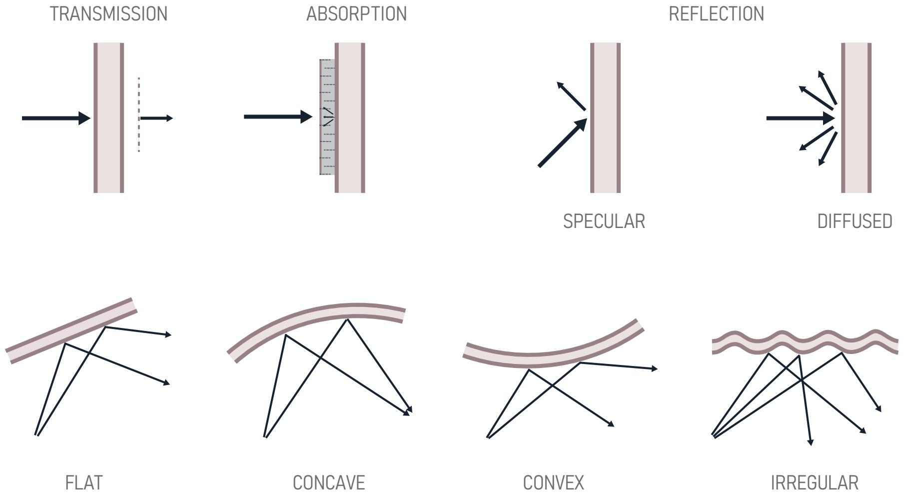


Figure 3.3 : Sound interaction with surface

A diffuser obfuscates the sound so that when that sound hits the wall, it reflects it in such a way that when it comes back to your ears it no longer has directional cues and the brain instead of processing it ignores it considering it as background noise. Diffusion makes it much more difficult for human ears and brain to exactly determine where the sound is coming from and thus the sense of localization is reduced, tricking the brain into thinking the space is larger than what it is and yields a more spacious sound. Random depths in diffusion do not generate even random reflections. The width, height spacing, and patterns of the well are evenly calculated to make sure they generate a smooth, even yet random scattering of the waves over a 180-degree angle. Without this calculated spacing, reflected sound waves will interfere with the direct sound waves creating a comb filtering effect which rather than reaping benefits will provide more issues with the frequency response.

Schroeder Diffusor

The phase grating diffuser commonly known as the Schroeder diffusor is one of the most significant developments in the design of diffusers. This diffuser offers the possibility of optimizing the diffusion distinctively just with adopting a few simple design equations (Trevor J. Cox & DÁntonio, 2004).

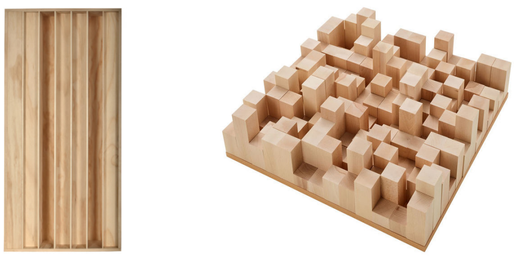


Figure 3.4 : Schroeder Diffusers: linear (1D) and skyline (2D) (ATS Acoustic Diffuser, n.d.)

The figure above shows a typical 1D Schroeder diffusor. It consists of a series of wells having the same width but different depths. It uses thin fin-like surfaces to separate the wells. The depth is determined using quadratic residue sequence.

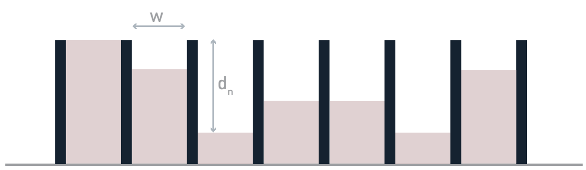


Figure 3.5 : Typical P7 QRD diffuser (Author)

Thumb Rules

Based on the studies of existing diffusor typologies and the theory behind it given by Cox and DÁntonio, it is possible to deduce some thumb rules for the design of surface having an affective scattering and absorption effect. As the focus is on human auditory range, the following rules apply in the defined frequency range of 125Hz to 4000 Hz (Vomhof et al., n.d.) :

1. The surface/panel depth should be around twice the width size for a good diffusion of the lower range frequencies. The value is derived from a fourth of the wavelength of the lowest frequency.
2. In case of higher range frequencies, the surface/panel should be discretized in width with a maximum step size of 10cm. Since we are dealing with mid-range frequencies, the block width could be bigger. This dimension is in correlation with half wavelength of the highest frequency.
3. In addition, the discretization pattern adopted should have an aperiodic repetition for enhanced scattering of the reflected sound waves.

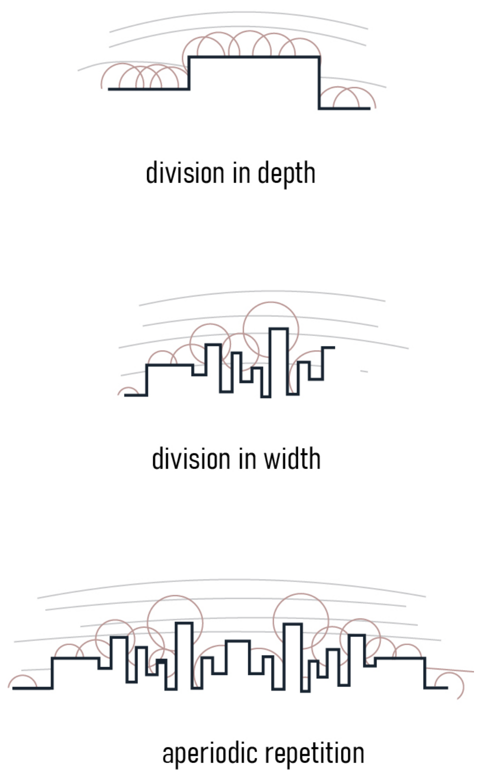


Figure 3.6 : Thumb rules for sound scattering surface (Vomhof et al., n.d.)

HUMAN VOICE AS SOUND SOURCE

One of the most critical sound sources in a stadium or a lecture room is the human noise. Human voice is considered as an acoustic signal whose character and sound varies from person to person. It can be defined using two characteristics i.e., sound level and speech level. The vocal effort exerted by an individual varies from a mellow whisper to loud shouting. Thus, it is difficult to assign a fixed number to speech level. The table below lists down the range of average A-weighted speech levels depending on the sound level of the speaker in relation to the listening distance (DPA Microphones, 2016). Looking at the table it can be deduced that there is a difference of 20 dB between normal speech and shouting.

Although the spectrum of speech includes a wide portion of the complete audible frequency spectrum ranging from roughly 150 Hz to 6000 Hz, the fundamental frequency of voice speech of a typical adult male ranges from 85-180Hz, whereas in adult females it is one octave higher i.e.; 165 to 255 HZ (DPA Microphones, 2016).

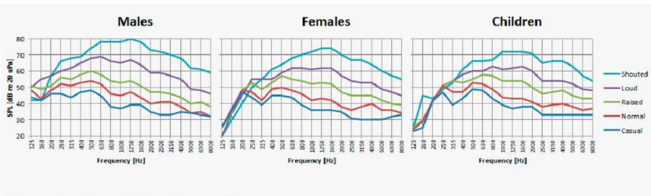


Figure 3.7 : Voice frequency spectrum of human beings (DPA Microphones, 2016)

Other sources present are the use of speakers, amplifiers, and electro acoustic devices to increase the decibel levels. The design of these systems is usually 10-12 dB louder for it to be recognizable over crowd noise (Navvab, Heilmann, & Sulisz, 2009). With these noise sources the stadiums can go as loud as 115dB which is unfavourable for human hearing and can cause damaging effects. This emanates the need for a balanced acoustic system for the ultimate user experience inside stadiums.

DIGITAL SIMULATION

Methods & tools

Digital tools provide for an early insight into the design process and are reliable in conducting an evaluative analysis on the acoustic performance of a space. Simulation tools have been firmly recognized as a regulating factor in the early design stages of buildings (Krymsky, 2011). Early simulation progresses the design process, boosting efficiency and with a provision of comparative study among the design variants, ensuring a mature design output. Simulation forecast the design consequences, being a catalyst in effective design process (Loukissas, 2012). Acoustic software such as CATT acoustics, Odeon and Pachyderm have been in use for detailed acoustic calculations. These require the architects to have a technical knowledge about the field.

Parametric acoustic design

Predicting acoustic consequences on the geometric models allows for acoustical improvements in a space. New methods to achieve explicit acoustic conditions for architectural design and spaces need to be developed. Complex acoustic software takes time and detailed drawings & models for getting simulation results. At the detailed development stage, it is difficult to amend the design, or make big

Speech level [dB re 20 µPa]

Listening distance [m]	Normal	Raised	Loud	Shout
0.25	70	76	82	88
0.5	65	71	77	83
1.0	58	64	70	76
1.5	55	61	67	73
2.0	52	58	64	70
3.0	50	56	62	68
5.0	45	51	57	63

geometrical changes. Due to this, only a few parameters like material properties and insulation can be tweaked. However, with a simple calculation tool, the architects can be made aware of acoustic phenomena by incorporating basic acoustic properties into the early stage of design.

There is a limited integration of acoustical testing by architects for both their digital and physical models of concepts designs (Peters, Tamke, Nielsen, Andersen, & Haase, 2011). This research demonstrates and proposes simple and fast calculation tools and solutions that allow the implementation of basic acoustic characteristics into the architectural design solution. The investigation provides a chance to modify a definite architectural surface such as walls, floors, and ceilings. It inculcates sound as a generative parameter for architectural design. The digital tool must respond with dynamic changes in design for quick adaptation and modification of design changes.

Geometrical Setup

In physical sense, a sound propagates by creating directional sound waves aimed at a receiving object/person. For architectural acoustics, this phenomenon is not practically applicable in getting results in a computer simulation. The sound waves are thus, substituted for sound rays. A sound ray is visualized as a straight line originating from a source point and is directed towards either a focused zone or in all directions. These rays carry a small portion of the sound energy to the receiver. The rays tend to interact with the space geometry along their traction path. Geometrical acoustics engages in collecting the travel path of these rays connecting the source and the receiver (Peters, 2007).

Properties such as diffraction, transmission, and interference are ignored. In a ray-based simulation method, wavelength or frequency of sound can add to the complexity in calculations (Rindel, 2000). Geometrical acoustics just offers an estimate of the acoustical environment which is advantageous in early design studies. However, ray tracing is conclusive in giving results when the room size matches the wavelength of sound (Kuttruff, 2009). The studies provide enough evidence to prioritize ray tracing methods for their significantly fast computation time. The results are precise and can be compared to those from wave acoustic theory.

Ray Tracing

For imitation of sound, manifold of rays is emitted from a source point in numerous directions. Each ray transports a percentage of the initial sound energy towards their directional path. Rays confronting the room periphery (mostly walls) face reduction in energy by the physical properties of the colliding surface such as absorption and reflection as described in the previous chapter. Energy carried by a ray reduces over time and with the hits depending on the absorption coefficient of the surfaces it hits.

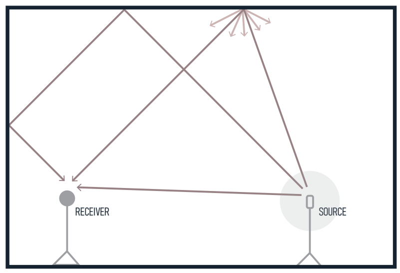


Figure 3.8 : Ray tracing in a closed space (Author)

This process is controlled by the order of incidences. In physical sense, this order is unlimited until the energy in a ray diminishes to zero. In simulations, it is necessary to cap it as the endless run means more computation time. The receivers must have a surface and a volume for the rays to collide with. This collision is recorded and computed to get the required acoustic data.

Image Source : Dennis Foley. acousticfields.com

DESIGN CONSIDERATION

Swift hinge movement
Limited number of actuators & controllers

Sturdy parts to reduce wear & tear
Modular assembly with **simple kit of parts**

Simple operative design
Space buffer in ceiling for movement

IV

t h e

s o u n d

b e n d i n g

p r o j e c t

RESPONSIVENESS

Kinetics is the potential in an object to cause an impact with a mere geometrical change in whole or part. This change is short term and reversible with no bearing on system integrity. (Majed & Alkhayyat, 2013). Buildings are in constant conjunction with influential forces such as time, weather, human beings, and operative functions. These are dynamic in nature and the buildings thus, must be designed using complex systems that can adjust and adapt to these changing demands (Nashaat, 2018).

Responsive architecture is a complex shape-shifting ability of building systems to adapt themselves as a response to with environmental conditions and user activities. It is a reaction to the interaction between nature and artificial systems comprising of intelligent frames, skins and mechanics as illustrated in Figure 9 (Pan & Jeng, 2008).

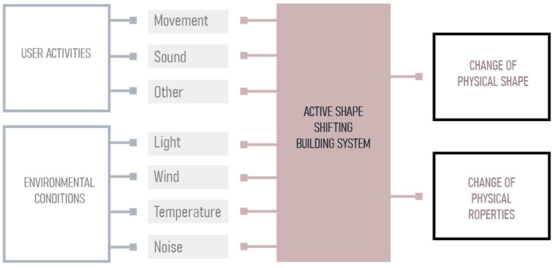


Figure 4.1: Responsive architecture concept

Interaction design is a part of responsive architecture where the users and the building systems communicate. The users act as a stimulus for these built components to respond following the logic of IPO model i.e., input, processing, and output. The design space for interaction can be divided in three following aspects:

1. Sensible spaces
2. Thinker spaces
3. Responsive spaces (Dynamic output)

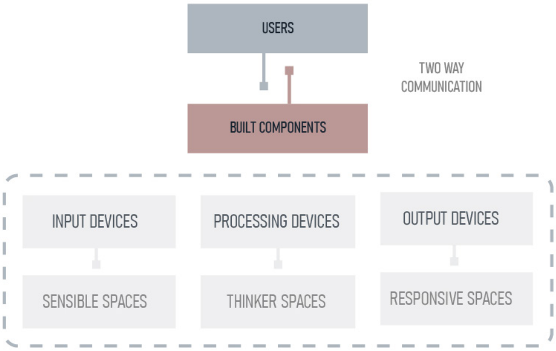


Figure 4.2 : IPO (Input - Processing - Output) model

The above figure explains the working of IPO model in architecture and space design. Application of kinetic surfaces in buildings is gaining popularity to address the issues of dynamic operations and functioning of a building. Some of the recent examples are, the Shanghai art centre designed by Thomas Heatherwick Architects, Al Bahar towers in Abu Dhabi designed by Aedas Architects. The response of these kinetic systems is a result of an intelligent procedure which they programmed for. The intelligent architecture system is a method to monitor and control the buildings based on communication with the user. By incorporating high tech abilities and machine learning, the building systems are controlled to meet user needs such as comfort, productivity, energy saving, high performance, return on investment and lowering life cost. The building systems can range from mechanical, electrical, HVAC, lighting control, acoustics, maintenance, local networking, energy management and much more (Sherbini & Krawczyk, 2004). The Figure 11 below illustrates this concept.

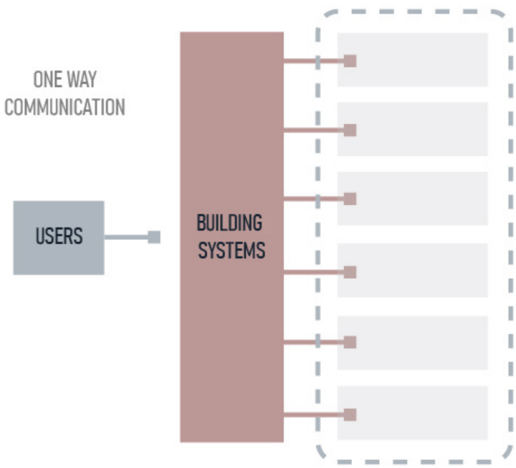
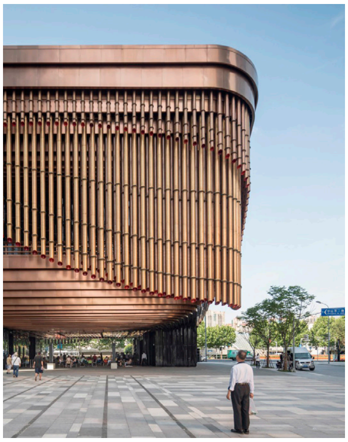


Figure 4.3 : Intelligent building systems

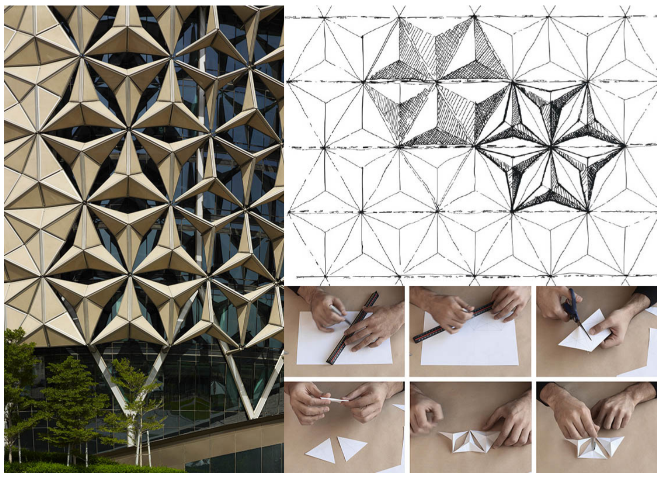
Although, having a kinetic surface comes with its pros and cons. Most of the surface whether on facades or indoor ceilings usually encompasses a complex interaction between various physical components. The facades solve the purpose of sealing the interior from extreme exterior environmental conditions whereas in indoor spaces, the ceilings are used to conceal the electrical and mechanical fixtures necessary for a space. Thus, the mechanical movement of kinetic surfaces need to be designed with these aspects in consideration. There are various types of kinetic structures such as embedded systems, deployable structures but for this exegesis we will focus on dynamic kinetic systems.

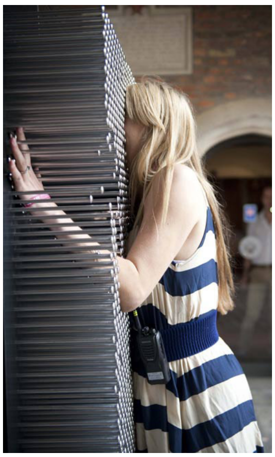
Examples in Architecture

Some of the examples in architecture-built environment where such systems prove to be beneficial in improving the building performance are highlighted below.



In Architecture | Responsive surface are gaining popularity in the field of architecture to allow building to respond to the changing environmental conditions.





In Interaction | Human perception is the focus and act as a stimulus for art to respond to the intuitional changes enacted or played by individuals.

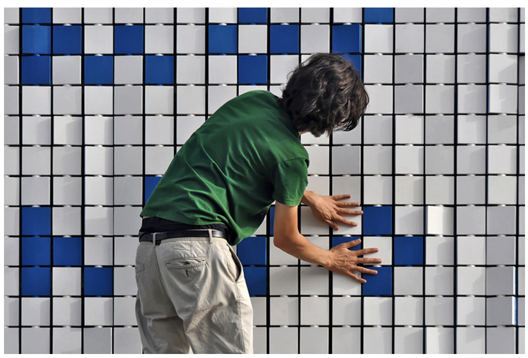


Figure 4.4 : (Top left clockwise) Shanghai Art centre, Shanghai (Laurian Ghinitoiu), Al Bahar Towers, Abu Dhabi (AHR Global), Rose Etherington (dezeen.com), Moradavaga (designboom.com)

CYBER PHYSICAL SYSTEMS

Cyber-Physical systems (CPS) are relatively new concept in building system integration. It is the transformative technology for supervising and controlling the inter-relation between the physical components and computational abilities of a system (Baheti & Gill, 2017). These systems provide a critical infrastructure to establish design principles with the idea of improving the quality of life of humans in various aspects. This technology draws a lot of similarities to the embedded systems but possesses an additional scope of physical asset integration and management. Embedded systems have the capability of computing, communicating, and controlling which are connected to the physical world through sensors and actuators. The significance of CPS is growing with the major shift towards Industry 4.0 in the manufacturing and building construction sector.

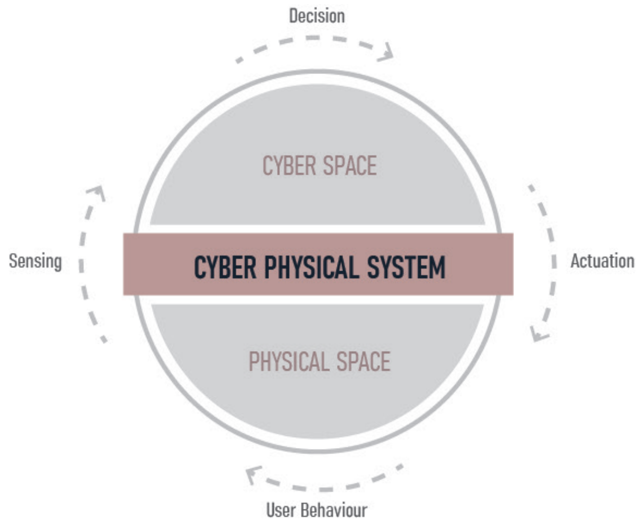


Figure 4.5 : Cyber Physical system - Information flow

The communication between physical space and cyber space occurs through a continuous flow of information such as the user behaviour, sensing, decision-making and actuation. This flow is understood with a simple example of an air conditioner. The temperature of the room is sensed, based on the data and user requirements a feedback is sent and accordingly an actuation takes place, i.e., turning on the air conditioner. Some of the salient feature of CPS are explained further (Lee, Bagheri, & Kao, 2015).

REACTIVE COMPUTATION

- Interaction with environment in an ongoing manner
- Sequence of observed input and output

CONCURRENCY

- Multiple processes running concurrently
- Processes exchange information to achieve desired results
- Synchronous or asynchronous modes of operation

FEEDBACK

- Equipped with feedback control loop
- Sensors sense the environment and actuators influence it
- Hybrid control system for complex tasks

REAL-TIME COMPUTATION

- Time sensitive operations such as coordination, resource allocation

SAFETY-CRITICAL APPLICATIONS

- Precise modelling and validation prior to development

5C Architecture of CPS

Cyber physical system is widely applicable in manufacturing and building industry to achieve the Industry 4.0, which is the new revolution impacting industrial developments (Lee et al., 2015). The 5 main architecture goals of CPs system are:

1. Connection
2. Cognition
3. Cyber
4. Conversion
5. Configuration

The research intensifies on establishing a real-time response of the ceiling system according to the changes in user behaviour. This integration of CPS in this research proposal is done by adapting the 5C model in realizing the end-product requirements. The diagram Figure 4.6 explains the related steps to the 5c's.

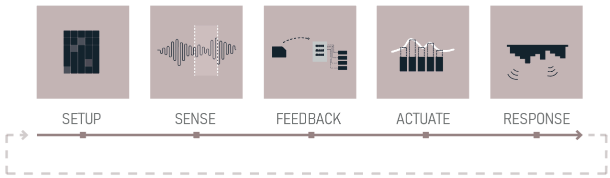


Figure 4.6 : Design Application of 5C cyber physical system

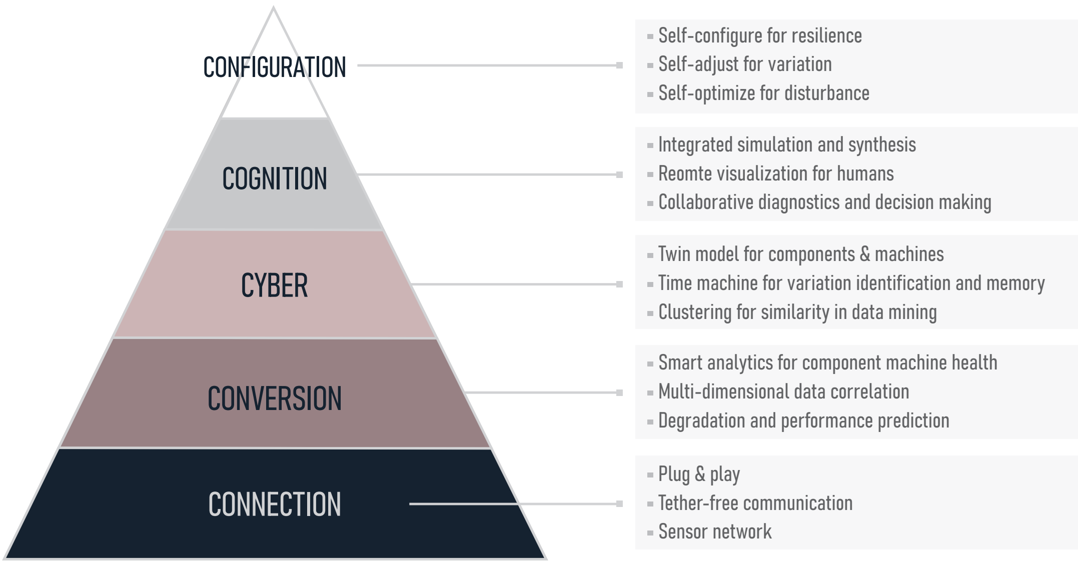


Figure 4.7 : 5C architecture for implementation of cyber physical system

PHYSICAL SPACE

Despite being part of the large architecture system, the dynamic structure acts independently with respect to control and operation (Moloney, 2011). They can be categorized as:

- Moving Systems | Portable setup to move from one place to another (detachable roofs, moving components such as louvers)
- Transformable systems | Shape/material changing elements to enhance the performance (Foldable roof, PCM walls)
- Incremental systems | Adding or removing elements from a building setup (portable partitions)

These kinetic components for intuitive application can be organized in different patterns to achieve desired enhancements in the building be it energy control or higher comfort levels. These patterns need a control and support structure to operate, which can again be divided into the following movement typologies (Stevenson, 2017):

1. CENTRIC CONFIGURATION | This system is controlled with centre point as the focal point. In this as well there are two configurations i.e., pivotal, and peripheral. Pivotal systems are controlled and supported from the centre point (pivot). The movement types are rotation, scaling, folding. In peripheral systems, this support and control is at the periphery of the structure for example retractable stadium roofs.

2. LINEAR CONFIGURATION | This system is axis dependent (straight or curved), where the components (single or series) are linked to the axis points to translate the movement e.g. shading devices on windows.

Most of the kinetic systems use either one of these or a combination of both the configurations for kinetic operability and support framework. It depends on the type of geometric transition required for the system to work and respond to the stimulus.

Composition Structure

The kinetic system is composed of the following elements:

1. Response source
2. Active surface
3. Support structure
4. System Control

Geometric Transition

In indoor applications such as walls and ceilings, the geometric transformation must happen without interfering with the building structure. The movement is thus optimized

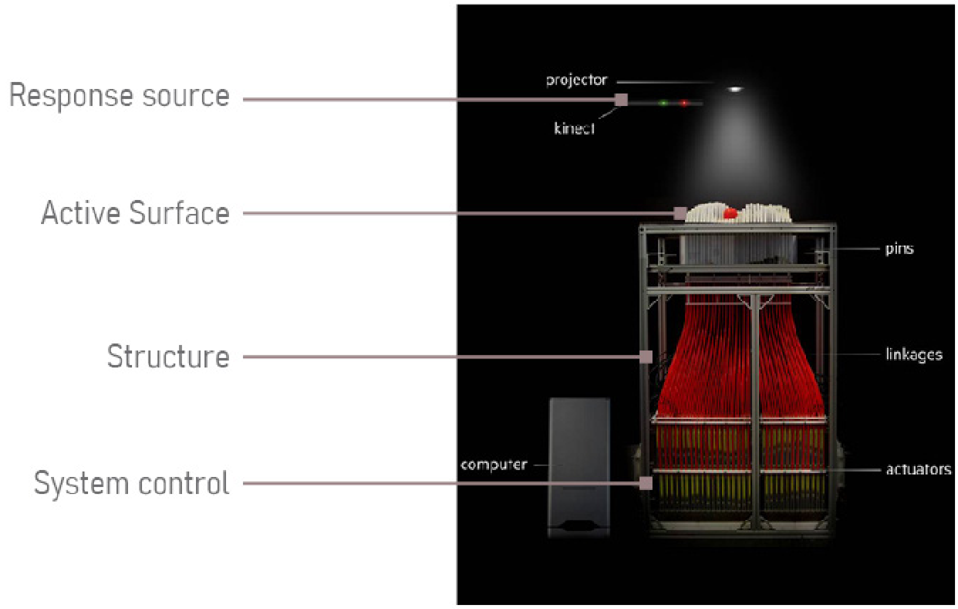


Figure 4.8 : inFORM design, Tangible media lab (Daniel Leithinger, 2013)

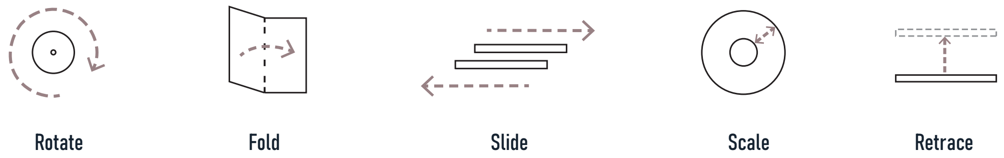


Figure 4.9 : Movement Types

in relation to the space availability and response needed. As shown in Figure 11, the movements can be classified in four geometric transitions (Velasco, Brakke, & Chavarro, 2015):

1. Translation | The motion occurs in a vector direction
2. Rotation | The object is moved around a central axis
3. Scaling | It is an expansion or contraction in size
4. Deformation | The motion occurs with changeable material properties such as, mass, elasticity, foldability

Pattern

A pattern is a series of numbers, shapes, or objects that follow a certain rule while repeating or changing. It is controlled by variables that influence the size, number of divisions, direction and even shape. Patterns with variable geometries can define an architecture surface creating a modular grid for easier and repetitive application along the length of the building element such as façade, wall, or ceiling. Language of the pattern inspired from nature, can be as diverse as possible ranging from abstract Voronoi to rigid structural grids. The basic element of a kinetic pattern is the module having a dynamic movement. This module can act autonomously or can be clustered into small groups for higher efficiency of the kinetic system (Nagy et al., 2016).

ORIGAMI

Rigid origami has underlying properties such as structural stiffness, foldability leading to expansion and contraction and scope for surface reconfigurability. Despite having a temporary feel, origami structures are versatile and have applications in robotics, aerospace and architecture (Sroka & Ku, n.d.). The above discussed case study of Al Bahar towers in Abu Dhabi is a good example of origami application.

PATTERN CLUSTERING

A cluster of modules can focus on a specific space and help in simplifying the mechanism by reducing the number of unique operation controls. As the modules in a cluster can have identical or independent movements in response to the varying user influences, complex pattern configurations can emerge without the need for extensive mechanical operations and complex design geometries (Nagy et al., 2016). Patterns along with their cluster configurations are vital to the elements or components that are involved in the process of movement. The complexity of configurations generated is based on the behavioural change instead of using non-standard components to create the pattern.

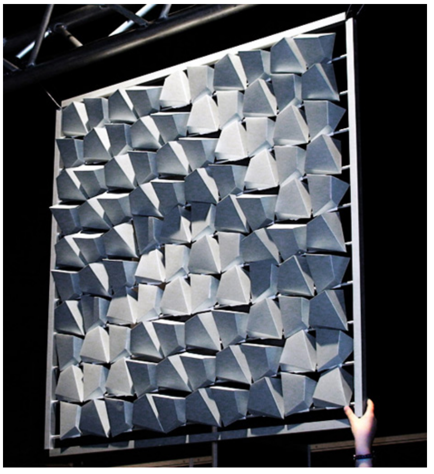
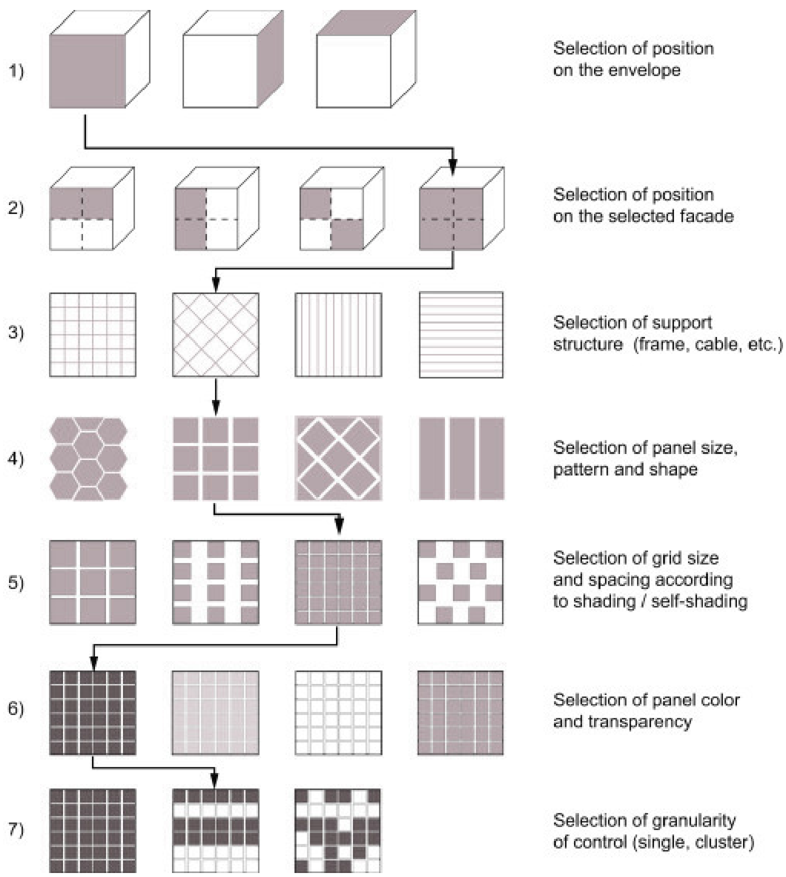


Figure 4.10 Pattern Clustering (Aart van Bezooijen)

SCALABILITY & MODULARITY | The tiling pattern is not restricted to a predetermined size, geometry, or number. It can be scaled all along the length of the given surface with a single module unit. It allows to cover the entire surface without the need to have extensive changes in the module design itself. The module can also follow the design language of the architecture space. In Figure 4.12, the general design process is elaborated in 7 steps.

Steps 1-2	Selecting the surface and position on the surface
Step 3	A suitable support structure (can be in line with or utilize the existing building structure e.g. a frame or a cable-net solution)
Steps 4-6	Visual expression based on variables such as shape, size, geometry, relative position and spacing. It can also include material definitions (colour, texture, chemical and physical properties)
Step 7	Control granularity by defining whether the movement is unique for every panel or cluster based

Figure 4.11 : Pattern design process


1)
Selection of position
on the envelope
2)
Selection of position
on the selected facade
3)
Selection of support
structure (frame, cable, etc.)
4)
Selection of panel size,
pattern and shape
5)
Selection of grid size
and spacing according
to shading / self-shading
6)
Selection of panel color
and transparency
7)
Selection of granularity
of control (single, cluster)

Surface

Architecture is represented by the form that shapes it and the surface that covers it. Surfaces are made of concrete, metal, glass, or other materials and have numerous physical and chemical properties which are not merely superficial, they become the language for communication of design and its spatial qualities. An architecture space expresses its autonomy and its engagement with the surroundings through its skin (Leatherbarrow & Mostafavi, 2002). Surface is the last layer in the set of building systems that physically encounters the environmental conditions or user behaviour. This equally plays an important role in defining and realizing the response a kinetic system generates.

Surface Irregularity

The modules when put in patterns generate configurations that define the extreme boundary line for a surface. Depending on the complexity of configurations and movement type, it gets impacted altering the smoothness of this line. In case of acoustics, the sound waves also behave differently with the changing smoothness. As shown in Figure 15, the order of reflection of sound rays depict a proportional relation to the irregularity of the surface, as the crevices and peaks affect the reflection angle, direction, and number.

Surface Material

Surfaces have some properties that govern the way it behaves and communicates in a kinetic system. Some of these properties are listed below:

1. Colour & Transparency
2. Texture & Finish
3. Chemical properties
4. Physical Properties

Figure 4.13 : Surface material with varying acoustic properties (Material district)

They are dependent on the building requirement and performance expected from the kinetic system. For instance, transparency will influence the natural light filtering in a building whereas the physical properties such as porosity can impact the wind force on a façade. In a similar way, in indoor condition, there are various reactions these material properties can have on the user behaviour. In acoustics, the absorption and scattering of sound rays depend on material's physical and chemical properties. With the plethora of material available, the reaction behaviour can be aligned to the response required form the movement of these surfaces.

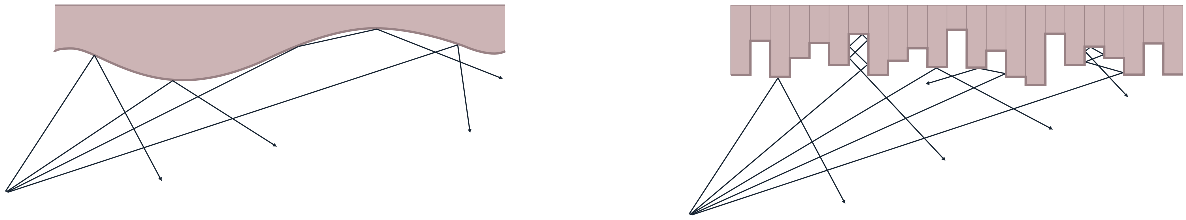


Figure 4.12 : Surface irregularity

CYBER SPACE

The use of various actuation technologies can be noticed after reviewing some of the existing responsive systems both in the realm of architecture and interaction design. These technologies have been in use for several years and have evolved to provide exact actuation response required from a system (Matin et al., 2017). Advancement in actuation components are represented by mechanical actuators, electrical actuators, pneumatics actuators, hydraulic actuators, and material actuators. Various sensors have also been developed such as :

1. System without sensor – user preference
2. System without sensor – specific algorithm
3. System with sensor – switches
4. System with sensor – Central control
5. System with sensor – decentralized control
6. System with sensor – Material based

Operability and Maintenance

Most of the surface whether on facades or indoor ceilings usually encompasses a complex interaction between various physical components. The facades solve the purpose of sealing the interior from extreme exterior environmental conditions whereas in indoor spaces, the ceilings are used to conceal the electrical and mechanical fixtures necessary for a space. Thus, the mechanical movement of kinetic surfaces need to be designed with these aspects in consideration. It is necessary that the efficiency performance of the system be regularly monitored for high operative performance results.

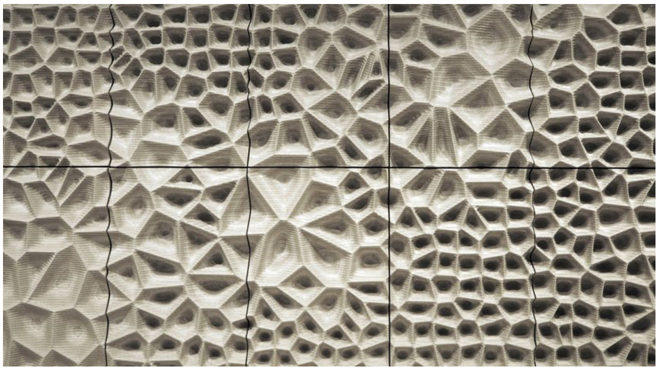


Figure 4.14 : Acoustic panels at Elbphilharmonie (Gilda Fernandez)

Maintenance is tricky when there are moving parts in a building system and often is the main failure reason for kinetic designs. Once installed, accessibility to the surfaces for maintenance purpose can be challenging. It is also divided in two types, software, and hardware. While the former can be controlled digitally with the whole system connected to a server, the latter is usually difficult due to limitation of working space and complex system. Thus, it is crucial to go for a simple operative mechanism with less moving parts that can be replaced without hindering the working of the entire system.

Monetary Analysis

The ceiling surface in a stadium or concert halls have a large area to cover. Considering a small module size, the quantity of actuators and controls required can incur a huge cost and in relation to the comfort benefits reaped out of the system. Thus, it is advisable to opt for a simple and cost-effective mechanism to control the system with standardized elements for an efficient kinetic design. The Elbphilharmonie concert hall in Germany designed by Herzog de Meuron Architects, consists of 10000 unique ceiling panels computationally designed to optimize the acoustic performance of the space. These acoustic panels ensure all sound details are heard clearly at every seat in the hall and improve the acoustic quality of the performances (Elbphilharmonie, n.d.). Designing and fabricating numerous unique panels is not a cost-effective solution and is suitable only for places where the quality of results required overpowers the cost factor.

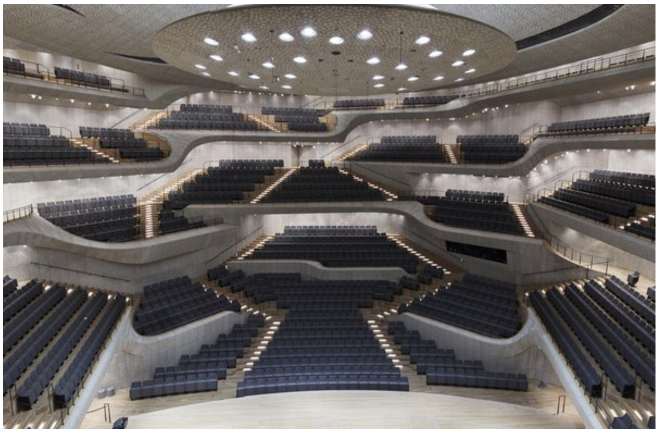


Figure 4.15 : Grand Hall at Elbphilharmonie (Maxim Schulz)

Most of the responsive systems require an independent energy source to power their operations. They hardly harvest energy, and nothing is fed back to the system. However, a comparative analysis can be made on the cost of energy utilized to work the system versus the energy saved with the responsive system. This is not possible in some cases, where the benefits are in terms of human comfort. Certainly, this brings in new challenges for architects and engineers to design adaptive façades that would optimize but energy consumption and energy generation.

Actuation Mechanics

Various technologies are utilized in responsive systems dependent on control, sensing, actuation, and material properties. They can be broadly categorized in five heads: mechanical technology, electro-mechanical technology, information technology, passive technology and advanced material technology (Matin et al., 2017). The ones relevant to this thesis are explained in detail with examples.

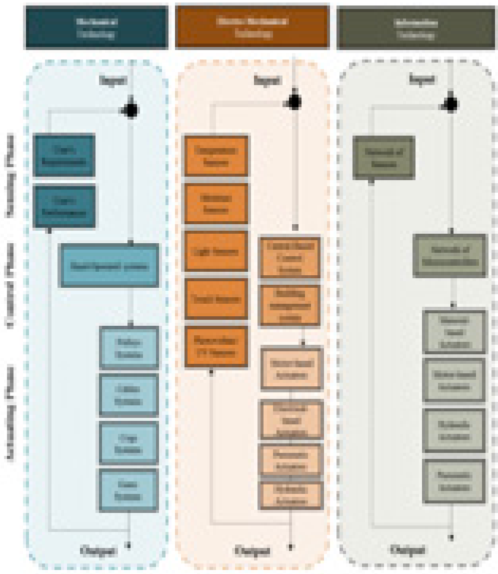


Figure 4.16 : Actuation and control Mechanisms in responsive systems

MECHANICAL TECHNOLOGY

The common idea in the field of architecture during 1960's was to make buildings work like a system resulting in independent entity for every building component (Moloney, 2011). The designs had a major industrial influence involving mechanics and pneumatic principles to meet the multiple functional requirements associated with kinetic movement. As a legacy of the industrial revolution, the components were bulky, intricate and exotic in physical and chemical composition (Schumacher, Schaeffer, & Vogt, 2010). Independent mechanical elements such as pulleys, wheels, hinges, gears, rollers, and cables were taken into use to influence the magnitude, direction, and application of point forces. The mechanical components utilized external forces such as environmental stimuli or human effort to make translational, rotational or combined movements in the facade mechanisms (Decker & Zarzycki, 2014).

A good example for mechanical technology is the Penumbra system designed by Tyler Short in 2014. The hand-operated system works on the actuation by two interdependent cogs and gears mechanism that alters between vertical and horizontal configuration of louvers. The main objective was to reduce the sun glare effect as presented in figure below (Rogers, 2015).

Figure 4.17 Rendering of Penumbra system (Rogers, 2015)

ELECTRO-MECHANICAL TECHNOLOGY | With availability of electrical components and control devices after 1960's, the façade mechanisms were upgraded to have electrical control system (Ahmed, Abdel-Rahman, Bady, Mahrous, & Suzuki, 2016). An early application of this technology was the United States pavilion at Montreal Expo 67 designed by Buckminster Fuller as shown in figure below. It is still fresh in today's context of a responsive façade actuated by environmental conditions effected by scalar movement (Sharaidin, 2014). It was a self-regulated shading system with integrated sensors and actuators that controlled the interior environmental conditions using thermostats (Massey, 2006).

Some of the most used electro-mechanical components used in responsive facades are pneumatic actuators, hydraulic actuators and servo motors (Matin et al., 2017). Electronically operated mechanical systems allow for a centralized control and monitoring. These systems are reliable, inexpensive and require less maintenance with time, specifically when they are designed using modular components (Decker & Zarzycki, 2014). Although, having

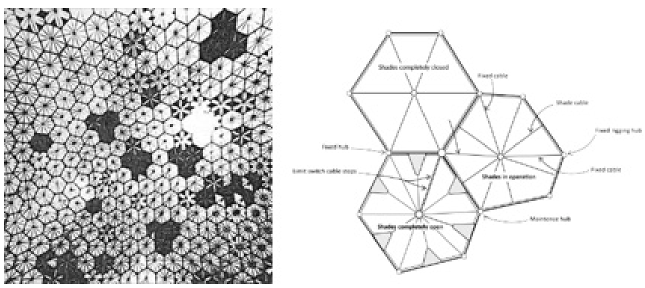


Figure 4.18 : The canvas sunshades in Montreal Expo Dome by Buckminster Fuller's 1967 (Gorman, 2006)

a complex system with many mechanical parts possess a high risk of failure due to material fatigue, difficulty with parts replacement, limited durability and dependency on electrical power (Adriaenssens et al., 2014). This system is also not suitable for variable control of components to generate exact movement patterns.

INFORMATION TECHNOLOGY | A new generation of responsive facades extensively use information technology to give way for a distributed control system with interconnected panels having separate micro controllers. The intent is to individually control the mechanical components responsible for the movement and share the information with other components or main server. In some façade cases, every module of interconnected works individually as a sensing and actuating device (Decker & Zarzycki, 2014). This allows for a decentralized control while maintaining peer to peer communication approach to ensure a cohesive response among individual modules. The system continues to perform even if some of the modules/components stop working. Machine learning algorithms are the next step in this technology that can provide more efficient solutions to the responsive system.

Figure 4.19 : ETFE cushion panels on ICT Medi Building (Poli, n.d.)

Decentralized control has certain benefits over a central control server such as individualistic response of panels, low cost components and parts, functional and compositional freedom, and efficient results with separate data for panels/clusters. For a responsive system, information sensors play a fundamental role in guiding the response movement according to the sensor data. There are various sensors available to measure environmental effects and user behaviours. Some of the widely used sensors are light, temperature, touch, and sound.

The first façade designed with a decentralized control system was for the ICT- media building in Barcelona, Spain as shown in the above figure. Each panel is made of pneumatic ethylene tetrafluoroethylene (ETFE) air cushion that are embedded with heat and light sensors. These panels are controlled by an Arduino-based microcontroller that inflate, deflate, or increase the nitrogen density inside the cushions. This impacts the visual appearance of the façade and control the heat and light penetrated inside the building (Mondia, 2014).

Image Source : Author

DESIGN CONSIDERATION

Pattern design: Simple and repetetive geometry

Transition: **Rotate & Retrace**

Easy Operation: Clustering & modularity

Actuation: **Electro-mechanical technology**

STATE OF ART

Benefits of thermal and lighting responsive facades both in terms of energy saving and environmental impact are huge. In contrast, for acoustical improvements there are only a few research projects that shed light on its potential. Sound plays an important role in concerts and live venues. These spaces can exhibit the recognizable impact of responsive acoustics. Although real time responsive surfaces are yet to become a reality and still in the nascent stage of research and prototyping.

The first breakthrough in the field of controlled acoustical environment during 1895 made it evident that a single solution does not work for different listening needs. Highly cumbersome mechanical and hydraulic systems were developed to provide a variable acoustical environment with tweaking just a few parameters. Use of sophisticated hydraulic systems is made in experiments done at the IRCAM in Paris, SARC in Belfast, or EMPAC in Troy, New York. Concert halls for contemporary music provide opportunity to experiment with simple operative solutions. Vertical displacement of suspended ceilings, multi surface wall panels with rotational movement having absorptive and reflective acoustical properties (Geoffrey Thun, 2015).

Case Study 1

Resonant Chamber | RVTR, University of Michigan

The RVTR research group at the University of Michigan have designed and prototyped an interior envelope system, dynamic in nature to create a transformable acoustic environment. A full-scale rigid origami structure transcends the acoustic environment with the help of dynamic, spatial, material, and electro-acoustic technologies. A combination computationally driven sensors used to configure kinetic components is experimented to transform the acoustic environment in relation to user behaviour and sonic input.

Dynamic Surface Geometries

Use of rigid origami shapes to achieve a desired flexible geometry system. Predefined spatial configurations of different folding patterns are made to suit a variety of spaces, potential aural volumes, and uses. Flat foldability and easy operability give way to for managing the exposed surfaces. Th ratio of surfaces with variable material and acoustic properties and linkages is monitored. Flat foldability lets the surface to tuck down in a compact deployable structure.

Performative Material Systems

Three types of panel composites with different material properties to absorb, reflect and generate electro-acoustic sound are used to fabricate the entire surface as seen in the

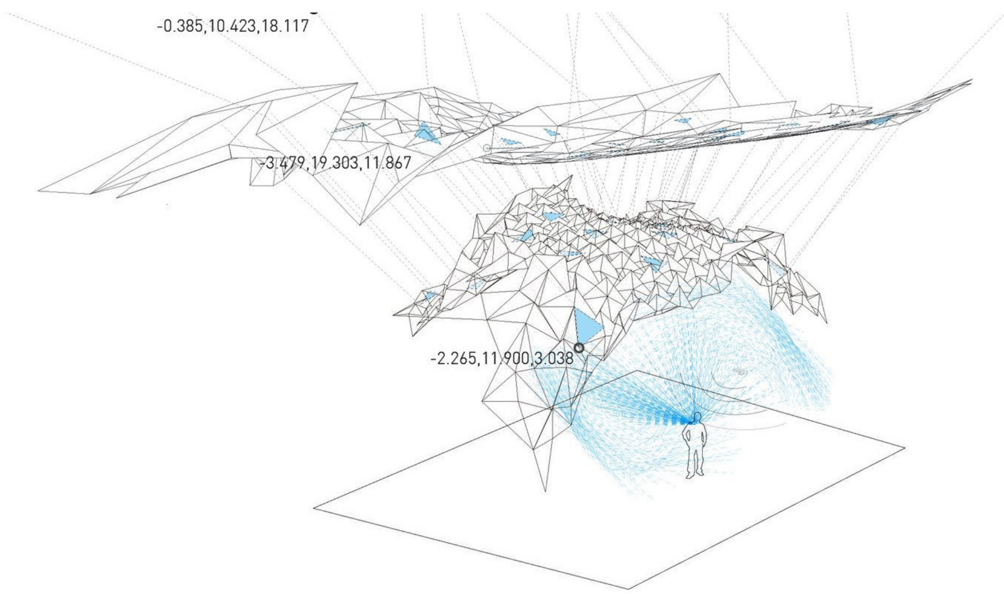


Figure 4.20 : Resonant chamber (RVTR)

Figure 4.23. Joint details and connections used have an equal impact on performance both mechanically and acoustically.

Variable Actuation and Response

Suspension and actuation technologies embedded within the panel framework cater to the folding of origami and vertical movement of the entire surface as seen in the figure below. Arduino micro-controllers control the localized folding movements. Digital model simulations are used to communicate the pre-configured data via Firefly software to achieve desired movements.

Figure 4.21 : A module of the resonant chamber (RVTR)

Design Take-aways & Further Research

In the next stage of development of this project, there is an intent to:

1. Refining the sensing and control parameters based on the installation space.
2. Blend the aural and occupancy feedback to reconfigure the relationships between the audience and the performers.
3. The design needs to be less complex for better operability and maintenance. IT is crucial to have as few as possible moving parts to avoid failure and mechanical difficulties (Geoffrey Thun, 2015).

Case Study 2

Acoustic Brick Wall | Gramazio & Kohler research group, ETH Zurich

This project was a research on robotically fabricated acoustic wall system, that functions as a zoning element to manipulate the acoustic performance in office spaces. They emphasize on the rarely considered phenomenon of diffusion and scattering of sound waves in their research. The geometric configuration of the wall or surface is the dominant factor for affecting change rather than its material composition. Thus, increasing the scattering coefficient of the entire wall to provide for a non-uniform reflection pattern of the sound waves. This concept also diminishes the flutter echoes and distributes the sound energy equally over the entire space.In the research experiments, the main objectives were to have a more flexible design that could achieve the following aspects:

1. Positive effects of diffusion
2. Enhanced speech intelligibilty
3. Minimization of flutter echoes
4. Enhancement of self in a space
5. Improved efficiency of existing absorption surfaces
6. Applicability in various spatial conditions

Design Viability

An explicit module is designed named as the "Acoustic Brick" considering the fabrication, installation, and acoustic viability. These bricks can be stacked with some tolerance in the placement offset creating scattering patterns in geometry. A custom design algorithm is scripted to achieve variety of experimental design iterations, while keeping the structural, functional and production feasibility in check as sown in the figure below. A robotic installation system was used to ensure accuracy in placement of these bricks.

Figure 4.22 : Acoustic Brick Wall (GKR, ETH Zurich)

Acoustic Correctness

With fixed acoustic performance benchmarks, use of computational design tools was made to measure the acoustic depths between the deepest and the shallowest bricks. These measurements were supported with physical testing of the prototypes in a stereotypical place. Tests included active speaking and passive listening by users and analysing their feedback in terms of speech intelligibilty, perception of space and the overall listening experience. The results of both physical and digital testing showed reduction in reverberation time, diminished flutter echoes and improved speech intelligibilty.

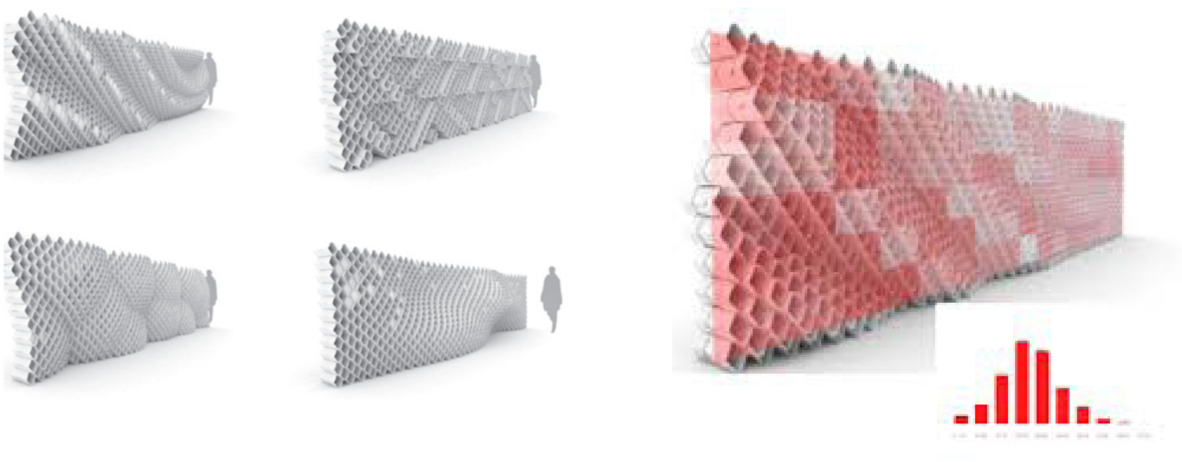


Figure 4.23 : Potential design configurations with visual feedback, Acoustic Brick wall (GKR, ETH Zurich)

Design Take-aways & Further Research

Customizable design typology was achieved using single object module. Although, there are a few design take-aways for further research:

1. Clear guidelines need to be formulated to distinguish for various spatial configuration with different functional requirements.
2. Validation of fixed benchmarks by considering digital acoustic simulations and advanced geometry processing.
3. Change in brick dimension to achieve similar results.

Case Study 3

Tuneable Sound Cloud – Mani Mani, Fishtnk Design Factory

Tuneable sound cloud is a research project to create a responsive architectural system for tuning the acoustical performance of a space. It is designed for real-time modifications in its geometry impacting the reflection direction and intensity of the sound waves. Inspired by origami, the surface is divided into triangle shaped modular tiles that are connected at the edges permitting it the freedom to move and bend. The setup is divided in three zones namely :

1. Sound reflection surface – The bottom most layer is a reflection surface that is suspended from the ceiling with the help of suspension cables to achieve a flexible surface. The reflection layer has movable modular tiles, that open for sound rays to penetrate the system.
2. Acoustic chamber – It is the buffer zone created in between the absorption and reflective layer allowing a free movement for the suspended surface. This gap can also be tweaked for performance enhancement.
3. Sound absorption layer – Attached to the ceiling itself, sound waves reach this layer only when the reflective surface opens to trap the sound. The curtain like design made of highly absorptive fabric captures the sound waves to reduce the order of reflections.

Design Viability

The surface has a space frame modular structure with hinged connections. The modular tiles have a specific design; they consist of a triangular framework with three smaller triangles inside it. These are made from sound reflective material which are embedded with muscle wires for micro actuation technology.

Actuation Response

The entire system works on dual movement mechanism:

1. Shape change – Due to the origami like design, the pattern of the surface can be altered to redirect the sound waves in all possible directions. For change in suspension height, linear actuator is used with higher strength and powerful drive to achieve a real-time response.

Figure 4.24 : Tuneable Sound Cloud (Fishtnk Design Factory)

2. Operable openings - The three small triangles within a tile are made of shape memory alloy, which deforms its shape when heat is applied. This is a lightweight and less costly alternative to conventional actuators.
3. Sound sensors – The nodal joints in the space frame are embedded with microphone sensors to measure the sound input and trigger the system with desired response movement.

The design is interfaced through a modelling software that is actuated using Arduino microcontrollers and stepper motors. Like other case studies, prior digital simulations helped in achieving the right movement patterns. The response system was thus configured accordingly.

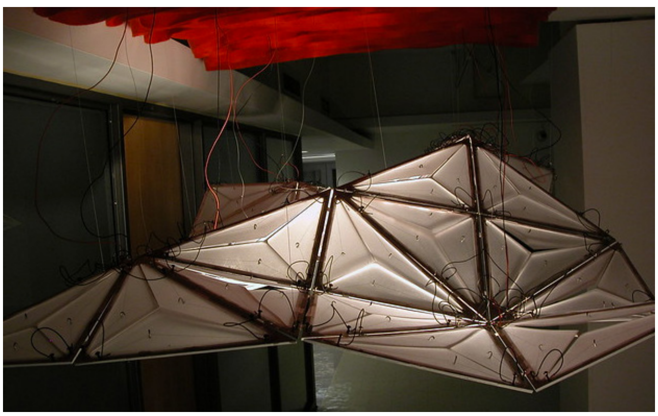
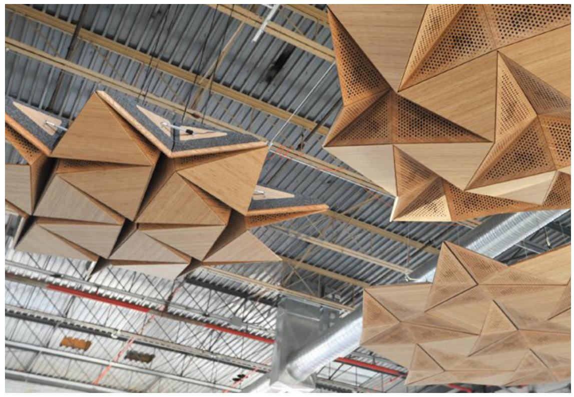


Figure 4.25 : Surface origami pattern (Fishtnk Design)

Design Take-aways & Further Research

This project entails similar objectives as intended in this design research thesis. Few of the important take-aways are :

1. It is very crucial to undergo digital simulations to foresee the performance of system for extreme auditory cases and explore the maximum limits of the actuation system.
2. With multiple moving parts the system becomes vulnerable to operational failure as different actuation techniques are applied.
3. The existing suspension system for interior ceilings can be utilized to minimize the system cost and complexity involved in designing a new one.
4. The research offers a perspective into real time auditory impact on the design. The placement and data reading algorithm should be properly worked out before implementation.

	RESONANT CHAMBER
Reference	
Research association	**RVTR,** Michigan University
Activity/ Function	Exhibition / Concert hall
Placement	Ceiling suspended
Response Mechanism	Origami folding
Acoustic Character	Three different pieces for absorption, diffusion and electro-acoustics

STATE OF THE ART

	ACOUSTIC BRICK WALL	TUNABLE SOUND CLOUD
		
	Gramazio & Kohler Research Group, ETH Zurich	**Fishtnk Design Factory**
	Studio & Lecture spaces	No specific space
	Floor standing wall	Ceiling suspended
	Static	Vertical motion and origami folding
	Diffusion	Absorption and diffusion separately

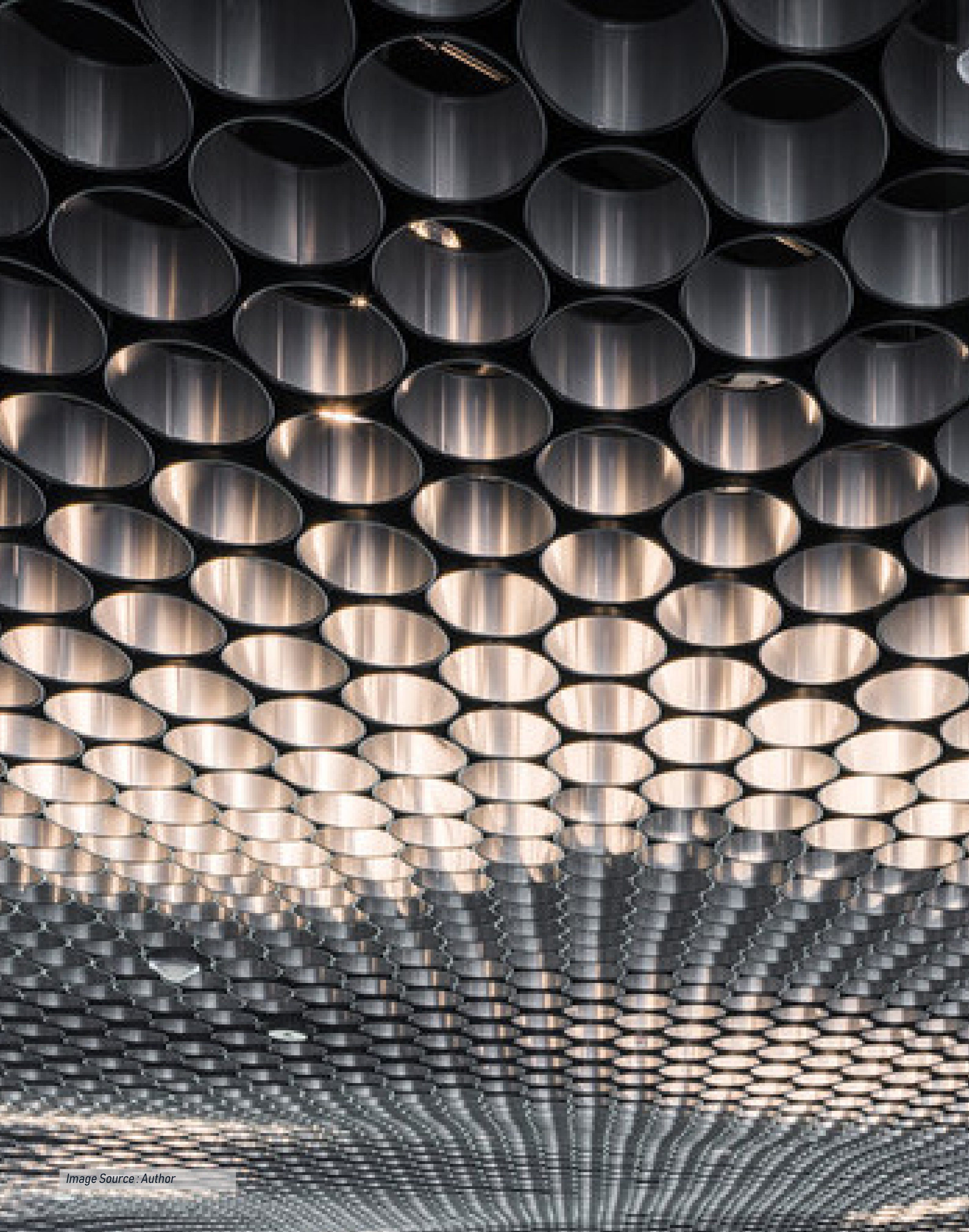


Image Source : Author

DESIGN CONSIDERATION

Swift hinge movement
Limited number of actuators & controllers

Sturdy parts to reduce wear & tear
Modular assembly with **simple kit of parts**

Simple operative design
Space buffer in ceiling for movement

V

t h e

s o u n d

b e n d i n g

p r o j e c t

BENCHMARKING

The next step is to fix certain parameters that have an influence on the research outcome. It is thus important to first benchmark these parameters with the pre-established notions that are in use in the conventional calculation methods and or have been proven to work in earlier research. The predetermined parameters allow for an unbiased comparison between the test results in order to validate the accuracy of the developed research method.

Experiment setup	Geometry Input	**INPUT**
Source localisation	Sound source Input	
Custom definition	Acoustic calculations	**PROCESS**
Result Optimization	Optimum Solution	**OUTPUT**

Figure 5.1 : Input Process output standards

This is achieved by dividing the parameters based on the principle of IPO (input, process and output) as discussed in the previous chapter.

The input will have constraints such as the experiment setup, source localization and clustering methods for blocks. The process entails the logic behind the custom definition created to reduce the runtime compared to conventional models by processing limited data. The output results from this data are compared with sophisticated acoustic softwares for verification and checking the accuracy of results. With the available data, a stringent way of finding the optimum solution from the gene pool has to be defined. Shortlisting of solutions based on input requirements reduces the processing time to be able to perform in a real-time configuration.

EXPERIMENT SETUP

For research by design, a few test rooms are modeled for validation of concept. Two test scenarios are created, one with a closed setup and another without the walls for a stadium like mock-up to see the impact of responsive surfaces in the given context. These will be further referred as:

a) **Test Case A – Closed small room**
b) **Test case B – Open stand in a stadium**

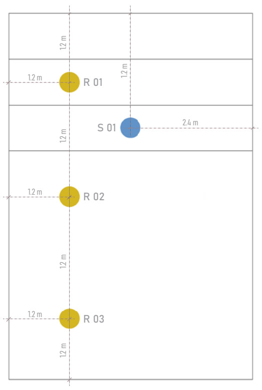
which will be further referred as 'Test Case A'. A simple room is effective in getting precise results. This also functions as a benchmark to compare different simulations for achieving an optimum design solution. To gain higher accuracy in results the research product is then also tested in another room model having different size and shape, which will be further referred as 'Test Case B'. The two test cases are illustrated below with room dimensions and material properties.

The sound ray reflections are divided in three main zones namely, the floor, walls, and the ceiling. As the design research is focused on the stadium, the maximum impact is caused by the reflections from ceilings as there are no walls. Thus, the research will focus on the possible differences in reflections caused from the ceiling surface. To see the results for one surface, a custom definition is needed which will have the following variable inputs:

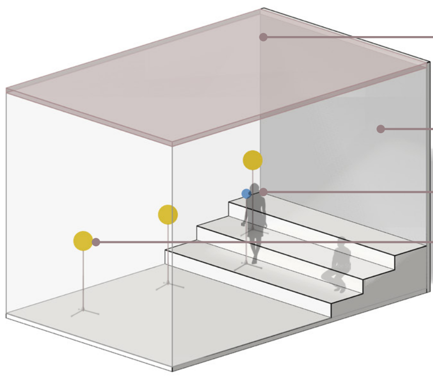
1. Surface placement
2. Surface Pattern
3. Pattern size
4. Pattern in-between spacing
5. Movement height
6. Blocks material (Reflection coefficient)

SOURCE LOCALIZATION

To verify acoustic consequences of the geometric compositions, the sound source needs to be identified. The



FLOOR PLAN



AXONOMETRIC VIEW

TEST case A | **CLOSED ROOM**

DIMENSIONS	
Room size	4.8m (w) X 7.2m (l) X 4.2m (h)
Number of Receivers	03
Source Point	Fixed location with dynamic sound value

MATERIAL	
Walls	Plastered brick wall
Floor & Bleechers	Rough finish Concrete
Ceiling	As per design

Figure 5.2 : Test Case Setup A | Closed Room

defining characters that can control the movement of blocks are the intensity of the sound and its position. While intensity can be easily measured using microphones, finding the source position can be difficult. Various techniques are available for detecting and visualizing the location of sound source also known as source localization. Some systems such as sound cameras employ microphone arrays to predict the source location. They are widely used in live video conferencing where the camera view is adjusted as per the sound source detection.

Figure 5.3 : Microphone Arrays (acoustic-camera.com)

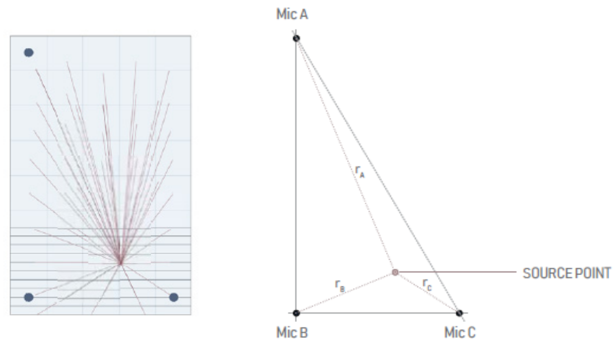
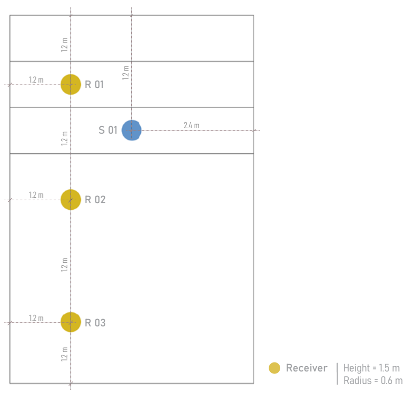
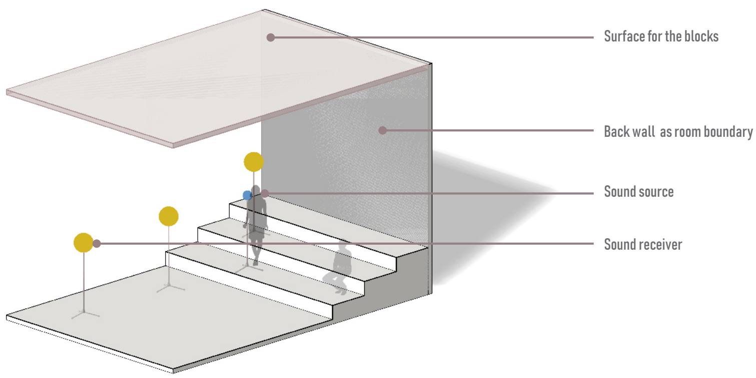


Figure 5.4 : Source Localization using three mic setup

However, as we need multiple source detectors and can do with some tolerance for the accuracy, a simple and low-cost solution is preferred. In a closed room setup, a three-microphone arrangement can be used to calculate the position of the source using Pythagoras theorem. The equations and the definite solution can be seen in the Appendix A.



FLOOR PLAN



AXONOMETRIC VIEW

TEST case B | **OPEN ROOM (Stadium Mock-p)**

DIMENSIONS

Room size	4.8m (w) X 7.2m (l) X 4.2m (h)
Number of Receivers	03
Source Point	Fixed location with dynamic sound value

MATERIAL

Back Wall	Plastered brick wall
Floor & Bleechers	Rough finish Concrete
Ceiling	As per design

Figure 5.5 : Test Case Setup B | Open Room(Stadium mock up)

Dual-Kinect Device Arrangement

Although, this method is beneficial when there is only one sound source at a time. With multiple sound sources having different intensities, it becomes challenging to get accurate results. A research by Ryo Yamasaki is taken into consideration where the use of Kinect device is made to find the source position (Yamasaki, Yabuki, Fukuda, Michikawa, & Motamedi, 2016). To do this, first; the blocks need to be grouped in smaller chunks based on the tracking range of the Kinect devices.

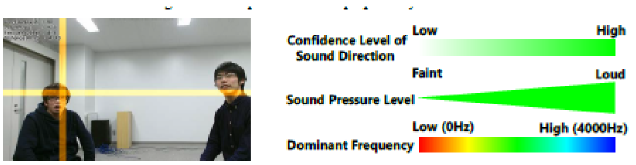


Fig. 3 Sample of output system

Fig. 4 Legend for AR lines

Figure 5.6 : Sample of Kinect system (Yamasaki et al., 2016)

This method is known as pattern clustering as defined earlier. The cluster movement is in response to the information received by its respective Kinect device (source reader). These devices can also provide the sound pressure level data. An image from the research explains how it maps the location. In case of multiple inputs, the system selects the one with higher sound levels as seen in the image below.

The two peak lines in the horizontal and vertical direction help in locating the source point. This technique has been duly tested by the researcher and is concluded to give appropriate results. The technique is assumed to work and is adopted directly into the working without validating as this is not the focus of this research.

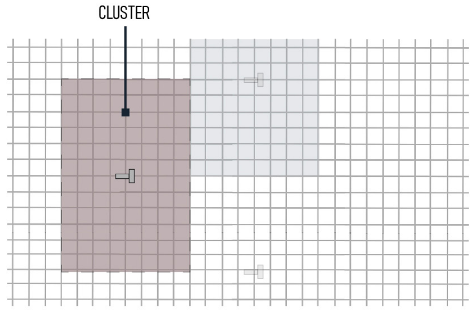


Figure 5.8 : Clustering of the grid

Cluster Format

A Kinect device has a traction range of 0.7-6m (Yamasaki et al., 2016). Based on this, the clusters perimeter dimensions should not exceed 6m. The number of rows and columns that can be accommodated in one cluster will depend on the grid size of the system. In the sample case A, room size of 4.8m X 7.2m means, it is better to divide the room in two clusters for optimum results.

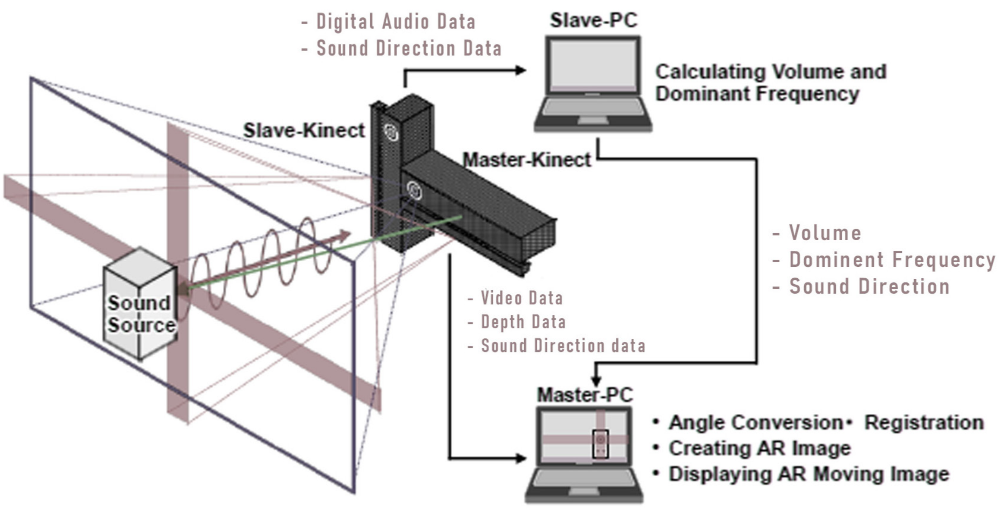


Figure 5.7 : Data flow with setup diagram (Yamasaki et al., 2016)

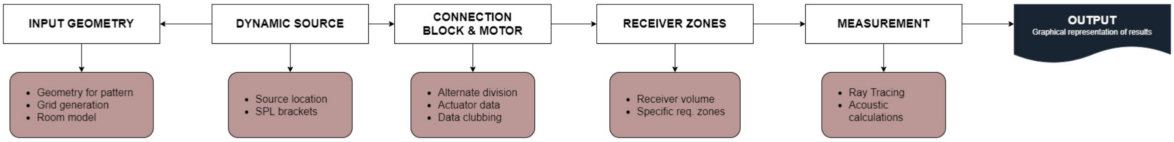


Figure 5.9 : Custom definition workflow

NEED FOR CUSTOM DEFINITION

Predicting acoustic consequences on the geometric models allows for acoustical improvements in a space. New methods to achieve explicit acoustic conditions for architectural design and spaces need to be developed. Complex acoustic software takes time and detailed drawings & BIM models for getting simulation results. The other drawback is that existing acoustic software is designed for static geometries, hence the calculations need to be re-run with every design iteration.

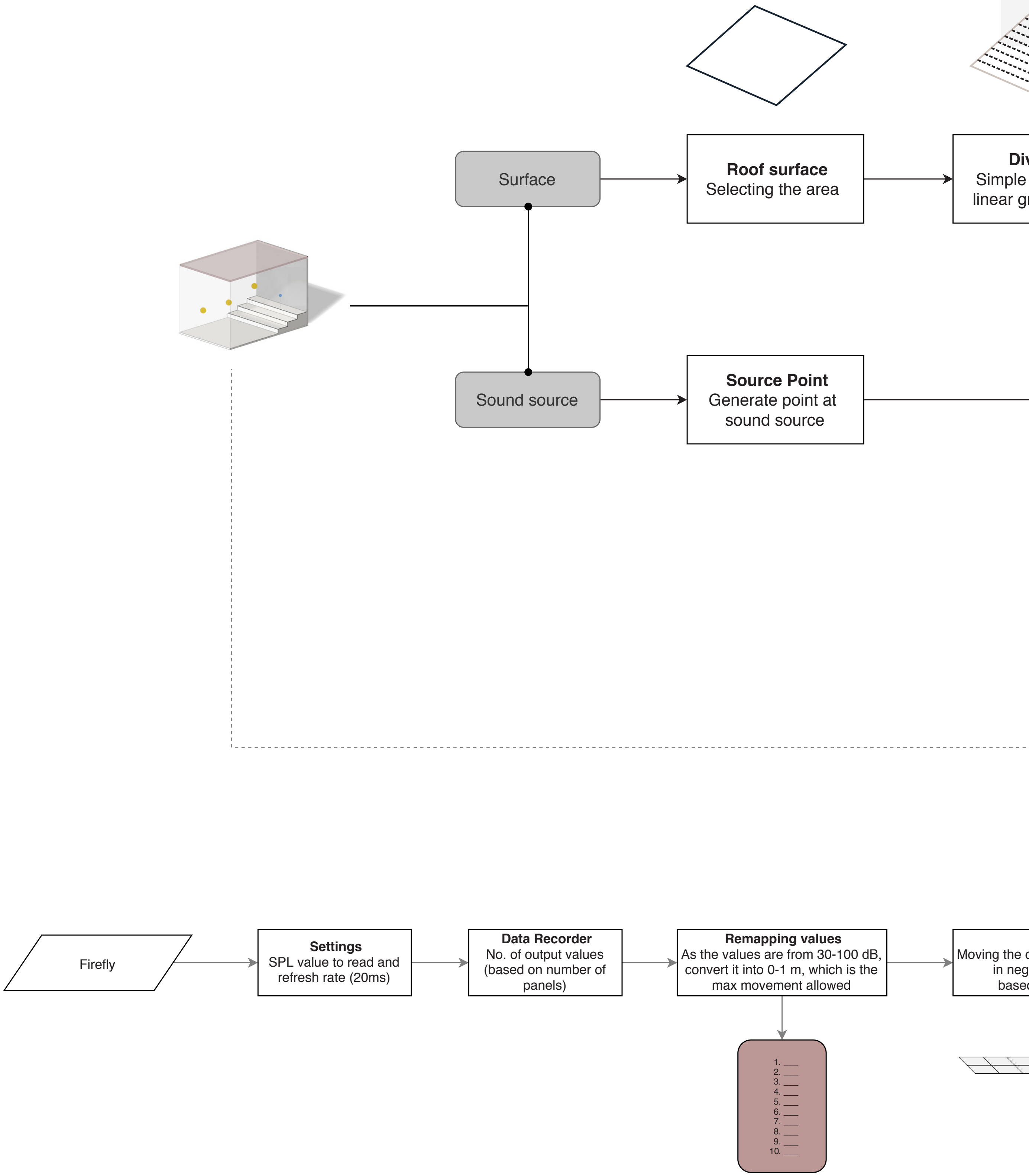
A dynamic evaluation tool is required to assess the design for different iterations and evaluate them based on their acoustic performance. The changing variables must be integrated into the tool for effective analysis of these iterations (Selkowitz, 2001). Therefore, it is essential to develop a custom definition that runs adequate acoustic simulations on a real time basis in accordance to changing geometries of the dynamic design solutions. The results provided by sophisticated acoustic software is more accurate but takes more calculation run-time. The custom definition provides with limited and basic calculations in real time, giving some basic data such as :

- Number of rays reaching the receiver
- Order of incidence of these rays
- Distance travelled by rays
- Energy retained by the rays
- Sound Pressure level

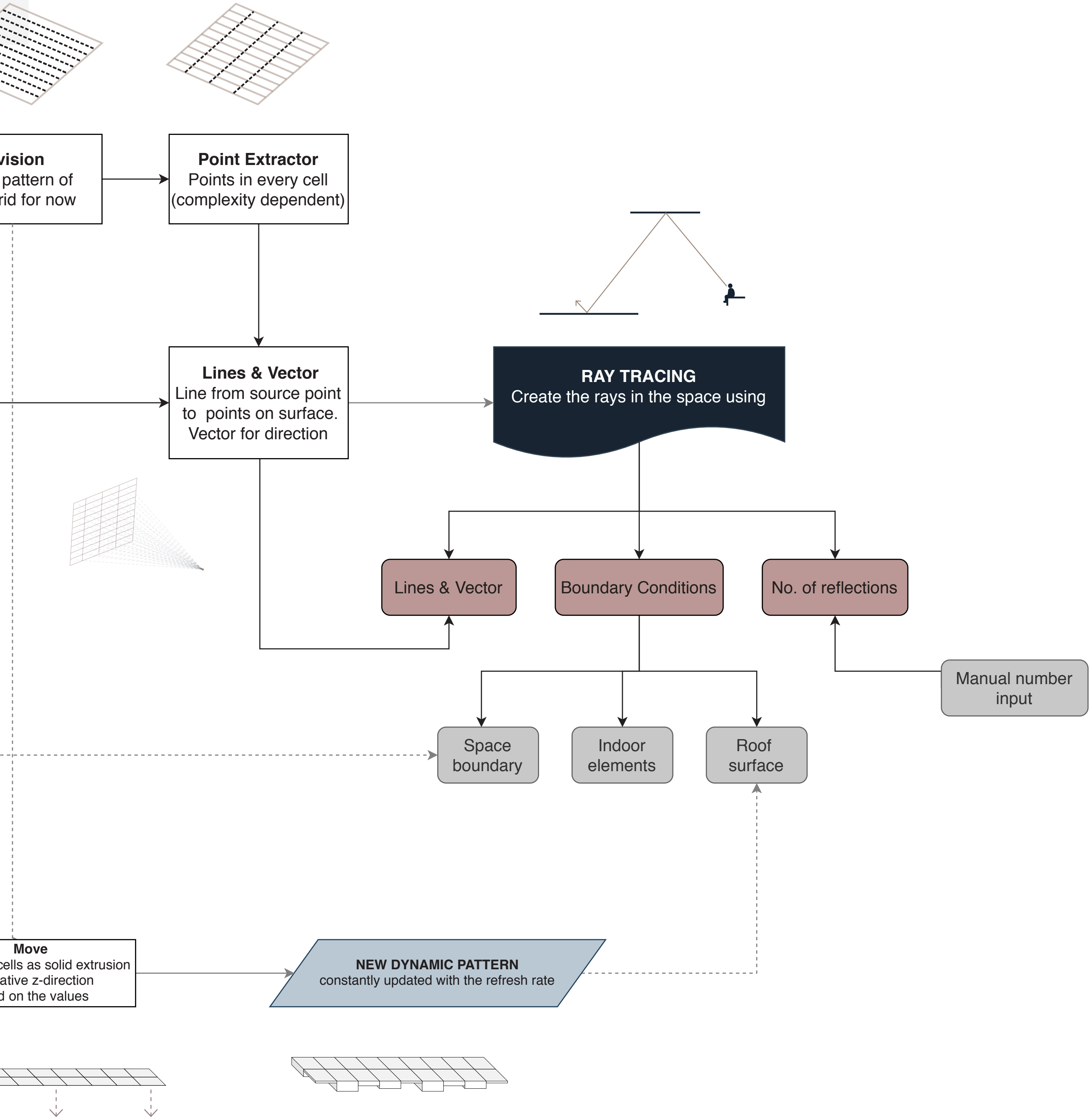
The custom definition is used to calculate for all possible combinations of input parameters and the optimum results are shortlisted from the data pool. A formal testing on the optimized solutions is done for counter checking the acoustic results. The definition workflow is explained further.

		CATT ACOUSTICS	PACHYDERM	CUSTOM DEFINITION
GEOMETRY	Multiple Source	✓	✓	✓
	Dynamic Source	×	-	✓
	Multiple Receiver	✓	✓	✓
	Changing Geometry	×	✓	✓
ACOUSTICS	All Frequency Spectrums	✓	✓	-
	Absorption	✓	✓	✓
	Scattering	✓	✓	✓
PROCESSING	Real-time Calculation	×	-	✓
	Parametric Optimization	×	-	-
	Run Time - 1000 rays	5 min.	2 min.	-

Table 5.1: Acoustic software comparison



GEOMTERY MODELLING

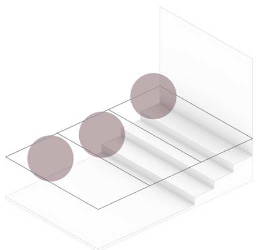


vision
pattern of
rid for now
Point Extractor
Points in every cell
(complexity dependent)
Lines & Vector
Line from source point
to points on surface.
Vector for direction
RAY TRACING
Create the rays in the space using
Lines & Vector
Boundary Conditions
No. of reflections
Manual number
input
Space
boundary
Indoor
elements
Roof
surface
Move
cells as solid extrusion
ative z-direction
d on the values
NEW DYNAMIC PATTERN
constantly updated with the refresh rate

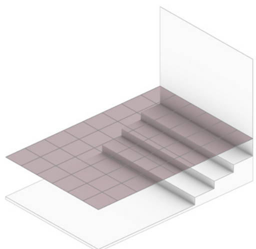
GEOMETRY MODELLING

Receiver

For prediction of sound energy results, the receiver needs to have a definite volume, preferably a sphere for the ray vectors to collide with the receiver in 3D modelling. A spherical volume is considered as it provides an omnidirectional sensitivity. In theory, enough rays should be able to penetrate or collide with the receiver surface to achieve statistically valid results. The volume of the sphere is critical in finding the optimum number of rays required for a simulation.



Spherical Receiver geomtery
1 receiver in every zone



Surface mesh geomtery
1 x 1 grid

Figure 5.10 : Receiver and floor geometry

The ground plane can also be taken as the receiver but due to the large surface area, the number of rays increases and makes the simulation run-time longer. Although, the surface can be divided into a smaller grid to see the impact of sound energy in every corner and study the sound distribution patterns.

Source Point & Ray Tracing

For a digital simulation, a definite source point is required for projecting the rays. With the sound source mapping method explained later, the system will also detect a locus point. The sound source is taken as an omnidirectional source as the direction is unknown. The emittance of the rays has to be uniformly distributed in a spherical setting with equal intensity on each ray (Vorlaender & Summers, 2008). The number of rays emitted is critical as it reflects the sensitivity on the accuracy of the model (Ondet & Barbry, 1989). This equation is used to calculate the optimum number of rays based on the room model

$$N_{ray} = \frac{10 \times V_{space}}{V_{receiver}}$$

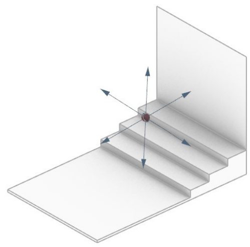
N_{ray} = number of rays
V_{space} = volume of space [m³]
$V_{receiver}$ = volume of receiver [m³]

The number of rays (Nray) should not be less than the number derived from this formula. With the number of rays, the acoustic energy (E0) carried out by each ray is calculated based on the sound power level of the source.

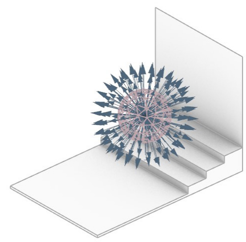
$$E_0 = \frac{10^{\frac{L_w}{10}}}{N_{ray}} \times 10^{-12}$$

L_w = sound power level [dB]
N_{ray} = number of rays

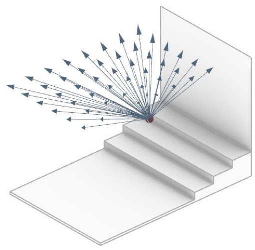
The vectors for generating these rays are created using three different methods: Star method, surface centroid and an Icosahedron dome. With the surface centroid method, it is possible to shoot more rays towards the targeted surface and have a better feedback of ray diffusion as the number of rays are capped.



Star vector method
Control parameters :
- Star type
- Resolution (Number of vectors)



Geodesic vector method
Control parameters :
- Geodesic type
- Resolution(Number of vectors)



Surface centroid vector method
Control parameters :
- Resolution (surface sub-division)

Figure 5.11 : Ray Vectors generation methods

Ray Propagation

The custom definition is divided into two parts. For the first part, a ray propagation algorithm is written to bounce the rays emitting from the source point within the defined geometry. Ther are some input parameters that can be played with to tweak the ray propagartion. These parameters are: source point, ray vectors, room geometry and the number of incidences. The number of incidences is a slider input which influence the number of reflections till the ray continues to bounce of surfaces. This can be increased for higher accuracy.

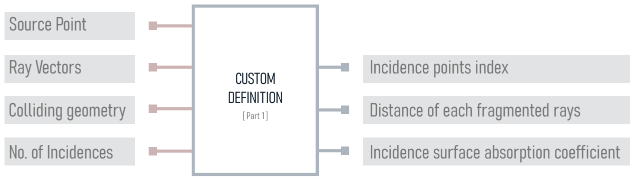


Figure 5.12 : Custom definition [Part 1]

Although, a right balance has to be ensured between accuracy and computation time. The first part of the definition generates the incident point indexes, distance of every ray fragment, and the absorption coefficient of incidence surface. These outputs become the input for the second part of this definition.

ENERGY CALCULATION

With every incidence, the initial energy (E0) of every ray is reduced based on the reflection coefficient of the surface material it collides with. The energy after n number of incidents will be En. When the ray reaches the receiver, the energy retained by the receiver (E') after all the incidences is calculated using this formula.

$$E' = E_0 \times e^{-h.d} \prod_i (1 - \alpha_i)$$

- E' = retained energy in the ray [Pa]
- E_0 = initial energy on one ray [Pa]
- h = absorption coefficient of air
- d = distance travelled by the ray [m]
- α = absorption coefficient of colliding material

The sound energy is converted into sound intensity. A cumulative summation of all the rays that collide with the receiver provide the total sound pressure level at the receiver.

$$I_R = \sum_i E_i / \pi r^2$$

- I_r = sound intensity at receiver [W/m²]
- E_i = energy of ray [Pa]
- r = radius of rceiver [m]

The rays collide with the receiver after certain number of incidences. The order of incidence for each ray colliding with the receiver is calculated to get the number of collisions for each incidence number. The total number of rays colliding with receiver is also calculated. This is done to manipulate the number of rays reaching the receiver.

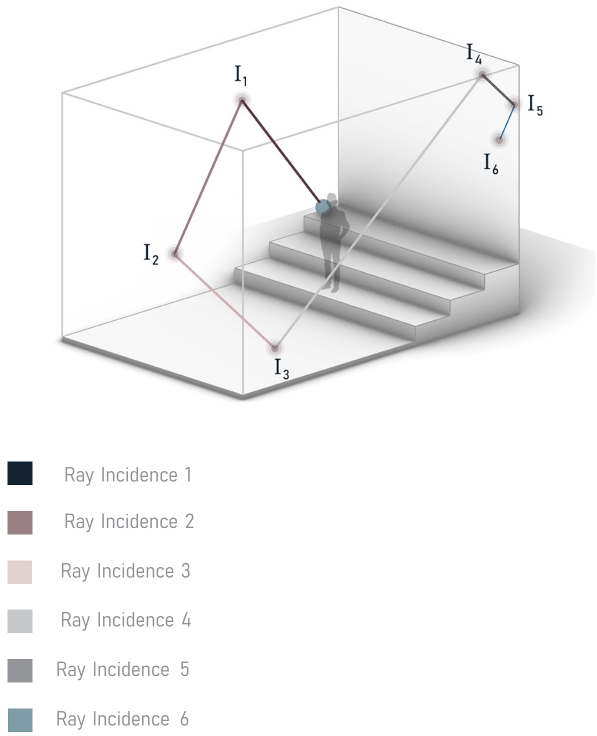


Figure 5.13 : Ray order of incidence

The rays are broken into segments and colour coded to represent the order of reflection. The same colour code is used for the incident points of the rays reaching the receiver.

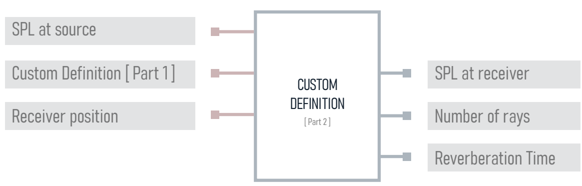


Figure 5.14 : Custom definition [Part 2]

RESULT CORROBORATION

A result comparison is drawn to check the result difference between CATT Acoustics and Pachyderm. Test case A is modelled in both platforms and the results are calculated with a flat ceiling. The surface acoustic properties are also kept same for precise results. The result data is in Appendix F.

Input		Test case	Room A
Zero position		Source position	B2
		SPL	60 dB
	RECEIVER	PACHYDERM	CUSTOM DEFINITION
SPL	R1	52.61 dB	53.91 dB
	R2	51.71 dB	52.64 dB
	R3	50.39 dB	49.51 dB
RT 60		1.55 s	1.61 s
Number of Rays	R1	-	297
	R2	-	224
	R3	-	

Table 5.2 : Acoustic result corroboration

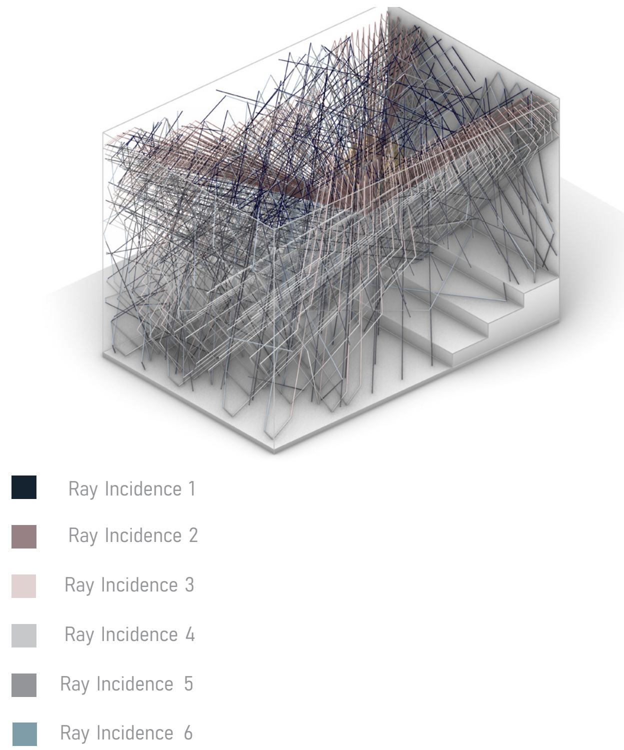
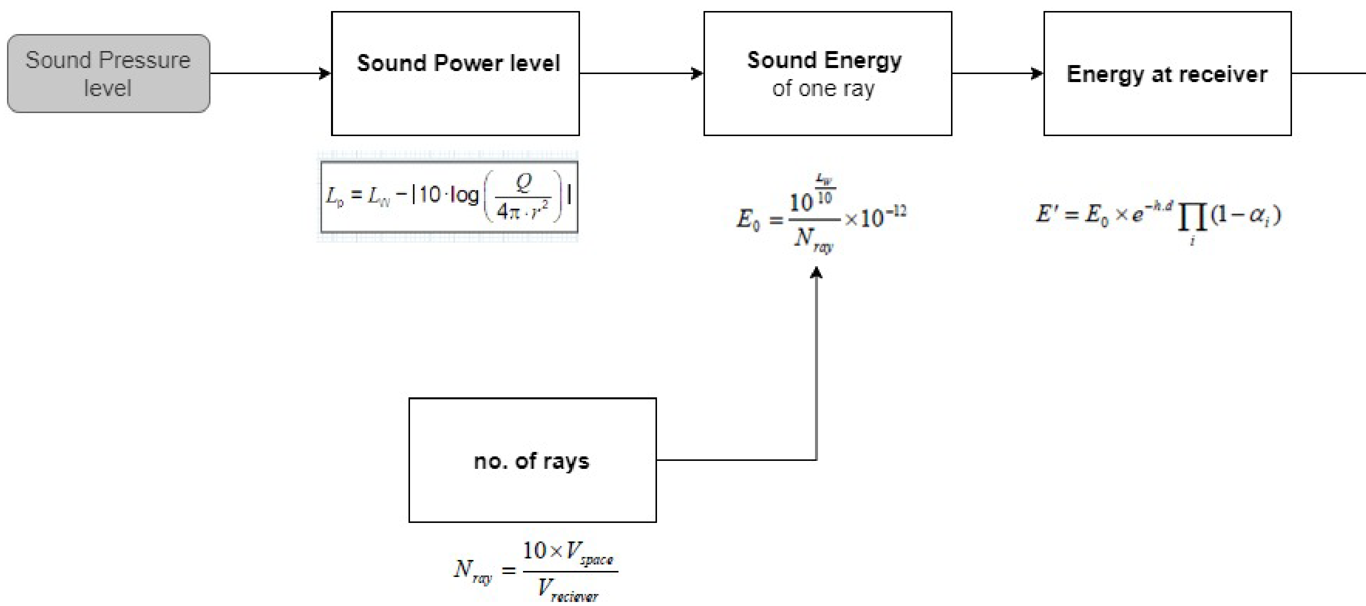
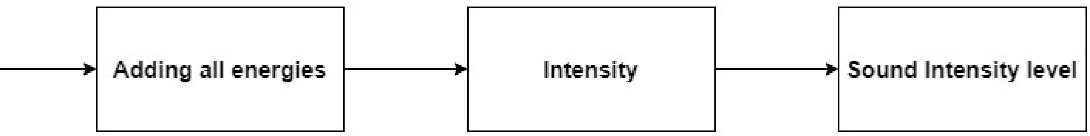


Figure 5.15 : Custom definition result output



ACOUSTIC CALCULATION



$$I_R = \sum_i E_i / \pi r^2,$$

$$L_I = 10 \log_{10}\left(\frac{I}{I_0}\right)\ \mathrm{dB}$$

$I_0 = 10^{-12}\ \mathrm{W/m^2} \equiv 0\ \mathrm{dB}$

VI

the
sound
bending
project

RESEARCH BY DESIGN | ACTUATION

ACTUATION MECHANISM

While the computational tool designed helps in optimizing the blocks position to the desired position, it must be translated into the physical domain to create the responsive surface. With the actuation technologies already explored and discussed in the previous chapters, the design output is tested on a scaled prototype to test the real-time response mechanism. The factors to consider while selecting an appropriate mechanism are:

1. Actuation response time
2. Output power and refresh rate
3. Travel distance
4. Size and complexity of operation

These factors can become a comparison benchmark amongst the various mechanisms. The focus is on validation of concept; thus, the mechanism is chosen based on the prototype scale. The real scale surface might entail a totally different mechanism which is not touched upon in this thesis. Arduino UNO is used as the main drive for guiding the mechanism with the computational inputs. This is considered for the prototyping and testing as it allows a lot of freedom in tweaking and controlling the parameters to a great extent. The design output provides a complex combination which can be easily tinkered both physically by adjusting the wires and computationally by updating the code.

Method 1

PULLEY & CABLE SYSTEM

Pulley and cable system work using a simple rotary mechanism supported by pulleys to guide the cables. The initial design for the prototype generates flexible sliding movement for the blocks which create a random active pattern. The blocks are placed in a linear arrangement and connected to the axel with individual ropes. The ropes pass through a guide bar just above every block row which has pulleys attached to it. The pulleys enable a smooth movement of the rope when the axel is rotated. The axel made of a steel wire is bent based on the sine wave curve designed earlier. One end of the axel is fixed in the wall and the other end is connected to a single stepper motor that generates a rotary movement.

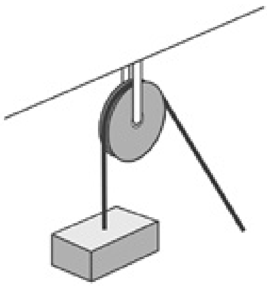


Figure 6.1 : Pulley & cable system | Inspiration

The suspension height of the blocks is manipulated using variable rope lengths attached to the rotary axel as seen in the maquette picture below. The rotary axel has a definitive sinewave curve and the peaks and troughs of the sinewave act as the controlling point for the threads. The advantage of gravitational force keeps the rope in tension tolerating for the blocks to create movement configurations.

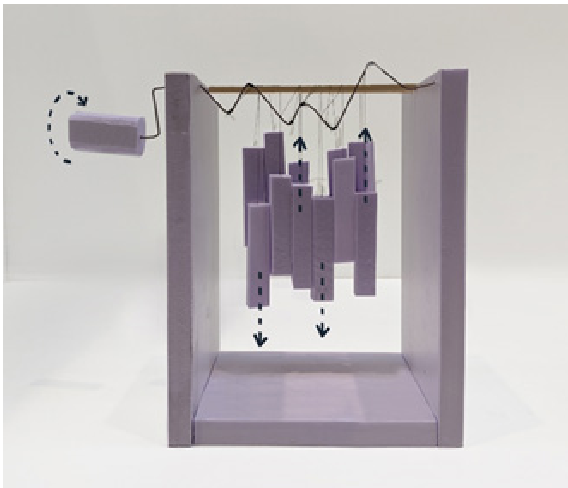


Figure 6.2 : Physical prototype 1 illustrating the movement

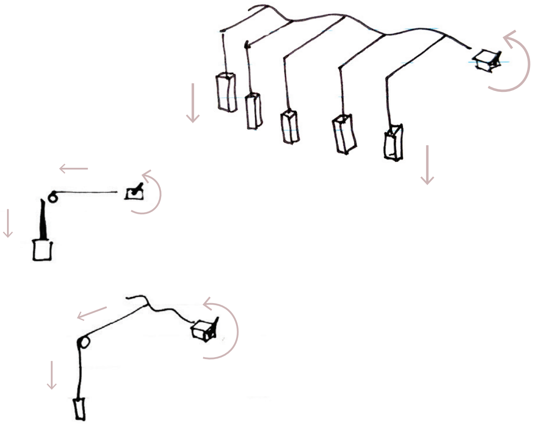


Figure 6.3 : Pulley & cable system | Vector diagram

Design Issues

- The system uses gravitational force and thus is not possible to change the plane of the surface.
- The blocks are freely suspended using ropes. This generated a horizontal movement in the blocks as well. This affects the movement of neighbouring blocks.
- Once in place it is difficult to alter the rope length.
- Being a single control mechanism and a fixed sinewave in the axel, limited combinations are possible with no feasibility for logic-based control.

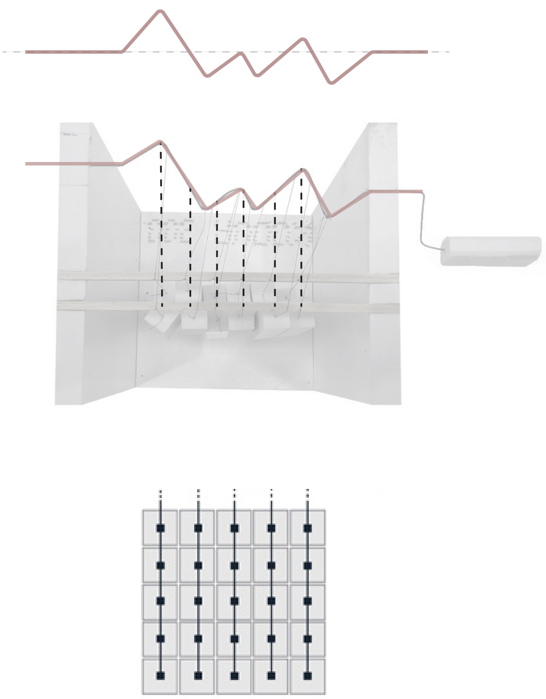


Figure 6.4 : Sine-wave to control the movement

Design Development

- The rows of blocks can have an individual stepper motor to have more control over the movement of individual rows.
- The blocks can pass through a grid that acts as a guide and restricts the horizontal displacement.
- The ropes can be replaced with levers and then the surface can be oriented in different planes.

Method 2

SLIDER CRANK MECHANISM

In the second prototype, the pulley system is replaced with a slider-crank mechanism. Taking inspiration from piston engine, the rotational movement of the crank is translated into a horizontal movement of the connecting rod. The connecting rod is attached to the block which moves it in the same direction. The setup is simply rotated to align it vertically and check for the gravitational resistance. For the rotation of the crank it is attached to a servo motor which is digitally controlled. The vector diagrams explain the movement logic.

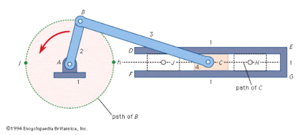


Figure 6.5 : Slider crank mechanism | Inspiration

MDF laser cut pieces function as the connecting rod. Pin holes are made in the rod to adjust the vertical movement to precise dimensions. The initial position of the blocks can be adjusted initially but remains fixed during the movement. This arrangement allows more combinations considering each row has an individual motor control.

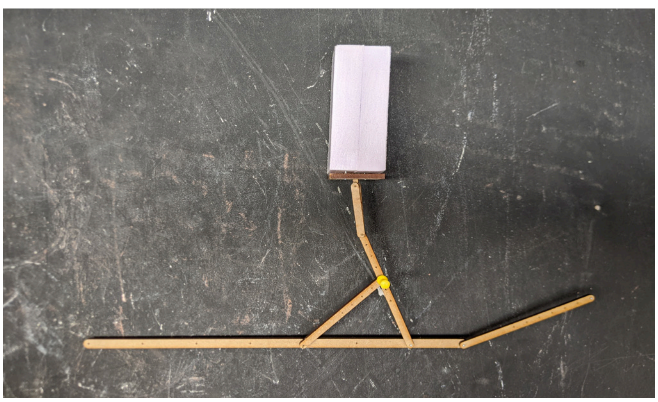


Figure 6.6 : Physical prototype 2 | slicder crank mechanism

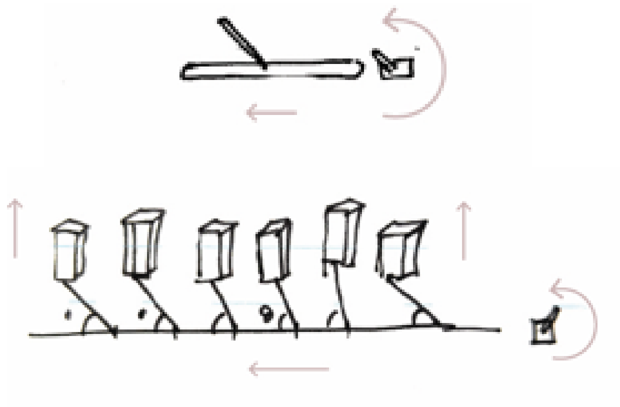


Figure 6.7 : Slider crank mechanism | Vector diagram

The block has a rod extension that linked to the connected rod to ensure smooth transition of angular vector to z-axis vector. A guiding grid is made to resist the remaining horizontal movement. A flat grid is not enough to control the movement, so the grid is made into a waffle-like structure to enact as a secure guiding chamber for the blocks.

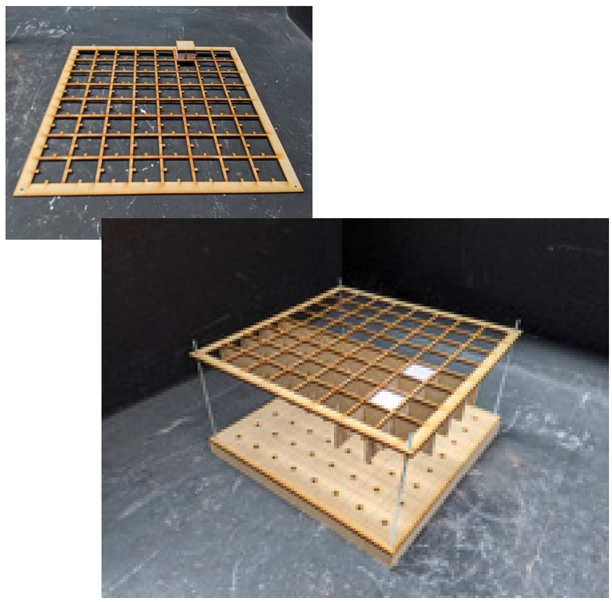


Figure 6.8 : Flat grid and waffle grid | Physical prototype 2

Method 3

PISTON CRANK MECHANISM

The movement is still not smooth as the vector gets translated from rotation to horizontal to angular to vertical motion. The mechanism is updated to match the piston movement in an engine, where the translation happens in just three steps: rotation-angular – vertical..

Figure 6.9 : Piston crank mechanism | Inspiration

A cylindrical rod is attached to the servo motor directly that rotates it in clockwise motion. Connecting levers are fixed to the rod on one end and the other end relates to the block. With the rotation of the rod, the rotation vector gets translated into a vertical motion of the block. The height of the lever determines the distance of vertical displacement. The movement is smoother and controlled.

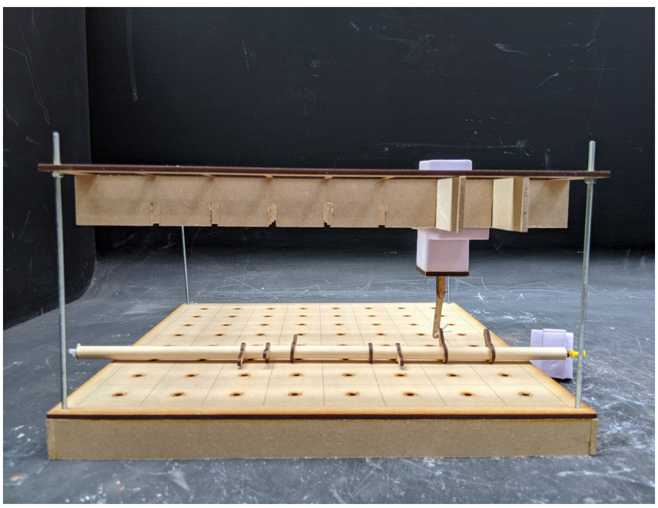


Figure 6.10 : Physical prototype 3 | piston crank mechanism

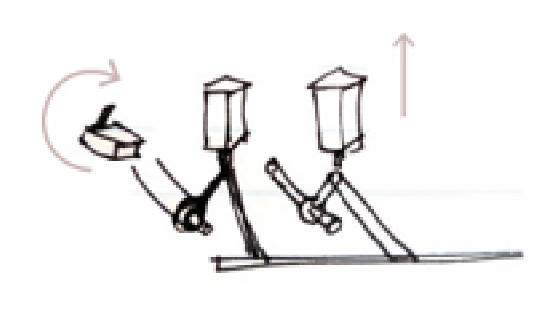


Figure 6.11 : Piston crank mechanism | Vector diagram

A possibility of compound movement is also tested where a lever is attached to two servos sending in different dat. The compound vector movement is not smooth and can be a hindrance in swift response to the sound. This conclusion is derived from the physical testing as seen in the prototype maquette below. Although, the number of possible combinations increase, this adds to the complexity of the mechanism is thus refuted.

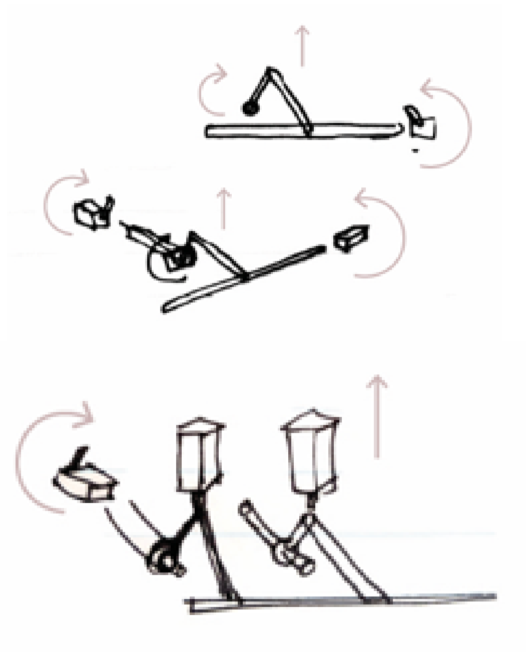


Figure 6.12 : Piston crank compound movement | Vector diagram

In the complete setup there is a rod for every row with secondary connectors for every block. This setup is selected as it limits the number of controls to one motor per row and the connection combinations are tried in the next stage.

Figure 6.13 : Physical prototype 4 | Alternate grid system using Piston crank mechanism

The mechanism is then tested for its response to real time sound. Three factors are tested:

1. Reaction time
2. Speed of movement
3. Refresh rate

The rows move independently, but the blocks within a row, move in the same manner, only the starting position can be adjusted. The way around for this is to create an alternate block grid. In this the rods are laid in both x and y axis. The alternate blocks are connected respectively to the x-axis and y-axis rods. This creates a chess pattern and allows for different depths between adjacent blocks, creating valleys and troughs between two immediate blocks.

With this arrangement, the number of configuration increases exponentially based on the number of rows and columns. This can be understood by looking at the number of combinations possible between two adjacent blocks.

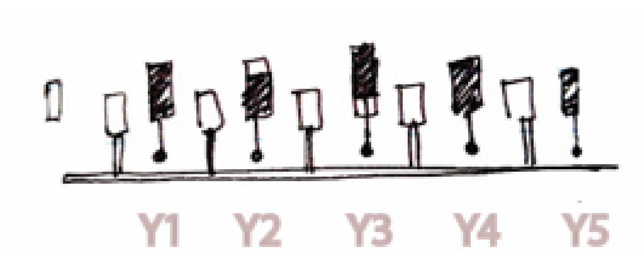


Figure 6.14 : Alternate control | Block division

Acoustic Co-relation

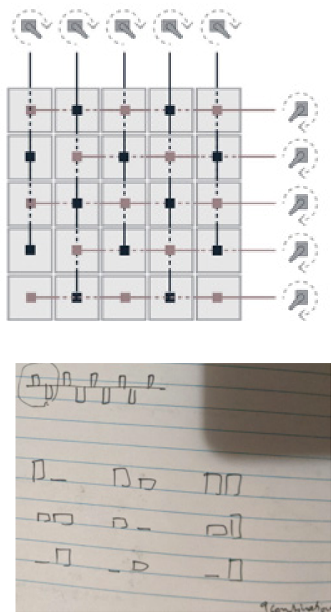


Figure 6.15 : Alternate control | Sample configurations

The blocks can have custom designed surfaces with unique absorptions coefficients depending on varying frequency ranges. The movement of blocks can be controlled accordingly. If there is high sound of low spectrum frequency, Blocks designed for this configuration will come down. Similarly, when a high frequency sound source needs to be controlled, the respective block can come down. So, the blocks need to be divide based on a spectrum classification. Although the placement must be staggered to create a diffusion in the sound rays.


FrequencyGenerator
2
Hz
HUAWEI P40 Pro | 5G

Design issues

- The square waffle-grid still provide friction in the movement, due to large surface area in contact.
- The corners of waffle create resistance in movement and increase the horizontal push affecting the vertical movement.
- The size of the first and second lever needs to be adjusted to achieve the desired vertical travel distance.
- As the blocks will be place upside down in the ceiling, a simpler locking system has to be devised to bring the blocks to zero position.
- The mechanism needs to be made quieter and smoother, for that washers need to be added when the block is fully retraced.

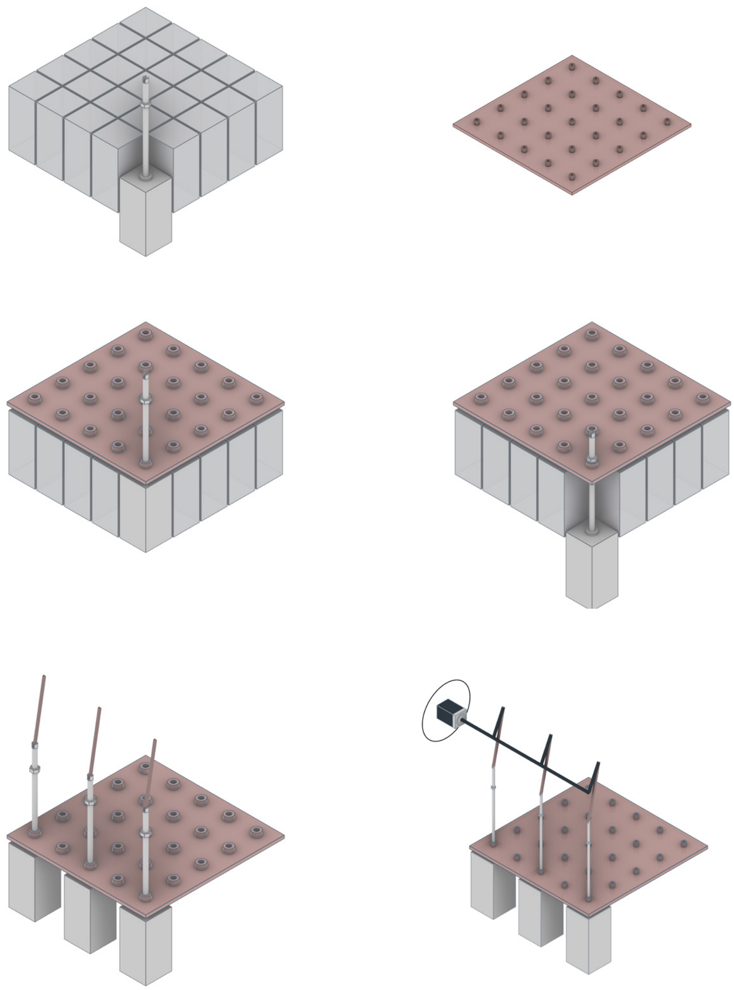
FINAL DESIGN

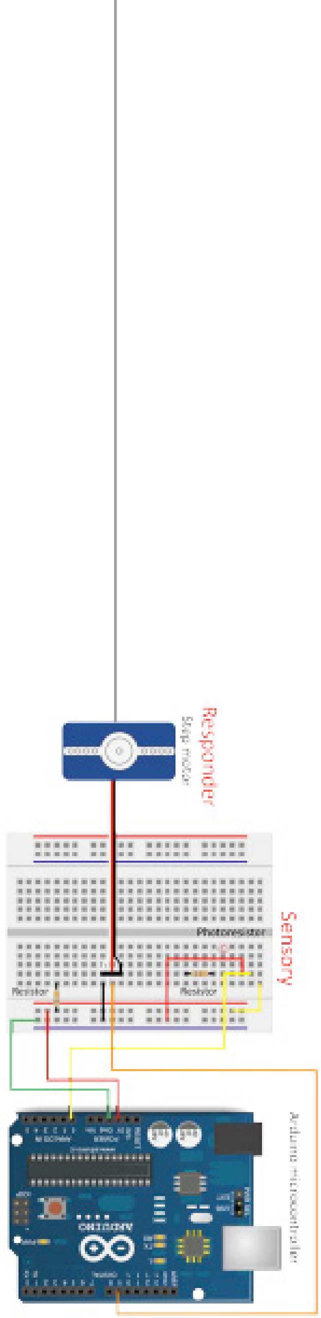
A cleaner and simpler design is made with all the earlier development inputs. The true scale proportions are taken into consideration for getting a real picture of the mechanism. The waffle grid is replaced with a peg hole grid. The vertical shaft of the blocks is made cylindrical to avoid any kind of friction. The cylindrical shaft passes through the peg holes, ensuring smooth and straight movement.

To ensure the maximum height is not breached, a nut is added to secure the block in its max position. When the block fully retraces to zero position a washer ensures the block doesn't make any sound on coming in contact with the grid plate. The following images explain the process in detail.

Figure 6.16 : (Preveious page) Physical prototype 4

Figure 6.17 : Digital prototype 5 | Step-wise explanation




Responder
Step motor
Photoresistor
Sensory
Resistor
Resistor
Arduino microcontroller

ARDUINO & REAL-TIME SOUND INPUT

For prototyping, an Arduino setup is used to test the response time and movement relation with a dynamic sound input. This is done using firefly to read the sound input and extract the sound data. The real-time sound input is received from the laptop microphone and is set to a refresh rate of 50ms. Firefly provides SPL and frequency data which is broadly divided to link with the movement as explained in the table below.

Movement Table

The movement is simplified by restricting it to limited number of steps as shown in the diagrams below. The number of steps can be increased to achieve higher accuracy for acoustic correctness. The table also highlights two extra steps(0.5 and 1.5) that can be added easily.

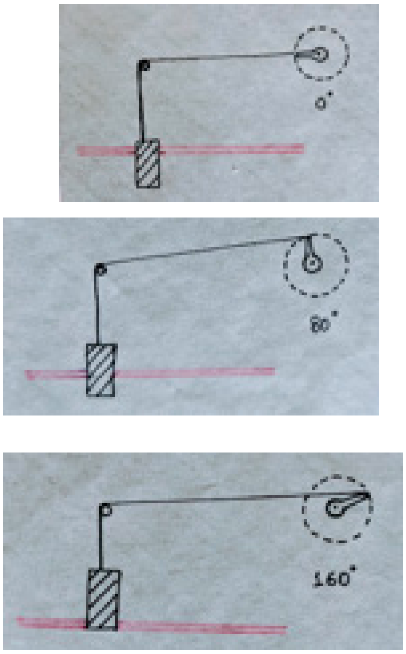
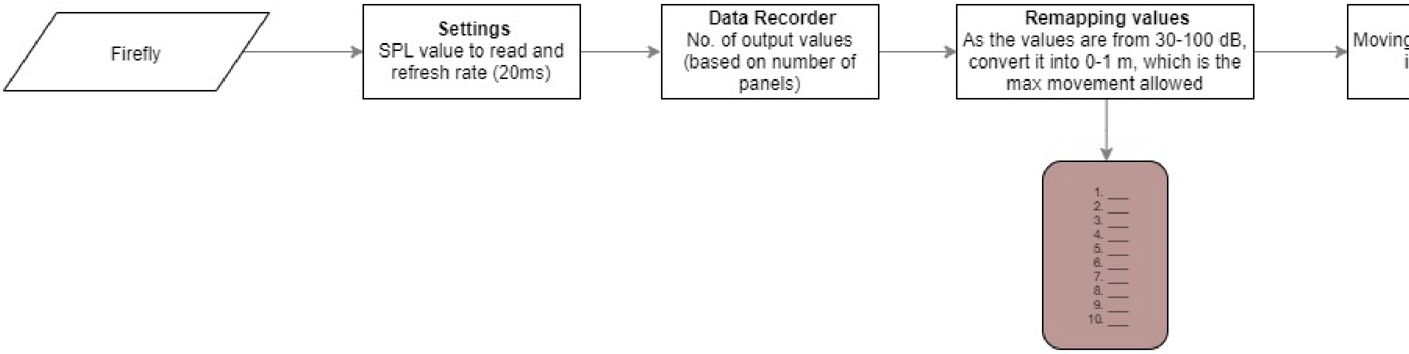


Figure 6.18 : (Previous page) Arduino setup

Figure 6.19 : Motor rotation steps



FIREFLY WORKFLOW

Input Value		0	0.5	1	1.5	2
Servo Rotation		0°	40°	80°	120°	160°
Block Movement	Prototype	0 m	0.01 m	0.02 m	0.03 m	0.04 m
	Simulation	0 m	-	0.3 m	-	0.6 m

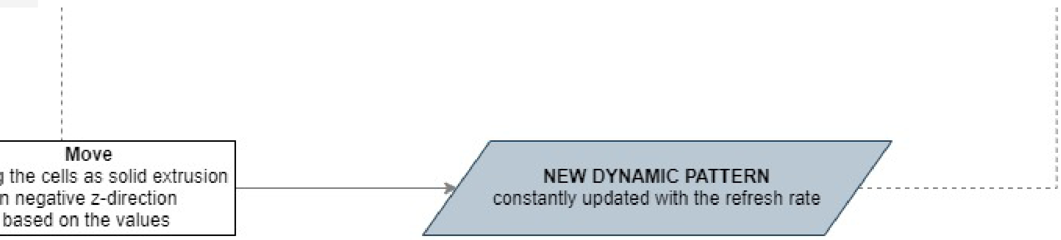
Table 6.1 : Rotation steps to movement co-relation

ACTUATOR MOTOR

The prototype is made using servo motors but there are better actuators and motors available that can impact the movement in terms of smoothness and time. These methods have not been physically tested in this research but can be beneficial in implementing in real scale systems. They are briefly explained below to draw a comparison between the affecting parameters.

PROTOTYPE IMPRESSIONS

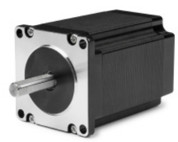
The blocks can have custom designed surfaces with unique absorptions coefficients depending on varying frequency ranges. The movement of blocks can be controlled accordingly. If there is high sound of low spectrum frequency, Blocks designed for this configuration will come down.
Similarly, when a high frequency sound source needs to be controlled, the respective block can come down. So, the blocks need to be divide based on a spectrum classification. Although the placement must be staggered to create a diffusion in the sound rays.



Closed loop feedback
High torque at high speed
Low pole count | 4-12
Increased cost

SERVO MOTOR
Rotary or linear actuator control

STEPPER MOTOR
Rotary or linear actuator control



Pricision drive control
High pole count | 50-100
Good for acceleration and accuracy
Low-cost and easy availability

ACTUATION MECHANISM

Belt driven slide pot
Small DC motor
Simple uni-control mechanism
Directional motion instead of steps

POTENTIOMETER
Motorized linear control

LINEAR ACTUATOR
Micro linear control

Straight line telescopic motion
Pneumatic cylinder mechanism
Sophisticated position control
different gear ratios for varied speed

VII

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RESEARCH BY DESIGN | COMPUTATIONAL

With the physical actuation strategy in place, the next step is to figure out the composition of the surface and develop a movement logic. The surface needs to be fragmented into smaller modules to achieve the irregularity in movement which is necessary for the diffusion principle as discussed previously. The surface and its movement patterns are developed by parallelly testing the design iterations for their acoustic performance in the predetermined test setup. The focus is on achieving optimum results with minimal movement and simplest design alternative.

The objective to limit the number of controls/ actuators has a major significance in forming the logic for movement of blocks. For this, various strategies are investigated representing different control systems. This investigation helps in deciding various parameters affecting the design such as, block size and height, maximum displacement and number of actuators required. The material properties of the blocks having varied acoustical characteristics are determined as they influence the acoustic calculations impacting the overall movement configuration.

Furthermore, this chapter explains the detailed mechanism of the kinetic component and its fitting in a given space. The mechanism illustrated is representative of the concept and not intended to be a functioning prototype on true scale. The mechanism in real application will vary depending on the space type and level of detail required for acoustic corrections.

CONCEPT

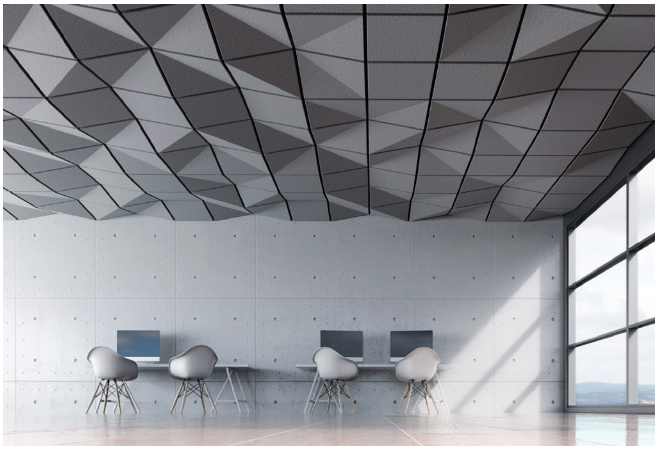


Figure 7.1 : Ceiling acoustic panel design (Turf Design)

The main intention is that the design should fit in every case irrespective of the building type, structural shape, or size. Acoustic ceilings are a part of the building system and should not have a unique design structure of its own. Thus, to accommodate in all design solutions a few examples are investigated to study the various ceiling design and grids possible. Taking cue from existing ceiling systems, it is efficient to incorporate the design logic within their structure framework.

SURFACE DESIGN

Grid Pattern

Based on the example case studies of ceiling grid patterns, the basic geometry patterns are modelled in a 3x3 grid setup and are simulated for ray tracing. Rays originating from a common source point are propagated to check the behaviour of ray reflections of every pattern. The study is conducted using a 2D planar ray and a 3D ray vector. The rays are shouted towards the central block which has different vertical placement than the neighbouring blocks. Study shows a direct relation between the number of edges to the ray diffusion. Cylindrical shape (curved edge) diffuses the ray in all possible directions, while the triangle (3 edges) focus the ray at one point.

Although in a cylinder the rays have a higher reflection within the surface as they keep bouncing against each other. This would impact the energy of the ray, so if the surface has a high absorption coefficient, the ray will die within the ceiling itself. To verify this, a simulation is run where 1000 rays are projected towards the ceiling and are checked for their incidence number when they collide with the ground surface. This is further explained in detail in appendix G. With this study, it can be assumed that square and hexagon perform in a balanced way and is possible to tweak the results as the rays reaching the ground have a mix of all incidence reflections.

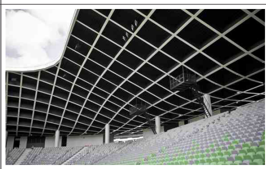
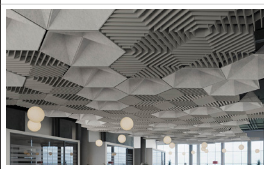
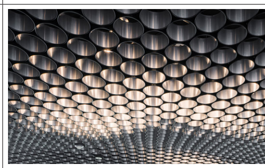
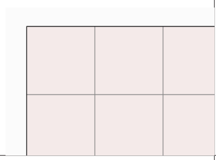
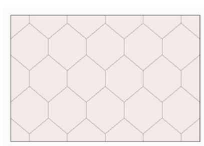
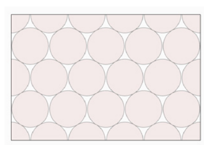
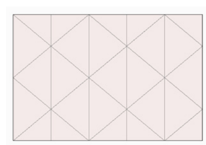
	FOOTBALL STADIUM	OFFICE WORKSPACE	LECTURE ROOM	AUDITORIUM
SPACE TYPE	Outdoor large open stand	Indoor small-size closed room	Indoor medium-size closed room	Indoor large-closed closed hall
CEILING IMAGE				
GRID TYPOLOGY				
SUPPORT FRAMEWORK	Structural grid roof support	Suspended false ceiling	Suspended false ceiling	Structural Coffered slab

Table 7.1 : Ceiling grid patterns

Shortlisted Pattern

Out of the many patterns possible considering the variables, three patterns are used for the design simulations. These are derived from the sqaure and hexagonal grids. The grid is placed on the ceiling surface of the test case resulting in three design variants named as :

1. QUAD-Klein
2. QUAD-Groot
3. HEXA - Klein

BLOCK DESIGN

Tile to Block

The three selected patterns are plotted in the conventional acoustic tile sizes of 0.6 m and 0.3 m. The tiles are then extruded to double the width as corresponding to the design guidelines. From here on, these blocks will be referred as ACUTE blocks.

A minimum gap is created between blocks for avoiding friction during the movement. For swift movement, the block needs to be lightweight, hence a box skeleton is designed with the walls having a higher absorptive material padding. The bottom and top surface is high on reflection. A detailed exploded view illustrated on the next page entails all the material properties and joinery involved in the designing the block. The design is kept simple with limited screws and more of snap joinery for easy installation. A level is attached to the blocks which will guide the movement distancing the block from the moving mechanism. This is to avoid any damage to the exposed surfaces of the blocks and limiting the contact surface for movement to reduce friction.

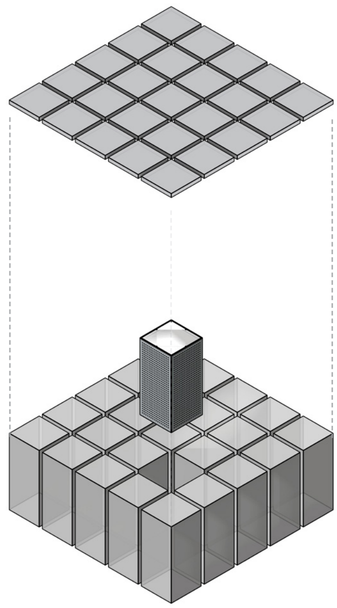


Figure 7.2 : ACUTE Block design

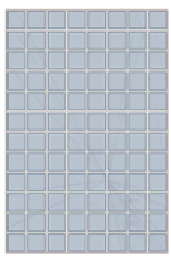
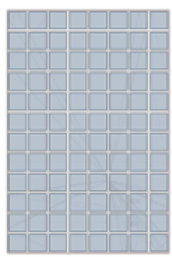
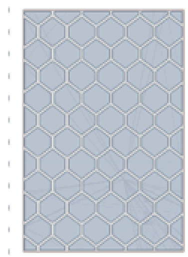
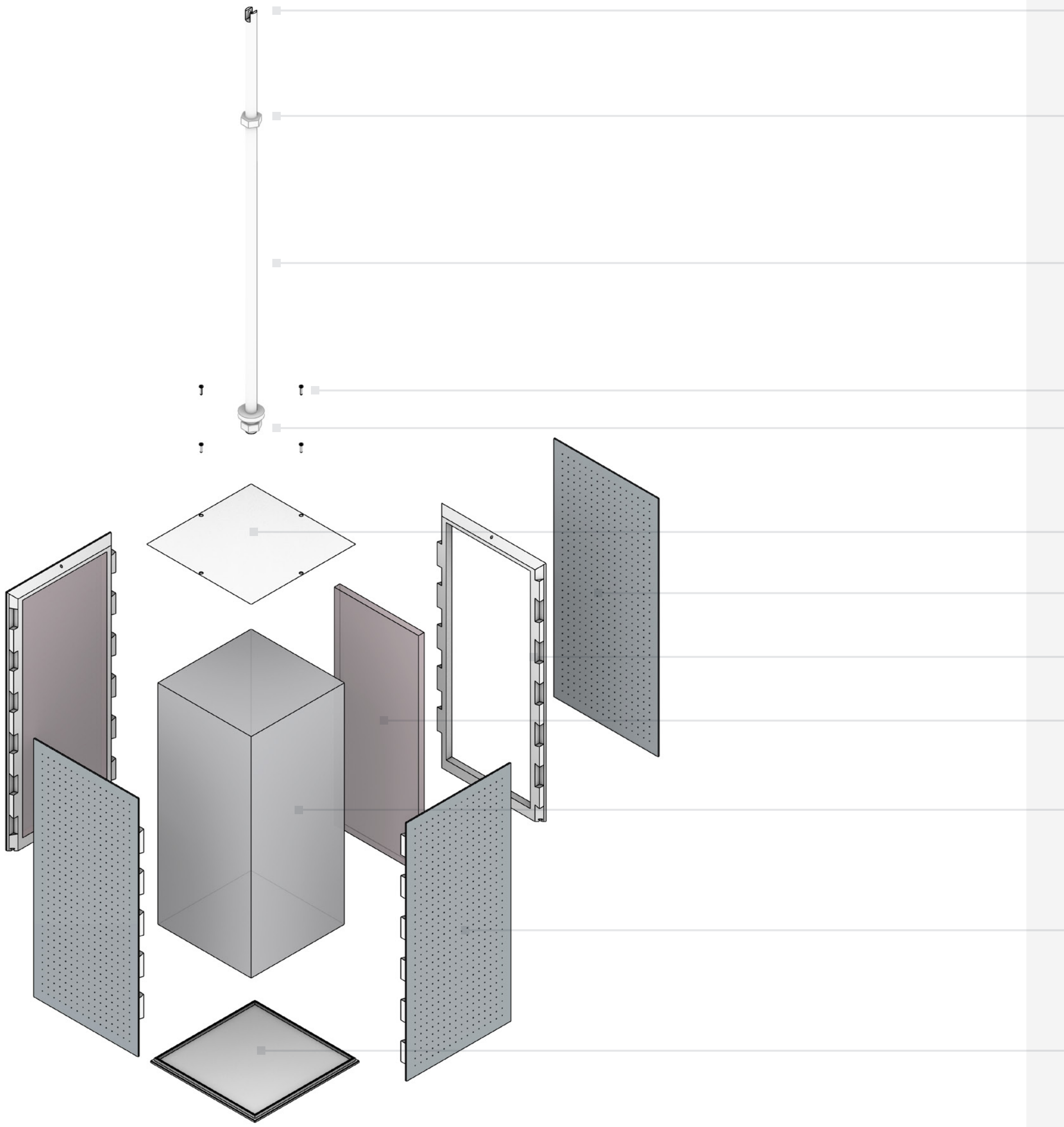
	QUAD - Klein	QUAD - Groot	HEXA - Klein
ACUTE blocks			
Block size	0.6 m	0.3 m	0.4 m
Block height	1 m	0.6 m	1 m
Number of blocks	96	384	72
Block spacing	0.02 m	0.01 m	0.01 m
Number of edges	4	4	6

Table 7.2 : Pattern grid design



Perforated sheet

Nut to adjust the vertical displacement
height

20 mm hollow aluminium rod with
custom cut at the top

Rubber wahser to
Nut to secure the rod into the block

8mm fibre sheet top flap

3mm perforated fibre sheet

12mm galvanised steel frame with dove tail joinery

12mm mineral fibre block

Glasswool filling

Custom acoustic tile

3mm fibre sheet bottom flap with snap joinery
and painted finish under surface

Surface Properties

The blocks have walls and a bottom surface that can have different acoustical characteristics to affect the ray energy. The bottom surfaces can have a high reflection coefficient, as the bottom surface is exposed all the time. Whereas the walls can be absorptive. The degree of absorption coefficient can differ depending on the treatment needed for the space.

Figure 7.3 : (Previous page) ACUTE Block exploded axonometric

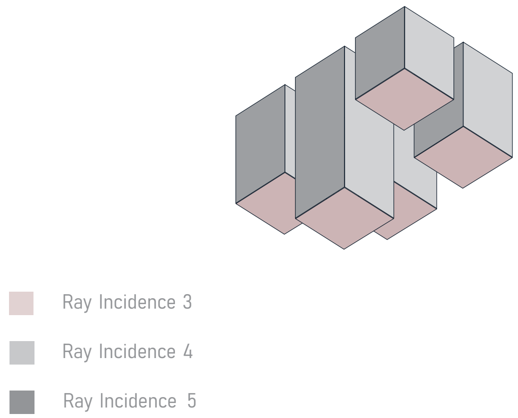


Figure 7.4 : Block surface | Acoustical properties

1. The four walls of a block can be alternated for higher and lower absorption coefficient.
2. The blocks controlled by X-axis motors can be high absorptive and the blocks controlled by Y-axis can be less absorptive.
3. Zone based division of blocks. Blocks in a specific zone can have high absorptive and the remaining can be less absorptive.

The mix of these three types of treatment can be specifically designed considering the space requirements and the mean sound pressure levels generated in the space.

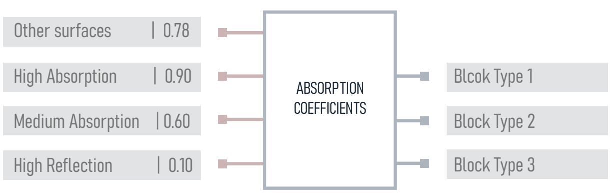


Figure 7.5 : Absorption coefficients of surfaces

MOVEMENT CONSTRAINTS

A similar movement strategy to the physical prototyping is adopted to create simulation models. With the prototype modelling, many queries that could not be addressed then, can now be taken into consideration by evaluating design solutions using variable parameters. These parameters will guide in controlling the actuation in respect to enhancing the acoustical environment.

For generating the movement, the research focuses on rotation as the main trigger force which is eventually translated into a traction motion using simple axels and gears. Most stepper or servo motors come with continuous loop movement in one direction. The input for such motors is the number of steps or the speed of rotation. Thus, the motor needs to be set to zero position every time a unique solution is required.

Rotation Steps

A bidirectional rotation motor is preferred as there is a possibility to go back and forth reducing the time to reach a specific position. The number of steps must be limited to use this as a variable for acoustic calculations. The rotation is restricted just for half circle as the other half gives the same result in this case. The semi-circle rotation is restricted to just three movement steps for limited variables and controlled movement of the blocks. The diagram below illustrates the three steps and their response on the vertical movement of ACUTE blocks.

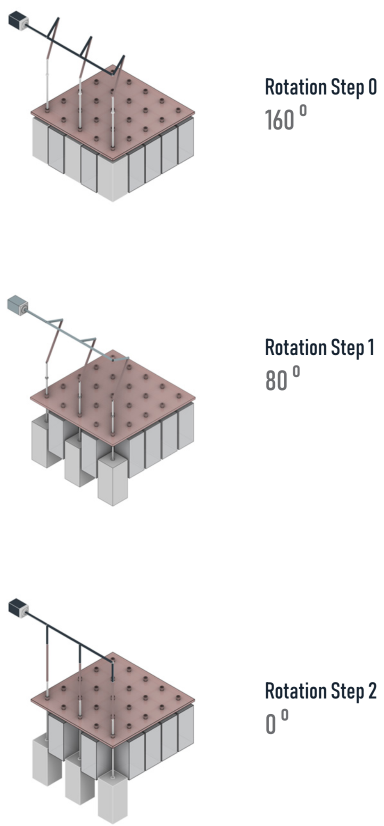


Figure 7.6 : Three step rotation movement

Number of Motors

Connecting a single motor to several blocks reduces the overall number of controls. This is like an array logic used in piston engines. With every motor there is an added cost and it increases complexity of the system. Apart from the physical constraints, the simulation runtime upsurges with every motor as the movement combinations have multi-fold possibilities. The rows and columns can act as a series. The rows and columns can further be also connected with a single control. The chart below shows the number of movement combinations in relation to the number of motors for The Quad-Groot design grid.

Design		Quad- Groot
Number of blocks	8 x 12	96
Rotation Steps		3
TYPE	**NUMBER OF MOTORS (N)**	**TOTAL COMBINATIONS (3^N)**
One-curve Control	1	3
Two-curve Control	(1+1)	9
One-axis Control (x axis)	8	6,561
One-axis Control (y axis)	12	531,441
Two-axis control (compound movement - 2^N)	(12 + 8)	1,048,576
Alternate block control	(12 + 8)	3,486,784,401
Unique motor for each block	96	6.36 X 10^45

Table 7.3 : Number of motors and combinations

MOVEMENT CONFIGURATIONS

One-curve Control

This is a single motor control design variant. The motor is used to rotate the sine curve to create the three combinations possible. The sinewave curves shape must be definite in a physical system; however, the design of sinewave can be tweaked for the digital simulation to achieve better results. The curve is divided as per the number of grids in the axis and each point controls the respective grid. All the blocks in one grid have an identical movement. As the curve rotates the distance from the curve division points to the start line points of the grid changes. The image below explains the how the change in distance is translated to the vertical movement of the blocks. The configurations generated by this method have a similar sinewave like patterns.

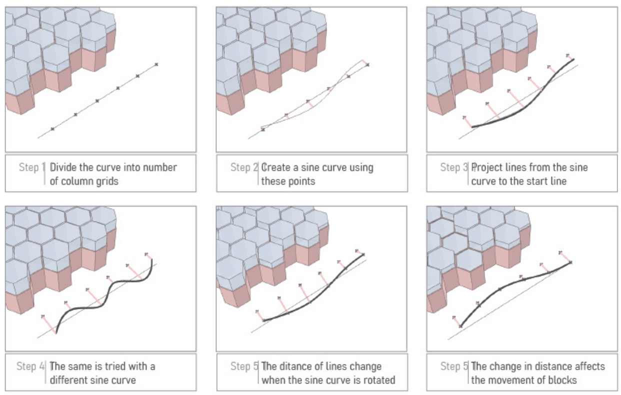


Figure 7.7 : Sinewave curve design process

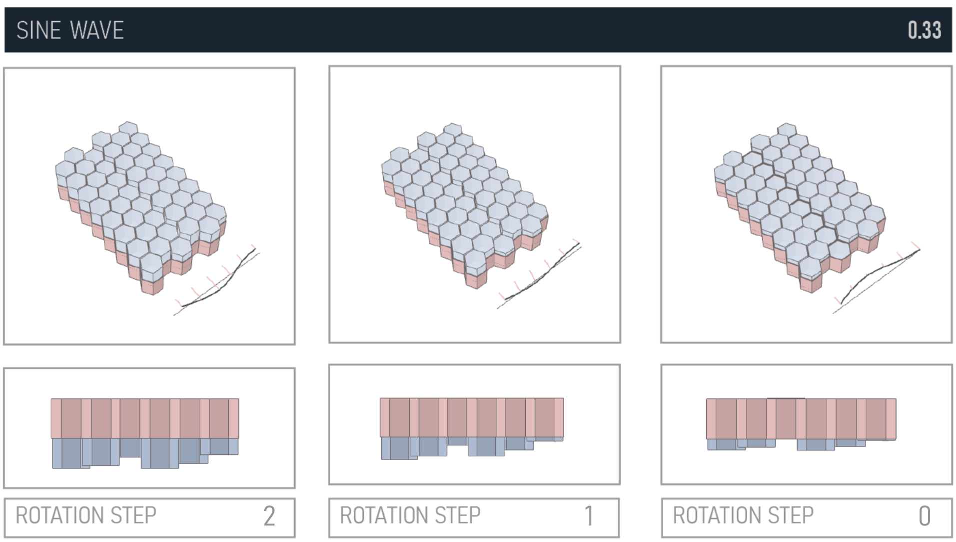


Figure 7.8 : One curve control | Rotation steps

The diagram depicts the difference in movement with the step rotation of motor. This specific diagram is generated using a sine wave of 0.33. This method creates a difference in block heights in just one direction. From these simulations it can be stated that the rotation just affects the height of the blocks in unison. There are no interchangeable patterns created. A few other simulation tests for this method are in Appendix E.

Two-curve Control (2 step motors)

Two-way control works exactly in the same manner but with two motors, synchronously controlling the two sinewave curves in respective direction. The two axes can have a different sine wave and a unique movement. The physical arrangement is complicated as the blocks have a compound movement from both directions. The rotation steps for the motors are restricted to 2 steps. The blocks have following movement configuration :

1. Both the controls are at Step 0
   No movement
2. One of the controls is at step 1
   Move the block by 0.3m
3. Both the controls are at Step 2
   Move the block by 06m

This method can create a preset configuration that has a high diffusion effect on the sound rays. However, the movement of the blocks is till in unison. Different combinations have an unnoticeable difference both in visual appearance and in calculation results. One such combination with a sine wave of 0.33 in both axis is shown below, the remaining ones are in Appendix E.

Single-axis Controls

The curve is the above case is replaced by individual motors for each grid, giving the possibility of changing the initial position. Although the movement of blocks in one grid remains homogeneous. The method also co

Dual-axis Controls (2 step motors)

This also uses a compound movement for every block based on the information coming from their respective grid control motor. For instance, the block highlighted in the diagram is controlled by the input of X2 and Y4 grid.

Alternate Axial control

Compound movement is not a reliable solution in terms of physical working. Thus, a method is deduced where the grid is divided in a chess pattern format. Alternate blocks

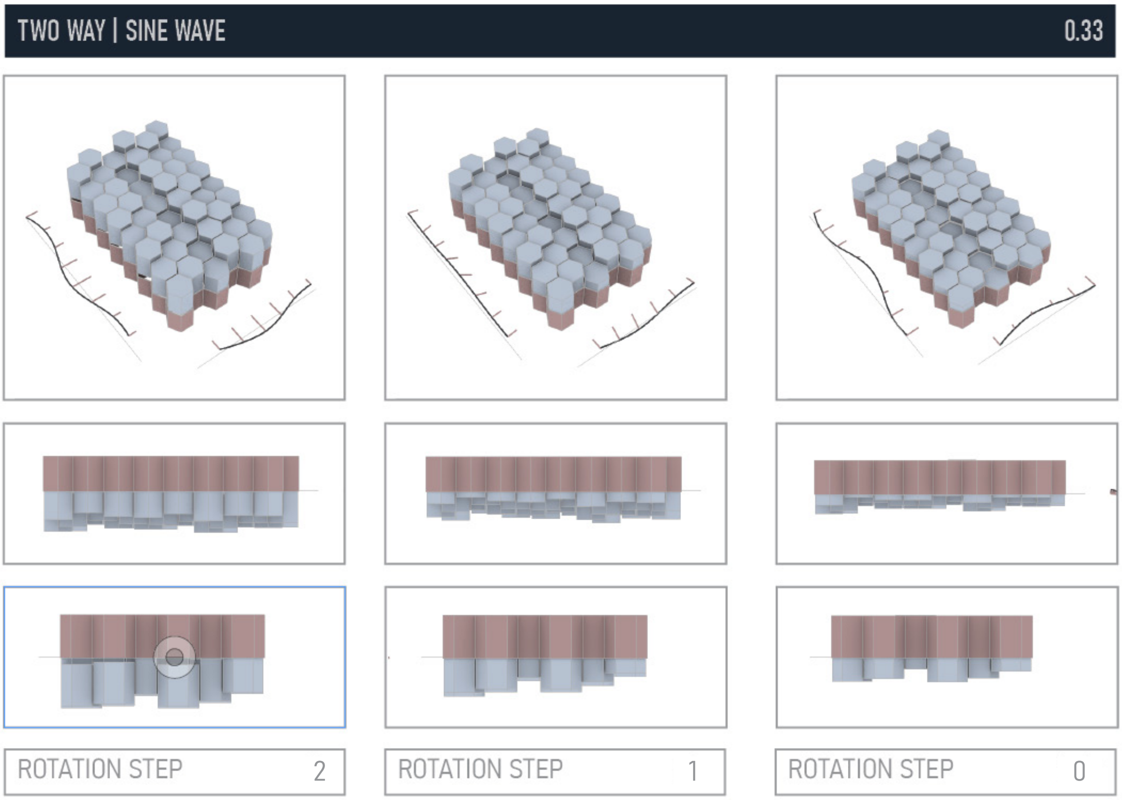


Figure 7.9 : Two curve control | Rotation steps

are put in single series. As seen in the diagram the blocks with pink marker are controlled by y axis motors and the blue marker blocks are controlled by X-axis motors. This way, the monotony of the pattern is also broken, permitting an aperiodic repetition. The highlighted block in the right diagram is controlled just by Y-4 motor.
The diagram below explains how the alternately divided blocks are controlled for a hexagonal grid. The first image shows the highlighted blocks controlled by X-axis motors and second image shows the blocks controlled by Y-axis motors. Due to this, numerous combinations are possible, and the periodicity of movement is broken.

The blocks can be brought to zero position by putting all motors to step 0. The result sheet below shows some of the combination possibilities and the respective motor positions. The patterns can be symmetrical as well if required. With this arrangement, it is also possible to change the configurations of a specific zone in the room as seen in the third case.

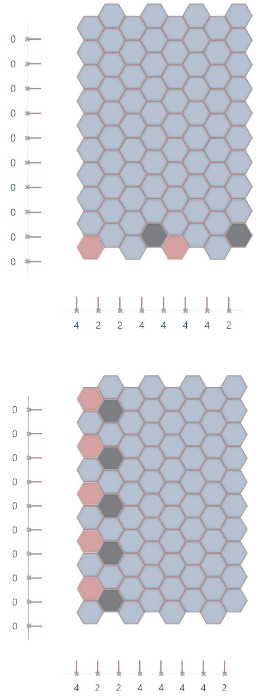


Figure 7.11 : Alternated axis | Block division strategy

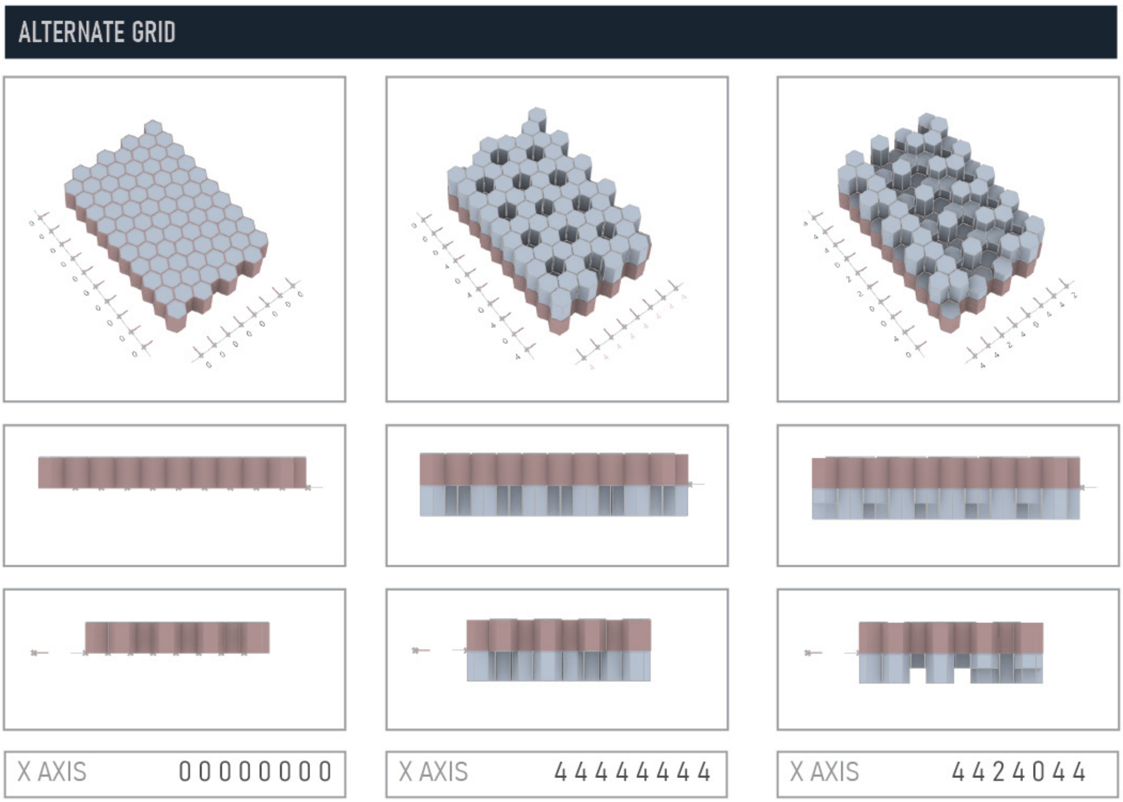
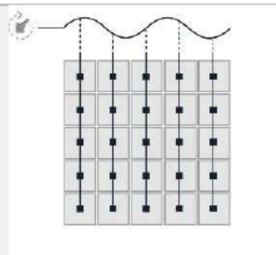
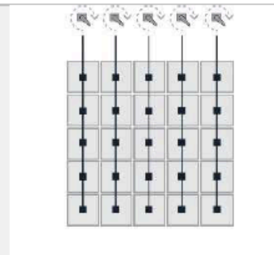
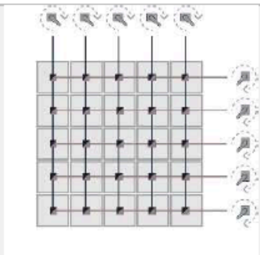
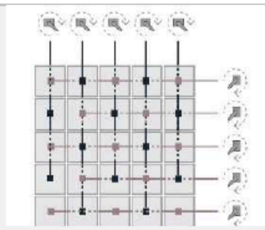
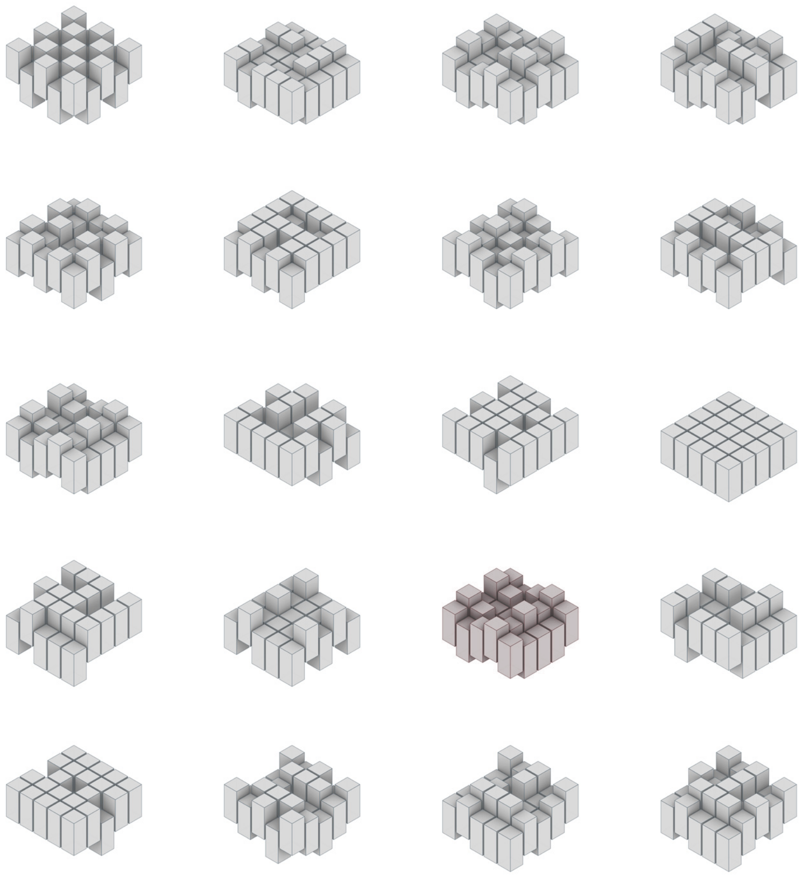


Figure 7.10 : Alternate axis control | Rotation steps

	Sinewave Control	One-axis Control
Control Diagram		
No. of controls	1	Number of rows (5 in this example)
Permutation count	Rotation steps (2 - 4)	(Rotation steps) N^{Rows}
Fixed Parameters	Sine wave	Starting position of blocks
Resultant Vector Diagram		

Two-axis Control	Alternate Control
	
Number of rows + number of columns (10 in this example)	Number of rows + number of columns (10 in this example)
(Rotation steps) $N^{Rows+} N^{columns}$	(Rotation steps) NRows+ Ncolumns
Starting position of blocks	Nothing



MEASUREMENTS

An early testing of these pattern combinations with various movement configurations is done using Pachyderm. The sound pressure level and reverberation time is calculated at the receiver. All the possible iterations generated with the movement logic explained earlier are exported using Colibri plugin. This data is then analysed in design explorer for understanding the acoustic behavioural change between different movement combinations.

Figure 7.12 : (Previous page) Iterations for block movement configurations

The table below shows an analysis chart of twenty results. A noticeable difference in the sound pressure level and reverberation time is evident across all frequency spectrums. The focus is on mid-range frequencies, so an optimal solution is chosen from that range bracket. Two results; one with least reverberation time and one with maximum sound pressure levels are highlighted. The results are manually shortlisted to realize the validation of concept and understand the peak differences in the values.

With this small data of results, it can be inferenced that there is a difference in results with a responsive surface. space.

1. The input geometry required in Pachyderm must be a closed room setup. Thus, the results are not just ceiling specific.
2. The computation time of Pachyderm is high; thus, all the pattern configurations cannot be calculated.
3. The results for all frequency spectrums are not required. This computation time should be reduced.
4. It is not advisable to manually scrum the results to find an optimal solution. An algorithm to find the optimised solution should be incorporated.
5. The input geometry should remain same in all tests to have a valid comparison.

A custom definition is scripted to extract the effect on acoustical performance from the just the ceiling surface. The intent is to research the difference in acoustic environment and not produce completely accurate acoustic results. Hence some of the basic ray tracing principles and sound intensity levels are measured, instead of SPL and reverberation time. The working of this script is explained in the following chapter.

RESULT OPTIMIZATION

The result for a specific feedback input is optimized using octopus. A result comparison is drawn to check the result difference between CATT Acoustics and Pachyderm. Test case A is modelled in both platforms and the results are calculated with a flat ceiling. The surface acoustic properties are also kept same for precise results. The result data is in Appendix H.

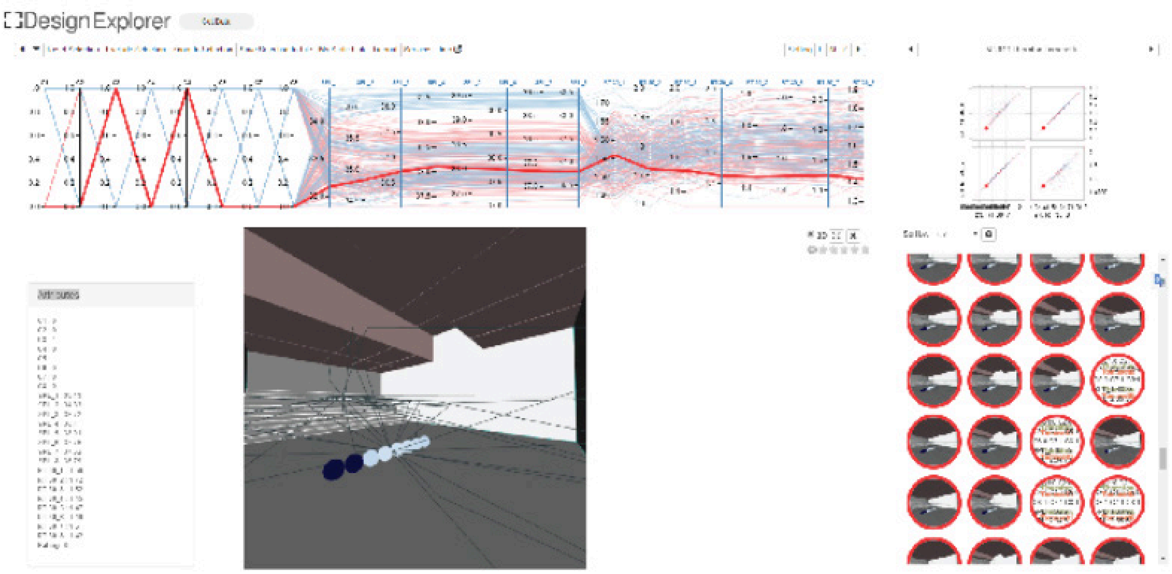


Figure 7.13 : Design explorer for optimal result selection

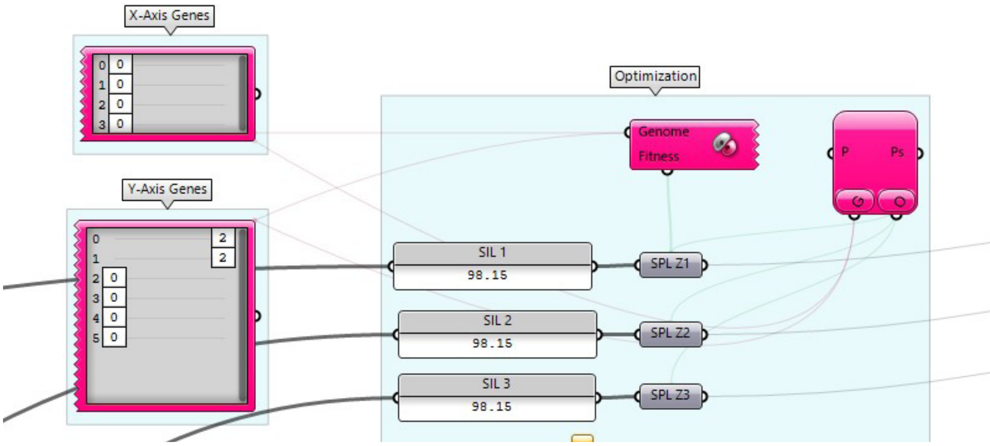
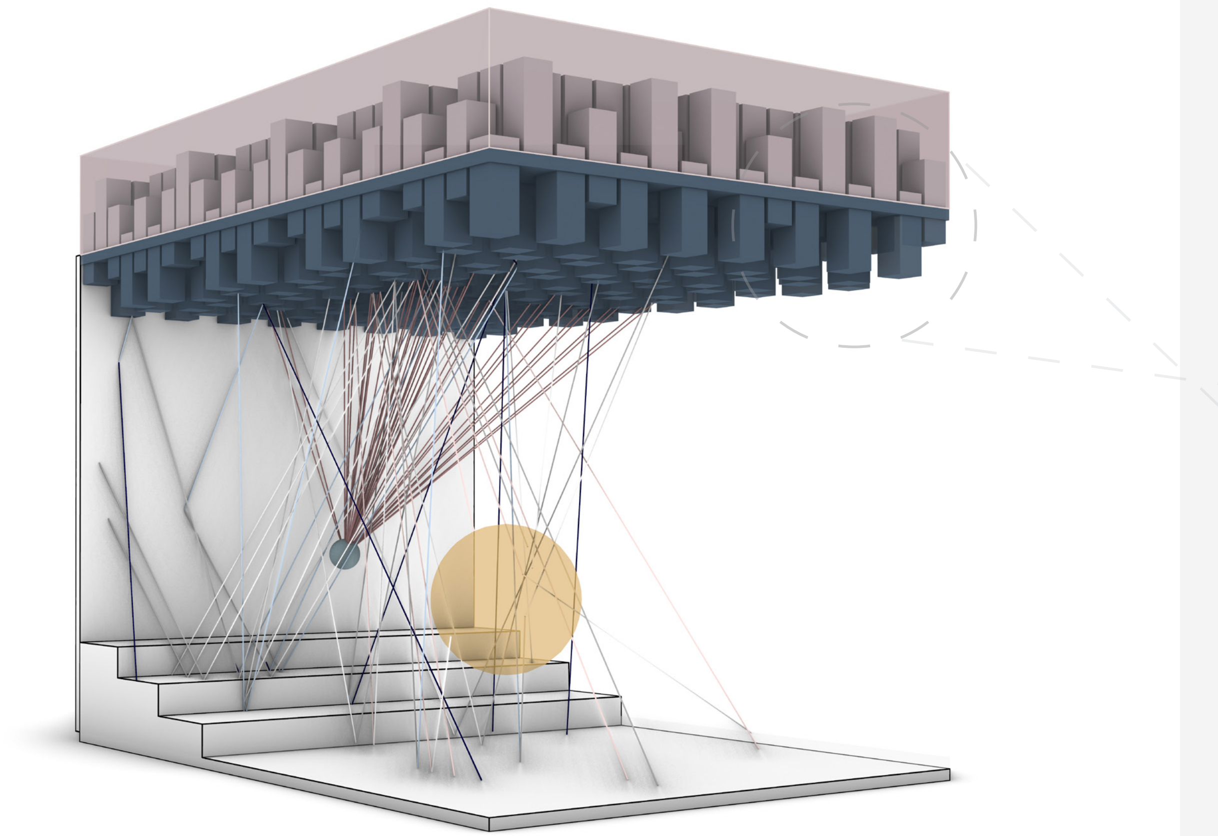


Figure 7.14 : Optimization tool for solution selector



VIII

the
sound
bending
project

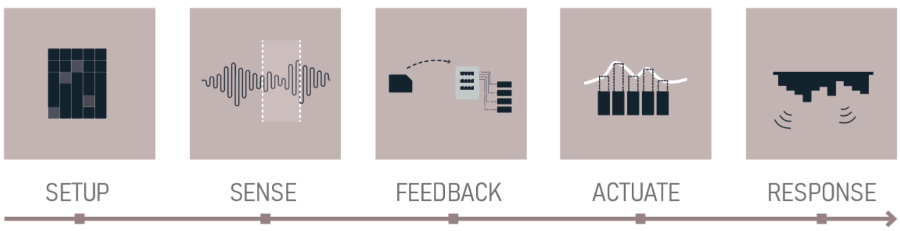
RESEARCH OUTCOME

As a result of the research conducted through physical actuation and computational modeling and simulations in the previous chapters, that demonstrates the alternative methods and protocols for modeling and testing the kinetic movement and configuration, the next step is to execute a full-run from start to end stressing on the necessary decisions made with fixed and variable parameters. The design will be tested in different scenarios in full scale for its acoustic performance. This is undertaken in five steps based on the 5C principle of cyber physical systems:

1. Setup - Connection
2. Sense – Conversion
3. Feedback - Cyber
4. Actuate - Cognition
5. Response - Configuration

The proposed solution works diligently in improving the acoustic performance considering the real-scale factors, such as room size and space usage. Although, the mechanism proposed for the kinetic movement needs to be further developed to suit the physical requirements of a space. The ACUTE blocks developed for this project can be modified in terms of scale and movement to impact the acoustic correction to a noticeable level.

Figure 8.1: (Next page) Research Flow


SETUP
SENSE
FEEDBACK
ACTUATE
RESPONSE

SETUP

The blocks in the grid are then divided using the alternate grid method into series that connects to an actuator. This configuration helps in achieving an aperiodic distribution and movement of blocks, the number of blocks controlled by every actuator change with the pattern type, but the distribution logic remains the same.

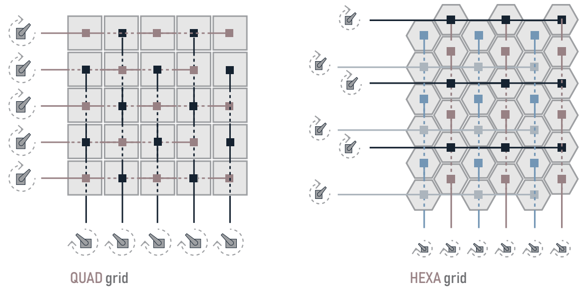


Figure 8.2 : Alternate setup in the two design grids

Alternate Grid

The test case ceiling surface is replaced by the three design grids proposed in the earlier chapter. The grid size is kept like the conventional acoustic tile size. The blocks in the grid are then divided using the alternate grid method into series that connects to an actuator. This configuration helps in achieving an aperiodic distribution and movement of blocks, the number of blocks controlled by every actuator change with the pattern type, but the distribution logic remains the same.

Data Simplification

As the number of actuators increase, the input variable for acoustic simulations also increase. As the refresh rate for the movement of these blocks has a direct relation to the simulation time for calculating the acoustic performance, a right balance has to be found between the level of detail of acoustic correctness and the refresh rate. Thus, to limit that the actuators can be grouped together depending upon the acoustic preference of the space. The grouped actuators are fed with same output data to reduce the number of simulations. The grouping can be digitally tweaked according to the spatial requirements.

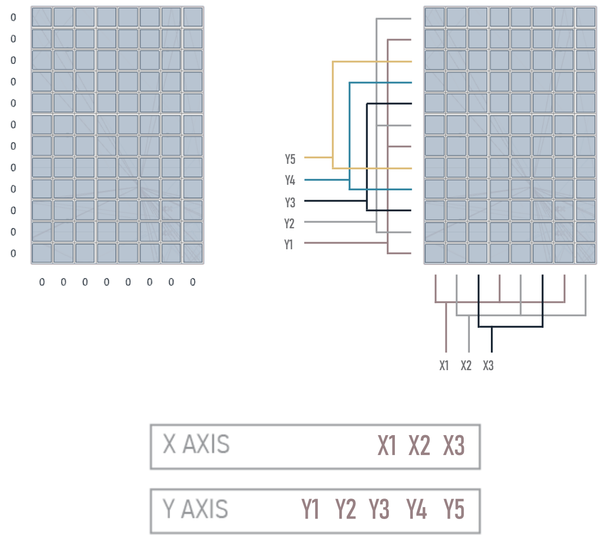


Figure 8.4 : Actuator data simplification

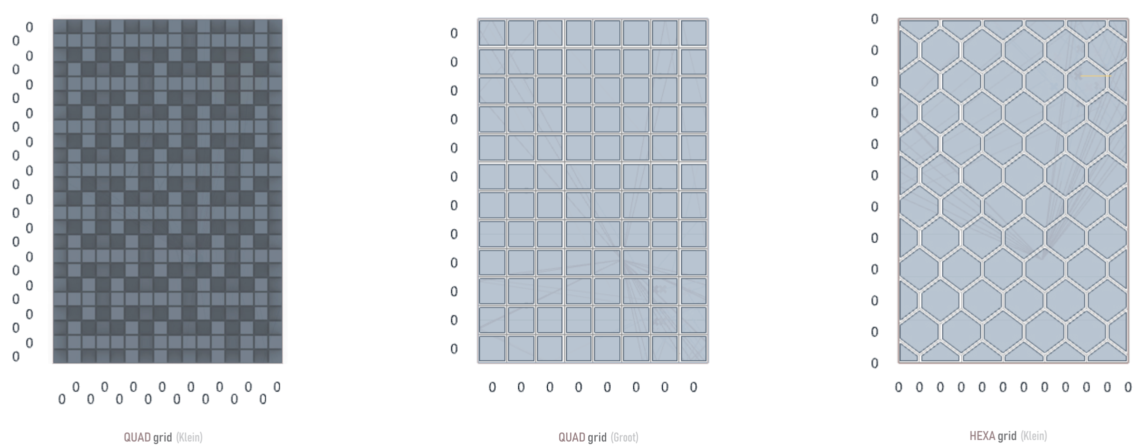


Figure 8.3 : Actuator setup in the final designs

SOUND READ

To read a sound source, two major information needs to be extracted from the sound source.

1. Position at which sound is generated
2. Sound pressure level of this sound

For finding the position and SPL data, the above benchmarked Kinect device method is used for mapping this information. Measurable area clusters need to be defined and for every cluster a separate interpretation arrangement is required. As the test case room size lies within the traction range limits of Kinect device, a single device configuration is placed in the centre of the room at a height of 3.9m.

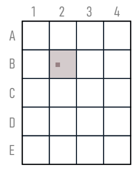


Figure 8.5 : Floor grid division

Source position

When a sound is generated, the dual device arrangement finds the peak sound in horizontal and vertical axis. These two peaks help in locating the source point. As it is complex to get data for every point on the floor, the floor of the test case is gridded with a grid size of 0.6 X 0.6 meter as illustrated below in figure below. The identified source point is referenced to the respective grid block using point in surface method.

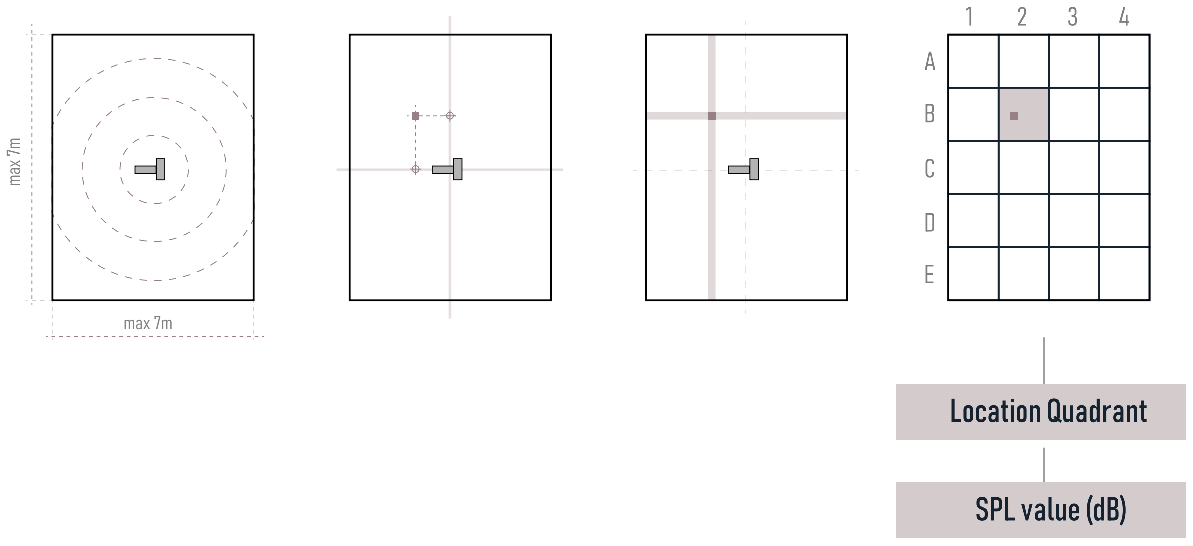


Figure 8.6 : Source position detection with Kinect system

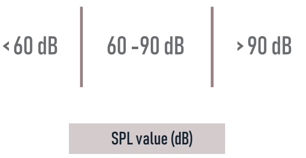


Figure 8.7 : Sound range sub-categorization

Sound Pressure Level

For the identified point, a mean SPL value can be derived using the information recorded in both the Kinect devices. This gives the sound pressure level at the device location. Using the trigonometric algorithm explained above, the SPL at the source position is calculated which provides the second input value required for the feedback. The SPL value is then referenced to the sub-categorized ranges to limit the complexity of calculations. The number of categorized can be increased for higher accuracy.

FEEDBACK

Feedbacks required by the system can be grouped into three input categories.

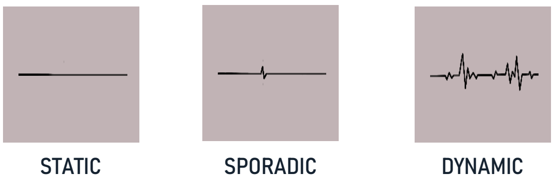


Figure 8.8 : Types of feedback input

Static Input

Space/Room type based

Static feedback is drawn from the fixed elements in a setup and it includes:

A. Room type | Dimensions and open/close space

B. Block design | Dimensions and material specifications

C. Actuator system | Number of actuators in both axis and rotation steps for every actuator

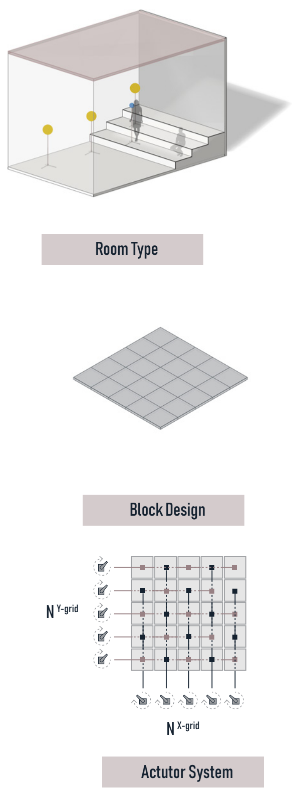
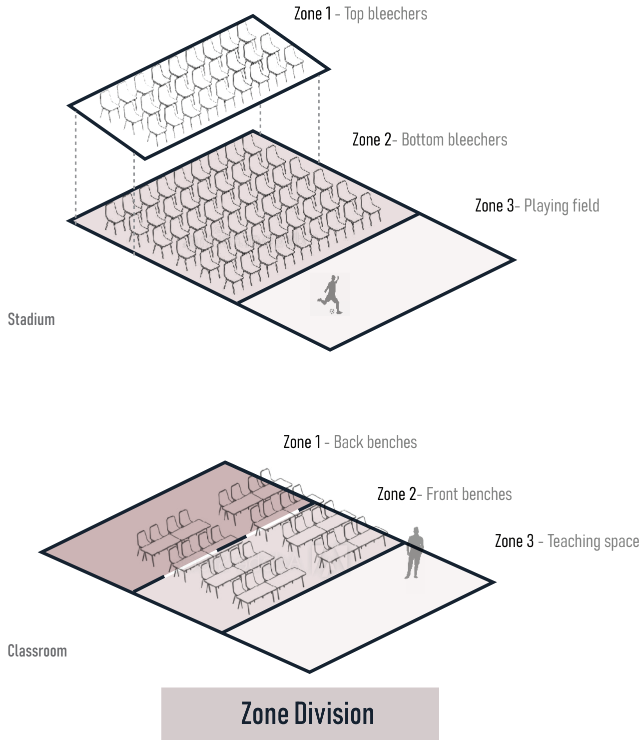


Figure 8.9 : Static Input

Sporadic Input

Activity/Function based

This is based on the acoustic requirements depending on the function or use of the space. For this the space can also be divided into zones for efficient results with each zone can have a unique acoustic preference. The zones can be made according to the room layout or as per the acoustic requirement. The below illustration shows two examples: a stadium with three zones (bleachers, buffer, and field) and a lecture room with three zones (Front, middle and back seating)



Fuigure 8.10 Sporadic Input | Zone division for specific acoustic requirements

For each zone, the acoustic preferences can be narrowed down using acoustic properties. There can be a different property associated with each zone as well. In this research, the tests are done using the sound pressure level and the total number of rays. There is a sub choice for the properties where the maximum and minimum is searched for from all the data.

SPL

Ray incidence count

High | Low

Acoustic preference

Figure 8.11 : Acoustic Properties preference

Dynamic Input
User based

This input feedback makes the whole system real-time as the source input in constantly changing both in terms of position and intensity. The sound input data is fed in this feedback loop.

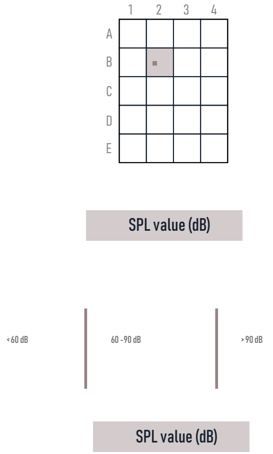


Figure 8.12 : Dynamic Input

The table below shows the type of input data required per category for the feedback loop. The inputs are taken as integers, float numbers, text, or choice (value listener).

ACTUATE

With the input data for the feedback loop, the system finds the right match from the total list of pre-simulated solutions and retrieves the corresponding actuator data. With the pre-defined parameters in this research solution, there is a data pool of 87,480 solutions which gets narrowed down as the three input feedbacks are fed into the loop.

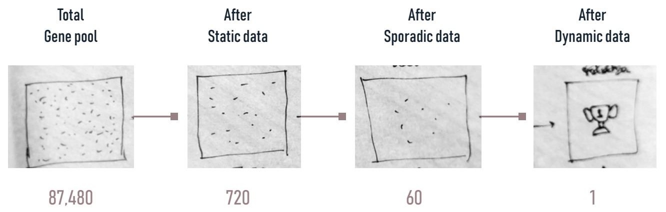


Figure 8.13 : Reduction in Gene pool with 3 stages of feedback

Based on the above explained trimming down of data, there is asset of 60 values as seen in the table below. This is the only value set the system must refer when the sound source changes. This reduces the processing time and makes it possible for a real-time translation of the actuation movement.

FEEDBACK LOOP INPUT					
STATIC		SPORADIC		DYNAMIC	
Room Type	Choice (A, B)	Number of Zones	Integer	Source Quadrant	Text + Integer
Block Design & Size	Choice (Quad G, Quad K, Hexa K)	Acoustic property preference	Choice (Number of Rays, SPL value)	SPL value range (dB)	Integer
Acoustic Properties	Room & block surfaces	Task	Choice (Maximize, Minimize)		
Number of Actuators	Integer (x-axis) + Integer(y-axis)				
Rotation steps	Integer				

Table 8.1 : Feedback loop input

With the final solution from the data list, the actuator data can be retrieved which gives the rotation step number for every actuator/ motor. This number is preconfigured to the rotational movement of the motors as already explained in the actuation mechanics. The image below shows one of the result sheets and the data provided for actuation.

RESPONSE

The numbers in the actuator data output corresponds to the movement of specific motors. The motors are triggered on receiving the data to configure their position accordingly generating a movement response on the whole surface. The movement rotates the spindle translating into a vertical movement for the blocks.

A refresh rate of 5 seconds is considered for the new output values to replace as the configuration positions. This keeps the movement real-time in response to the user behaviour and sound input. A typical result sheet is shown on the adjacent page illustrating all the outputs from the software. Theis sheet is for scenario 1. Four other scenarios are tested and are explained in the appendix H. The conclusion table below signifies the impact on SPL due to the change in ceilign pattern. Hence, it can be concluded that the system is effecient in enhancing the acoustic performance of a space.

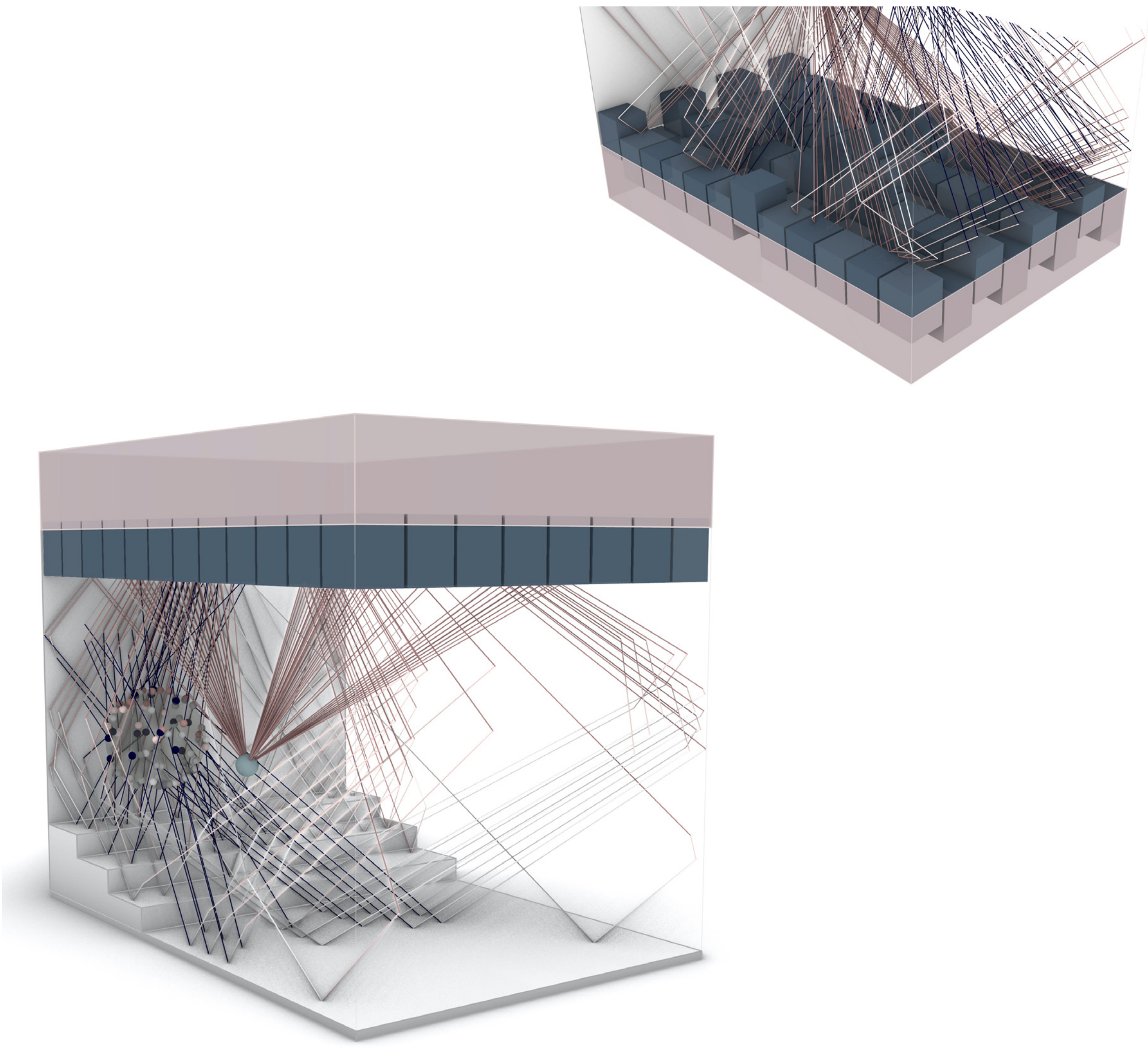
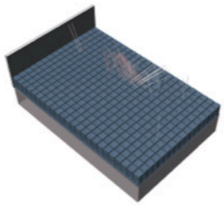
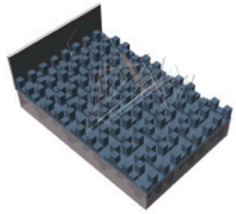
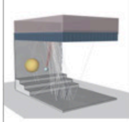
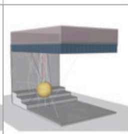
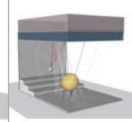
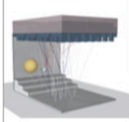
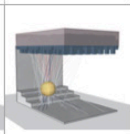
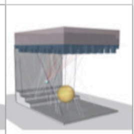
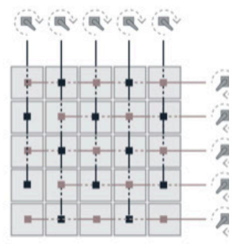


Figure 8.14 : Optimized position of the ACUTE blocks (Inverted representation)

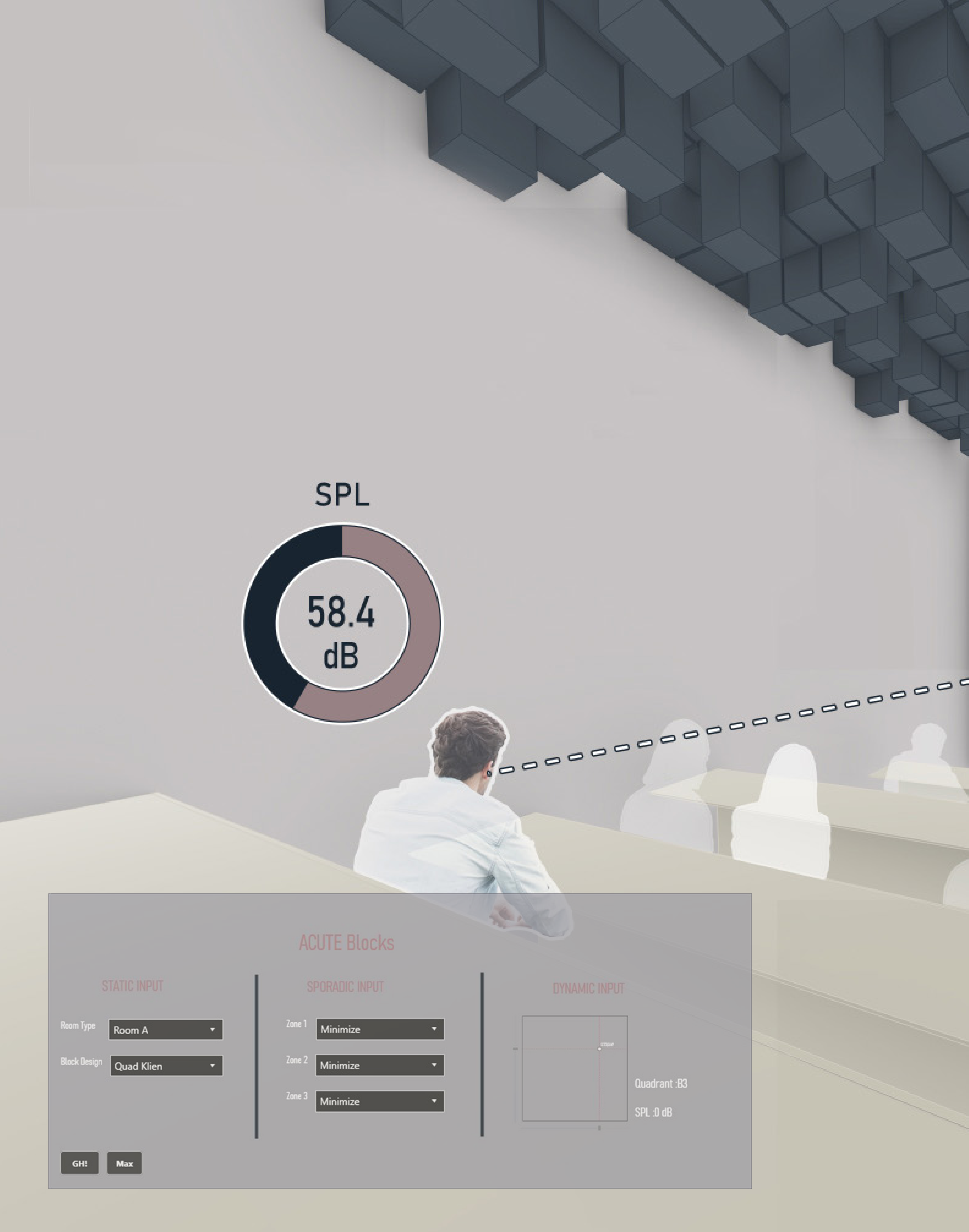
RESULT SHEET	OPEN ROOM		
Test Case	SCENARIO I		
Design Type	ACUTE block | Quad Klein		
Block Size - l x w x h (m)	0.3 x 0.3 x 0.6		
Source Position	B2		
Source Height	1.8 m		
Source Sound Pressure level	120 dB		
Task	Zone 1	Zone 2	Zone 3
	Minimize	Minimize	Minimize

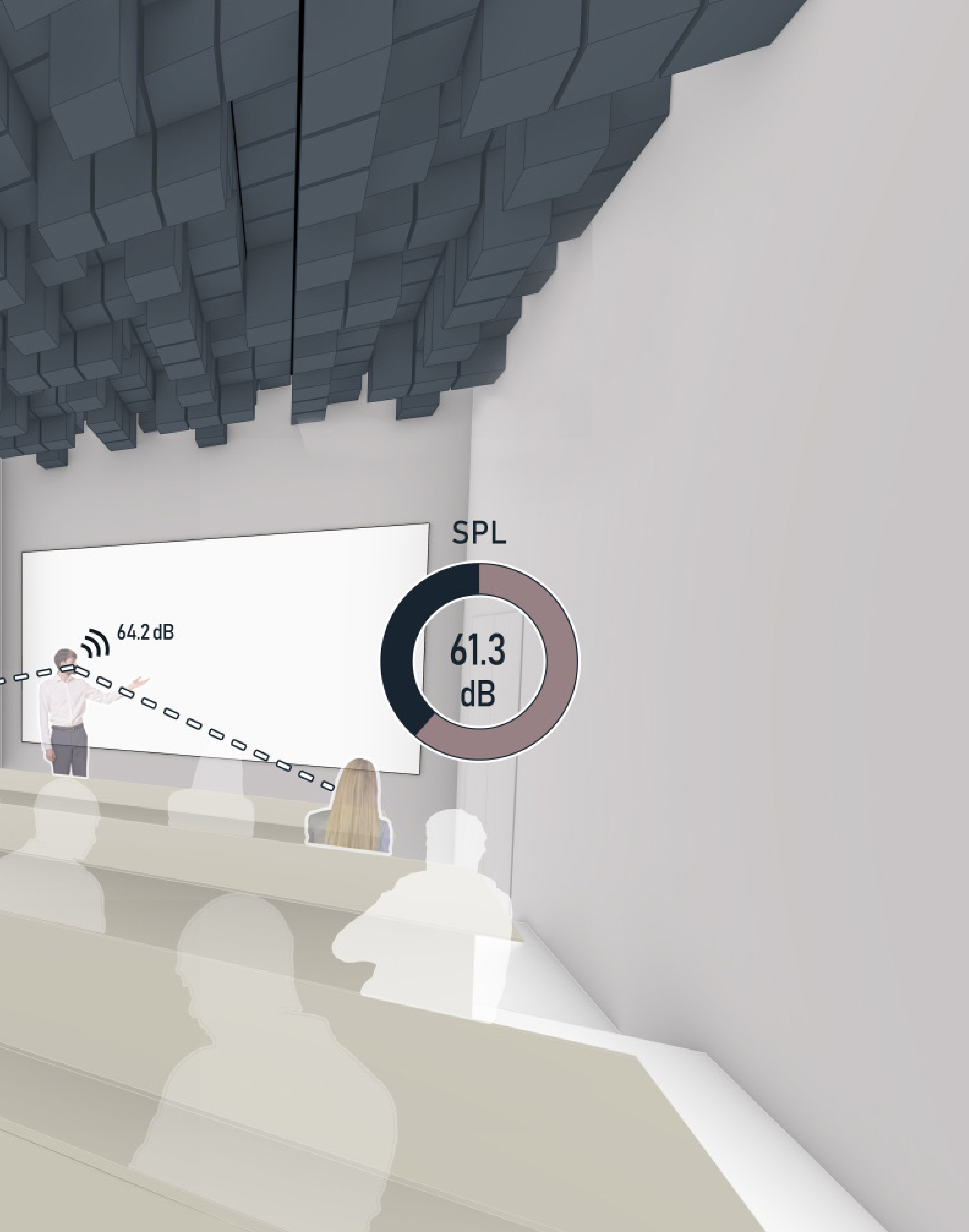
		INITIAL POSITION				OPTIMIZED POSITION			ACTUATOR DATA
Block Configuration									The numbers represent the angle that the respective actuator has to move to configure the blocks in the optimized position. The data is based on the preset algorithms created based on the acoustic simulations. The algorithm can be tweaked in order to achieve customized results.
Zone Number		Receiver - Zone 1	Receiver - Zone 2	Receiver - Zone 3		Receiver - Zone 1	Receiver - Zone 2	Receiver - Zone 3	
Ray Tracing Diagram									
Order of Incidence	1	0	0	0	1	0	0	0	
	2	15	11	15	2	14	8	11	
	3	4	6	9	3	10	9	15	
	4	2	2	4	4	4	11	8	
	5	1	4	1	5	1	5	3	
	6	4	4	4	6	4	9	4	
Total number of rays		35	27	33		33	42	44	X axis | 2 | 1 | 1 |
Sound Pressure Level (dB)		105.82	107.57	108.85		89.93	83.19	92.62	Y axis | 1 | 1 | 2 | 1 | 0 |

SCENARIO I	OPEN ROOM | 120 dB					
	SPL (dB)			Number of Rays		
	INITIAL	OPTIMIZED	CHANGE	INITIAL	OPTIMIZE	CHANGE
Zone 1	105.82	89.93	▼ 15.89	35	33	▼ 2
Zone 2	107.57	83.19	▼ 24.38	27	42	▲ -15
Zone 3	108.85	92.62	▼ 16.23	33	44	▲ -11

Table 8.2 : Result sheet of Scenario 1, Conclusion table of Scenario 1

Figure 8.15 : (Next page) Lecture room visualization with the ACUTE block system


SPL
58.4
dB
ACUTE Blocks
STATIC INPUT
Room Type
Room A
Block Design
Quad Klien
SPORADIC INPUT
Zone 1
Minimize
Zone 2
Minimize
Zone 3
Minimize
DYNAMIC INPUT
Quadrant :B3
SPL :0 dB
GH!
Max


SPL
61.3 dB
64.2 dB

IMPLEMENTATION

To make the systme work efficiently, a wall monitoring device is designed to be put in the room similar to the light and temperature control device. This device gives out the live acoustic data of the oom and has some settings with which the room acoustics can be manipulated. The images on the next page show the three modes namely:

1. Automatic mode
2. Scene mode
3. Manual mode

The three modes provide the flexibility to operate the kinetic system with more efficiency and limited physical monitoring. The automatic mode has low tolerance to changing sound and the systme moves even with slight change in the acoustic values. Whereas in the scene mode, the tolerance is higher, depending on the scene set such as lectur, discussion or presentation. The preset modes can be configured depending on the space functionality. The change in geometry happens only when there is a major change in sound values. The manual mode provides the freedom to tweak the setting and change the position of blocks to achieve zone focused results. In this mode, it is also possible to have a different quality for every zone.

AUTO MODE

LOW TOLERANCE

Maximum SPL or any other property

SCENE MODE

HIGH TOLERANCE

Preset settings
Lecture
Discussion
Presentation

MANUAL MODE

CUSTOM TOLERANCE

Custom settings
Zone control
Volume control

IX

the
sound
bending
project

CONCLUSIONS

GENERAL INFERENCE

With the tests, it can be inferred that this model is suitable for reducing the sound intensity and controlled distribution of sound rays. However, it is not proven in this research that the system could efficiently increase the sound intensity or focus the sound at a specific point location. This is dependent on the refinement of floor grid or number of zones considered to test the responsive surface.

Reflection of Research Question and Design Intent

What is the design and operational feasibility of sound responsive surfaces and can they have a noticeable impact on the acoustic performance in a space?

To make the design feasible in terms of application, the research is based on conventional acoustical ceiling grids and various tile sizes. For spaces where noise is a major concern, the ACUTE blocks can be beneficial in regulating the sound. Although, a cost to effectiveness relation is not worked out.

Based on the test results, it can be concluded that the responsive surfaces can have a noticeable impact on the acoustical performance of a space. However, the accuracy of calculations and specificity of acoustic requirements can be further detailed to get situation specific results.

Sub Questions

ACOUSTICS & PROCESSING | How to read the sound source and which acoustic properties should affect the movement of panels?

With the custom arrangement of two Kinect devices and the source localization calculations, the source point and sound pressure level at the source can be read. For affecting the movement of panels, basic ray tracing method and sound pressure level calculation are used.

PATTERN LANGUAGE | What are the different patterns and techniques to create responsive surfaces?
The deign foundation is to use existing structural and ceiling grid systems as the support framework to reduce the system complexity. A study of various patterns based on design and movement logic prove that all patterns have a varying impact on acoustic environment. Two such patterns are elaborately researched and developed to realise a responsive surface. The pros and cons of each design is also discussed in the research.

DESIGN FOR INTERACTION | How to make the surface move effectively in response to the sound? The movement must be deliberate and controlled for optimum results.
The effectiveness of the movement is established based on stipulated calculations done for the movement configurations in response to the acoustical environment needed. The movement is deliberate in the chosen design of alternate grid control as there is no fixed position of the blocks. Every individual block can be triggered by operating a specific actuator/motor.

RESPONSE & FEEDBACK | Will the outcome of said design approach have a significant impact on the acoustic performance?
In most case scenarios, a difference of 4-6 decibels in the sound pressure level is achieved. This is a significant impact in open stadiums as there are no wall surfaces to correct the acoustic nuisance. For closed spaces, the system is efficient in directing the sound in specific corners or zones in a room.

Volume control & Sound Distribution

It is possible to control the sound by minimizing or maximising the sound pressure level. Sound distribution is attained by ensuring a fair distributions rays in all the zones or a specific zone as required.

Design

- Height to width ratio of blocks must be minimum 2: 1 for optimum results. They provide deep and narrow wells, which increases the ray incidence within the block surface geometries.
- A simple square geometry can have similar results as a complex hexagon geometry. The major impact is caused by trapping the rays in the well formations between blocks irrespective of the shape. Even when the shape of the geometry influences the direction of the ray reflection, it does not have a visible difference.
- The spacing in between blocks seems to influence the ray tracing. This must be further explored.

IMPROVEMENTS

Script & Acoustic results

- Acoustic calculations should be tested and compared with sophisticated acoustic software for validation of results.
- The test modelled must be further detailed by adding elements such as furniture, ceiling fixtures (light and ventilation), human beings. These can also impact the movement of rays.
- Parameters such as number of rays, order of reflection, direction of sound should be improved/increased for higher accuracy of test results.
- Manually shortlisting for the optimised solution from the test results should be replaced with a custom definition for finding the optimized solution.

Physical Actuation

To sample acoustic consequences of our geometric actions. New methods must be developed to create

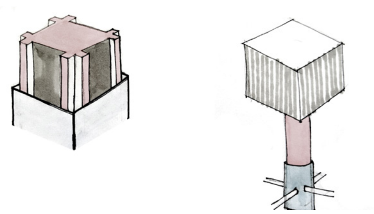


Figure 9.1 : Friction reduction strategies

FURTHER RESEARCH

Block Design & Movement

The design for the block can be further explored by looking into the other combinations for the parameters in designing the block. The surface of the blocks can have a 3-dimensional design/texture to include the concept of scattering to the micro level. The bottom surface of the blocks can be at an angle instead of flat for directional focus of sound rays.

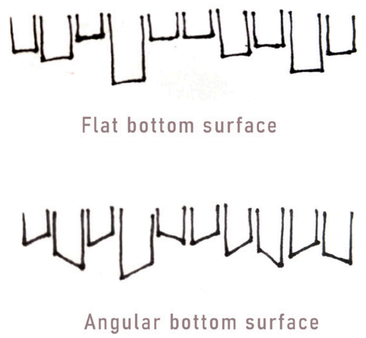


Figure 9.2 : Bottom surface angle

The solid block can be replaced with a stretchable material walls to reduce the negative space required by these blocks when in zero position. This will ease the movement and logistics of this responsive surface.

Real-time Movement Speed

SOUND INTERPRETATION

The sound input interpretation is the first step that takes a lot of time to convert this information into useable feedback for the loop. The output from the feedback loop is fine as the output results are pre calculated. This also depends on the sound input range brackets. Instead of three bigger range brackets used in this research, a smaller bracket of 10 decibel difference can be used for higher accuracy.

ACTUATION MOTORS

With use of swift actuation motors, the response representation through block movement can be made quicker. In a true-scale circumstance, a sophisticated actuator must be used to avoid response delay. The change of the arrangement must be smoother and seamless to avoid creating a distraction for the users.

REFRESH RATE

The system works on a refresh rate, that is how often the configuration is updated. This is directly related to the time taken by system for sound interpretation. It can be concluded that a real-time system (zero second refresh rate) is not necessarily required. A suitable refresh rate of 5-10 seconds can create the desired impact. The intent is to correct major changes and ignore small peaks and drops in sound pressure level.

Supervised Machine Learning

MULTIPLE SOURCE POINTS

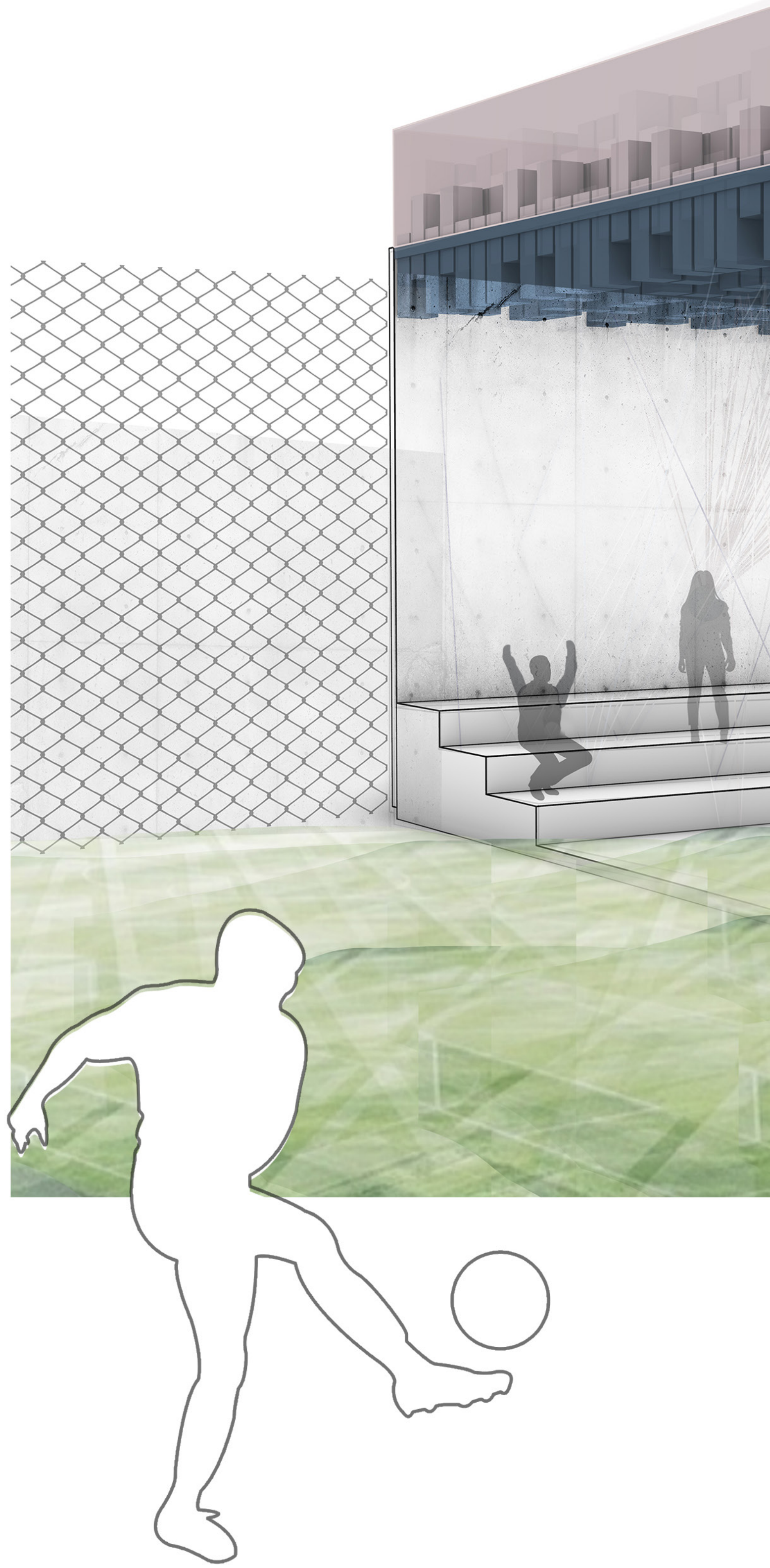
This research does not take into consideration multiple sound sources being emitted at the same time. A combination result based on the data of these sound sources can be generated using supervised learning methods.
Multiple results are grounded on just the dynamic input feedback. For all feedback input a supervised machine learning method must be put in place for prior calculation.

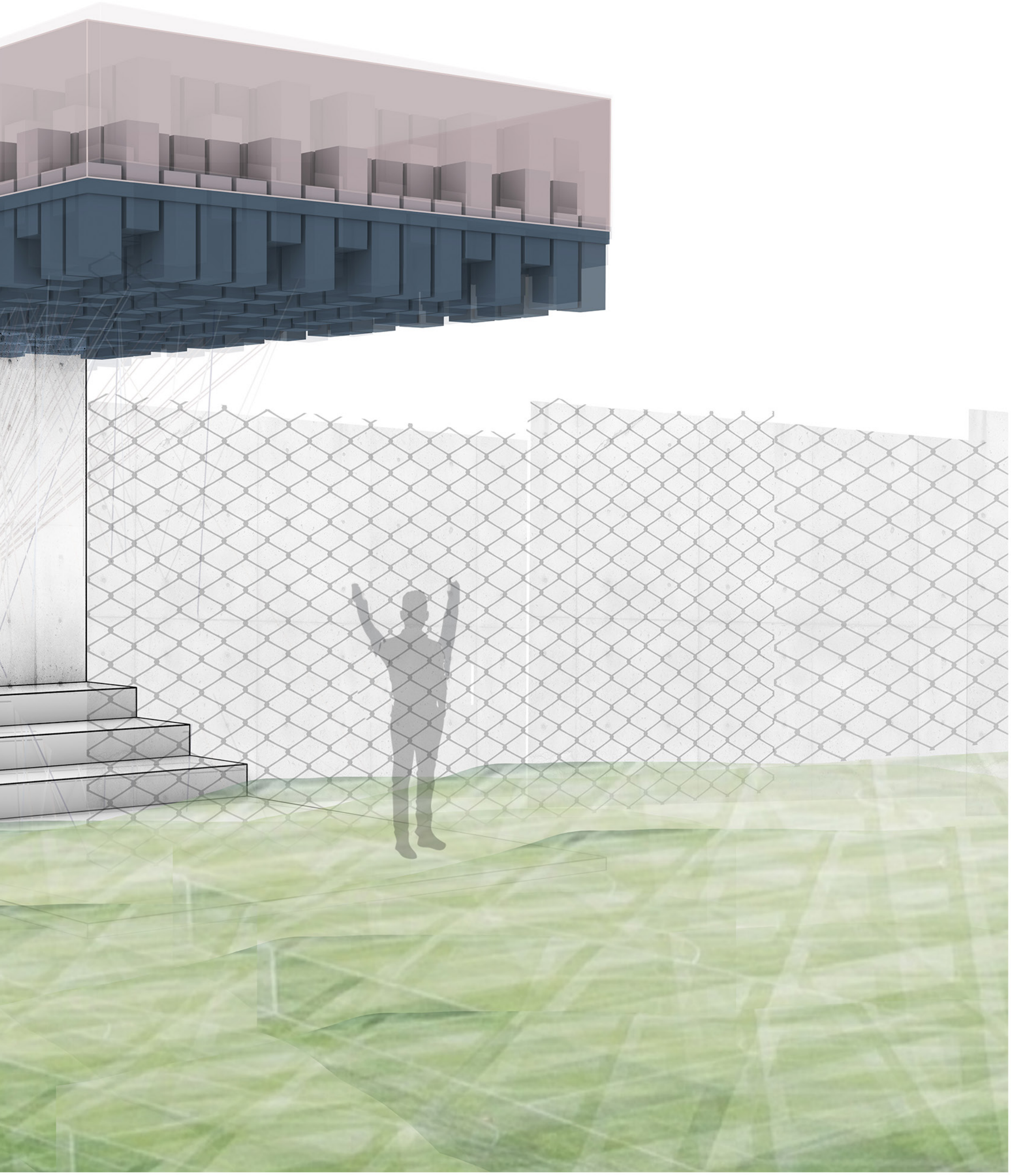
DATA INTERPRETATION

Creating a list of predetermined configurations for a larger space can be daunting task for the system. An algorithm to directly calculate and output the optimized solution would make the task quicker and easily tweakable. This would omit the process of calculating all results and then finding the optimum solution.

THE SOUND BENDIING PROJECT

Sound is a tricky genre unlike light and temperature. It is highly complex to predict and control the user behavior in terms of sound. Thus, the intention is to correct the acoustics as a post-activity but in a real-time response.





X

t h e

s o u n d

b e n d i n g

p r o j e c t

REFLECTION

Even before starting the masters at TU Delft, my personal interest has always been towards merging allied fields with architecture. Kinetics in architecture opens many possibilities as a building technologist to engage in developing energy efficient built environments. While a lot of experimentation and research is being undertaken in respect to daylight and temperatures, less thought is being put in using this technology for improving acoustic perceptions. The trend is to correct the acoustics post-design stage even when sound is the main character in a specific space such as concert halls, stadiums and even lecture rooms. The thesis focuses on bringing acoustic design on the forefront and incorporating its parameters from the beginning. Developing a digital tool that can feed this approach of design becomes a necessity.

Studio theme and graduation topic

Sound is one of the major sensory for humans, yet acoustics is in a nascent stage when it comes to incorporation in every aspect of design. The earlier designs in the built environment emphasized on the importance of the acoustic character of a space. This experiential phenomenon of acoustic excellence can still be noted in some of the churches and other prestigious buildings. Although, the current technology concentrates mostly on sound reduction, isolation, and absorption.

Sustainability can be looked in two parallels: consumption and comfort. With the increase in demand of adaptive and multi-functional spaces, the spaces should be able to respond according to the specific function's requirements. Designing a space for various acoustical requirements becomes key in enhancing the acoustical comfort.

Electronic enhancers and speakers are used to achieve this feat, whereas most of it can be corrected using architectural elements itself. The other driving force is to inculcate acoustically responsive design in regular practice for both interior and exterior spaces. Noise pollution is the next big problem that can be addressed by manipulating the built forms to tackle the issue. Thus, creating a simple tool for calculating the basic acoustic principles in real time helps in early integration in the design process.

Research & Design

The main intent of this research is to develop a sound responsive surface and understand the impact it can create in improving the acoustic character in a space. The research from the beginning was undertaken in two parallel streams; one where the physical possibilities of generating a sound based response in the surface was developed and the other, where the acoustic analysis for the changing geometries was dealt with. The third and final step was to create a coordination between the physical response and the acoustic preferences for the defined system.

For the physical system, prototypes were made and tested for response. It was an ongoing process of design, prototype, observe, update. With every step new possibilities and directions helped in making the system more sophisticated and reliant. Although, due to the lockdown, the physical prototyping strategy had to be revised by making digital iterations of the design. With this, the actuation mechanisms which were not available physically were also considered such as the motorized potentiometers and linear actuators. But, with no physical testing on the response time and refresh rate, the methods are still open for research.

The computational tool for calculating the acoustics for changing geometries was emphasized upon leading to development of a custom definition for faster calculation of acoustic properties in the concept design stage for architects and designers. This tool can help in incorporating acoustics from the initial stage of design and the acoustics can have an influence on the design.

Relevance

Societal

As hearing is one of the most critical senses for humans, it is important to find solutions to protect it from the loud noises inside a live stadium. Noise can have damaging effects that most individuals are unaware about. At the same time, the noise that escapes outside the stadium adds to the city's noise pollution. It is indeed a challenge to take up this problem where the stadium experience must be maintained while lowering the sound pressure level to the bearable levels. Responsive surfaces behave as a stimulus for interaction between individuals having a positive effect on their sociological behaviour.

Scientific

Acoustics are rarely considered while designing a space. The state of research in sound responsive kinetic surfaces is still in its nascent stage but holds a huge potential in improving the acoustic performance in a space. Movement of surface in response to sound can be imagined but there is a need to have a controlled responsive movement, to be able to have quantifiable effect on the acoustic performance as well in addition to the positive sensory effects it can have on human beings. With some research already happening, there is a possibility of further exploration to improve the idea in terms of simplicity of design and ease of operations. Responsive panels can be used in various spaces to attain the required acoustic experience. This research might serve as a reference for the state of research in the domain of sound responsive surfaces.

TU Delft programme

Responsive architecture is a growing field and the architectural engineering department incorporates a large part of it in their study curriculum for building technology. Design informatics chair resonates with this by bridging the gap between buildings and computational methods. The course Bucky lab also encourages the idea of responsive design to improve building condition. With research already happening for improving acoustics using computational tools, this research can contribute to it. Merging interactive design with acoustics gives a possibility for improving architecture and the way it is perceived.

Ethical Responsibility

The main ethical dilemma in this project was the use of extra technology and energy to achieve the desired results. It comes down to the development of a technology pertaining to the field of acoustics. With sound being an equally important phenomenon, further research and development is always beneficial in improving the technology. The initial steps in this direction tend to look complex but it is the further research and development that makes its more efficient and acceptable.

Responsive architecture provides the user with another dimension to experience a space and interact with the surroundings. Adaptive designs within the built environment must be equally responsible for the way they react with the natural habitat.

Challenges & Opportunities

Recent pandemic restrictions provide an opportunity to re-evaluate the initial research approach and finding other possible ways to reach the final objective. The prior assumption of testing the design solution using conventional software did not turnout as planned. This provided an opportunity to develop a custom definition as there was none specific to the research requirements. The tool can be further developed to make is easily usable for architects and designers to be integrated in regular practice.

With limitation of time and resources, the physical testing of new and smart mechanisms could not be done that pose a great opportunity for the system to become less energy reliant. To keep moving ahead, many constraints were fixed as it is not possible to solve everything in the given time span. These constraints can be further explored and can influence the design proposal to work with more specificity.

Approach towards addressing this research topic and presenting the conclusions has become more refined. This gives an insight into first understanding the practicality and potential of this topic before diving into research. The different aspects of this thesis, changeable ceiling surface, real time response, and acoustic calculator can all be used separately to support another research and can be implemented individually as well.

This research contributes to the computation realm of building physics, focused on acoustics. It is successful as a conclusive study at the Faculty of Architecture, TU Delft as it can make further research in acoustics quite smooth and provides possibilities to research on the minute acoustic corrections possible. This thesis has made me realize the direction for my future endeavours. I will continue working in enhancing and incorporating the computational power in the field of Architecture and Built Environment.

THE SOUND BENDING PROJECT

What cannot be easily reproduced is the perception or experience of the environment that is always transient, always unique.

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APPENDIX

APPENDIX A

Source Localization calculations.

Point A

$$L_W = L_{P_A} - 10\log\left(\frac{Q}{4\pi r_A^2}\right) \quad \text{———} \quad (1)$$

Point B

$$L_W = L_{P_B} - 10\log\left(\frac{Q}{4\pi r_B^2}\right) \quad \text{———} \quad (2)$$

Point C

$$L_W = L_{P_C} - 10\log\left(\frac{Q}{4\pi r_C^2}\right) \quad \text{———} \quad (3)$$

eq. 1 with (1) & (2)

A + B → A = B
B + C → C = B
C + A
B = C

$$L_W = 55 - 10\log\left(\frac{Q}{4\pi r_A^2}\right)$$

$$L_W = 56 - 10\log\left(\frac{Q}{4\pi r_B^2}\right)$$

$$L_{P_A} - 10\log\left(\frac{Q}{4\pi r_A^2}\right) = L_{P_B} - 10\log\left(\frac{Q}{4\pi r_B^2}\right)$$

$$+10\log\left(\frac{1}{4\pi r_A^2}\right) = -\frac{1}{10} + 10\log\left(\frac{1}{4\pi r_B^2}\right)$$

$$10\log\left(\frac{1}{4\pi r_A^2}\right) = +10\log\left(\frac{1}{4\pi r_B^2}\right) \quad \text{———} \quad (4)$$

$L_{P_A} - L_{P_B}$

eq (2) & (3)

$$\text{LPA} - \text{LPB}$$

$$\cancel{56} + 10 \log\left(\frac{Q}{4\pi r_B^2}\right) = \cancel{56} + 10 \log\left(\frac{Q}{4\pi r_C^2}\right)$$

$$-L_{P_B} + L_{PA} - 10 \log\left(\frac{Q}{4\pi r_B^2}\right) = -10 \log\left(\frac{Q}{4\pi r_C^2}\right) \quad -(5)$$

eq (1) & (3)

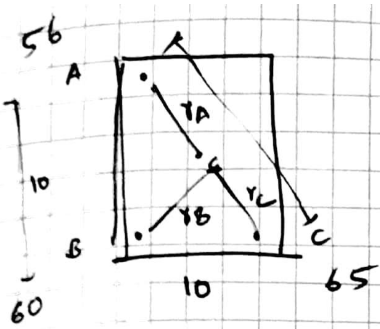
$$55 - 10 \log\left(\frac{Q}{4\pi r_A^2}\right) = 56 - 10 \log\left(\frac{Q}{4\pi r_C^2}\right)$$

∴ replacing A & C with eq (4) & (5)

$$\cancel{55 - 10 \log\left(\frac{Q}{4\pi r_B^2}\right)} = 56 - \cancel{10 \log\left(\frac{Q}{4\pi r_B^2}\right)}$$

$$L_{PA} - 10 \log\left(\frac{Q}{4\pi r_A^2}\right) = L_{PC} - 10 \log\left(\frac{Q}{4\pi r_C^2}\right)$$

$$\cancel{L_{PA}} - \cancel{L_{PA}} + \cancel{L_{PB}} - 10 \log\left(\frac{Q}{4\pi r_B^2}\right) = L_{PC} - 2L_{PB} + L_{PA} - 10 \log\left(\frac{Q}{4\pi r_B^2}\right)$$



$$L_S = L_A - 10\log\left(\frac{Q}{4\pi r^2}\right)$$

$$L_B = L_A - 10\log\left(\frac{Q}{4\pi r^2}\right)$$

$$L_B = L_A + 30.9920$$

$$L_A = L_B - 30.9920 \quad \text{— (1)}$$

$$L_S = L_B - 10\log\left(\frac{Q}{4\pi r^2}\right) \quad \text{— (2)}$$

$$L_S = L_B - 30.992 - 10\log\left(\frac{Q}{4\pi r^2}\right) \quad \text{— (3)}$$

$$L_S = 60 - 10\log\left(\frac{Q}{4\pi r_B^2}\right) \quad \text{— (2)}$$

$$L_S = 29.008 - 10\left(\log\frac{Q}{4\pi r_A^2}\right)$$

$$+10\log\left(\frac{Q}{4\pi r_A^2}\right) = -30.992 + 10\log\left(\frac{Q}{4\pi r_B^2}\right) \quad \text{— (4)}$$

$$L_s = L_C - 10\log\left(\frac{Q}{4\pi r_C^2}\right)$$

$$L_B = L_C - 10\log\left(\frac{Q}{4\pi r^2}\right)$$

$$L_B = L_C - 30.992$$

$$L_C = L_B + 30.992 \quad \text{—— (5)}$$

$$L_s = L_B - 10\log\left(\frac{Q}{4\pi r_B^2}\right) \quad \text{—— (6)}$$

$$L_s = L_B + 30.992 - 10\log\left(\frac{Q}{4\pi r_B^2}\right) \quad \text{— (7)}$$

So, $$10\log\left(\frac{Q}{4\pi r_B^2}\right) = 10\log\left(\frac{Q}{4\pi r_C^2}\right) - 30.992$$

$$L_s = L_C - 10\log\left(\frac{Q}{4\pi r_C^2}\right) \quad \text{—— (8)}$$

$$L_A = L_C - 10\log\left(\frac{Q}{4\pi r^2}\right)$$

$$L_A = L_C - 34.002$$

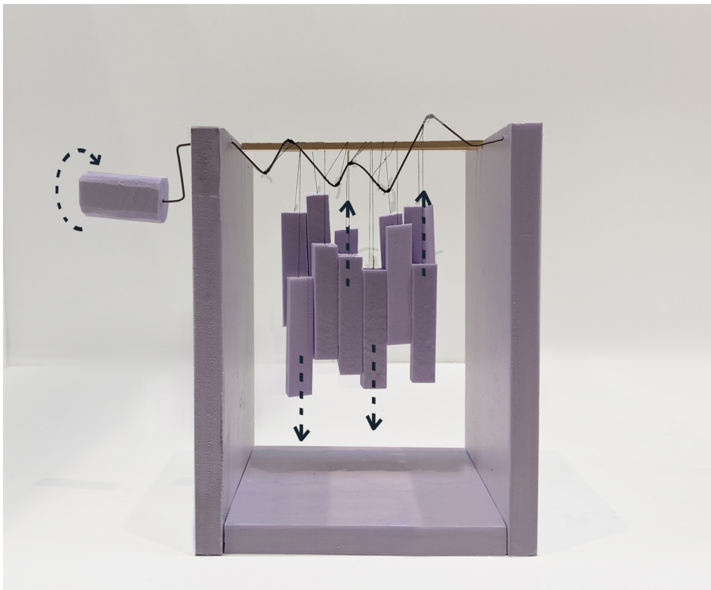
$$L_s = L_A - 10\log\left(\frac{Q}{4\pi r_A^2}\right)$$

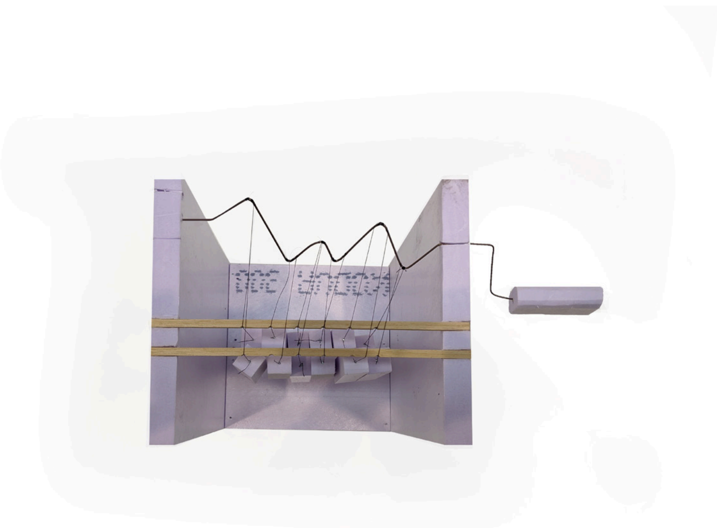
$$L_s = L_C - 34.002 - 10\log\left(\frac{Q}{4\pi r_A^2}\right) \quad \text{— (9)}$$

$$10\log\left(\frac{Q}{4\pi r_C^2}\right) = +34.002 + 10\log\left(\frac{Q}{4\pi r_A^2}\right) \quad \text{— (10)}$$

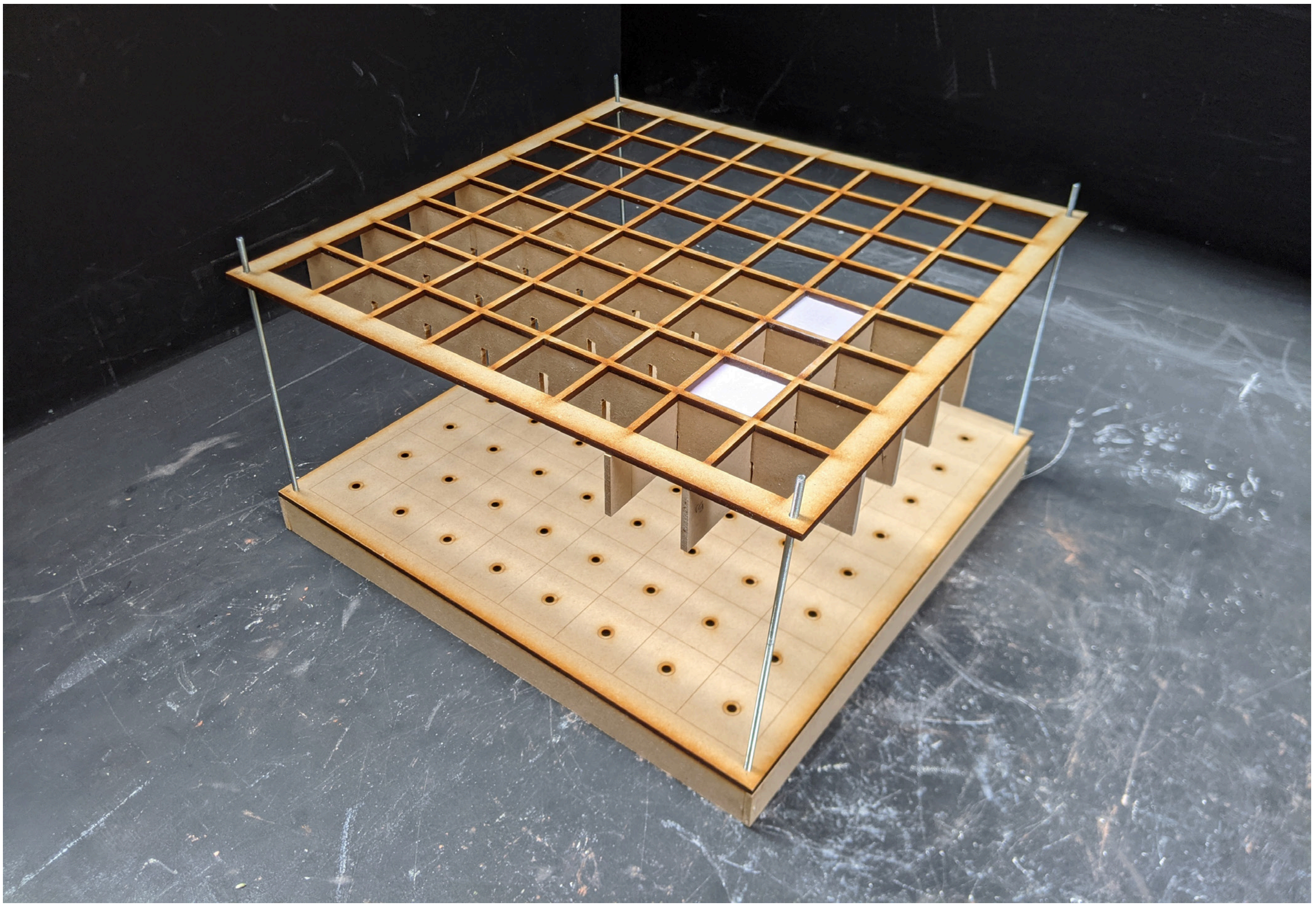
APPENDIX B

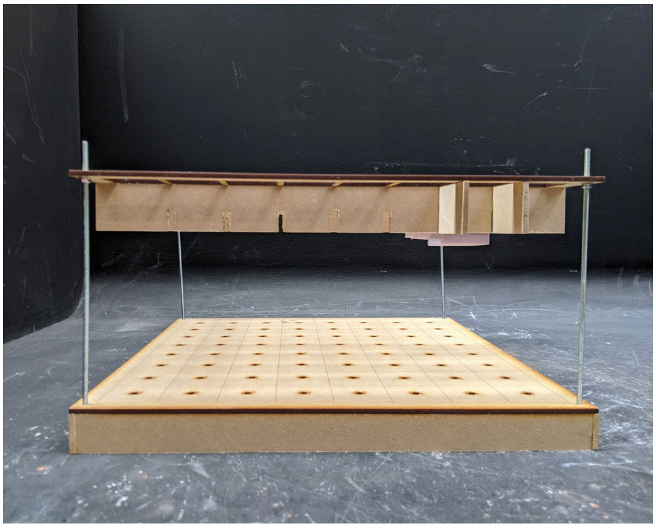
Physical prototype 1 pictures

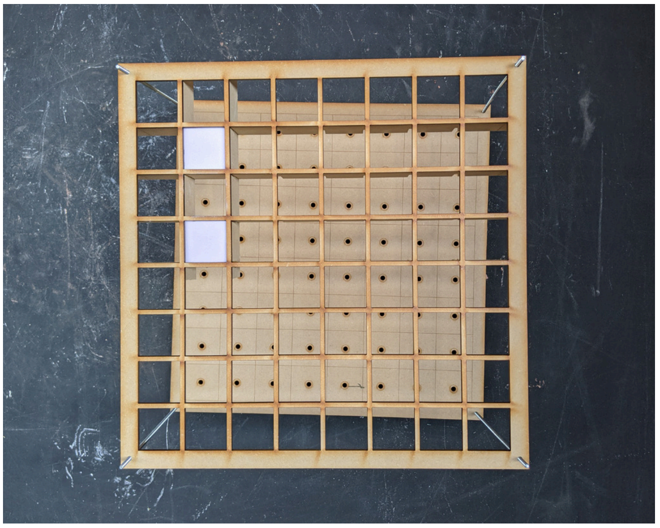


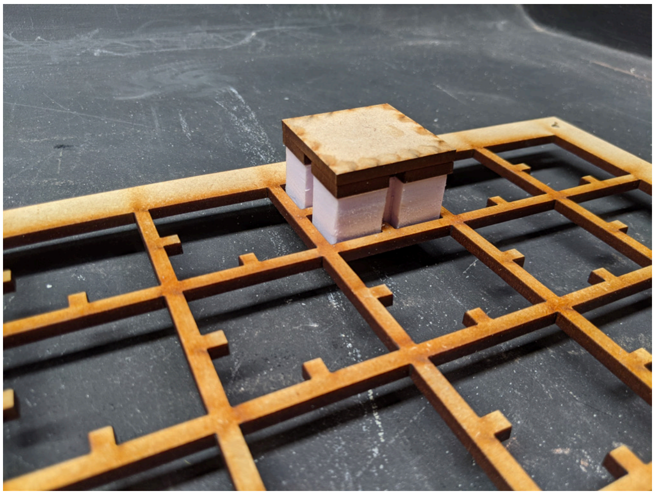


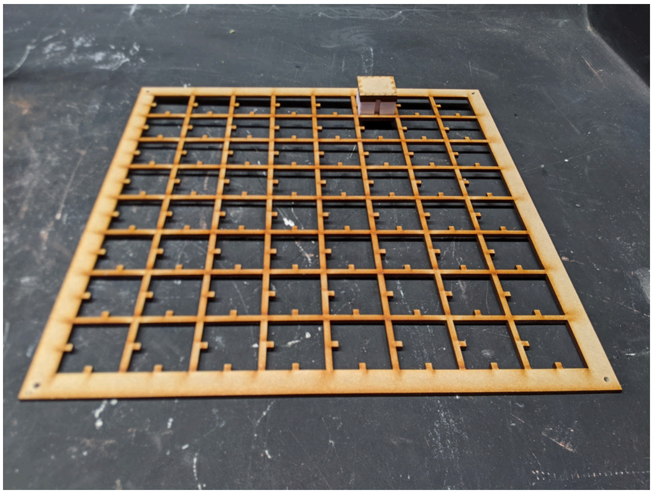
Physical prototype 2 pictures

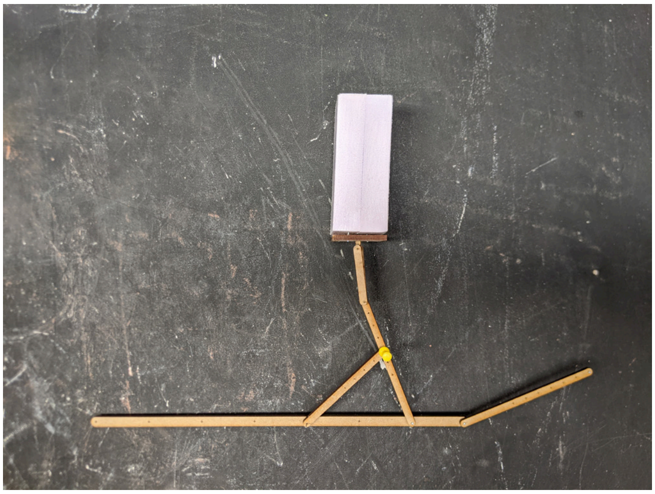


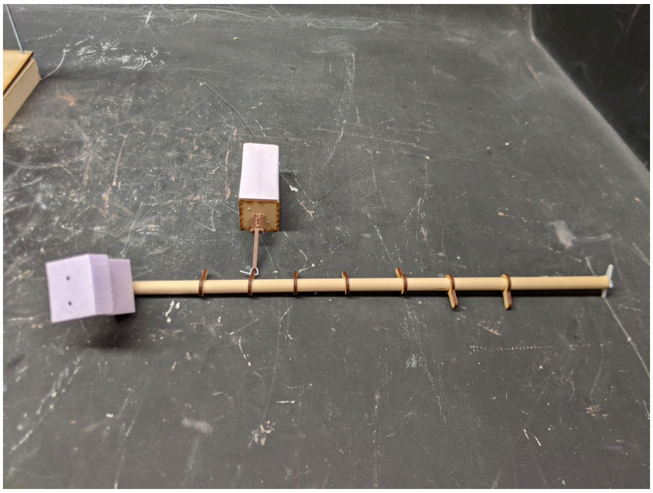


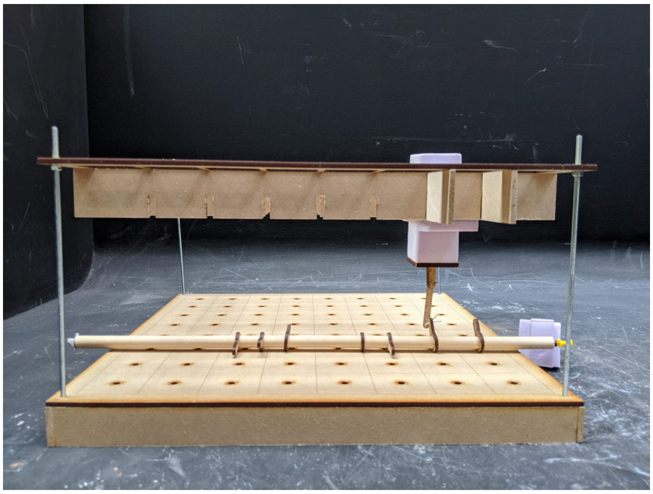




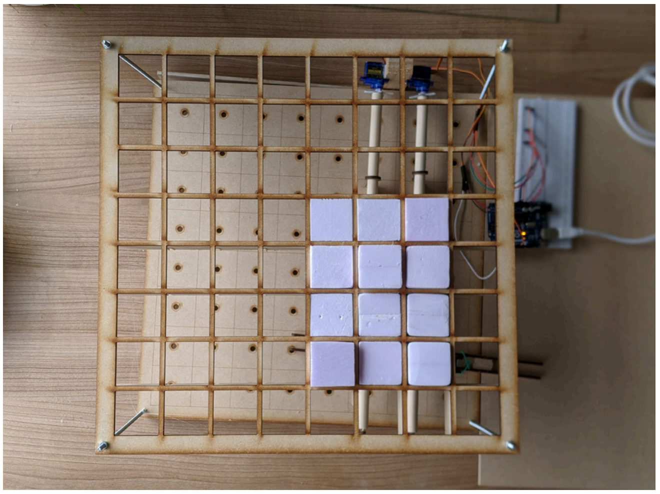


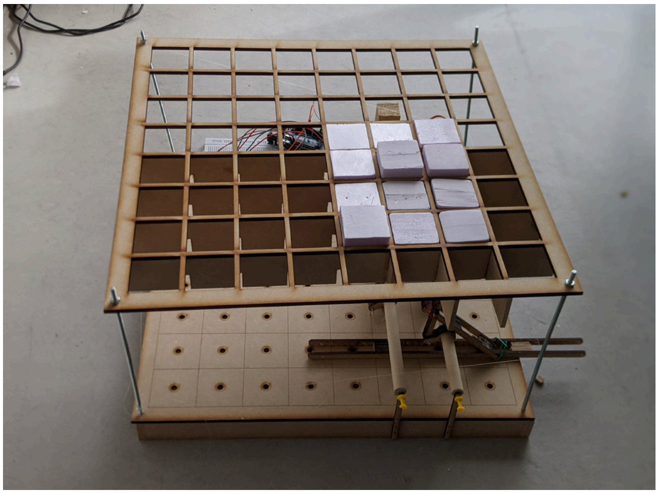


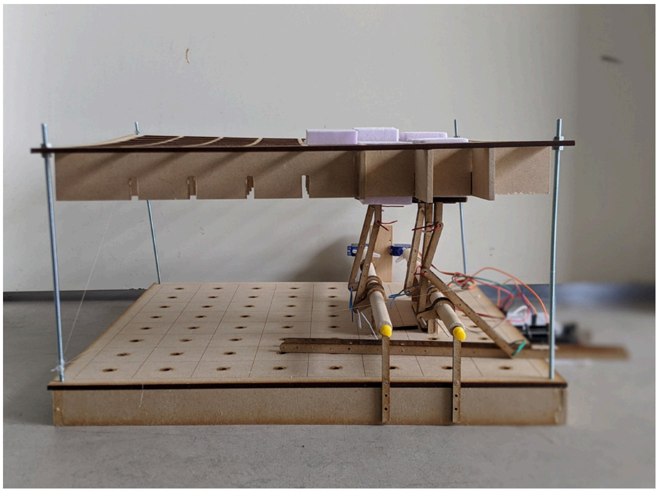


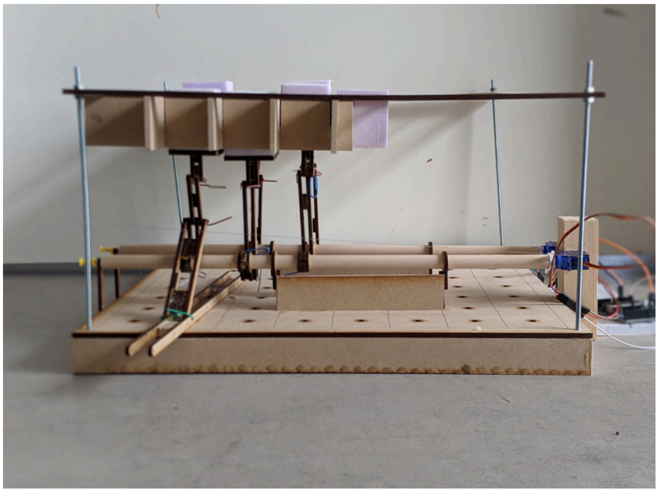


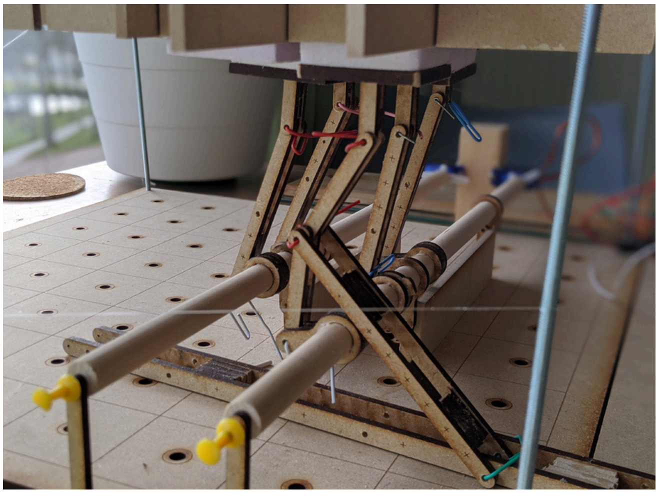
Physical prototype 3 pictures





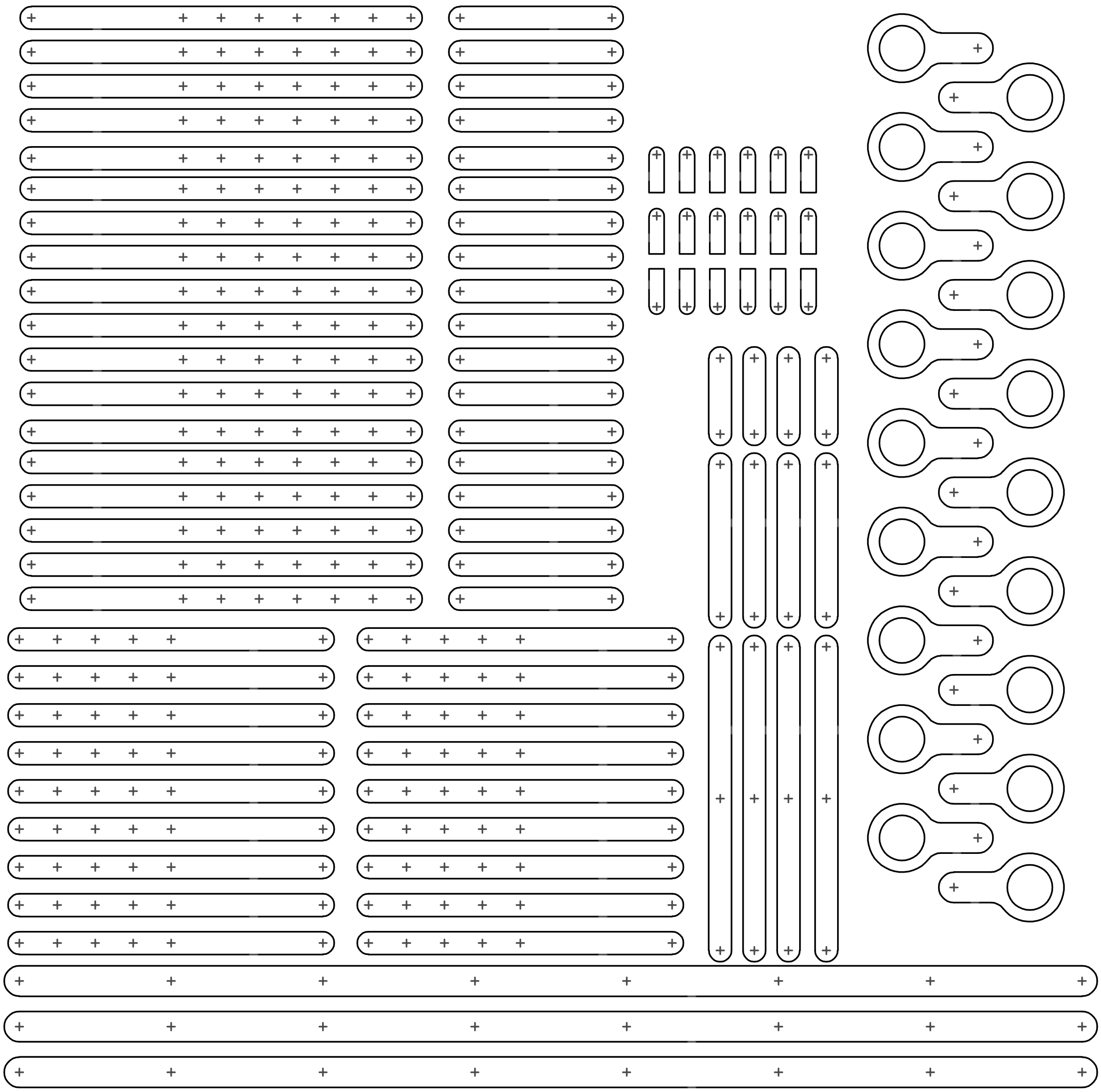






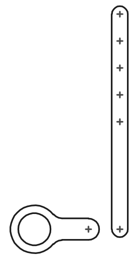
APPENDIX C

Laser cut drawings for levers and spindle turner wheels.

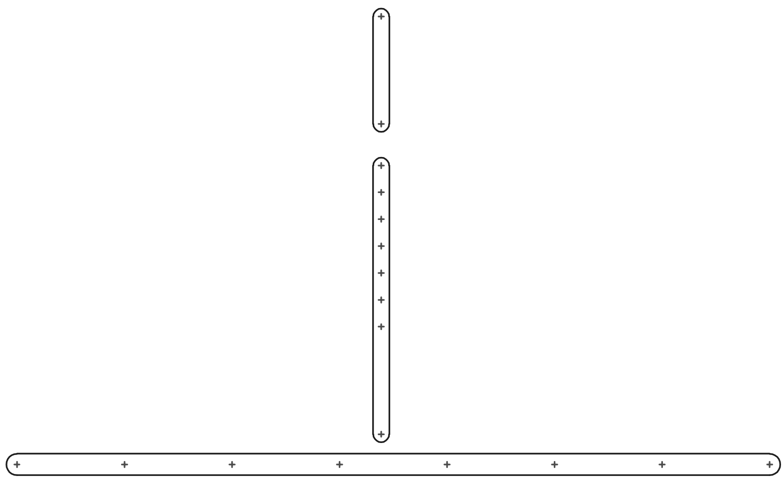


Lever 1.0 A = 0.04m
Lever 0.5 A = 0.02m

Lever 2.0 A = 0.08m



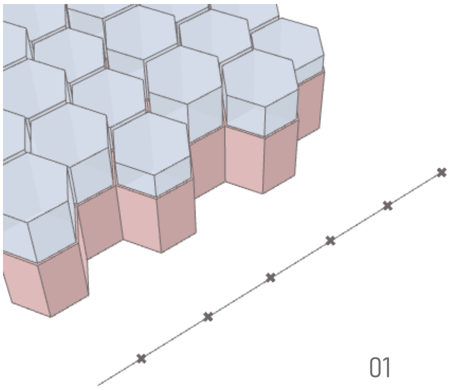
Spindle pin A = 0.02m
Lever 2.0 B = 0.08m



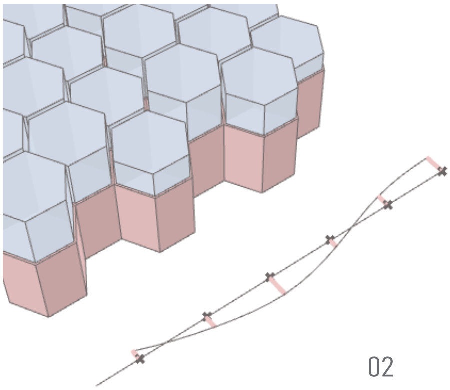
Lever 8.0 A = 0.28 m
Lever 2.5 A = 0.10 m
Lever 1.0 A = 0.04 m

APPENDIX D

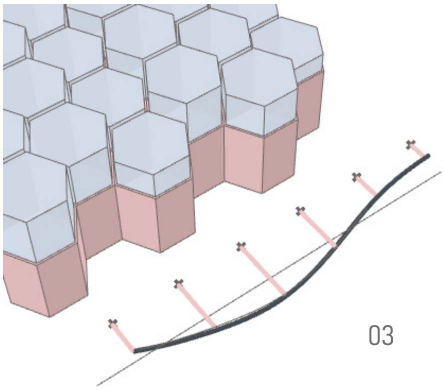
Result corroboration of the custom definition with the pre existing softwares such as CATT Acoustics and Pachyderm.



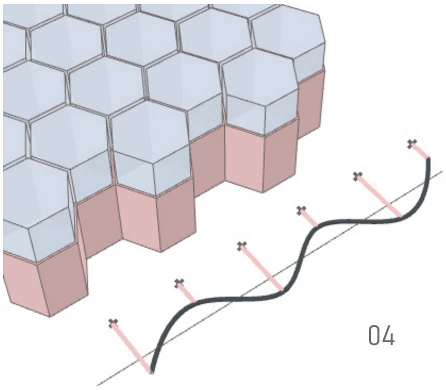
01



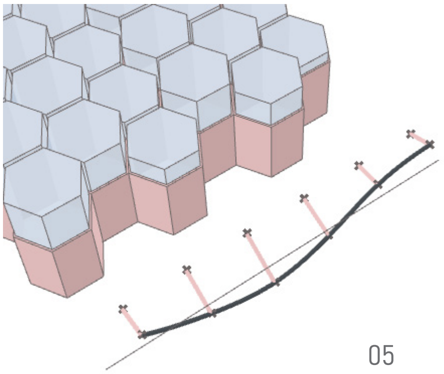
02



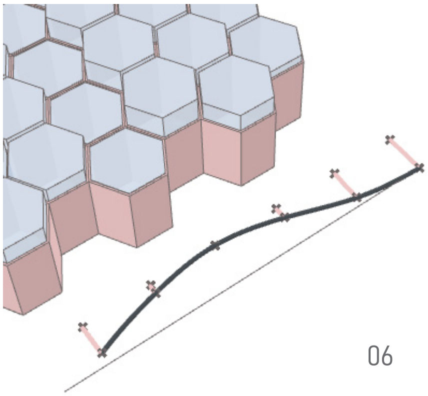
03



04

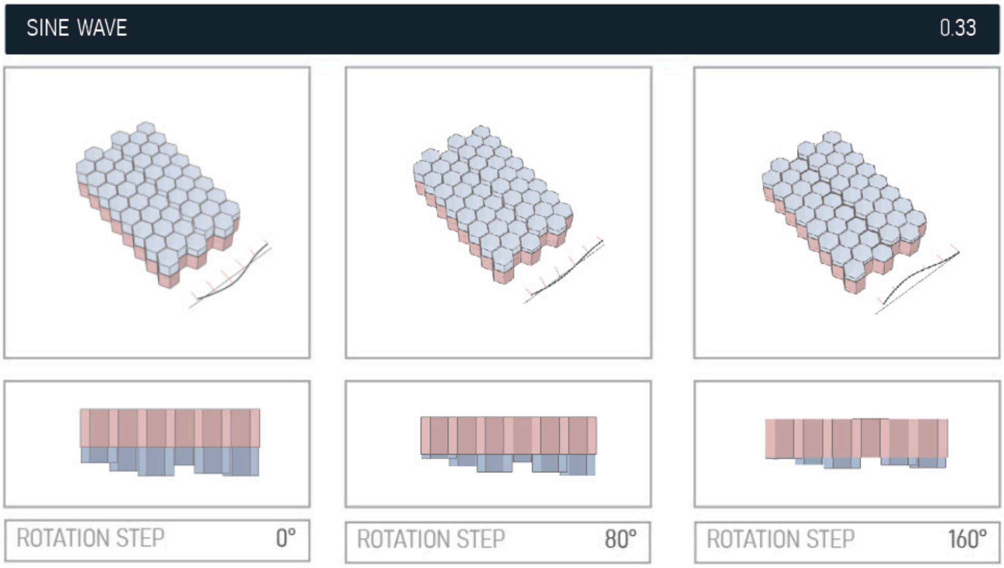


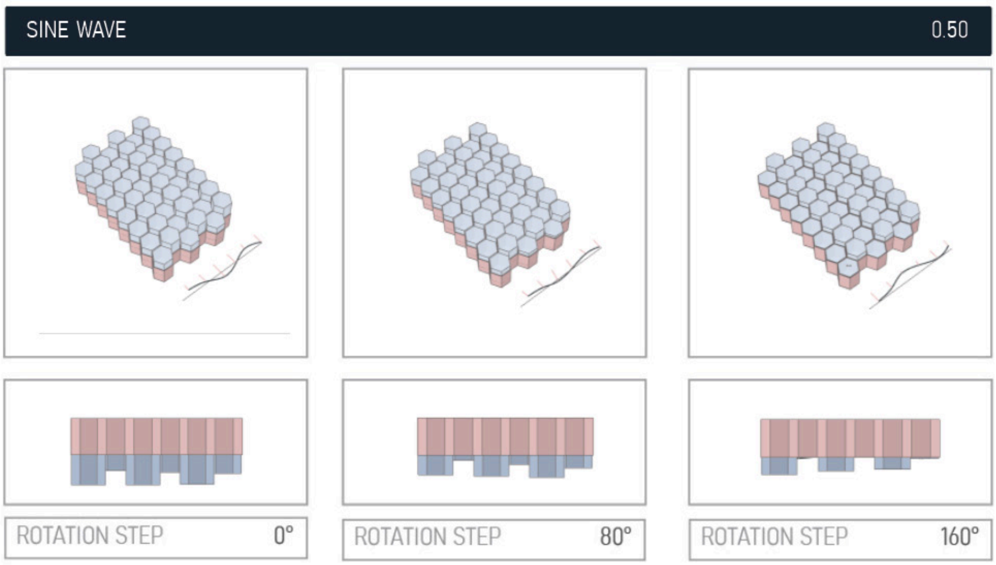
05

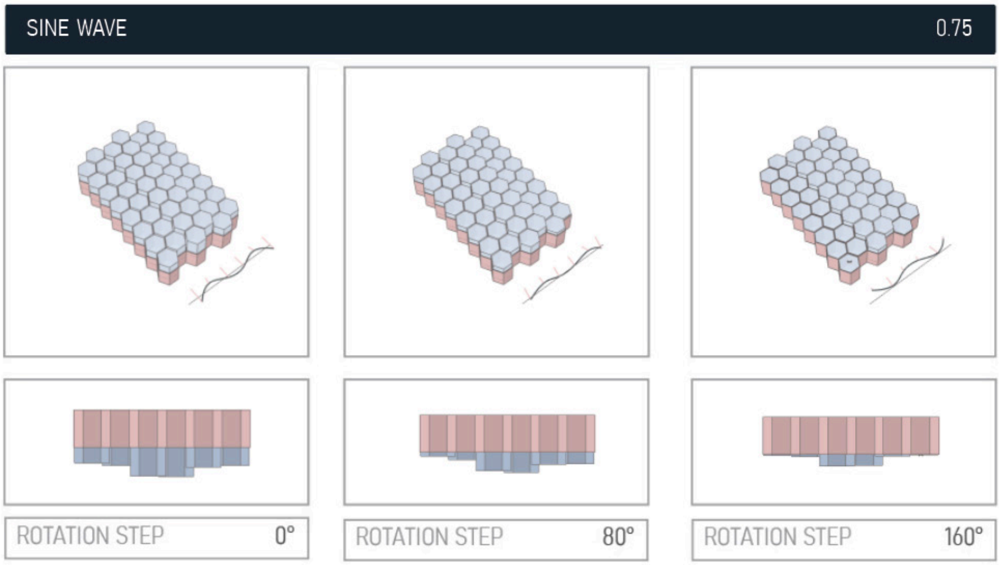


06

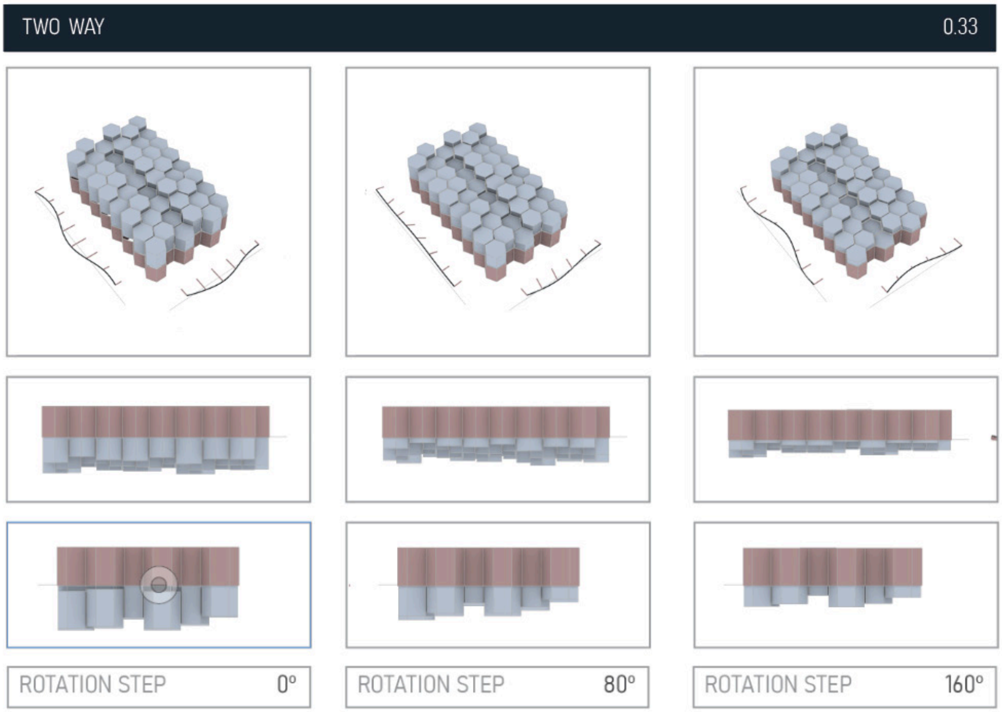
One Control Motion

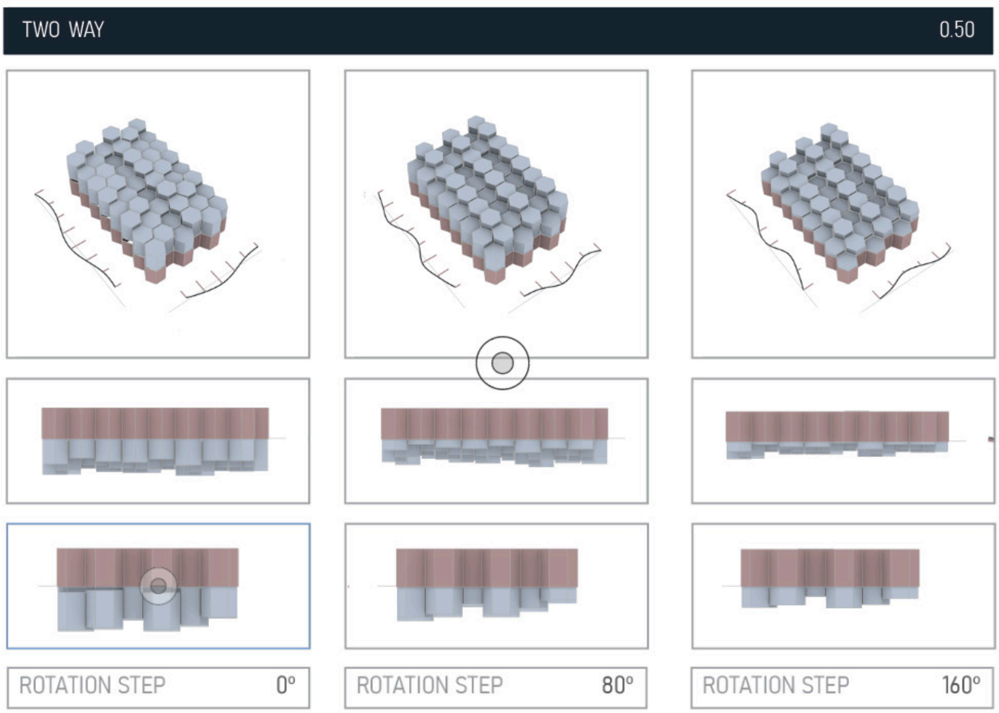


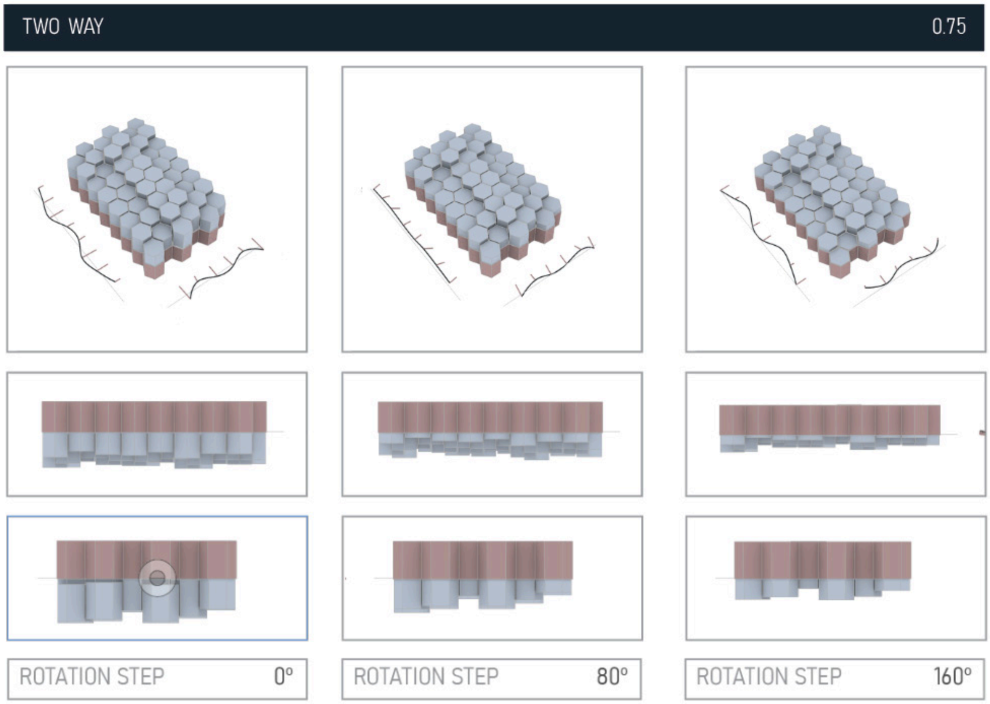



SINE WAVE
0.75
ROTATION STEP
0°
ROTATION STEP
80°
ROTATION STEP
160°

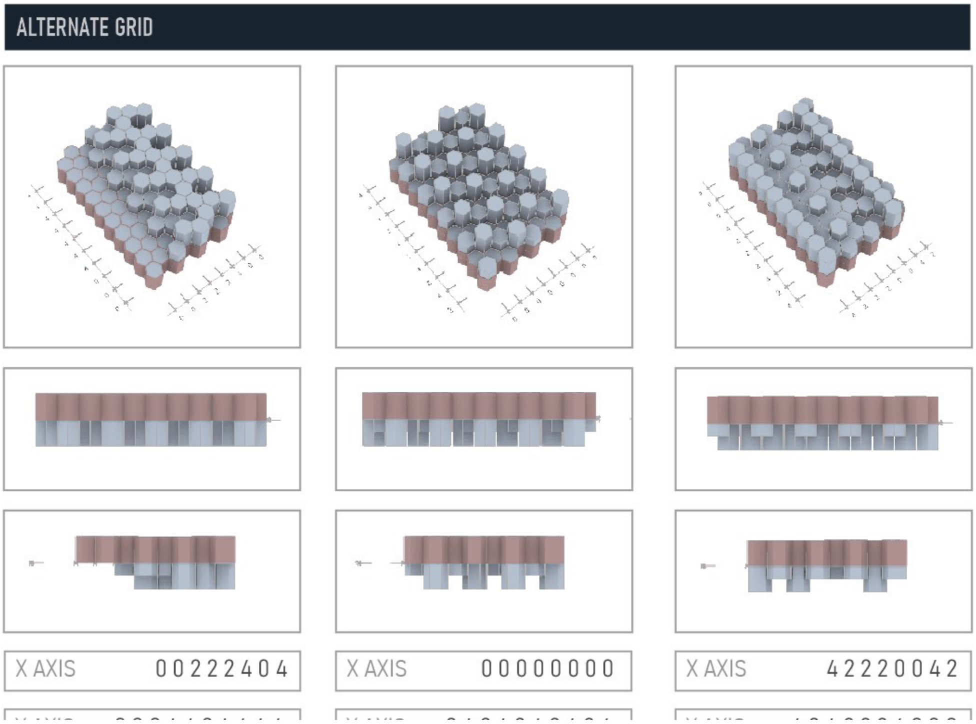
Two-way Control Motion

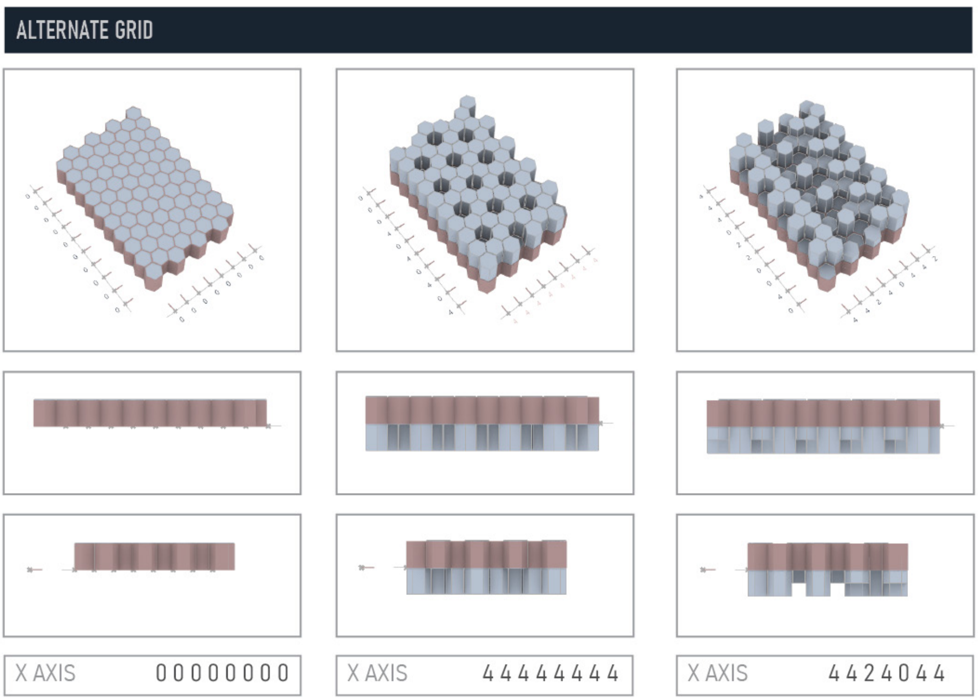





TWO WAY
0.75
ROTATION STEP
0°
ROTATION STEP
80°
ROTATION STEP
160°

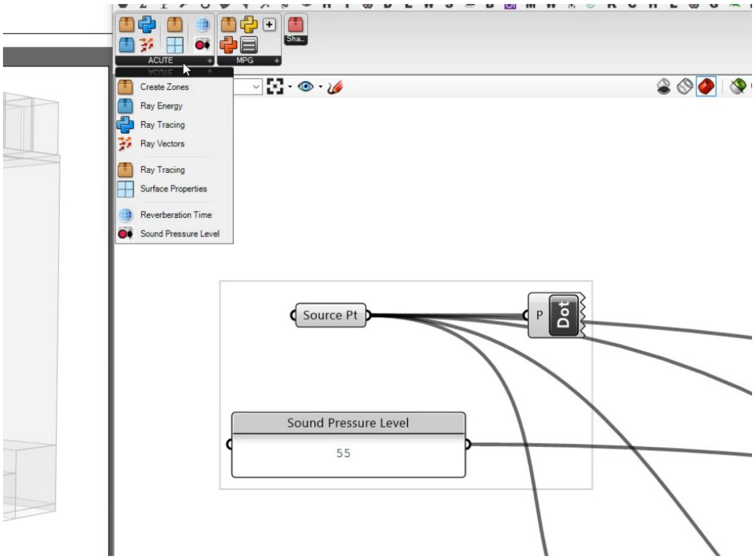
Alternate grid Control Motion

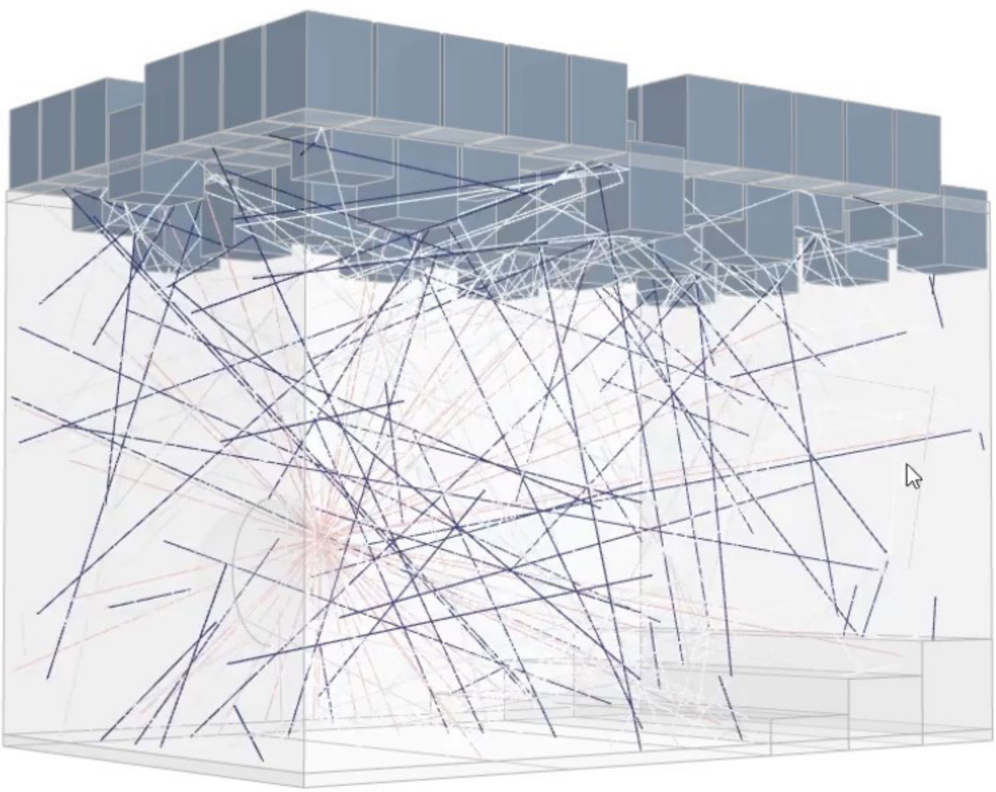


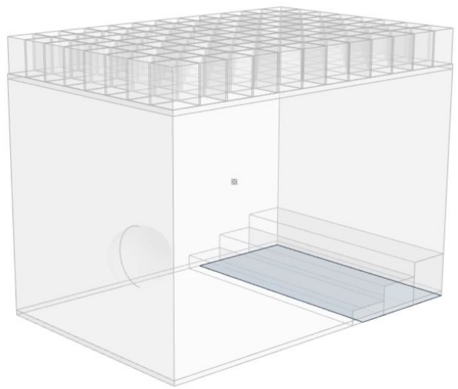


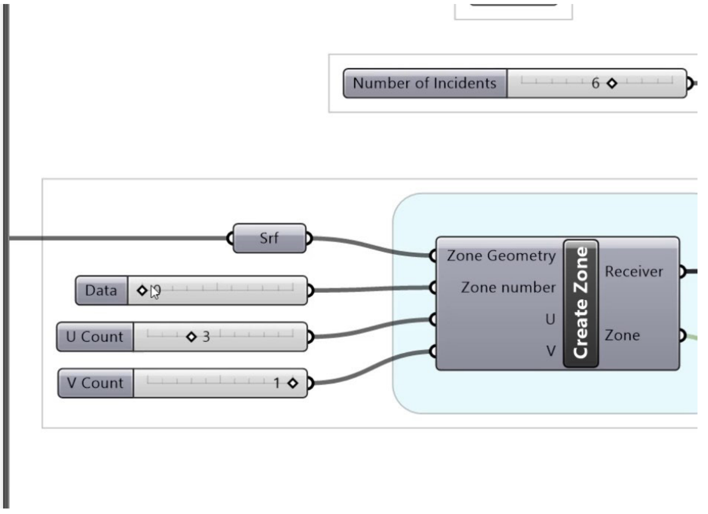
APPENDIX E

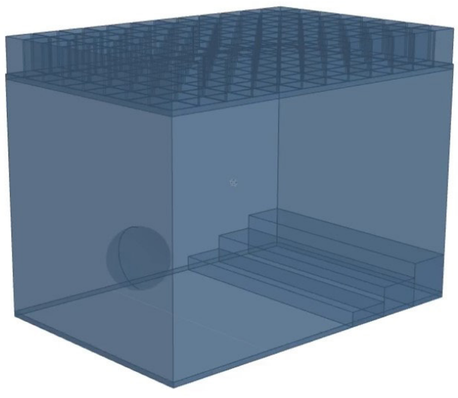
Acoustic Plugin design and custom definition.

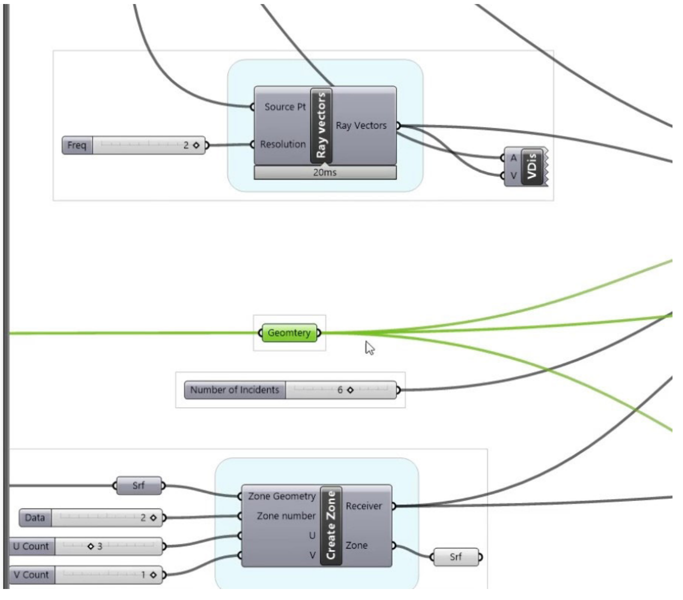


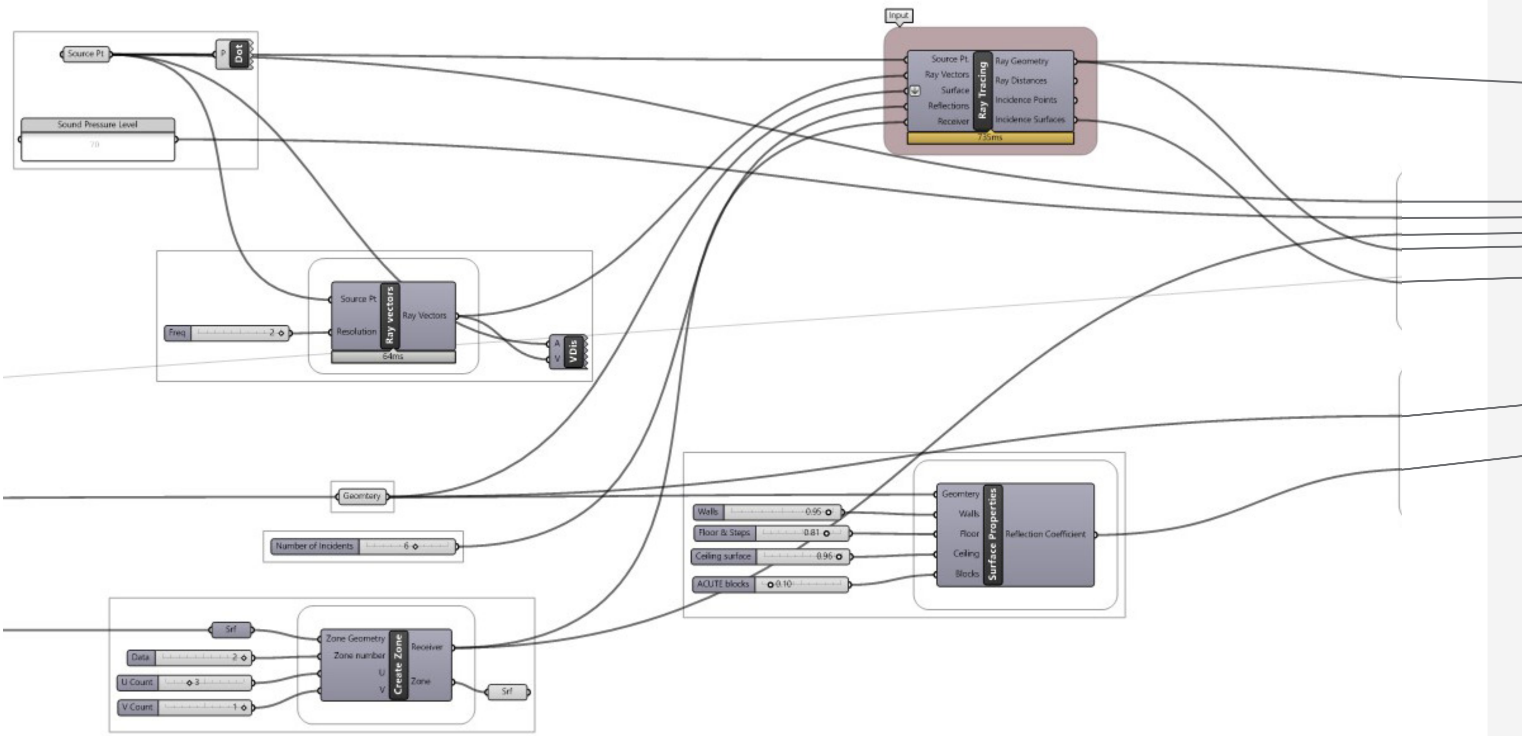


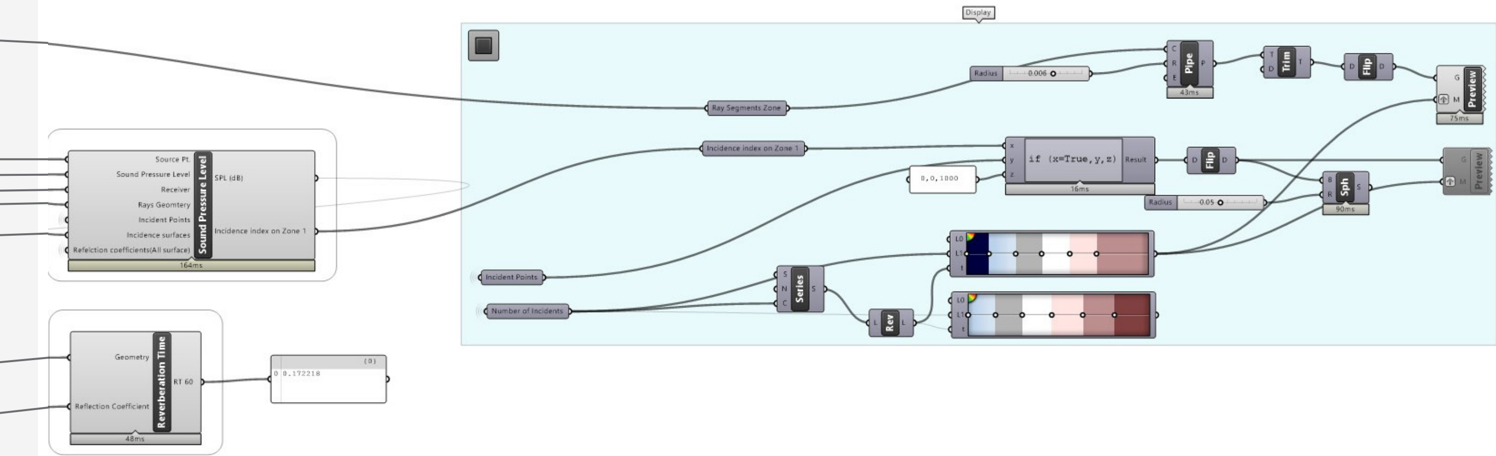



Number of Incidents
6
Srf
Data
U Count
3
V Count
1
Zone Geometry
Zone number
U
V
Create Zone
Receiver
Zone




Source Pt
Resolution
Ray vectors
Ray Vectors
Freq
2
20ms
A
V
VDis
Geomtery
Number of Incidents
6
Srf
Data
2
U Count
3
V Count
1
Zone Geometry
Zone number
U
V
Create Zone
Receiver
Zone
Srf

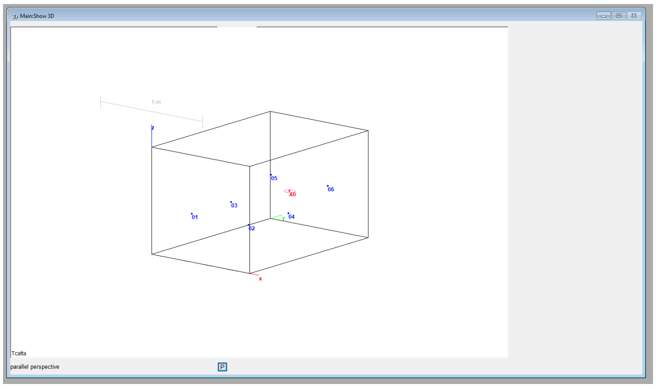

Input
Source Pt
Dot
Sound Pressure Level
Source Pt
Ray Vectors
Surface
Reflections
Receiver
Ray Tracing
Ray Geometry
Ray Distances
Incidence Points
Incidence Surfaces
735ms
Source Pt
Resolution
Ray vectors
Ray Vectors
Freq
64ms
VDis
Geometry
Number of Incidents
Walls
0.95
Floor & Steps
0.81
Ceiling surface
0.96
ACUTE blocks
0.10
Geometry
Walls
Floor
Ceiling
Blocks
Surface Properties
Reflection Coefficient
Srf
Data
U Count
V Count
Zone Geometry
Zone number
U
V
Create Zone
Receiver
Zone
Srf



Display
Ray Segments Zone
Radius
0.006
Pipe
Trim
Flip
Preview
Incidence index on Zone 1
if (x=True,y,z)
Result
0,0,1000
Sph
Source Pt.
Sound Pressure Level
Receiver
Rays Geomtery
Incident Points
Incidence surfaces
Refelction coefficients(All surface)
SPL (dB)
164ms
Incident Points
Number of Incidents
Series
Rev
Geometry
Reflection Coefficient
Reverberation Time
RT 60
48ms
0.172218

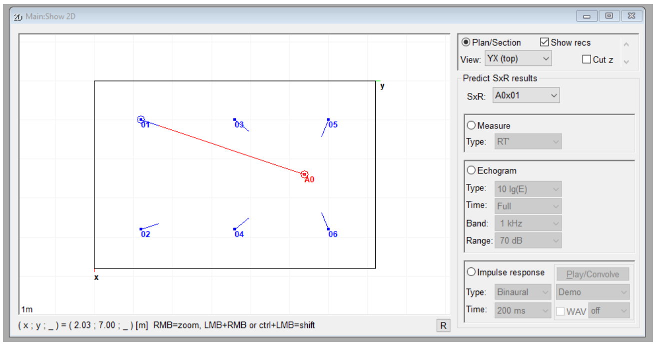
APPENDIX F

Result corroboration of the custom definition with the pre existing softwares such as CATT Acoustics and Pachyderm.



Isometric view of the geomtery

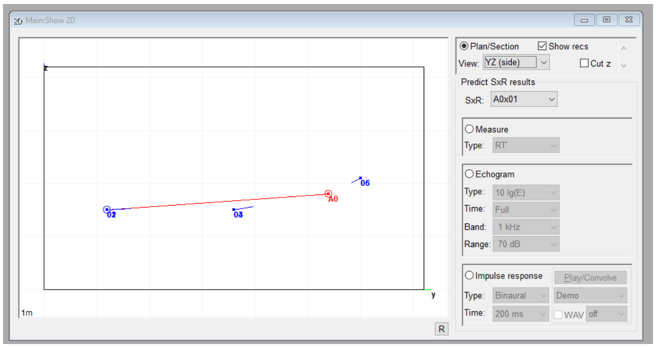
Room width = 4.8 m
Room length = 7.2 m
Room height = 3.9 m



Plan view of the geomtery

Source Point coordinate = (6.0m, 2.4 m)

Receiver point coordinates
R 1 = (0.9m, 0.9m)
R 2 = (3.6m, 0.9m)
R 3 = (6.3m, 0.9m)
R 4 = (0.9m, 3.9m)
R 5 = (3.6m, 3.9m)
R 6 = (6.3m, 3.9m)

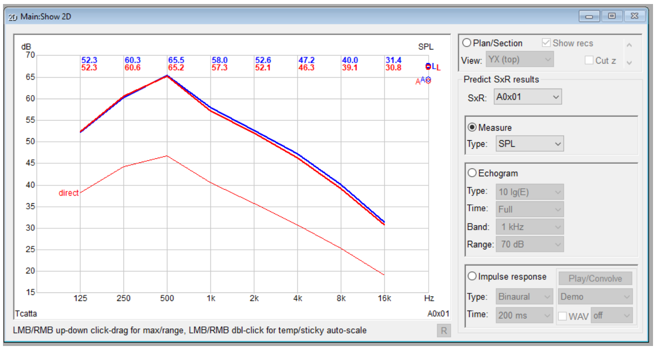


Elevation view of the geomtery

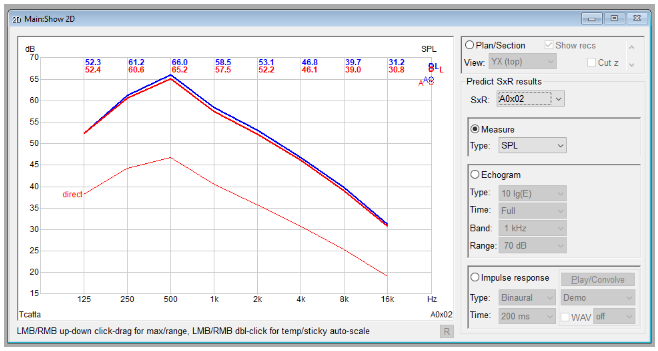
Source Point height = 1.5 m

R 1 height = 1.2 m
R 2 height = 1.2 m
R 3 height = 1.2 m
R 4 height = 1.2 m
R 5 height = 1.8 m
R 6 height = 1.8 m

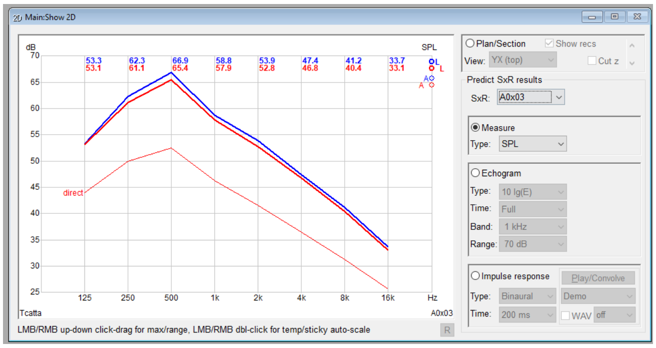
Sound Pressure level at the 6 defined receiver points in the respective order.



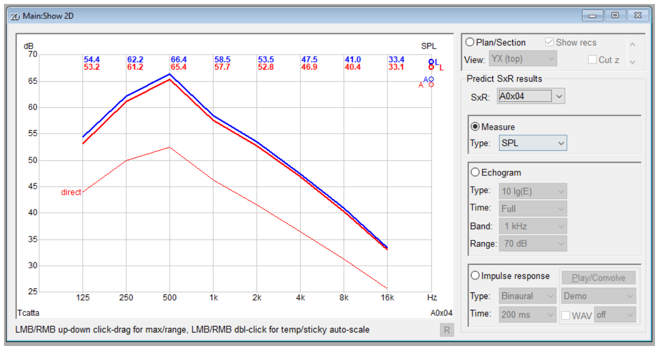
Receiver 1



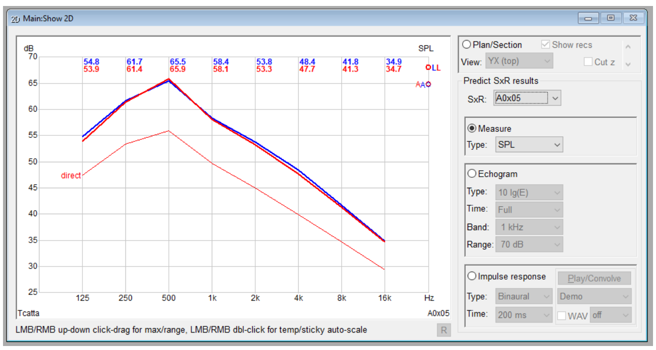
Receiver 2



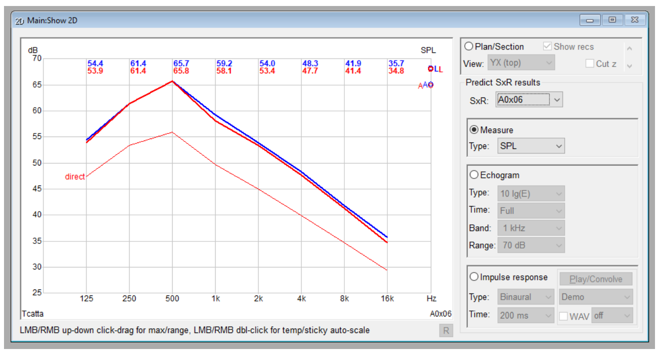
Receiver 3



Receiver 4

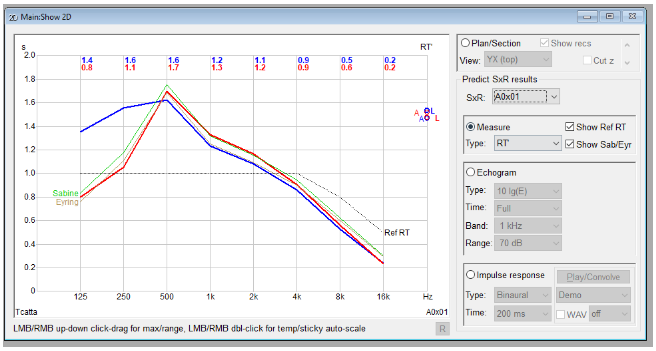


Receiver 5

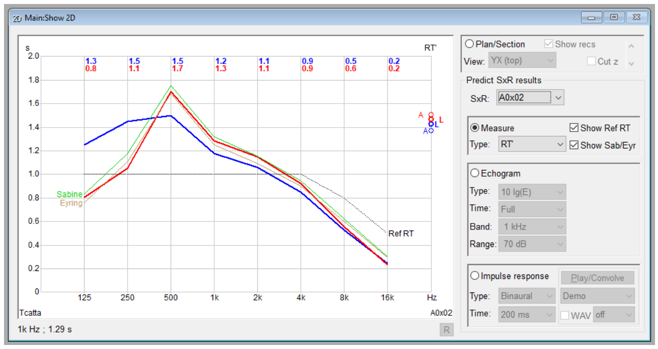


Receiver 6

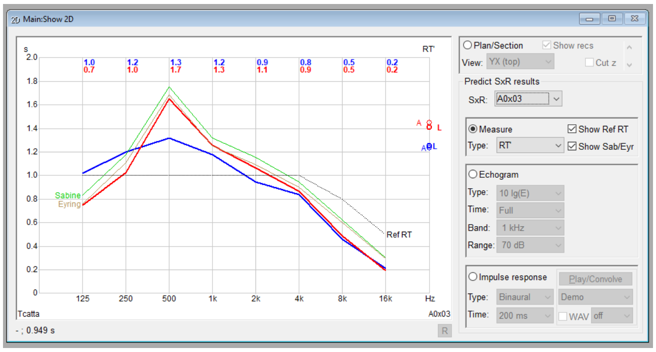
Reverberation time at the 6 defined receiver points in the respective order.



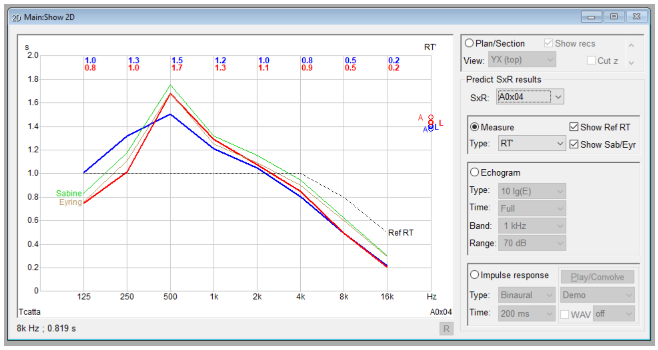
Receiver 1



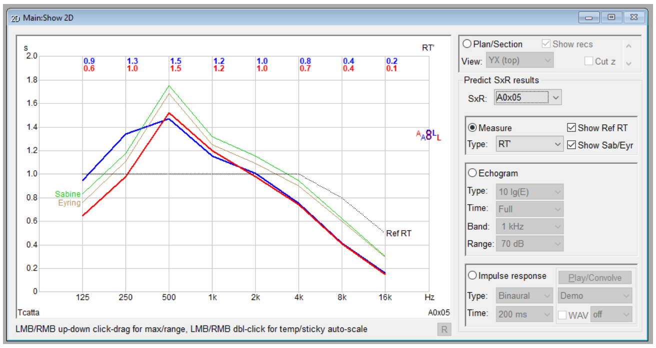
Receiver 2



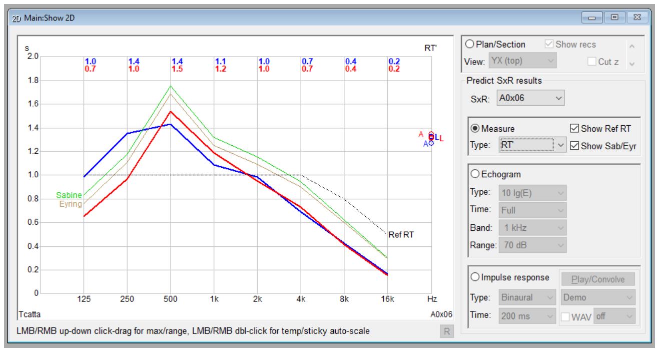
Receiver 3



Receiver 4

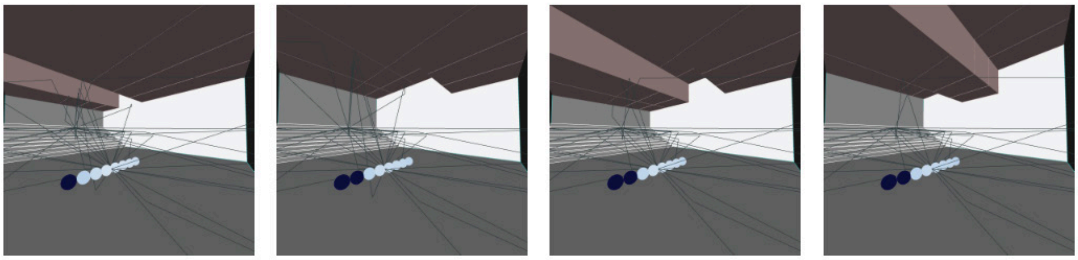


Receiver 5



Receiver 6

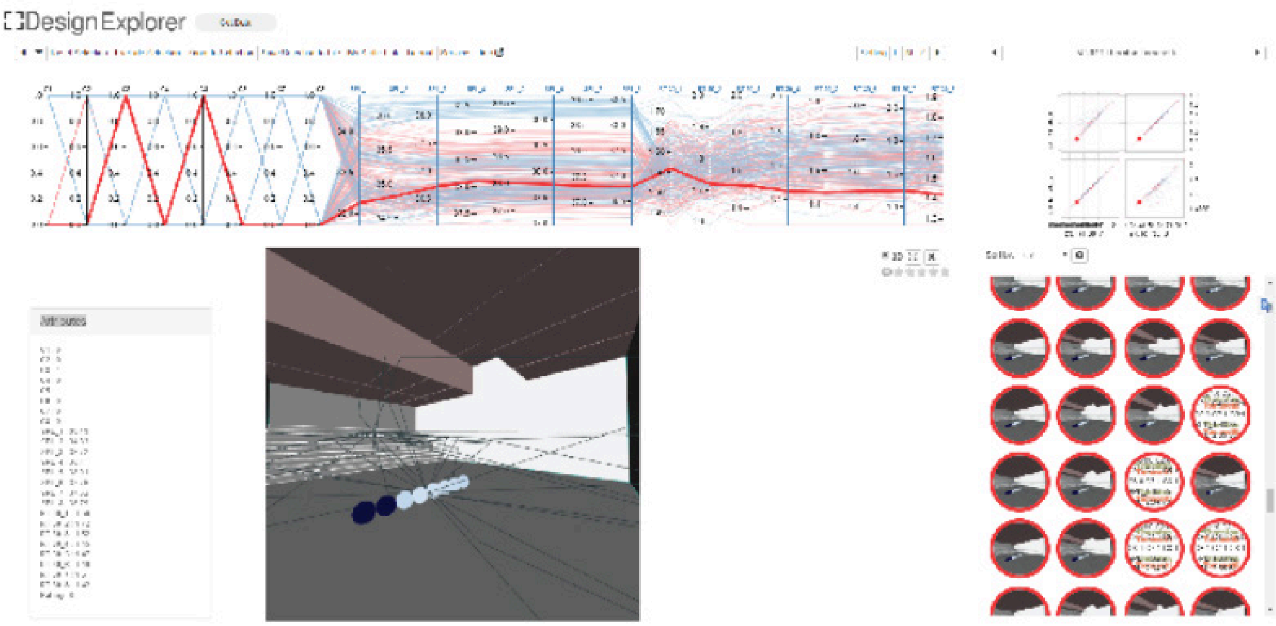
Pachyderm testing data.



Least reverberation time (row 11)

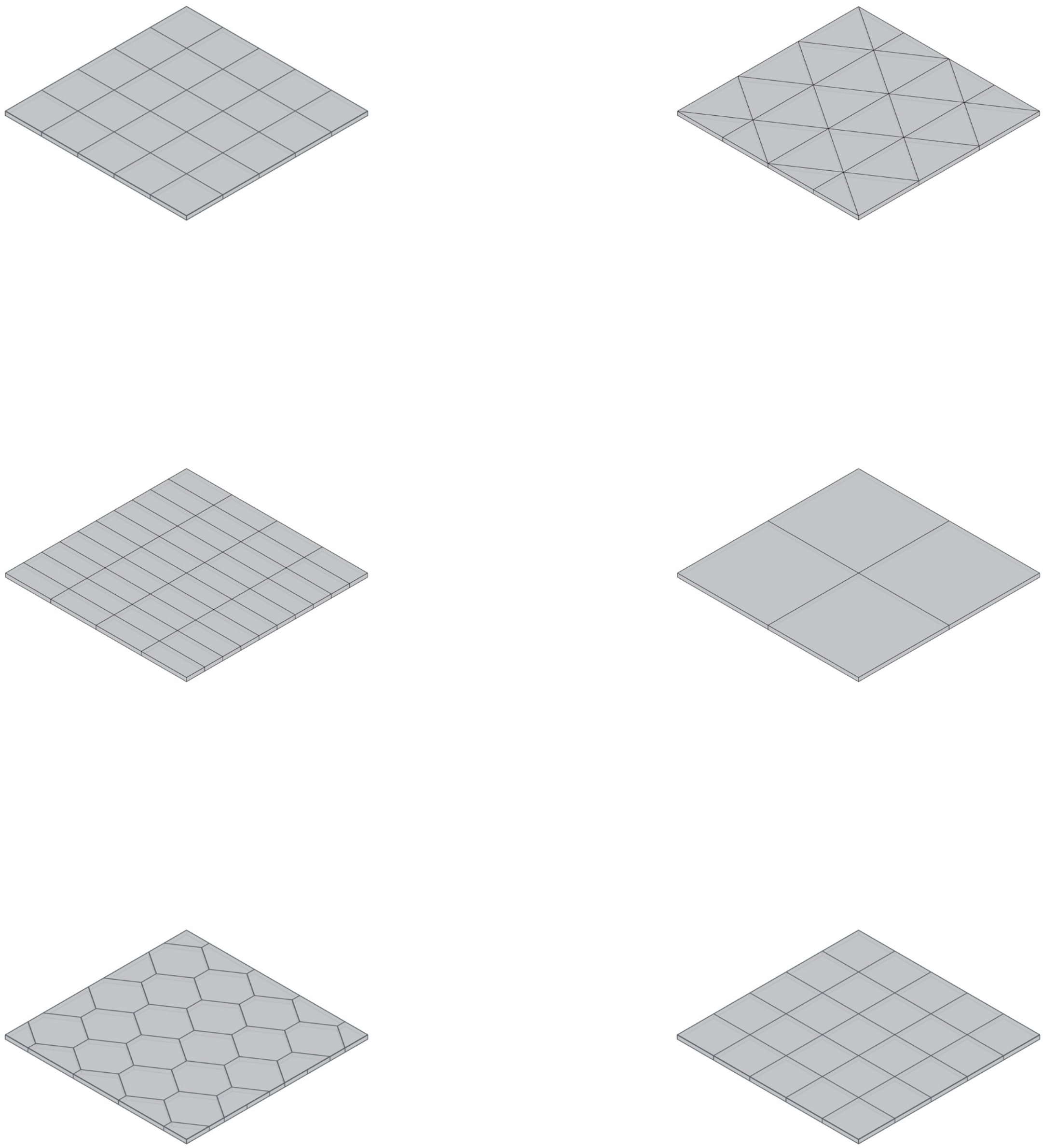
Highest sound pressure levels (row 17)

	SPL Spec 1	SPL Spec 2	SPL Spec 3	SPL Spec 4	SPL Spec 5	SPL Spec 6	SPL Spec 7	SPL Spec 8	RT30 Spec 1	RT30 Spec 2	RT30 Spec 3	RT30 Spec 4	RT30 Spec 5	RT30 Spec 6	RT30 Spec 7	RT30 Spec 8
1	39,86	39,41	39,60	40,23	40,23	39,94	39,68	39,37	1,62	1,81	2,17	2,28	2,38	2,42	2,39	2,29
2	39,75	39,35	39,60	40,21	40,23	39,96	39,73	39,41	1,67	1,79	2,12	2,27	2,38	2,42	2,41	2,21
3	39,75	39,32	39,48	40,15	40,15	39,83	39,55	39,22	1,68	1,86	2,24	2,28	2,19	2,25	2,43	2,31
4	39,87	39,56	39,79	40,39	40,40	40,12	39,87	39,56	1,67	1,76	2,03	2,17	2,23	2,34	2,28	2,13
5	39,81	39,36	39,57	40,16	40,17	39,89	39,67	39,38	1,61	1,65	2,03	2,15	2,28	2,36	2,36	2,16
6	39,88	39,45	39,61	40,25	40,24	39,92	39,65	39,34	1,55	1,65	1,94	2,06	2,20	2,27	2,27	2,13
7	39,69	39,29	39,46	40,07	40,07	39,78	39,53	39,23	1,68	1,86	2,19	2,17	2,21	2,21	2,16	2,25
8	39,74	39,39	39,61	40,27	40,29	39,99	39,71	39,37	1,77	2,09	2,52	2,63	2,72	2,77	2,74	2,50
9	39,95	39,51	39,70	40,37	40,37	40,05	39,77	39,45	1,62	1,59	1,80	1,81	1,90	1,94	1,93	1,81
10	39,78	39,43	39,63	40,21	40,22	39,94	39,70	39,39	1,65	1,85	2,28	2,33	2,43	2,49	2,47	2,44
11	39,81	39,40	39,59	40,24	40,25	39,94	39,69	39,38	1,69	1,59	1,75	1,94	1,96	1,91	1,92	1,78
12	39,83	39,37	39,52	40,17	40,16	39,85	39,58	39,26	1,67	1,84	2,13	2,21	2,31	2,38	2,38	2,19
13	39,63	39,32	39,61	40,23	40,27	40,02	39,80	39,47	1,66	1,78	2,07	2,20	2,32	2,39	2,37	2,21
14	39,78	39,41	39,60	40,19	40,19	39,90	39,66	39,36	1,64	1,64	2,01	2,13	2,20	2,23	2,27	2,08
15	39,86	39,46	39,64	40,30	40,31	39,99	39,73	39,40	1,65	1,73	2,12	2,24	2,35	2,42	2,41	2,20
16	39,79	39,41	39,62	40,21	40,20	39,93	39,69	39,41	1,58	1,65	1,89	2,04	2,14	2,17	2,15	2,00
17	39,90	39,51	39,74	40,41	40,43	40,13	39,86	39,52	1,62	1,71	2,01	2,15	2,24	2,28	2,26	2,10
18	39,82	39,49	39,73	40,35	40,36	40,07	39,82	39,51	1,66	1,72	1,95	2,06	2,16	2,22	2,23	2,08
19	39,80	39,30	39,44	40,13	40,13	39,79	39,51	39,18	1,75	1,76	1,98	2,06	2,12	2,17	2,16	2,01
20	39,80	39,37	39,56	40,21	40,21	39,90	39,64	39,32	1,66	1,94	2,21	2,17	2,28	2,35	2,34	2,19

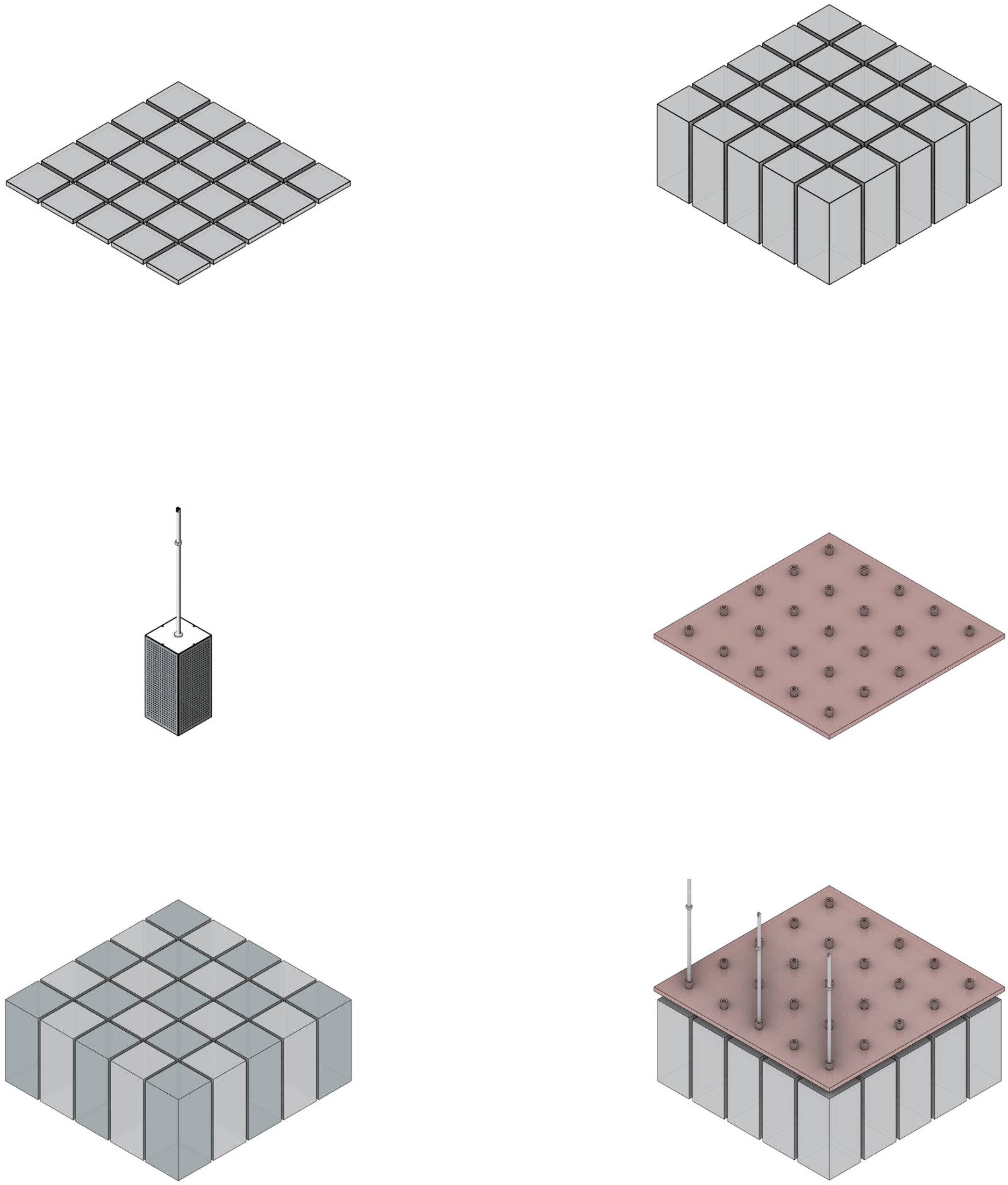


APPENDIX G

Pattern design.

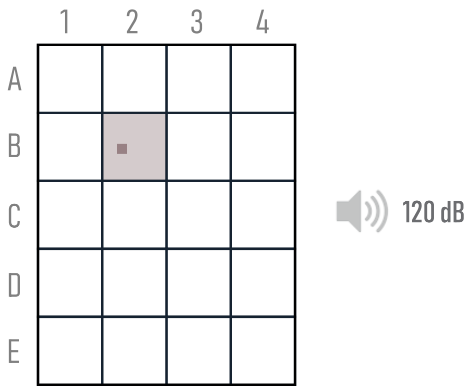


Block design.



APPENDIX H

Scenario 1
Open Room, B2, 120 dB, Quad Groot
Result data (Few of the 729 total results)



OPEN ROOM			
Test Case	SCENARIO I		
Design Type	ACUTE block | Quad Klein		
Block Size - l x w x h (m)	0.3 x 0.3 x 0.6		
Source Position	B2		
Source Height	1.8 m		
Source Sound Pressure level	120 dB		
Task	Zone 1	Zone 2	Zone 3
	Minimize	Minimize	Minimize

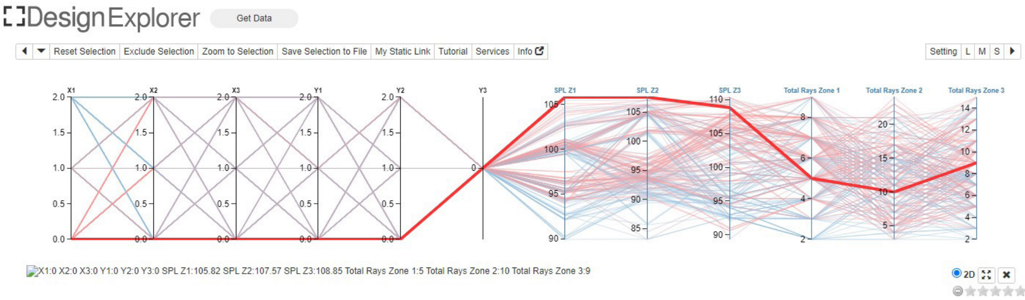
X1	X2	X3	Y1	Y2	Y3	SPL Z1	SPL Z2	SPL Z3	Total Rays Zone 1	Total Rays Zone 2	Total Rays Zone 3
0	0	0	0	0	0	108.28	108.45	108.99	7	8	8
1	0	0	0	0	0	107.65	107.25	108.46	8	6	9
2	0	0	0	0	0	106.98	106.5	107.91	10	8	11
0	1	0	0	0	0	108.36	108.49	108.44	8	10	9
1	1	0	0	0	0	107.74	107.31	107.83	10	8	11
2	1	0	0	0	0	107.09	106.26	107.19	12	10	13
0	2	0	0	0	0	108.36	108.67	108.44	8	14	9
1	2	0	0	0	0	107.74	107.46	107.83	9	13	10
2	2	0	0	0	0	106.98	106.46	107.09	10	11	11
0	0	1	0	0	0	108.36	108.45	109.05	8	8	9
1	0	1	0	0	0	107.74	107.25	109.15	10	6	12
2	0	1	0	0	0	107.08	106.5	107.99	11	8	12
0	1	1	0	0	0	108.43	108.49	108.51	9	10	10
1	1	1	0	0	0	107.83	107.31	106.24	12	8	14
2	1	1	0	0	0	107.18	106.26	107.28	13	10	14
0	2	1	0	0	0	108.43	108.55	108.51	9	11	10
1	2	1	0	0	0	107.82	107.3	106.01	11	10	13
2	2	1	0	0	0	107.08	106.35	107.18	11	10	12
0	0	2	0	0	0	108.36	108.45	109.05	8	8	9
1	0	2	0	0	0	107.74	107.25	109.15	10	6	12
2	0	2	0	0	0	106.98	106.4	107.91	10	8	11
0	1	2	0	0	0	108.43	108.45	108.51	9	9	10
1	1	2	0	0	0	107.83	107.26	106.24	12	7	14
2	1	2	0	0	0	107.09	106.19	107.19	12	8	13
0	2	2	0	0	0	108.43	108.45	108.51	9	9	10
1	2	2	0	0	0	107.82	107.17	106.01	11	8	13
2	2	2	0	0	0	106.98	106.19	107.09	10	8	11
0	0	0	1	0	0	108.36	106.83	109.05	8	15	9
1	0	0	1	0	0	107.65	106.56	108.46	8	12	9
2	0	0	1	0	0	106.89	106.76	107.84	10	14	11
0	1	0	1	0	0	108.36	106.59	108.43	8	12	9
1	1	0	1	0	0	107.66	106.3	107.75	9	9	10
2	1	0	1	0	0	106.9	106.31	107.01	11	10	12
0	2	0	1	0	0	108.36	106.59	104.12	10	12	12
1	2	0	1	0	0	107.66	106.3	104.12	10	9	12

2	0	0	2	0	0	106.98	106.64	107.91	10	15	11
0	1	0	2	0	0	108.41	106.78	106.17	9	17	11
1	1	0	2	0	0	107.72	106.39	104.95	10	14	12
2	1	0	2	0	0	106.89	106.4	107	10	14	11
0	2	0	2	0	0	108.42	106.78	108.17	11	16	14
1	2	0	2	0	0	107.72	106.4	106.48	11	13	14
2	2	0	2	0	0	106.79	106.39	103.43	10	12	12
0	0	1	2	0	0	108.43	106.92	108.62	11	16	13
1	0	1	2	0	0	107.74	106.54	107.61	12	13	15
2	0	1	2	0	0	106.9	106.55	107.85	11	13	12
0	1	1	2	0	0	108.36	106.76	106.08	10	14	12
1	1	1	2	0	0	107.67	106.37	104.2	12	11	15
2	1	1	2	0	0	106.81	106.38	106.92	11	11	12
0	2	1	2	0	0	108.36	106.76	105.96	10	13	12
1	2	1	2	0	0	107.66	106.38	104	11	10	14
2	2	1	2	0	0	106.7	106.37	106.81	9	9	10
0	0	2	2	0	0	108.36	106.75	109.05	8	15	9
1	0	2	2	0	0	107.66	106.44	107.8	9	12	11
2	0	2	2	0	0	106.88	106.46	107.83	9	12	10
0	1	2	2	0	0	108.28	106.6	108.36	7	14	8
1	1	2	2	0	0	107.58	106.27	104.49	9	11	11
2	1	2	2	0	0	106.79	106.29	106.9	9	11	10
0	2	2	2	0	0	108.28	106.6	108.36	7	13	8
1	2	2	2	0	0	107.57	106.29	104.3	8	10	10
2	2	2	2	0	0	106.67	106.29	106.79	7	10	8
0	0	0	0	1	0	108.28	108.55	108.99	7	11	8
1	0	0	0	1	0	107.65	107.34	108.46	8	9	9
2	0	0	0	1	0	106.98	106.5	107.91	10	12	11
0	1	0	0	1	0	108.36	108.56	108.44	8	13	9
1	1	0	0	1	0	107.74	107.34	107.83	9	11	10
2	1	0	0	1	0	107.08	106.29	107.18	11	14	12
0	2	0	0	1	0	108.36	108.74	108.44	8	17	9
1	2	0	0	1	0	107.74	107.49	107.83	9	16	10
2	2	0	0	1	0	106.98	106.51	107.09	10	16	11
0	0	1	0	1	0	108.36	108.45	109.05	8	8	9
1	0	1	0	1	0	107.73	107.25	108.53	9	6	10
2	0	1	0	1	0	107.08	106.39	107.99	11	9	12
0	1	1	0	1	0	108.43	108.45	108.51	9	10	10
1	1	1	0	1	0	107.82	107.25	107.91	10	8	11
2	1	1	0	1	0	107.17	106.18	107.27	12	11	13
0	2	1	0	1	0	108.43	108.51	108.51	9	11	10
1	2	1	0	1	0	107.82	107.25	107.91	10	10	11
2	2	1	0	1	0	107.08	106.29	107.18	11	12	12
0	0	2	0	1	0	108.36	108.45	109.05	8	9	9
1	0	2	0	1	0	107.73	107.26	108.53	9	7	10
2	0	2	0	1	0	106.98	106.3	107.91	10	10	11
0	1	2	0	1	0	108.43	108.45	108.51	9	9	10
1	1	2	0	1	0	107.82	107.26	107.91	10	7	11
2	1	2	0	1	0	107.08	106.19	107.18	11	9	12
0	2	2	0	1	0	108.43	108.45	108.51	9	9	10
1	2	2	0	1	0	107.82	107.17	107.91	10	8	11
2	2	2	0	1	0	106.98	106.19	107.09	10	9	11
0	0	0	1	1	0	108.36	106.59	109.05	8	11	9
1	0	0	1	1	0	107.65	106.4	108.46	8	10	9
2	0	0	1	1	0	106.89	106.49	107.84	10	14	11
0	1	0	1	1	0	108.36	106.4	108.43	8	10	9
1	1	0	1	1	0	107.65	106.2	107.74	8	9	9
2	1	0	1	1	0	106.89	106.19	107	10	12	11
0	2	0	1	1	0	108.36	106.4	104.11	10	10	12
1	2	0	1	1	0	107.66	106.2	104.11	10	9	12

0	0	1	1	1	0	108.28	106.48	108.99	7	8	8
1	0	1	1	1	0	107.57	106.29	108.39	7	7	8
2	0	1	1	1	0	106.79	106.39	107.76	9	10	10
0	1	1	1	1	0	108.28	106.38	108.36	7	7	8
1	1	1	1	1	0	107.57	106.18	107.66	7	6	8
2	1	1	1	1	0	106.79	106.18	106.9	9	8	10
0	2	1	1	1	0	108.28	106.38	108.36	7	7	8
1	2	1	1	1	0	107.57	106.18	107.66	7	6	8
2	2	1	1	1	0	106.69	106.18	106.8	8	8	9
0	0	2	1	1	0	108.29	106.41	109	8	9	9
1	0	2	1	1	0	107.58	106.3	108.4	8	8	9
2	0	2	1	1	0	106.8	106.4	107.77	10	11	11
0	1	2	1	1	0	108.29	106.3	108.37	8	8	9
1	1	2	1	1	0	107.58	106.19	107.67	8	7	9
2	1	2	1	1	0	106.8	106.19	106.91	10	9	11
0	2	2	1	1	0	108.29	106.3	108.37	8	8	9
1	2	2	1	1	0	107.58	106.19	107.67	8	7	9
2	2	2	1	1	0	106.7	106.19	106.81	9	9	10
0	0	0	2	1	0	108.48	106.79	108	10	16	12
1	0	0	2	1	0	107.8	106.48	107.23	10	13	12
2	0	0	2	1	0	106.98	106.49	107.91	10	17	11
0	1	0	2	1	0	108.41	106.63	106.05	9	16	11
1	1	0	2	1	0	107.72	106.31	104.77	9	13	11
2	1	0	2	1	0	106.88	106.3	106.99	9	16	10
0	2	0	2	1	0	108.42	106.63	107.41	11	16	14
1	2	0	2	1	0	107.72	106.32	105.29	11	13	14
2	2	0	2	1	0	106.79	106.3	103.41	10	16	12
0	0	1	2	1	0	108.43	106.68	107.94	11	12	13
1	0	1	2	1	0	107.74	106.37	107.16	11	9	13
2	0	1	2	1	0	106.9	106.38	107.85	11	12	12
0	1	1	2	1	0	108.36	106.59	105.95	10	11	12
1	1	1	2	1	0	107.65	106.26	104.64	10	8	12
2	1	1	2	1	0	106.8	106.26	106.91	10	10	11
0	2	1	2	1	0	108.36	106.59	105.95	10	11	12
1	2	1	2	1	0	107.65	106.27	104.64	10	8	12
2	2	1	2	1	0	106.7	106.26	106.81	9	10	10
0	0	2	2	1	0	108.36	106.61	109.05	8	13	9
1	0	2	2	1	0	107.65	106.38	108.46	8	10	9
2	0	2	2	1	0	106.88	106.4	107.83	9	13	10
0	1	2	2	1	0	108.28	106.51	108.36	7	12	8
1	1	2	2	1	0	107.57	106.27	107.66	7	9	8
2	1	2	2	1	0	106.78	106.29	106.89	8	11	9
0	2	2	2	1	0	108.28	106.51	108.36	7	12	8
1	2	2	2	1	0	107.57	106.29	107.66	7	9	8
2	2	2	2	1	0	106.67	106.29	106.79	7	11	8
0	0	0	0	2	0	108.34	108.68	108.73	8	13	10
1	0	0	0	2	0	107.65	107.51	108.46	8	11	9
2	0	0	0	2	0	106.98	106.51	107.91	10	11	11
0	1	0	0	2	0	108.37	108.62	107.31	10	14	12
1	1	0	0	2	0	107.74	107.42	107.83	10	12	11
2	1	0	0	2	0	107.09	106.4	107.19	12	13	13
0	2	0	0	2	0	108.37	108.61	107.31	10	15	12
1	2	0	0	2	0	107.74	107.32	107.83	10	14	11
2	2	0	0	2	0	106.99	106.29	107.1	11	12	12
0	0	1	0	2	0	108.41	108.59	108.79	9	13	11
1	0	1	0	2	0	107.73	107.44	108.53	9	11	10
2	0	1	0	2	0	107.08	106.42	107.99	11	11	12
0	1	1	0	2	0	108.43	108.53	107.39	10	14	12
1	1	1	0	2	0	107.82	107.35	107.91	10	12	11
2	1	1	0	2	0	107.17	106.31	107.27	12	13	13

Scenario 1 | Acoustic Results

Data Allocation using Design Explorer

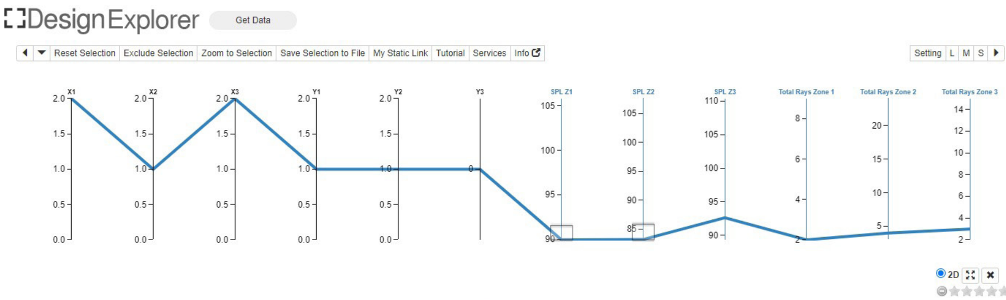


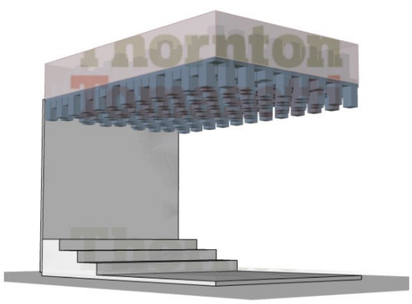
Attributes

X1 : 0
X2 : 0
X3 : 0
Y1 : 0
Y2 : 0
Y3 : 0
SPL Z1 : 105.82
SPL Z2 : 107.57
SPL Z3 : 108.85
Total Rays Zone 1 : 5
Total Rays Zone 2 : 10
Total Rays Zone 3 : 9
Rating : 0

Acoustic Standby mode

SPL Z1 = 105.82 dB
SPL Z2 = 107.57 dB
SPL Z3 = 108.85 dB



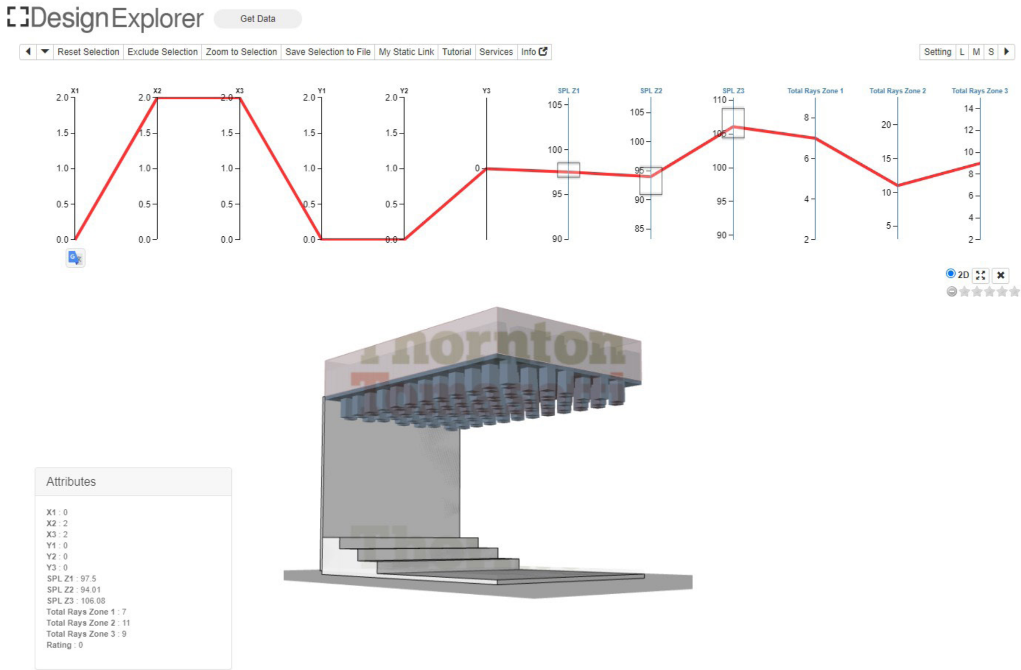


Attributes

X1 : 2
X2 : 1
X3 : 2
Y1 : 1
Y2 : 1
Y3 : 0
SPL Z1 : 89.93
SPL Z2 : 83.19
SPL Z3 : 92.62
Total Rays Zone 1 : 2
Total Rays Zone 2 : 4
Total Rays Zone 3 : 3
Rating : 0

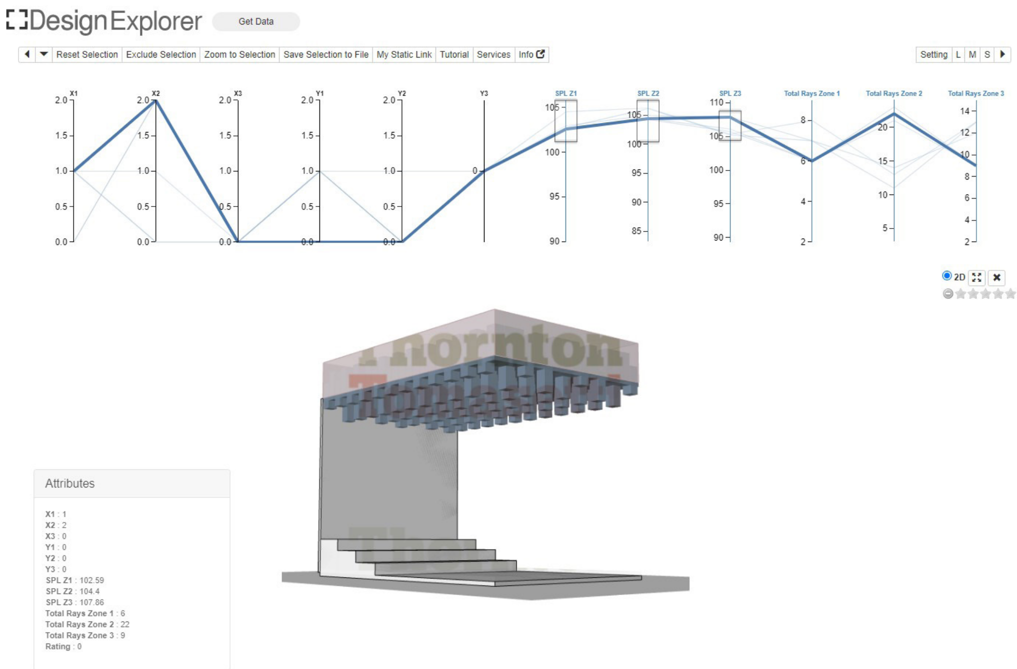
Acoustic Preference

SPL Z1 (low) = 89.93 dB
SPL Z2 (low) = 83.19 dB
SPL Z3 (low) = 92.62 dB



Acoustic Preference

SPL Z1 (bal) = 97.50 dB
SPL Z2 (bal) = 94.01 dB
SPL Z3 (max) = 106.08 dB



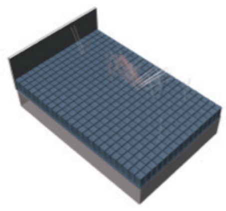
Acoustic Preference

SPL Z1 (max) = 102.59 dB
SPL Z2 (max) = 104.40 dB
SPL Z3 (max) = 107.86 dB

RESULT SHEET	OPEN ROOM		
Test Case	SCENARIO I		
Design Type	ACUTE block | Quad Klein		
Block Size - l x w x h (m)	0.3 x 0.3 x 0.6		
Source Position	B2		
Source Height	1.8 m		
Source Sound Pressure level	120 dB		
Task	Zone 1	Zone 2	Zone 3
	Minimize	Minimize	Minimize

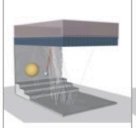
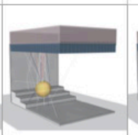
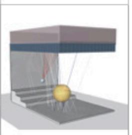
INITIAL POSITION

Block Configuration



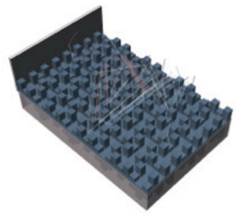
Zone Number	Receiver - Zone 1	Receiver - Zone 2	Receiver - Zone 3

Ray Tracing Diagram

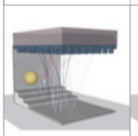
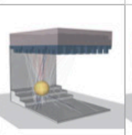
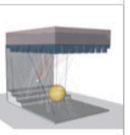




		Receiver - Zone 1	Receiver - Zone 2	Receiver - Zone 3
Order of Incidence	1	0	0	0
	2	15	11	15
	3	4	6	9
	4	2	2	4
	5	1	4	1
	6	4	4	4
Total number of rays		35	27	33
Sound Pressure Level (dB)		105.82	107.57	108.85

OPTIMIZED POSITION



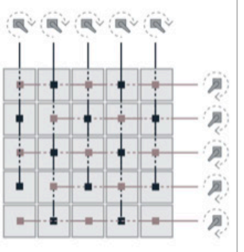
Ray Tracing Diagram

		Receiver - Zone 1	Receiver - Zone 2	Receiver - Zone 3
Order of Incidence	1	0	0	0
	2	14	8	11
	3	10	9	15
	4	4	11	8
	5	1	5	3
	6	4	9	4
Total number of rays		33	42	44
Sound Pressure Level (dB)		89.93	83.19	92.62

ACTUATOR DATA

The numbers represent the angle that the respective actuator has to move to configure the blocks in the optimized position.
The data is based on the preset algorithms created based on the acoustic simulations. The algorithms can be tweaked in order to achieve customized results.



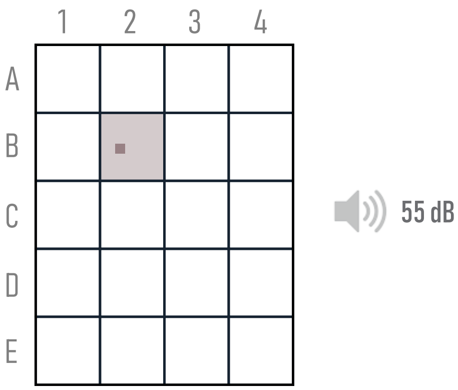
X axis	| 2 | 1 | 1 |
Y axis	| 1 | 1 | 2 | 1 | 0 |

SCENARIO I	OPEN ROOM | 120 dB					
	SPL (dB)			Number of Rays		
	INITIAL	OPTIMIZED	CHANGE	INITIAL	OPTIMIZE	CHANGE
Zone 1	105.82	89.93	▼ 15.89	35	33	▼ 2
Zone 2	107.57	83.19	▼ 24.38	27	42	▲ -15
Zone 3	108.85	92.62	▼ 16.23	33	44	▲ -11

Scenario 2

Close Room, B2, 55 dB, Quad Groot

Result data (Few of the 729 total results)



CLOSED ROOM			
Test Case	SCENARIO II		
Design Type	ACUTE block | Quad Grout		
Block Size - l x w x h (m)	0.6 x 0.6 x 0.6		
Source Position	B2		
Source Height	1.8 m		
Source Sound Pressure level	55 dB		
Task	Zone 1	Zone 2	Zone 3
	Minimize	Minimize	Minimize

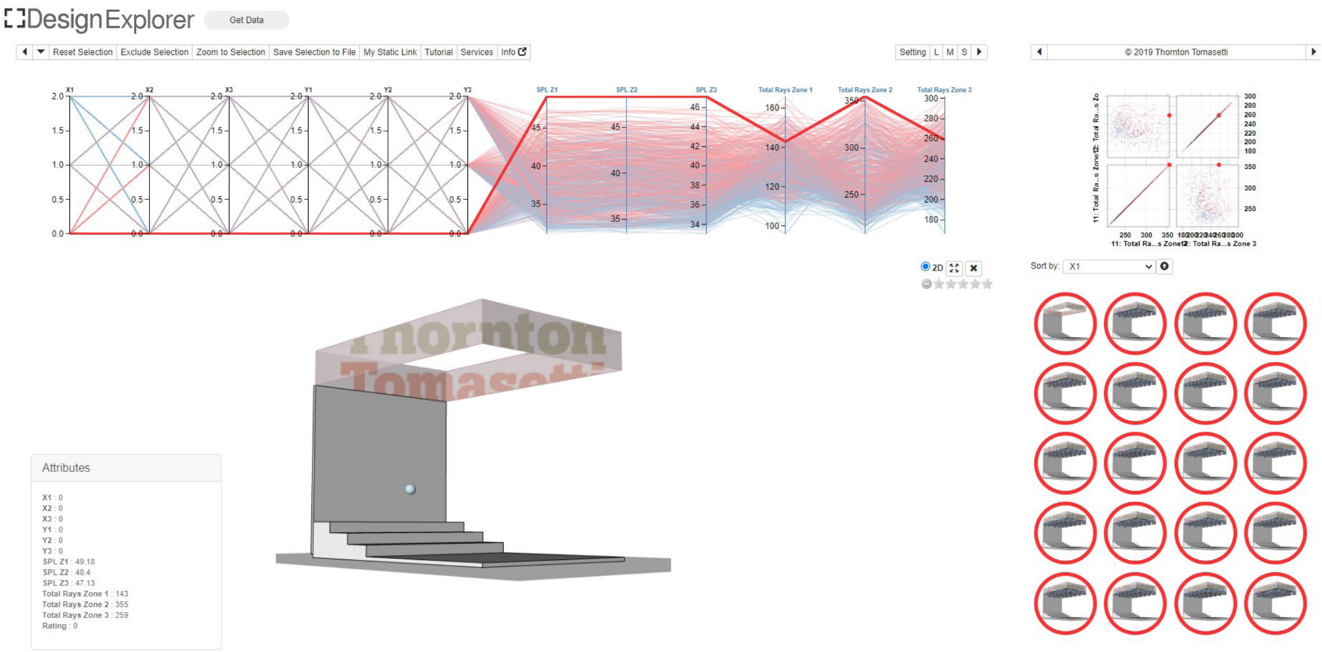
X1	X2	X3	Y1	Y2	Y3	SPL Z1	SPL Z2	SPL Z3	Total Rays Zone 1	Total Rays Zone 2	Total Rays Zone 3
0	0	0	0	0	0	108.28	108.45	108.99	7	8	8
1	0	0	0	0	0	107.65	107.25	108.46	8	6	9
2	0	0	0	0	0	106.98	106.5	107.91	10	8	11
0	1	0	0	0	0	108.36	108.49	108.44	8	10	9
1	1	0	0	0	0	107.74	107.31	107.83	10	8	11
2	1	0	0	0	0	107.09	106.26	107.19	12	10	13
0	2	0	0	0	0	108.36	108.67	108.44	8	14	9
1	2	0	0	0	0	107.74	107.46	107.83	9	13	10
2	2	0	0	0	0	106.98	106.46	107.09	10	11	11
0	0	1	0	0	0	108.36	108.45	109.05	8	8	9
1	0	1	0	0	0	107.74	107.25	109.15	10	6	12
2	0	1	0	0	0	107.08	106.5	107.99	11	8	12
0	1	1	0	0	0	108.43	108.49	108.51	9	10	10
1	1	1	0	0	0	107.83	107.31	106.24	12	8	14
2	1	1	0	0	0	107.18	106.26	107.28	13	10	14
0	2	1	0	0	0	108.43	108.55	108.51	9	11	10
1	2	1	0	0	0	107.82	107.3	106.01	11	10	13
2	2	1	0	0	0	107.08	106.35	107.18	11	10	12
0	0	2	0	0	0	108.36	108.45	109.05	8	8	9
1	0	2	0	0	0	107.74	107.25	109.15	10	6	12
2	0	2	0	0	0	106.98	106.4	107.91	10	8	11
0	1	2	0	0	0	108.43	108.45	108.51	9	9	10
1	1	2	0	0	0	107.83	107.26	106.24	12	7	14
2	1	2	0	0	0	107.09	106.19	107.19	12	8	13
0	2	2	0	0	0	108.43	108.45	108.51	9	9	10
1	2	2	0	0	0	107.82	107.17	106.01	11	8	13
2	2	2	0	0	0	106.98	106.19	107.09	10	8	11
0	0	0	1	0	0	108.36	106.83	109.05	8	15	9
1	0	0	1	0	0	107.65	106.56	108.46	8	12	9
2	0	0	1	0	0	106.89	106.76	107.84	10	14	11
0	1	0	1	0	0	108.36	106.59	108.43	8	12	9
1	1	0	1	0	0	107.66	106.3	107.75	9	9	10
2	1	0	1	0	0	106.9	106.31	107.01	11	10	12
0	2	0	1	0	0	108.36	106.59	104.12	10	12	12
1	2	0	1	0	0	107.66	106.3	104.12	10	9	12

2	0	0	2	0	0	106.98	106.64	107.91	10	15	11
0	1	0	2	0	0	108.41	106.78	106.17	9	17	11
1	1	0	2	0	0	107.72	106.39	104.95	10	14	12
2	1	0	2	0	0	106.89	106.4	107	10	14	11
0	2	0	2	0	0	108.42	106.78	108.17	11	16	14
1	2	0	2	0	0	107.72	106.4	106.48	11	13	14
2	2	0	2	0	0	106.79	106.39	103.43	10	12	12
0	0	1	2	0	0	108.43	106.92	108.62	11	16	13
1	0	1	2	0	0	107.74	106.54	107.61	12	13	15
2	0	1	2	0	0	106.9	106.55	107.85	11	13	12
0	1	1	2	0	0	108.36	106.76	106.08	10	14	12
1	1	1	2	0	0	107.67	106.37	104.2	12	11	15
2	1	1	2	0	0	106.81	106.38	106.92	11	11	12
0	2	1	2	0	0	108.36	106.76	105.96	10	13	12
1	2	1	2	0	0	107.66	106.38	104	11	10	14
2	2	1	2	0	0	106.7	106.37	106.81	9	9	10
0	0	2	2	0	0	108.36	106.75	109.05	8	15	9
1	0	2	2	0	0	107.66	106.44	107.8	9	12	11
2	0	2	2	0	0	106.88	106.46	107.83	9	12	10
0	1	2	2	0	0	108.28	106.6	108.36	7	14	8
1	1	2	2	0	0	107.58	106.27	104.49	9	11	11
2	1	2	2	0	0	106.79	106.29	106.9	9	11	10
0	2	2	2	0	0	108.28	106.6	108.36	7	13	8
1	2	2	2	0	0	107.57	106.29	104.3	8	10	10
2	2	2	2	0	0	106.67	106.29	106.79	7	10	8
0	0	0	0	1	0	108.28	108.55	108.99	7	11	8
1	0	0	0	1	0	107.65	107.34	108.46	8	9	9
2	0	0	0	1	0	106.98	106.5	107.91	10	12	11
0	1	0	0	1	0	108.36	108.56	108.44	8	13	9
1	1	0	0	1	0	107.74	107.34	107.83	9	11	10
2	1	0	0	1	0	107.08	106.29	107.18	11	14	12
0	2	0	0	1	0	108.36	108.74	108.44	8	17	9
1	2	0	0	1	0	107.74	107.49	107.83	9	16	10
2	2	0	0	1	0	106.98	106.51	107.09	10	16	11
0	0	1	0	1	0	108.36	108.45	109.05	8	8	9
1	0	1	0	1	0	107.73	107.25	108.53	9	6	10
2	0	1	0	1	0	107.08	106.39	107.99	11	9	12
0	1	1	0	1	0	108.43	108.45	108.51	9	10	10
1	1	1	0	1	0	107.82	107.25	107.91	10	8	11
2	1	1	0	1	0	107.17	106.18	107.27	12	11	13
0	2	1	0	1	0	108.43	108.51	108.51	9	11	10
1	2	1	0	1	0	107.82	107.25	107.91	10	10	11
2	2	1	0	1	0	107.08	106.29	107.18	11	12	12
0	0	2	0	1	0	108.36	108.45	109.05	8	9	9
1	0	2	0	1	0	107.73	107.26	108.53	9	7	10
2	0	2	0	1	0	106.98	106.3	107.91	10	10	11
0	1	2	0	1	0	108.43	108.45	108.51	9	9	10
1	1	2	0	1	0	107.82	107.26	107.91	10	7	11
2	1	2	0	1	0	107.08	106.19	107.18	11	9	12
0	2	2	0	1	0	108.43	108.45	108.51	9	9	10
1	2	2	0	1	0	107.82	107.17	107.91	10	8	11
2	2	2	0	1	0	106.98	106.19	107.09	10	9	11
0	0	0	1	1	0	108.36	106.59	109.05	8	11	9
1	0	0	1	1	0	107.65	106.4	108.46	8	10	9
2	0	0	1	1	0	106.89	106.49	107.84	10	14	11
0	1	0	1	1	0	108.36	106.4	108.43	8	10	9
1	1	0	1	1	0	107.65	106.2	107.74	8	9	9
2	1	0	1	1	0	106.89	106.19	107	10	12	11
0	2	0	1	1	0	108.36	106.4	104.11	10	10	12
1	2	0	1	1	0	107.66	106.2	104.11	10	9	12

0	0	1	1	1	0	108.28	106.48	108.99	7	8	8
1	0	1	1	1	0	107.57	106.29	108.39	7	7	8
2	0	1	1	1	0	106.79	106.39	107.76	9	10	10
0	1	1	1	1	0	108.28	106.38	108.36	7	7	8
1	1	1	1	1	0	107.57	106.18	107.66	7	6	8
2	1	1	1	1	0	106.79	106.18	106.9	9	8	10
0	2	1	1	1	0	108.28	106.38	108.36	7	7	8
1	2	1	1	1	0	107.57	106.18	107.66	7	6	8
2	2	1	1	1	0	106.69	106.18	106.8	8	8	9
0	0	2	1	1	0	108.29	106.41	109	8	9	9
1	0	2	1	1	0	107.58	106.3	108.4	8	8	9
2	0	2	1	1	0	106.8	106.4	107.77	10	11	11
0	1	2	1	1	0	108.29	106.3	108.37	8	8	9
1	1	2	1	1	0	107.58	106.19	107.67	8	7	9
2	1	2	1	1	0	106.8	106.19	106.91	10	9	11
0	2	2	1	1	0	108.29	106.3	108.37	8	8	9
1	2	2	1	1	0	107.58	106.19	107.67	8	7	9
2	2	2	1	1	0	106.7	106.19	106.81	9	9	10
0	0	0	2	1	0	108.48	106.79	108	10	16	12
1	0	0	2	1	0	107.8	106.48	107.23	10	13	12
2	0	0	2	1	0	106.98	106.49	107.91	10	17	11
0	1	0	2	1	0	108.41	106.63	106.05	9	16	11
1	1	0	2	1	0	107.72	106.31	104.77	9	13	11
2	1	0	2	1	0	106.88	106.3	106.99	9	16	10
0	2	0	2	1	0	108.42	106.63	107.41	11	16	14
1	2	0	2	1	0	107.72	106.32	105.29	11	13	14
2	2	0	2	1	0	106.79	106.3	103.41	10	16	12
0	0	1	2	1	0	108.43	106.68	107.94	11	12	13
1	0	1	2	1	0	107.74	106.37	107.16	11	9	13
2	0	1	2	1	0	106.9	106.38	107.85	11	12	12
0	1	1	2	1	0	108.36	106.59	105.95	10	11	12
1	1	1	2	1	0	107.65	106.26	104.64	10	8	12
2	1	1	2	1	0	106.8	106.26	106.91	10	10	11
0	2	1	2	1	0	108.36	106.59	105.95	10	11	12
1	2	1	2	1	0	107.65	106.27	104.64	10	8	12
2	2	1	2	1	0	106.7	106.26	106.81	9	10	10
0	0	2	2	1	0	108.36	106.61	109.05	8	13	9
1	0	2	2	1	0	107.65	106.38	108.46	8	10	9
2	0	2	2	1	0	106.88	106.4	107.83	9	13	10
0	1	2	2	1	0	108.28	106.51	108.36	7	12	8
1	1	2	2	1	0	107.57	106.27	107.66	7	9	8
2	1	2	2	1	0	106.78	106.29	106.89	8	11	9
0	2	2	2	1	0	108.28	106.51	108.36	7	12	8
1	2	2	2	1	0	107.57	106.29	107.66	7	9	8
2	2	2	2	1	0	106.67	106.29	106.79	7	11	8
0	0	0	0	2	0	108.34	108.68	108.73	8	13	10

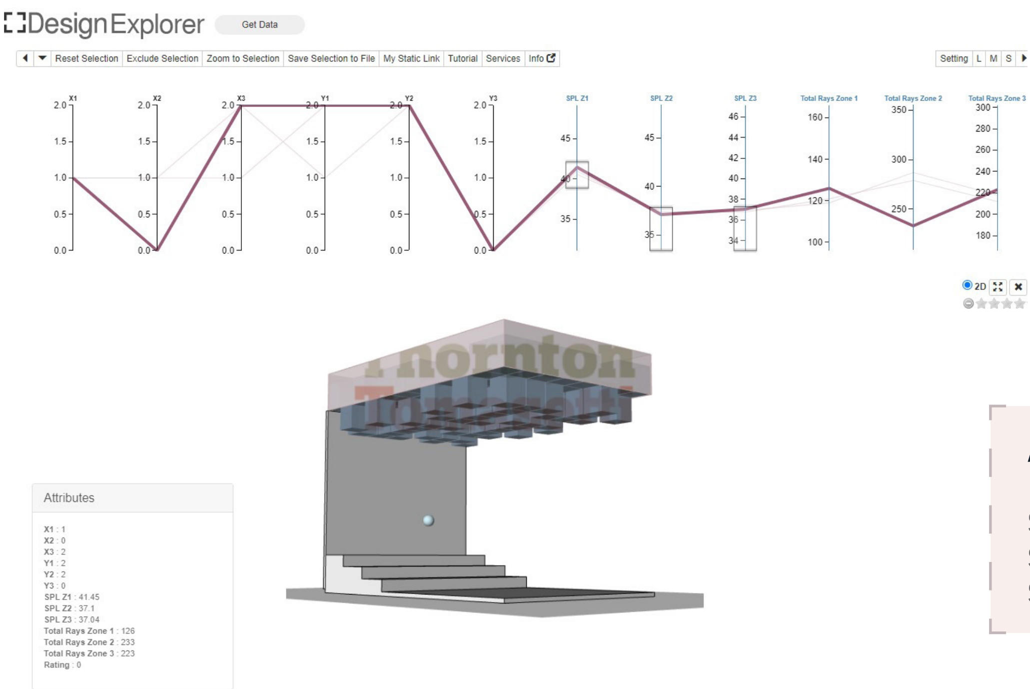
Scenario 2 | Acoustic Results

Data Allocation using Design Explorer



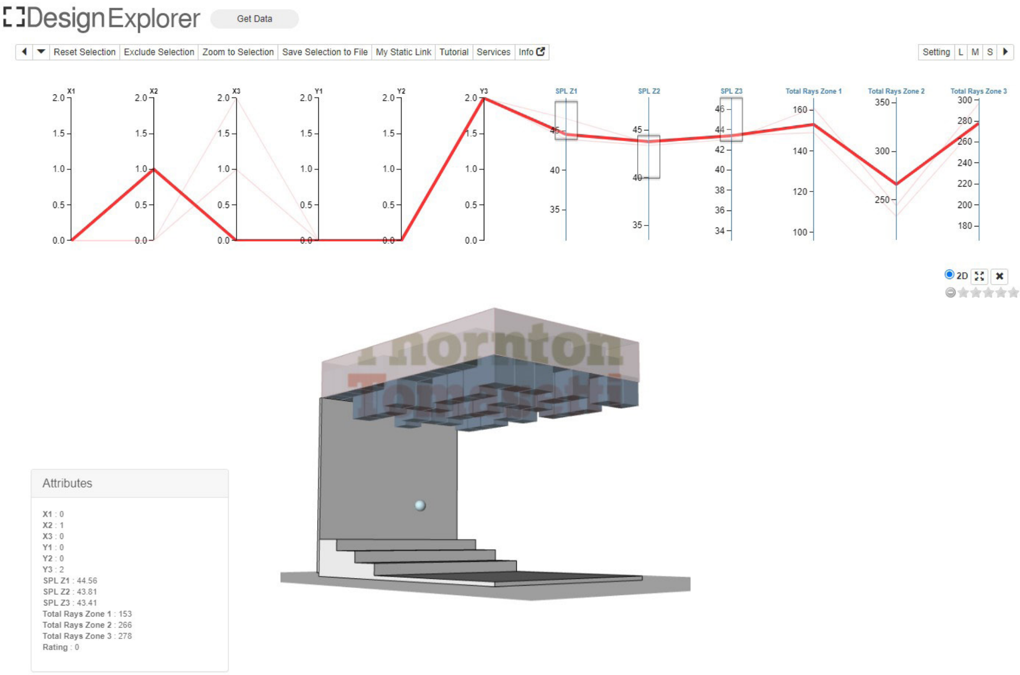
Acoustic Standby mode

SPL Z1 = 49.18 dB
SPL Z2 = 48.40 dB
SPL Z3 = 47.13 dB



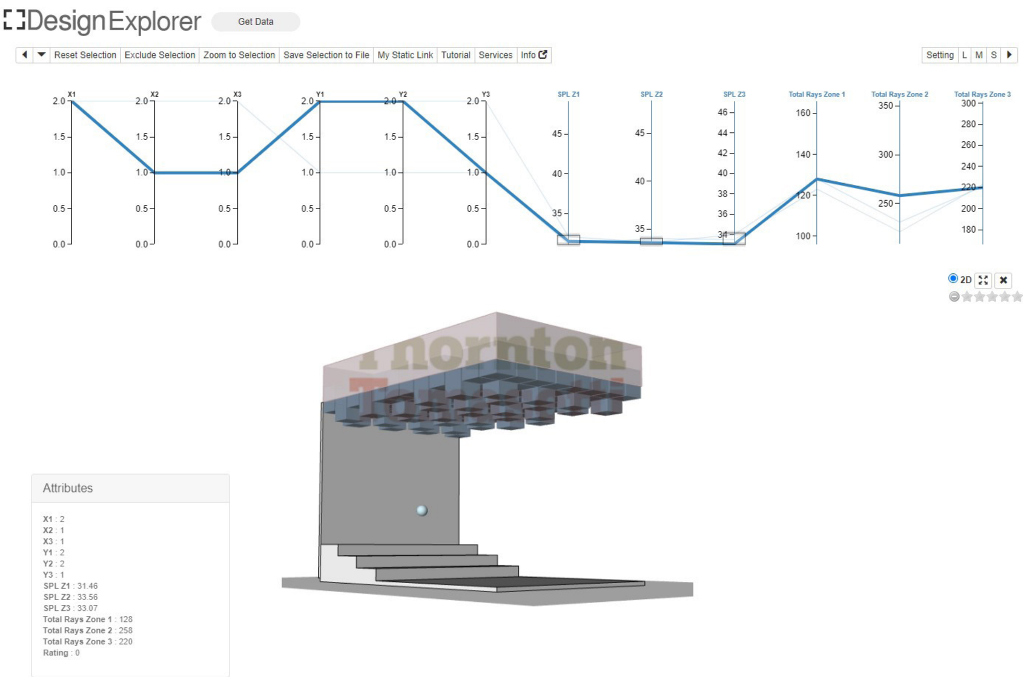
Acoustic Preference

SPL Z1 (bal) = 41.45 dB
SPL Z2 (min) = 37.10 dB
SPL Z3 (min) = 37.04 dB



Acoustic Preference

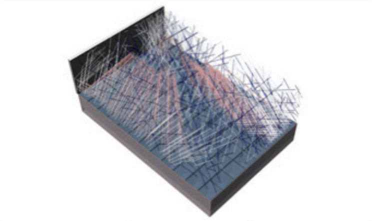
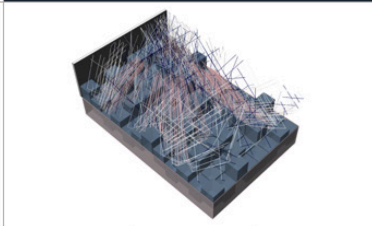
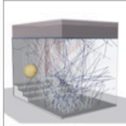
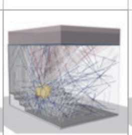
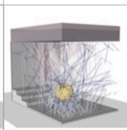
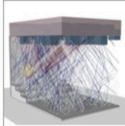
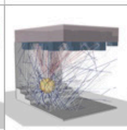
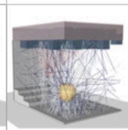
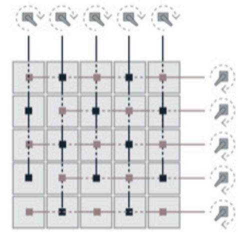
SPL Z1 (max) = 44.56 dB
SPL Z2 (bal) = 43.81 dB
SPL Z3 (max) = 43.41 dB



Acoustic Preference

SPL Z1 (min) = 31.46 dB
SPL Z2 (min) = 33.56 dB
SPL Z3 (min) = 33.07 dB

RESULT SHEET	CLOSED ROOM		
Test Case	SCENARIO II		
Design Type	ACUTE block | Quad Grout		
Block Size - l x w x h (m)	0.6 x 0.6 x 0.6		
Source Position	B2		
Source Height	1.8 m		
Source Sound Pressure level	55 dB		
Task	Zone 1	Zone 2	Zone 3
	Minimize	Minimize	Minimize

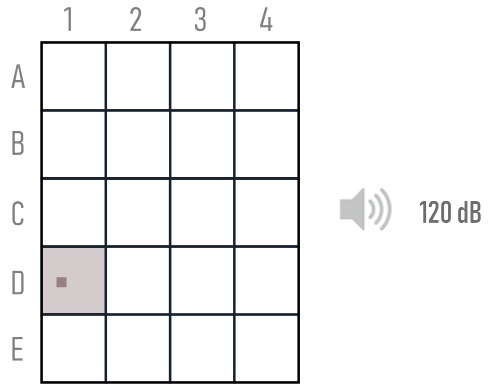
		INITIAL POSITION				OPTIMIZED POSITION			ACTUATOR DATA
Block Configuration									The numbers represent the angle that the respective actuator has to move to configure the blocks in the optimized position. The data is based on the preset algorithms created based on the acoustic simulations. The algorithms can be tweaked in order to achieve customized results.
Zone Number		Receiver - Zone 1	Receiver - Zone 2	Receiver - Zone 3		Receiver - Zone 1	Receiver - Zone 2	Receiver - Zone 3	
Ray Tracing Diagram									
Order of Incidence	1	0	0	0	1	0	0	0	
	2	14	14	14	2	18	12	18	
	3	35	51	49	3	41	38	59	
	4	38	87	73	4	20	63	61	
	5	29	102	67	5	32	71	52	
	6	27	101	56	6	25	75	56	
Total number of rays		143	355	259		136	259	246	X axis: | 1 | 0 | 2 |
Sound Pressure Level (dB)		49.18	48.4	47.13		41.45	37.10	37.04	Y axis: | 2 | 0 | 0 | 1 | 1|

SCENARIO II				CLOSED ROOM | 55 dB		
	SPL (dB)				Number of Rays	
	INITIAL	OPTIMIZED	CHANGE	INITIAL	OPTIMIZE	CHANGE
Zone 1	49.18	41.45	▼ 7.73	143	136	▼ 7
Zone 2	48.4	37.10	▼ 11.3	355	259	▼ 96
Zone 3	47.13	37.04	▼ 10.09	259	246	▼ 13

Scenario 3

Open Room, D1, 120 dB, Quad Klien

Result data (Few of the 726 total results)



OPEN ROOM			
Test Case	SCENARIO III		
Design Type	ACUTE block | Quad KLIEN		
Block Size - l x w x h (m)	0.6 x 0.6 x 0.8		
Source Position	D1		
Source Height	1.8 M		
Source Sound Pressure level	55 dB		
Task	Zone 1	Zone 2	Zone 3
	Minimize	Minimize	Balance

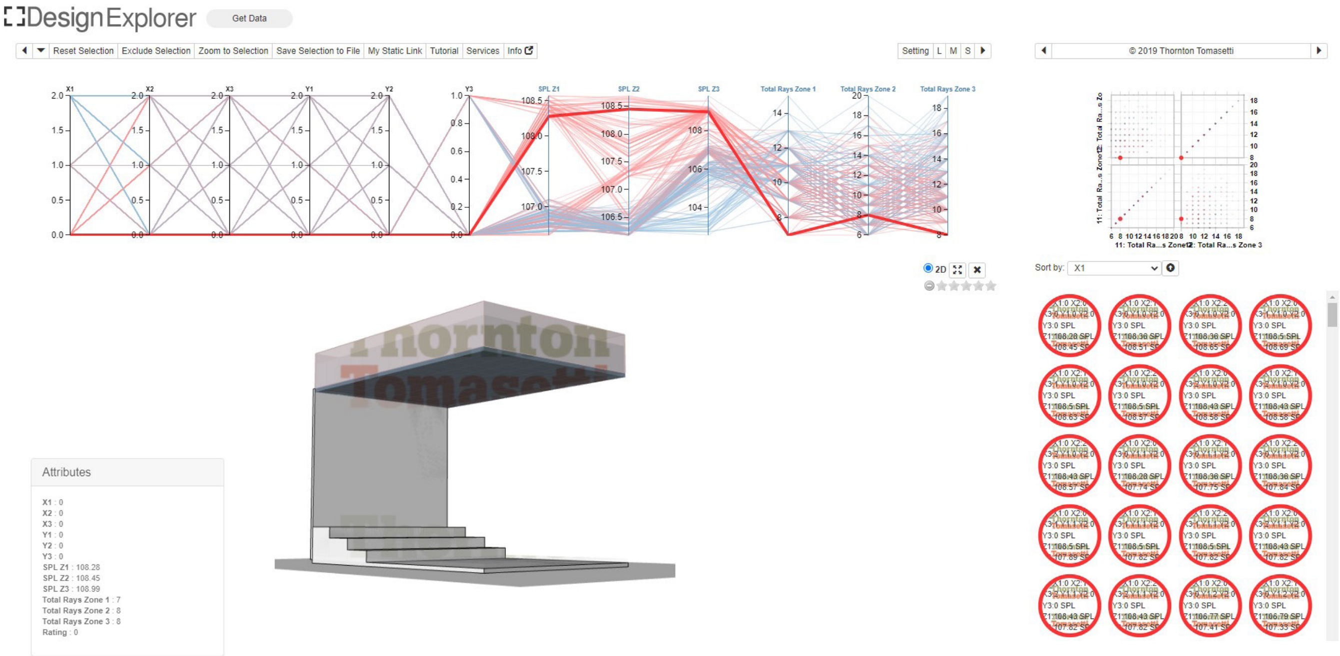
X1	X2	X3	Y1	Y2	Y3	SPL Z1	SPL Z2	SPL Z3	Total Rays Zone 1	Total Rays Zone 2	Total Rays Zone 3
0	0	0	0	0	0	108.28	108.45	108.99	7	8	8
1	0	0	0	0	0	107.65	107.25	108.46	8	6	9
2	0	0	0	0	0	106.98	106.5	107.91	10	8	11
0	1	0	0	0	0	108.36	108.49	108.44	8	10	9
1	1	0	0	0	0	107.74	107.31	107.83	10	8	11
2	1	0	0	0	0	107.09	106.26	107.19	12	10	13
0	2	0	0	0	0	108.36	108.67	108.44	8	14	9
1	2	0	0	0	0	107.74	107.46	107.83	9	13	10
2	2	0	0	0	0	106.98	106.46	107.09	10	11	11
0	0	1	0	0	0	108.36	108.45	109.05	8	8	9
1	0	1	0	0	0	107.74	107.25	109.15	10	6	12
2	0	1	0	0	0	107.08	106.5	107.99	11	8	12
0	1	1	0	0	0	108.43	108.49	108.51	9	10	10
1	1	1	0	0	0	107.83	107.31	106.24	12	8	14
2	1	1	0	0	0	107.18	106.26	107.28	13	10	14
0	2	1	0	0	0	108.43	108.55	108.51	9	11	10
1	2	1	0	0	0	107.82	107.3	106.01	11	10	13
2	2	1	0	0	0	107.08	106.35	107.18	11	10	12
0	0	2	0	0	0	108.36	108.45	109.05	8	8	9
1	0	2	0	0	0	107.74	107.25	109.15	10	6	12
2	0	2	0	0	0	106.98	106.4	107.91	10	8	11
0	1	2	0	0	0	108.43	108.45	108.51	9	9	10
1	1	2	0	0	0	107.83	107.26	106.24	12	7	14
2	1	2	0	0	0	107.09	106.19	107.19	12	8	13
0	2	2	0	0	0	108.43	108.45	108.51	9	9	10
1	2	2	0	0	0	107.82	107.17	106.01	11	8	13
2	2	2	0	0	0	106.98	106.19	107.09	10	8	11
0	0	0	1	0	0	108.36	106.83	109.05	8	15	9
1	0	0	1	0	0	107.65	106.56	108.46	8	12	9
2	0	0	1	0	0	106.89	106.76	107.84	10	14	11
0	1	0	1	0	0	108.36	106.59	108.43	8	12	9
1	1	0	1	0	0	107.66	106.3	107.75	9	9	10
2	1	0	1	0	0	106.9	106.31	107.01	11	10	12
0	2	0	1	0	0	108.36	106.59	104.12	10	12	12
1	2	0	1	0	0	107.66	106.3	104.12	10	9	12

0	0	1	1	1	0	108.28	106.48	108.99	7	8	8
1	0	1	1	1	0	107.57	106.29	108.39	7	7	8
2	0	1	1	1	0	106.79	106.39	107.76	9	10	10
0	1	1	1	1	0	108.28	106.38	108.36	7	7	8
1	1	1	1	1	0	107.57	106.18	107.66	7	6	8
2	1	1	1	1	0	106.79	106.18	106.9	9	8	10
0	2	1	1	1	0	108.28	106.38	108.36	7	7	8
1	2	1	1	1	0	107.57	106.18	107.66	7	6	8
2	2	1	1	1	0	106.69	106.18	106.8	8	8	9
0	0	2	1	1	0	108.29	106.41	109	8	9	9
1	0	2	1	1	0	107.58	106.3	108.4	8	8	9
2	0	2	1	1	0	106.8	106.4	107.77	10	11	11
0	1	2	1	1	0	108.29	106.3	108.37	8	8	9
1	1	2	1	1	0	107.58	106.19	107.67	8	7	9
2	1	2	1	1	0	106.8	106.19	106.91	10	9	11
0	2	2	1	1	0	108.29	106.3	108.37	8	8	9
1	2	2	1	1	0	107.58	106.19	107.67	8	7	9
2	2	2	1	1	0	106.7	106.19	106.81	9	9	10
0	0	0	2	1	0	108.48	106.79	108	10	16	12
1	0	0	2	1	0	107.8	106.48	107.23	10	13	12
2	0	0	2	1	0	106.98	106.49	107.91	10	17	11
0	1	0	2	1	0	108.41	106.63	106.05	9	16	11
1	1	0	2	1	0	107.72	106.31	104.77	9	13	11
2	1	0	2	1	0	106.88	106.3	106.99	9	16	10
0	2	0	2	1	0	108.42	106.63	107.41	11	16	14
1	2	0	2	1	0	107.72	106.32	105.29	11	13	14
2	2	0	2	1	0	106.79	106.3	103.41	10	16	12
0	0	1	2	1	0	108.43	106.68	107.94	11	12	13
1	0	1	2	1	0	107.74	106.37	107.16	11	9	13
2	0	1	2	1	0	106.9	106.38	107.85	11	12	12
0	1	1	2	1	0	108.36	106.59	105.95	10	11	12
1	1	1	2	1	0	107.65	106.26	104.64	10	8	12
2	1	1	2	1	0	106.8	106.26	106.91	10	10	11
0	2	1	2	1	0	108.36	106.59	105.95	10	11	12
1	2	1	2	1	0	107.65	106.27	104.64	10	8	12
2	2	1	2	1	0	106.7	106.26	106.81	9	10	10
0	0	2	2	1	0	108.36	106.61	109.05	8	13	9
1	0	2	2	1	0	107.65	106.38	108.46	8	10	9
2	0	2	2	1	0	106.88	106.4	107.83	9	13	10
0	1	2	2	1	0	108.28	106.51	108.36	7	12	8
1	1	2	2	1	0	107.57	106.27	107.66	7	9	8
2	1	2	2	1	0	106.78	106.29	106.89	8	11	9
0	2	2	2	1	0	108.28	106.51	108.36	7	12	8
1	2	2	2	1	0	107.57	106.29	107.66	7	9	8
2	2	2	2	1	0	106.67	106.29	106.79	7	11	8
0	0	0	0	2	0	108.34	108.68	108.73	8	13	10
1	0	0	0	2	0	107.65	107.51	108.46	8	11	9
2	0	0	0	2	0	106.98	106.51	107.91	10	11	11
0	1	0	0	2	0	108.37	108.62	107.31	10	14	12
1	1	0	0	2	0	107.74	107.42	107.83	10	12	11
2	1	0	0	2	0	107.09	106.4	107.19	12	13	13
0	2	0	0	2	0	108.37	108.61	107.31	10	15	12
1	2	0	0	2	0	107.74	107.32	107.83	10	14	11
2	2	0	0	2	0	106.99	106.29	107.1	11	12	12
0	0	1	0	2	0	108.41	108.59	108.79	9	13	11
1	0	1	0	2	0	107.73	107.44	108.53	9	11	10
2	0	1	0	2	0	107.08	106.42	107.99	11	11	12
0	1	1	0	2	0	108.43	108.53	107.39	10	14	12
1	1	1	0	2	0	107.82	107.35	107.91	10	12	11
2	1	1	0	2	0	107.17	106.31	107.27	12	13	13

1	2	1	0	2	0	107.82	107.17	107.91	10	12	11
2	2	1	0	2	0	107.08	106.19	107.18	11	12	12
0	0	2	0	2	0	108.41	108.58	108.79	9	10	11
1	0	2	0	2	0	107.73	107.42	108.53	9	8	10
2	0	2	0	2	0	106.98	106.4	107.91	10	8	11
0	1	2	0	2	0	108.43	108.51	107.39	10	9	12
1	1	2	0	2	0	107.82	107.33	107.91	10	7	11
2	1	2	0	2	0	107.08	106.29	107.18	11	7	12
0	2	2	0	2	0	108.43	108.45	107.39	10	8	12
1	2	2	0	2	0	107.82	107.16	107.91	10	7	11
2	2	2	0	2	0	106.98	106.18	107.09	10	6	11
0	0	0	1	2	0	108.41	106.31	108.79	9	7	11
1	0	0	1	2	0	107.65	106.2	108.46	8	8	9
2	0	0	1	2	0	106.89	106.19	107.84	10	9	11
0	1	0	1	2	0	108.37	106.29	107.31	10	6	12
1	1	0	1	2	0	107.66	106.19	107.75	9	7	10
2	1	0	1	2	0	106.9	106.18	107.01	11	8	12
0	2	0	1	2	0	108.37	106.29	107.31	10	6	12
1	2	0	1	2	0	107.66	106.19	107.75	9	7	10
2	2	0	1	2	0	106.8	106.18	106.91	10	8	11
0	0	1	1	2	0	108.34	106.31	108.73	8	9	10
1	0	1	1	2	0	107.57	106.21	108.39	7	10	8
2	0	1	1	2	0	106.79	106.21	107.76	9	10	10
0	1	1	1	2	0	108.29	106.3	107.21	8	8	10
1	1	1	1	2	0	107.57	106.19	107.66	7	9	8
2	1	1	1	2	0	106.79	106.19	106.9	9	9	10
0	2	1	1	2	0	108.29	106.3	107.21	8	8	10
1	2	1	1	2	0	107.57	106.19	107.66	7	9	8
2	2	1	1	2	0	106.69	106.19	106.8	8	9	9
0	0	2	1	2	0	108.34	106.29	108.74	9	6	11
1	0	2	1	2	0	107.58	106.19	108.4	8	7	9
2	0	2	1	2	0	106.8	106.19	107.77	10	7	11
0	1	2	1	2	0	108.3	106.28	107.22	9	5	11
1	1	2	1	2	0	107.58	106.18	107.67	8	6	9
2	1	2	1	2	0	106.8	106.18	106.91	10	6	11
0	2	2	1	2	0	108.3	106.28	107.22	9	5	11
1	2	2	1	2	0	107.58	106.18	107.67	8	6	9
2	2	2	1	2	0	106.7	106.18	106.81	9	6	10
0	0	0	2	2	0	108.48	106.54	107.17	10	13	12
1	0	0	2	2	0	107.8	106.31	106.22	10	12	12
2	0	0	2	2	0	106.98	106.3	107.91	10	13	11
0	1	0	2	2	0	108.41	106.54	106.17	9	13	11
1	1	0	2	2	0	107.72	106.31	104.93	9	12	11
2	1	0	2	2	0	106.88	106.29	106.99	9	12	10
0	2	0	2	2	0	108.41	106.54	106.26	10	13	12
1	2	0	2	2	0	107.72	106.32	105.05	10	12	12
2	2	0	2	2	0	106.78	106.29	106.89	9	12	10
0	0	1	2	2	0	108.43	106.52	107.09	11	13	13
1	0	1	2	2	0	107.74	106.29	106.13	11	12	13
2	0	1	2	2	0	106.9	106.3	107.85	11	13	12
0	1	1	2	2	0	108.36	106.51	106.07	10	12	12
1	1	1	2	2	0	107.65	106.27	104.81	10	11	12
2	1	1	2	2	0	106.8	106.27	106.91	10	11	11
0	2	1	2	2	0	108.36	106.51	106.07	10	12	12
1	2	1	2	2	0	107.65	106.29	104.81	10	11	12
2	2	1	2	2	0	106.7	106.28	106.81	9	11	10
0	0	2	2	2	0	108.36	106.5	109.05	8	10	9
1	0	2	2	2	0	107.65	106.27	108.46	8	9	9
2	0	2	2	2	0	106.88	106.3	107.83	9	10	10
0	1	2	2	2	0	108.28	106.49	108.36	7	9	8

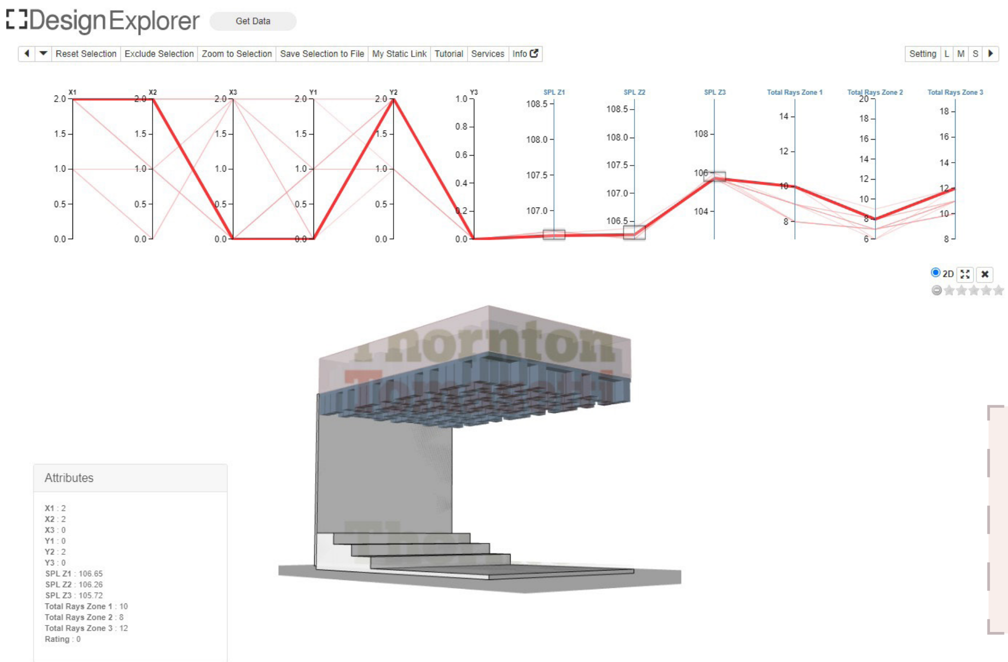
Scenario 3 | Acoustic Results

Data Allocation using Design Explorer



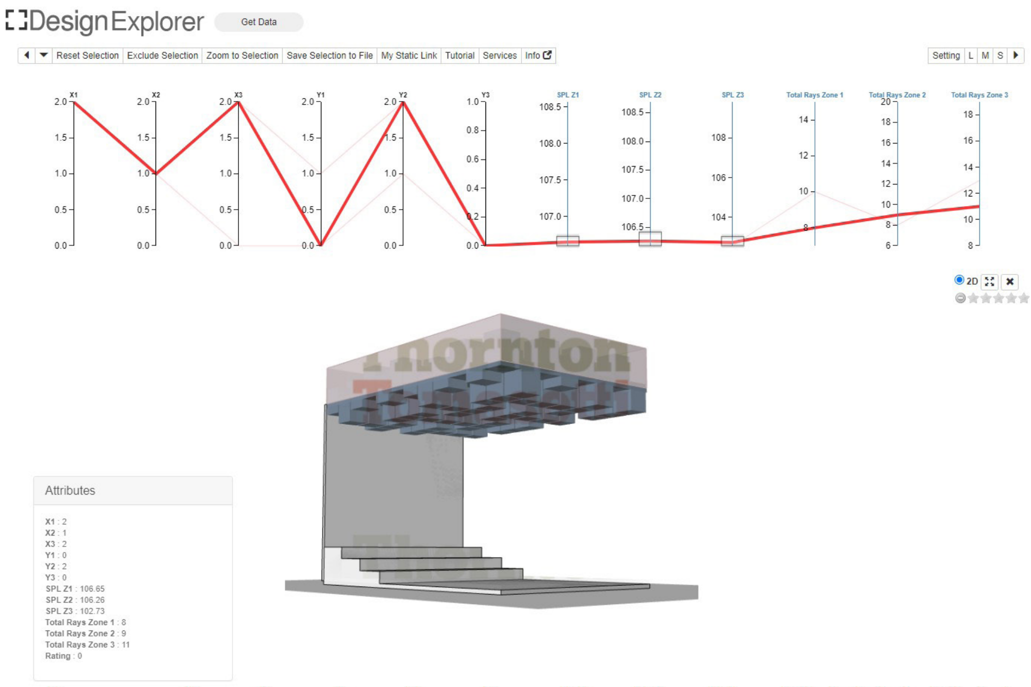
Acoustic Standby mode

SPL Z1 = 49.18 dB
SPL Z2 = 48.40 dB
SPL Z3 = 47.13 dB



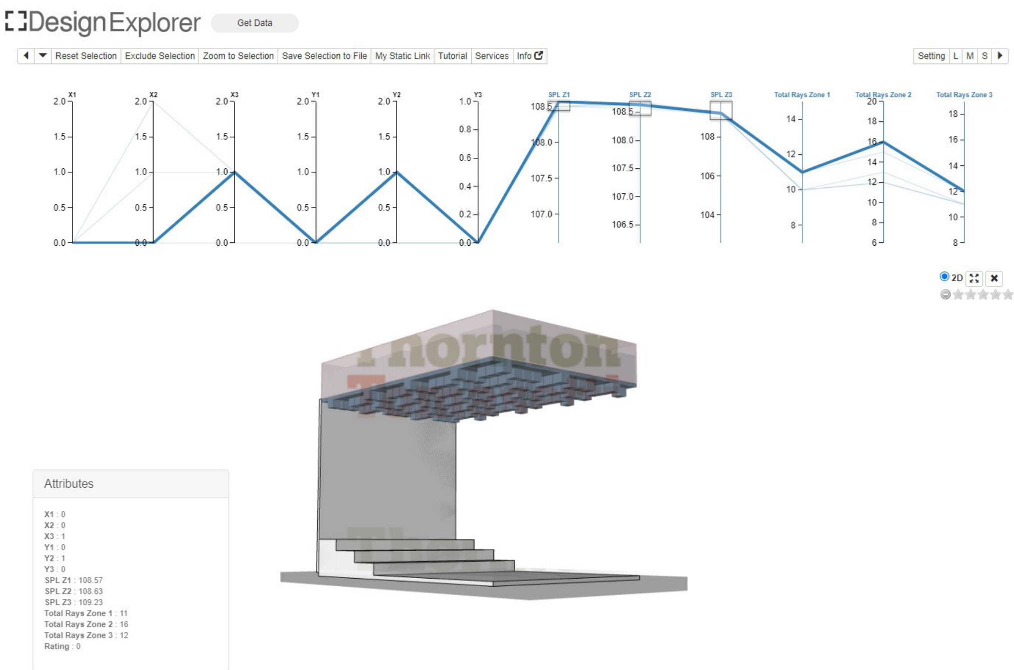
Acoustic Preference

SPL Z1 (low) = 106.65 dB
SPL Z2 (low) = 106.26 dB
SPL Z3 (mid) = 105.72 dB



Acoustic Preference

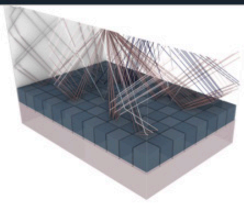
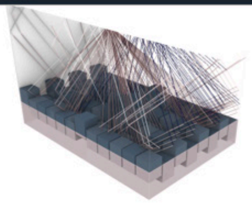
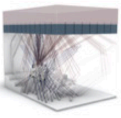
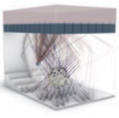
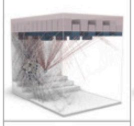
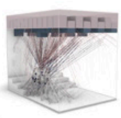
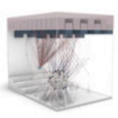
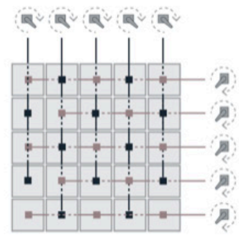
SPL Z1 (low) = 106.65 dB
SPL Z2 (low) = 106.26 dB
SPL Z3 (low) = 102.73 dB



Acoustic Preference

SPL Z1 (high) = 108.57 dB
SPL Z2 (high) = 108.63 dB
SPL Z3 (high) = 109.23 dB

RESULT SHEET	OPEN ROOM		
Test Case	SCENARIO III		
Design Type	ACUTE block | Quad KLIEN		
Block Size - l x w x h (m)	0.6 x 0.6 x 0.8		
Source Position	D1		
Source Height	1.8 M		
Source Sound Pressure level	55 dB		
Task	Zone 1	Zone 2	Zone 3
	Minimize	Minimize	Balance

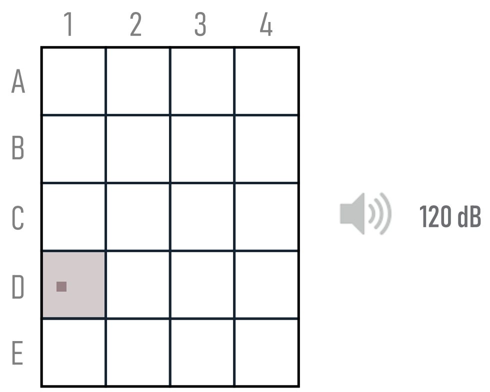
		INITIAL POSITION				OPTIMIZED POSITION			ACTUATOR DATA
Block Configuration									The numbers represent the angle that the respective actuator has to move to configure the blocks in the optimized position. The data is based on the preset algorithms created based on the acoustic simulations. The algorithms can be tweaked in order to achieve customized results.
Zone Number		Receiver - Zone 1	Receiver - Zone 2	Receiver - Zone 3		Receiver - Zone 1	Receiver - Zone 2	Receiver - Zone 3	
Ray Tracing Diagram									
Order of Incidence	1	0	0	0	1	0	0	0	
	2	13	12	12	2	11	5	8	
	3	12	17	32	3	27	16	27	
	4	13	22	19	4	32	14	24	
	5	32	20	12	5	37	21	6	
	6	16	12	14	6	23	18	10	
Total number of rays		86	83	89		130	74	75	X axis | 1 | 0 | 2 | 1 |
Sound Pressure Level (dB)		108.28	108.45	108.99		106.65	106.26	105.72	Y axis | 0 | 0 | 1 | 0 | 2 | 1 |

SCENARIO III					OPEN ROOM | 120 dB	
	SPL (dB)				Number of Rays	
	INITIAL	OPTIMIZED	CHANGE	INITIAL	OPTIMIZE	CHANGE
Zone 1	108.28	106.65	▼ 1.63	86	130	▲ -44
Zone 2	108.45	106.26	▼ 2.19	83	74	▼ 9
Zone 3	108.99	105.72	▼ 3.27	89	75	▼ 14

Scenario 4

Open Room, D1, 120 dB, Hexa Groot

Result data (Few of the 726 total results)



	OPEN ROOM		
Test Case	SCENARIO IV		
Design Type	ACUTE block | Quad Groote		
Block Size - l x w x h (m)	0.6 x 0.6 x 0.8		
Source Position	D1		
Source Height	1. 5m		
Source Sound Pressure level	120 dB		
Task	Zone 1	Zone 2	Zone 3
	Minimize	Minimize	Minimize

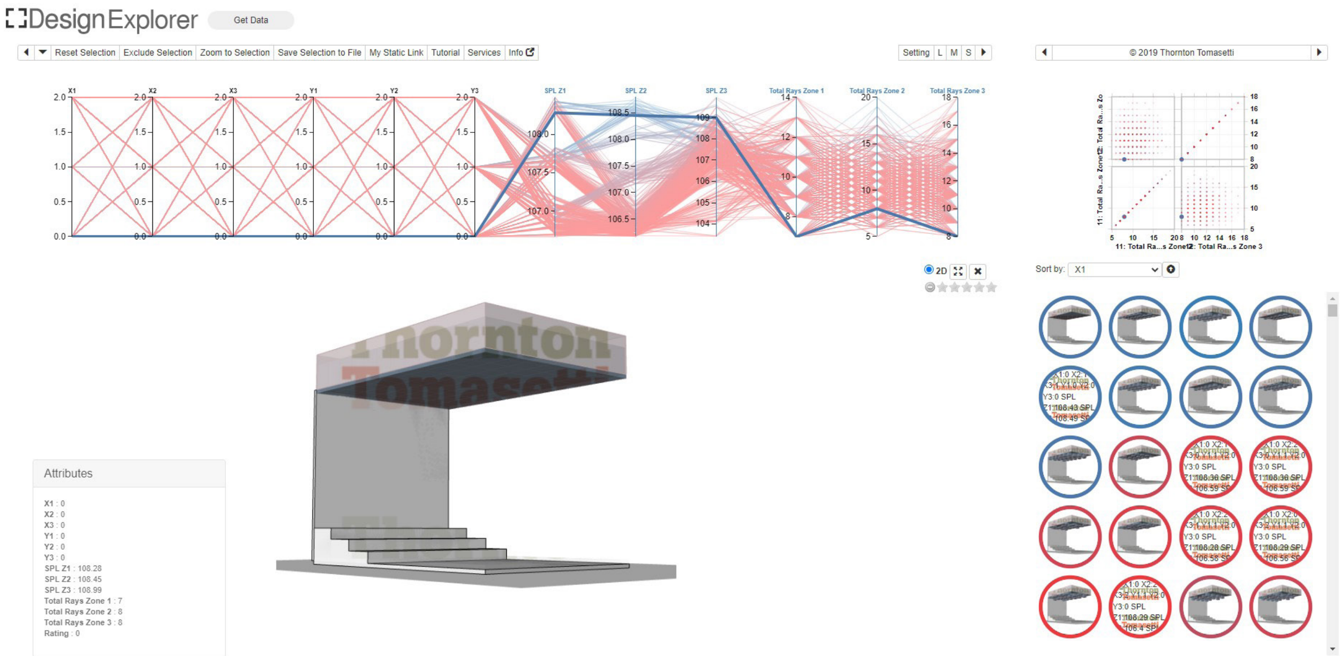
X1	X2	X3	Y1	Y2	Y3	SPL Z1	SPL Z2	SPL Z3	Total Rays Zone 1	Total Rays Zone 2	Total Rays Zone 3
0	0	0	0	0	0	108.28	108.45	108.99	7	8	8
1	0	0	0	0	0	107.65	107.25	108.46	8	6	9
2	0	0	0	0	0	106.98	106.5	107.91	10	8	11
0	1	0	0	0	0	108.36	108.49	108.44	8	10	9
1	1	0	0	0	0	107.74	107.31	107.83	10	8	11
2	1	0	0	0	0	107.09	106.26	107.19	12	10	13
0	2	0	0	0	0	108.36	108.67	108.44	8	14	9
1	2	0	0	0	0	107.74	107.46	107.83	9	13	10
2	2	0	0	0	0	106.98	106.46	107.09	10	11	11
0	0	1	0	0	0	108.36	108.45	109.05	8	8	9
1	0	1	0	0	0	107.74	107.25	109.15	10	6	12
2	0	1	0	0	0	107.08	106.5	107.99	11	8	12
0	1	1	0	0	0	108.43	108.49	108.51	9	10	10
1	1	1	0	0	0	107.83	107.31	106.24	12	8	14
2	1	1	0	0	0	107.18	106.26	107.28	13	10	14
0	2	1	0	0	0	108.43	108.55	108.51	9	11	10
1	2	1	0	0	0	107.82	107.3	106.01	11	10	13
2	2	1	0	0	0	107.08	106.35	107.18	11	10	12
0	0	2	0	0	0	108.36	108.45	109.05	8	8	9
1	0	2	0	0	0	107.74	107.25	109.15	10	6	12
2	0	2	0	0	0	106.98	106.4	107.91	10	8	11
0	1	2	0	0	0	108.43	108.45	108.51	9	9	10
1	1	2	0	0	0	107.83	107.26	106.24	12	7	14
2	1	2	0	0	0	107.09	106.19	107.19	12	8	13
0	2	2	0	0	0	108.43	108.45	108.51	9	9	10
1	2	2	0	0	0	107.82	107.17	106.01	11	8	13
2	2	2	0	0	0	106.98	106.19	107.09	10	8	11
0	0	0	1	0	0	108.36	106.83	109.05	8	15	9
1	0	0	1	0	0	107.65	106.56	108.46	8	12	9
2	0	0	1	0	0	106.89	106.76	107.84	10	14	11
0	1	0	1	0	0	108.36	106.59	108.43	8	12	9
1	1	0	1	0	0	107.66	106.3	107.75	9	9	10
2	1	0	1	0	0	106.9	106.31	107.01	11	10	12
0	2	0	1	0	0	108.36	106.59	104.12	10	12	12
1	2	0	1	0	0	107.66	106.3	104.12	10	9	12

2	0	0	2	0	0	106.98	106.64	107.91	10	15	11
0	1	0	2	0	0	108.41	106.78	106.17	9	17	11
1	1	0	2	0	0	107.72	106.39	104.95	10	14	12
2	1	0	2	0	0	106.89	106.4	107	10	14	11
0	2	0	2	0	0	108.42	106.78	108.17	11	16	14
1	2	0	2	0	0	107.72	106.4	106.48	11	13	14
2	2	0	2	0	0	106.79	106.39	103.43	10	12	12
0	0	1	2	0	0	108.43	106.92	108.62	11	16	13
1	0	1	2	0	0	107.74	106.54	107.61	12	13	15
2	0	1	2	0	0	106.9	106.55	107.85	11	13	12
0	1	1	2	0	0	108.36	106.76	106.08	10	14	12
1	1	1	2	0	0	107.67	106.37	104.2	12	11	15
2	1	1	2	0	0	106.81	106.38	106.92	11	11	12
0	2	1	2	0	0	108.36	106.76	105.96	10	13	12
1	2	1	2	0	0	107.66	106.38	104	11	10	14
2	2	1	2	0	0	106.7	106.37	106.81	9	9	10
0	0	2	2	0	0	108.36	106.75	109.05	8	15	9
1	0	2	2	0	0	107.66	106.44	107.8	9	12	11
2	0	2	2	0	0	106.88	106.46	107.83	9	12	10
0	1	2	2	0	0	108.28	106.6	108.36	7	14	8
1	1	2	2	0	0	107.58	106.27	104.49	9	11	11
2	1	2	2	0	0	106.79	106.29	106.9	9	11	10
0	2	2	2	0	0	108.28	106.6	108.36	7	13	8
1	2	2	2	0	0	107.57	106.29	104.3	8	10	10
2	2	2	2	0	0	106.67	106.29	106.79	7	10	8
0	0	0	0	1	0	108.28	108.55	108.99	7	11	8
1	0	0	0	1	0	107.65	107.34	108.46	8	9	9
2	0	0	0	1	0	106.98	106.5	107.91	10	12	11
0	1	0	0	1	0	108.36	108.56	108.44	8	13	9
1	1	0	0	1	0	107.74	107.34	107.83	9	11	10
2	1	0	0	1	0	107.08	106.29	107.18	11	14	12
0	2	0	0	1	0	108.36	108.74	108.44	8	17	9
1	2	0	0	1	0	107.74	107.49	107.83	9	16	10
2	2	0	0	1	0	106.98	106.51	107.09	10	16	11
0	0	1	0	1	0	108.36	108.45	109.05	8	8	9
1	0	1	0	1	0	107.73	107.25	108.53	9	6	10
2	0	1	0	1	0	107.08	106.39	107.99	11	9	12
0	1	1	0	1	0	108.43	108.45	108.51	9	10	10
1	1	1	0	1	0	107.82	107.25	107.91	10	8	11
2	1	1	0	1	0	107.17	106.18	107.27	12	11	13
0	2	1	0	1	0	108.43	108.51	108.51	9	11	10
1	2	1	0	1	0	107.82	107.25	107.91	10	10	11
2	2	1	0	1	0	107.08	106.29	107.18	11	12	12
0	0	2	0	1	0	108.36	108.45	109.05	8	9	9
1	0	2	0	1	0	107.73	107.26	108.53	9	7	10
2	0	2	0	1	0	106.98	106.3	107.91	10	10	11
0	1	2	0	1	0	108.43	108.45	108.51	9	9	10
1	1	2	0	1	0	107.82	107.26	107.91	10	7	11
2	1	2	0	1	0	107.08	106.19	107.18	11	9	12
0	2	2	0	1	0	108.43	108.45	108.51	9	9	10
1	2	2	0	1	0	107.82	107.17	107.91	10	8	11
2	2	2	0	1	0	106.98	106.19	107.09	10	9	11
0	0	0	1	1	0	108.36	106.59	109.05	8	11	9
1	0	0	1	1	0	107.65	106.4	108.46	8	10	9
2	0	0	1	1	0	106.89	106.49	107.84	10	14	11
0	1	0	1	1	0	108.36	106.4	108.43	8	10	9
1	1	0	1	1	0	107.65	106.2	107.74	8	9	9
2	1	0	1	1	0	106.89	106.19	107	10	12	11
0	2	0	1	1	0	108.36	106.4	104.11	10	10	12
1	2	0	1	1	0	107.66	106.2	104.11	10	9	12

0	0	1	1	1	0	108.28	106.48	108.99	7	8	8
1	0	1	1	1	0	107.57	106.29	108.39	7	7	8
2	0	1	1	1	0	106.79	106.39	107.76	9	10	10
0	1	1	1	1	0	108.28	106.38	108.36	7	7	8
1	1	1	1	1	0	107.57	106.18	107.66	7	6	8
2	1	1	1	1	0	106.79	106.18	106.9	9	8	10
0	2	1	1	1	0	108.28	106.38	108.36	7	7	8
1	2	1	1	1	0	107.57	106.18	107.66	7	6	8
2	2	1	1	1	0	106.69	106.18	106.8	8	8	9
0	0	2	1	1	0	108.29	106.41	109	8	9	9
1	0	2	1	1	0	107.58	106.3	108.4	8	8	9
2	0	2	1	1	0	106.8	106.4	107.77	10	11	11
0	1	2	1	1	0	108.29	106.3	108.37	8	8	9
1	1	2	1	1	0	107.58	106.19	107.67	8	7	9
2	1	2	1	1	0	106.8	106.19	106.91	10	9	11
0	2	2	1	1	0	108.29	106.3	108.37	8	8	9
1	2	2	1	1	0	107.58	106.19	107.67	8	7	9
2	2	2	1	1	0	106.7	106.19	106.81	9	9	10
0	0	0	2	1	0	108.48	106.79	108	10	16	12
1	0	0	2	1	0	107.8	106.48	107.23	10	13	12
2	0	0	2	1	0	106.98	106.49	107.91	10	17	11
0	1	0	2	1	0	108.41	106.63	106.05	9	16	11
1	1	0	2	1	0	107.72	106.31	104.77	9	13	11
2	1	0	2	1	0	106.88	106.3	106.99	9	16	10
0	2	0	2	1	0	108.42	106.63	107.41	11	16	14
1	2	0	2	1	0	107.72	106.32	105.29	11	13	14
2	2	0	2	1	0	106.79	106.3	103.41	10	16	12
0	0	1	2	1	0	108.43	106.68	107.94	11	12	13
1	0	1	2	1	0	107.74	106.37	107.16	11	9	13
2	0	1	2	1	0	106.9	106.38	107.85	11	12	12
0	1	1	2	1	0	108.36	106.59	105.95	10	11	12
1	1	1	2	1	0	107.65	106.26	104.64	10	8	12
2	1	1	2	1	0	106.8	106.26	106.91	10	10	11
0	2	1	2	1	0	108.36	106.59	105.95	10	11	12
1	2	1	2	1	0	107.65	106.27	104.64	10	8	12
2	2	1	2	1	0	106.7	106.26	106.81	9	10	10
0	0	2	2	1	0	108.36	106.61	109.05	8	13	9
1	0	2	2	1	0	107.65	106.38	108.46	8	10	9
2	0	2	2	1	0	106.88	106.4	107.83	9	13	10
0	1	2	2	1	0	108.28	106.51	108.36	7	12	8
1	1	2	2	1	0	107.57	106.27	107.66	7	9	8
2	1	2	2	1	0	106.78	106.29	106.89	8	11	9
0	2	2	2	1	0	108.28	106.51	108.36	7	12	8
1	2	2	2	1	0	107.57	106.29	107.66	7	9	8
2	2	2	2	1	0	106.67	106.29	106.79	7	11	8
0	0	0	0	2	0	108.34	108.68	108.73	8	13	10
1	0	0	0	2	0	107.65	107.51	108.46	8	11	9
2	0	0	0	2	0	106.98	106.51	107.91	10	11	11
0	1	0	0	2	0	108.37	108.62	107.31	10	14	12
1	1	0	0	2	0	107.74	107.42	107.83	10	12	11
2	1	0	0	2	0	107.09	106.4	107.19	12	13	13
0	2	0	0	2	0	108.37	108.61	107.31	10	15	12
1	2	0	0	2	0	107.74	107.32	107.83	10	14	11
2	2	0	0	2	0	106.99	106.29	107.1	11	12	12
0	0	1	0	2	0	108.41	108.59	108.79	9	13	11
1	0	1	0	2	0	107.73	107.44	108.53	9	11	10
2	0	1	0	2	0	107.08	106.42	107.99	11	11	12
0	1	1	0	2	0	108.43	108.53	107.39	10	14	12
1	1	1	0	2	0	107.82	107.35	107.91	10	12	11
2	1	1	0	2	0	107.17	106.31	107.27	12	13	13

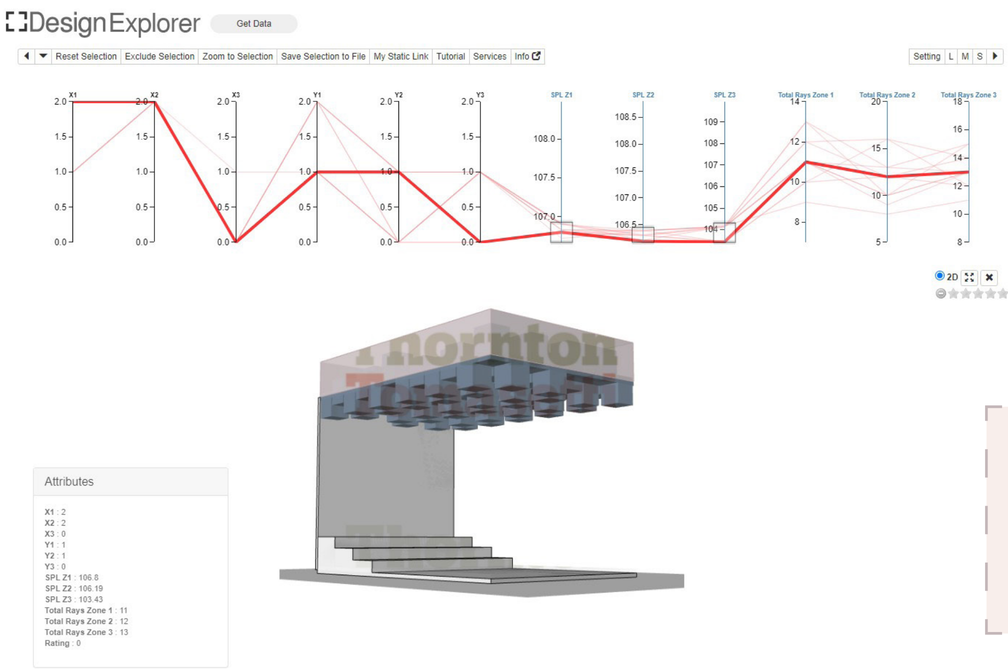
Scenario 4 | Acoustic Results

Data Allocation using Design Explorer



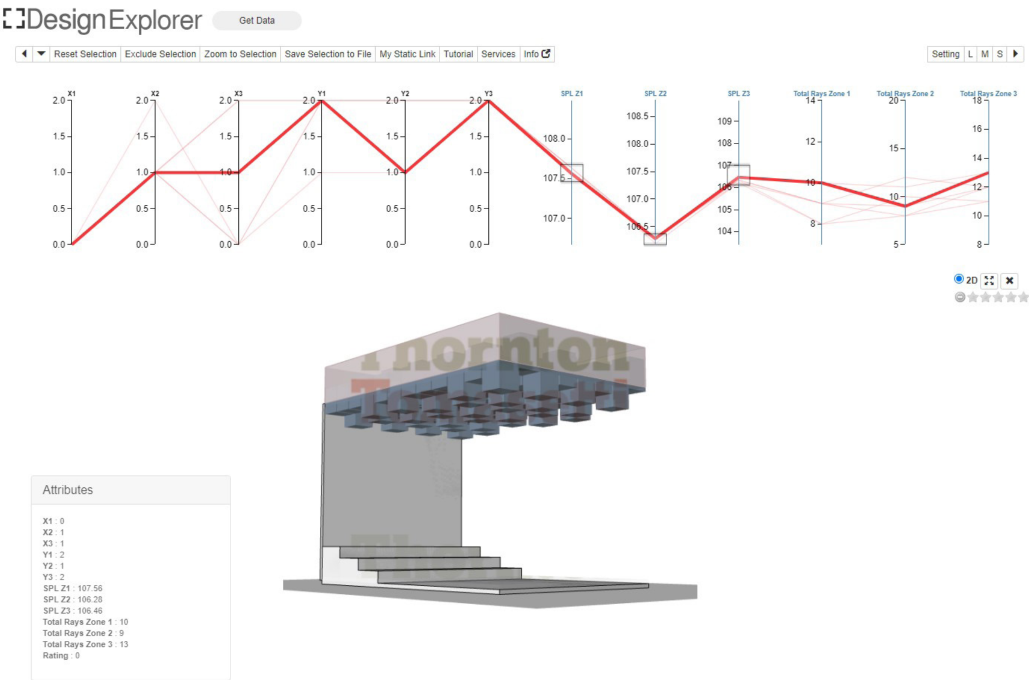
Acoustic Standby mode

SPL Z1 = 49.18 dB
SPL Z2 = 48.40 dB
SPL Z3 = 47.13 dB



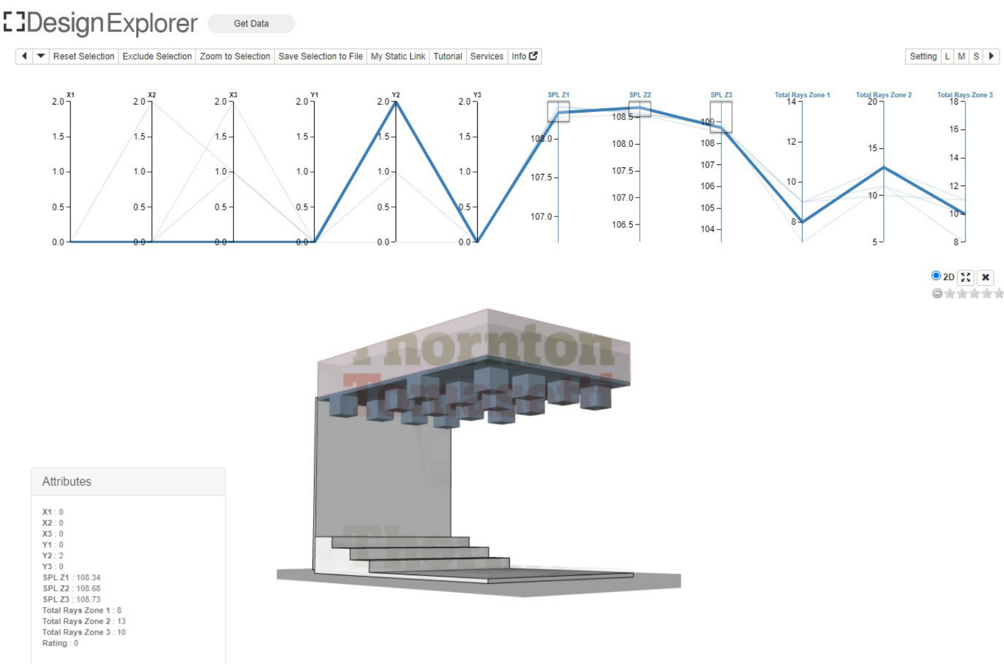
Acoustic Preference

SPL Z1 (min) = 106.8 dB
SPL Z2 (min) = 106.19 dB
SPL Z3 (min) = 103.43 dB



Acoustic Preference

SPL Z1 (bal) = 107.56 dB
SPL Z2 (min) = 106.28 dB
SPL Z3 (bal) = 106.46 dB



Acoustic Preference

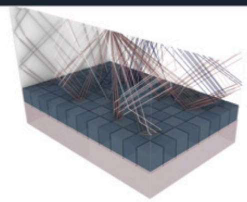
SPL Z1 (max) = 108.34 dB
SPL Z2 (max) = 108.68 dB
SPL Z3 (maxv) = 108.73 dB

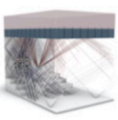
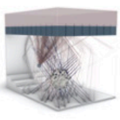
RESULT SHEET — OPEN ROOM

Test Case	SCENARIO IV
Design Type	ACUTE block | Quad Groote
Block Size - l x w x h (m)	0.6 x 0.6 x 0.8
Source Position	D1
Source Height	1. 5m
Source Sound Pressure level	120 dB
Task	Zone 1: Minimize; Zone 2: Minimize; Zone 3: Minimize

INITIAL POSITION

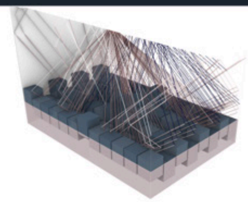
Block Configuration

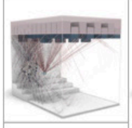
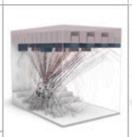
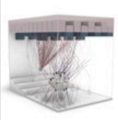


Zone Number	Receiver - Zone 1	Receiver - Zone 2	Receiver - Zone 3
Ray Tracing Diagram			
Order of Incidence 1	0	0	0
2	13	12	12
3	12	17	32
4	13	22	19
5	32	20	12
6	16	12	14
Total number of rays	86	83	89
Sound Pressure Level (dB)	108.28	108.45	108.99

OPTIMIZED POSITION

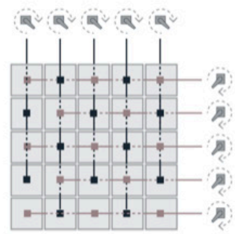
Block Configuration



Zone Number	Receiver - Zone 1	Receiver - Zone 2	Receiver - Zone 3
Ray Tracing Diagram			
Order of Incidence 1	0	0	0
2	11	5	8
3	27	16	27
4	32	14	24
5	37	21	6
6	23	18	10
Total number of rays	130	74	75
Sound Pressure Level (dB)	106.8	106.19	103.43

ACTUATOR DATA

The numbers represent the angle that the respective actuator has to move to configure the blocks in the optimized position.
The data is based on the preset algorithms created based on the acoustic simulations. The algorithms can be tweaked in order to achieve customized results.



X axis: | 1 | 0 | 2 | 1 |

Y axis: | 0 | 0 | 1 | 0 | 2 | 1 |

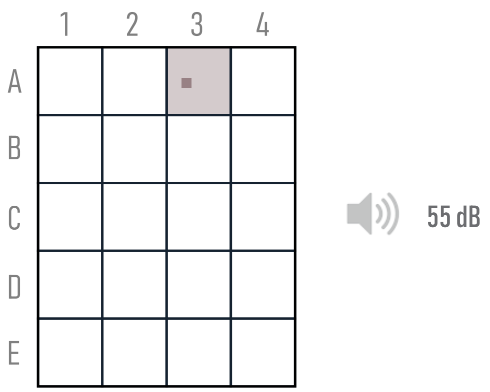
SCENARIO IV — OPEN ROOM | 120 dB

	SPL (dB)			Number of Rays		
	INITIAL	OPTIMIZED	CHANGE	INITIAL	OPTIMIZE	CHANGE
Zone 1	108.28	106.8	▼ 1.48	86	130	▲ -44
Zone 2	108.45	106.19	▼ 2.26	83	74	▼ 9
Zone 3	108.99	103.43	▼ 5.56	89	75	▼ 14

Scenario 5

Close Room, A3, 55 dB, Quad klien

Result data (Few of the 729 total results)



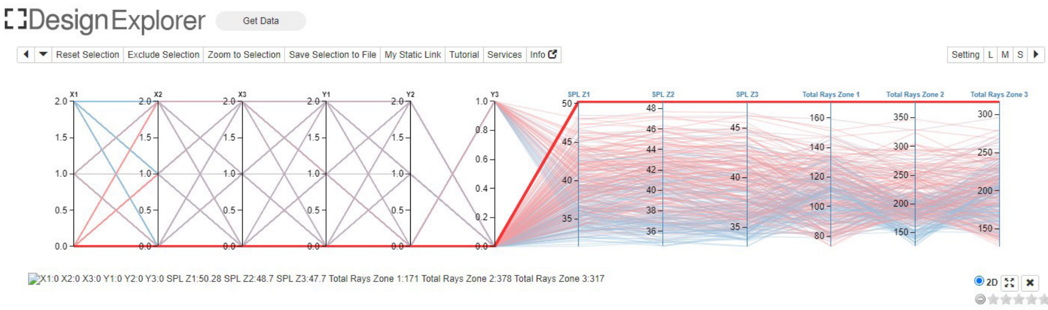
CLOSED ROOM			
Test Case	SCENARIO 5		
Design Type	ACUTE block | Quad Groote		
Block Size - l x w x h (m)	0.6 x 0.6 x 0.8		
Source Position	A3		
Source Height	1.8 meters		
Source Sound Pressure level	55 dB		
Task	Zone 1	Zone 2	Zone 3
	Balance	Balance	Balance

X1	X2	X3	Y1	Y2	Y3	SPL Z1	SPL Z2	SPL Z3	Total Rays Zone 1	Total Rays Zone 2	Total Rays Zone 3
0	0	0	0	0	0	50.28	48.7	47.7	171	378	317
1	0	0	0	0	0	48.48	47.23	46.23	159	328	296
2	0	0	0	0	0	46.49	45.01	44.58	134	224	250
0	1	0	0	0	0	47.44	46.09	44.35	139	292	255
1	1	0	0	0	0	45.48	43.79	41.75	133	252	246
2	1	0	0	0	0	41.41	42.01	39.72	119	190	221
0	2	0	0	0	0	46.71	44.48	42.71	133	224	234
1	2	0	0	0	0	44.81	41.69	40.42	131	194	234
2	2	0	v	0	0	40.33	39.27	37.8	113	143	207
0	0	1	0	0	0	47.91	47.7	46.59	151	347	278
1	0	1	0	0	0	45.15	46.03	44.89	138	294	255
2	0	1	0	0	0	42.16	43.82	43.3	116	210	216
0	1	1	0	0	0	44.47	44.5	42.91	124	268	227
1	1	1	0	0	0	39.8	41.32	39.63	117	225	216
2	1	1	0	0	0	37.13	39.58	37.74	106	179	198
0	2	1	0	0	0	42.54	42.85	41.66	124	208	220
1	2	1	0	0	0	37.96	38.88	39.1	121	175	218
2	2	1	0	0	0	36.88	36.21	36.93	108	138	200
0	0	2	0	0	0	46.79	46.99	45.55	127	302	232
1	0	2	0	0	0	43.72	45.16	43.52	110	249	203
2	0	2	0	0	0	40.55	42.76	41.72	91	185	169
0	1	2	0	0	0	43.26	43.93	42.11	110	239	200
1	1	2	0	0	0	38.71	40.28	38.09	102	196	187
2	1	2	0	0	0	35.28	38.51	35.97	91	165	169
0	2	2	0	0	0	41.41	42.49	40.58	112	195	198
1	2	2	0	0	0	36.49	38.11	37.35	108	162	194
2	2	2	0	0	0	33.33	35.85	34.82	98	140	180
0	0	0	1	0	0	48.18	45.97	46.31	153	281	280
1	0	0	1	0	0	45.06	44.31	44.66	147	271	272
2	0	0	1	0	0	42.75	43.08	42.87	125	197	231
0	1	0	1	0	0	44.36	43.32	43.65	147	249	268
1	1	0	1	0	0	42.17	40.7	40.9	145	245	268
2	1	0	1	0	0	39.53	39.55	38.8	132	181	243
0	2	0	1	0	0	43.11	42.08	41.96	132	185	230
1	2	0	1	0	0	39.49	39.2	39.53	131	181	234
2	2	0	1	0	0	37.51	37.79	36.91	111	134	205
0	0	1	1	0	0	45.62	45.34	45.14	136	284	248

0	1	1	2	0	0	38.1	41.37	41.06	99	219	173
1	1	1	2	0	0	35.77	38.41	37.6	94	213	168
2	1	1	2	0	0	33.75	37.62	35.76	88	204	161
0	2	1	2	0	0	39.97	40.07	40.11	126	192	220
1	2	1	2	0	0	36.52	37.26	37.69	120	189	214
2	2	1	2	0	0	36.23	36.21	35.87	108	180	202
0	0	2	2	0	0	42	43.89	42.68	101	248	172
1	0	2	2	0	0	38.63	42.06	39.98	91	237	158
2	0	2	2	0	0	36.96	40.93	37.6	80	219	144
0	1	2	2	0	0	37.91	41.13	40.46	93	215	161
1	1	2	2	0	0	34.87	37.91	36.66	88	210	155
2	1	2	2	0	0	33.42	37.35	34.28	83	206	149
0	2	2	2	0	0	39.82	39.95	39.33	121	197	211
1	2	2	2	0	0	35	37.03	36.79	115	195	204
2	2	2	2	0	0	33.56	36.34	34.52	107	191	197
0	0	0	0	1	0	47.2	47.28	44.89	125	324	226
1	0	0	0	1	0	45.78	45.79	43.44	133	288	241
2	0	0	0	1	0	42.35	43.6	41.87	112	191	205
0	1	0	0	1	0	45.6	44.74	41.56	122	268	224
1	1	0	0	1	0	44.13	42.29	39.55	135	238	248
2	1	0	0	1	0	39.47	40.11	37.73	120	172	221
0	2	0	0	1	0	44.15	43.23	39.63	104	205	187
1	2	0	0	1	0	43.71	40.2	38.06	124	183	220
2	2	0	0	1	0	37.96	37.17	36.3	110	133	200
0	0	1	0	1	0	44.96	46.36	43.99	115	305	206
1	0	1	0	1	0	42.91	44.71	42.21	121	265	218
2	0	1	0	1	0	39.25	42.63	40.69	101	190	184
0	1	1	0	1	0	42.1	43.29	40.47	114	258	209
1	1	1	0	1	0	38.83	40.07	37.79	125	224	230
2	1	1	0	1	0	36.02	38	35.95	111	176	205
0	2	1	0	1	0	39.2	41.76	38.8	101	199	182
1	2	1	0	1	0	36.44	37.78	37.01	119	173	212
2	2	1	0	1	0	34.92	35.02	35.06	106	139	194
0	0	2	0	1	0	43.73	45.77	42.98	97	273	171
1	0	2	0	1	0	41.41	44.03	40.82	100	235	179
2	0	2	0	1	0	38.4	41.87	38.97	82	173	149
0	1	2	0	1	0	41.47	42.88	39.76	100	237	182
1	1	2	0	1	0	37.66	39.44	36.34	111	205	203
2	1	2	0	1	0	34.13	37.37	34.22	98	166	181
0	2	2	0	1	0	38.46	41.53	37.79	93	191	165
1	2	2	0	1	0	33.1	37.43	35.32	110	167	194
2	2	2	0	1	0	31.73	35.09	33.1	100	142	182
0	0	0	1	1	0	43.7	44.26	43.25	110	241	199
1	0	0	1	1	0	41.65	42.74	41.6	124	245	226
2	0	0	1	1	0	39.11	41.66	39.99	103	173	188
0	1	0	1	1	0	42.35	41.39	40.96	132	237	243
1	1	0	1	1	0	39.32	38.7	38.99	149	243	275
2	1	0	1	1	0	38.49	37.44	37.4	135	172	248
0	2	0	1	1	0	39.52	40.24	38.69	103	172	185
1	2	0	1	1	0	38.11	37.22	37.22	125	176	223
2	2	0	1	1	0	34.14	35.89	35.85	110	129	202
0	0	1	1	1	0	42.2	43.74	42.3	105	250	188
1	0	1	1	1	0	40.3	42.27	40.3	117	257	212
2	0	1	1	1	0	37.78	41.19	38.66	97	185	176
0	1	1	1	1	0	40.18	40.46	40.1	128	248	235
1	1	1	1	1	0	36.56	37.67	37.7	143	257	264
2	1	1	1	1	0	36.06	36.45	36.18	130	186	239
0	2	1	1	1	0	35.73	39.16	38.13	101	183	182
1	2	1	1	1	0	36.2	36.05	36.6	121	190	217
2	2	1	1	1	0	34.26	34.88	34.98	107	143	198
0	0	2	1	1	0	41.32	43.34	41.2	88	233	154

1	0	0	2	1	0	38.32	41.88	39.24	97	221	171
2	0	0	2	1	0	36.33	41.06	38.33	88	201	158
0	1	0	2	1	0	38.05	40.71	39.07	92	211	165
1	1	0	2	1	0	36.74	38.24	37.28	106	215	191
2	1	0	2	1	0	34.2	37.57	36.37	99	200	179
0	2	0	2	1	0	37.95	39.75	37.16	107	185	193
1	2	0	2	1	0	35.83	37.25	36.67	124	189	221
2	2	0	2	1	0	34.15	36.48	35.71	111	181	206
0	0	1	2	1	0	38.94	42.83	40.16	80	220	138
1	0	1	2	1	0	37.08	41.35	37.88	90	222	158
2	0	1	2	1	0	35.67	40.56	36.53	82	203	147
0	1	1	2	1	0	35.32	39.83	38.19	87	215	155
1	1	1	2	1	0	35.27	37.28	36.14	99	220	178
2	1	1	2	1	0	33.39	36.78	34.8	94	206	170
0	2	1	2	1	0	34.18	38.84	36.35	103	190	185
1	2	1	2	1	0	33.49	36.41	36	118	195	210
2	2	1	2	1	0	32.66	35.89	34.81	107	188	199
0	0	2	2	1	0	38	42.7	39.25	81	219	135
1	0	2	2	1	0	35.86	41.28	36.19	89	224	152
2	0	2	2	1	0	35.37	40.48	34.04	79	204	139
0	1	2	2	1	0	36.02	39.85	37.64	82	215	143
1	1	2	2	1	0	34.45	37.33	35.21	95	223	167
2	1	2	2	1	0	32.91	36.84	33.55	91	208	162
0	2	2	2	1	0	35.43	38.92	35.59	103	197	181
1	2	2	2	1	0	33.45	36.58	35.17	118	205	206
2	2	2	2	1	0	32.66	36.1	33.75	110	197	201
0	0	0	0	2	0	43.37	45.84	42.51	94	248	166
1	0	0	0	2	0	40.4	44.24	41.01	94	215	166
2	0	0	0	2	0	41.04	42.71	39.83	97	161	175
0	1	0	0	2	0	40	43.3	38.79	87	210	156
1	1	0	0	2	0	38.17	40.58	37.62	93	182	166
2	1	0	0	2	0	40.82	39.37	36.41	103	152	182
0	2	0	0	2	0	40.02	41.77	37.92	104	178	190
1	2	0	0	2	0	37.36	38.41	36.93	113	153	202
2	2	0	0	2	0	36.14	36.67	35.42	120	132	215
0	0	1	0	2	0	41.94	45.25	41.62	88	245	153
1	0	1	0	2	0	39.21	43.62	39.78	86	206	151
2	0	1	0	2	0	37.59	41.84	38.52	90	161	161
0	1	1	0	2	0	38.88	42.34	37.68	82	210	146
1	1	1	0	2	0	36.5	39.31	36.04	86	176	154
2	1	1	0	2	0	34.62	37.7	34.57	98	155	173
0	2	1	0	2	0	37.84	40.78	37.23	101	178	184
1	2	1	0	2	0	34.29	37.14	36.02	108	147	194
2	2	1	0	2	0	32.7	34.85	34.57	118	133	212
0	0	2	0	2	0	40.99	44.67	40.85	83	234	142
1	0	2	0	2	0	38.53	42.96	38.72	80	196	139
2	0	2	0	2	0	35.22	41.1	37.61	82	161	146
0	1	2	0	2	0	36.75	41.97	36.96	74	202	130
1	1	2	0	2	0	36.08	38.69	34.9	79	169	140
2	1	2	0	2	0	33.55	37.16	33.69	91	156	160
0	2	2	0	2	0	36.03	40.7	36.48	96	181	174
1	2	2	0	2	0	35.52	36.95	34.94	103	151	185
2	2	2	0	2	0	32.7	35.17	33.8	114	145	206
0	0	0	1	2	0	40.2	43.05	40.46	80	198	143
1	0	0	1	2	0	38.55	41.51	38.93	85	200	154
2	0	0	1	2	0	37.6	40.59	37.58	91	145	165
0	1	0	1	2	0	37.13	40.11	37.54	92	197	167
1	1	0	1	2	0	36.78	37.66	36.68	101	201	184
2	1	0	1	2	0	36.51	36.74	35.81	111	150	199
0	2	0	1	2	0	38.92	39.17	36.49	102	160	187
1	2	0	1	2	0	36.48	36.59	35.87	112	161	203

Scenario 4 | Acoustic Results
Data Allocation using Design Explorer

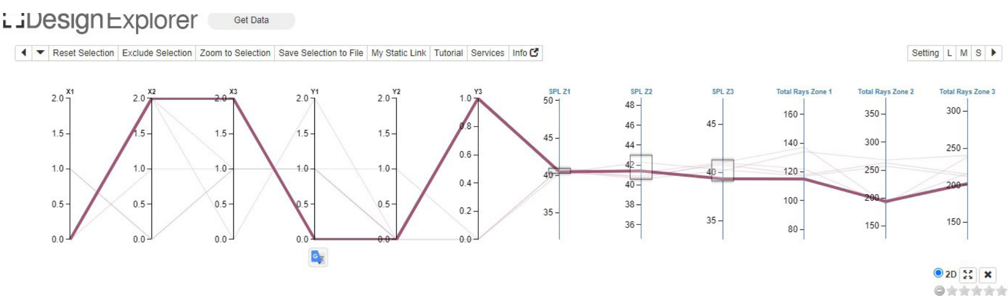


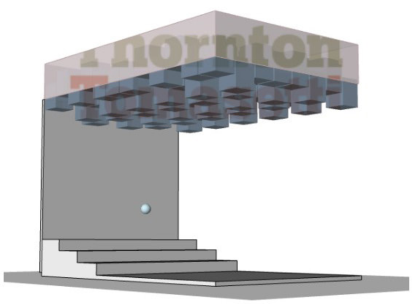
Attributes

X1 : 0
X2 : 0
X3 : 0
Y1 : 0
Y2 : 0
Y3 : 0
SPL Z1 : 50.28
SPL Z2 : 48.7
SPL Z3 : 47.7
Total Rays Zone 1 : 171
Total Rays Zone 2 : 378
Total Rays Zone 3 : 317
Rating : 0

Acoustic Standby mode

SPL Z1 = 50.28 dB
SPL Z2 = 48.70 dB
SPL Z3 = 47.70 dB



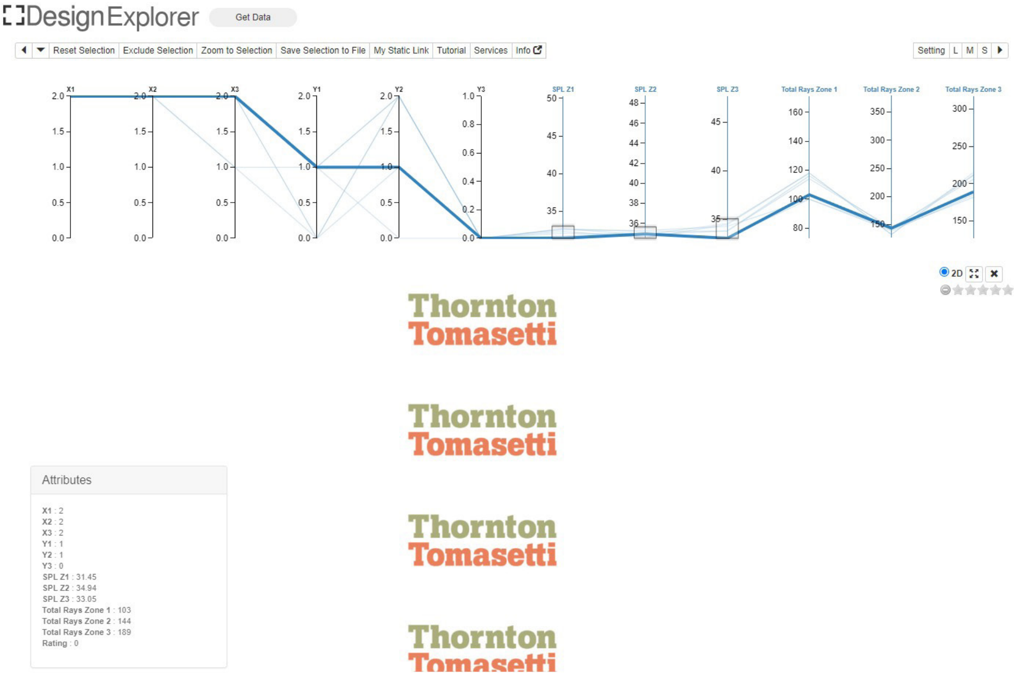


Attributes

X1 : 0
X2 : 2
X3 : 2
Y1 : 0
Y2 : 0
Y3 : 1
SPL Z1 : 40.47
SPL Z2 : 41.4
SPL Z3 : 39.35
Total Rays Zone 1 : 115
Total Rays Zone 2 : 194
Total Rays Zone 3 : 202
Rating : 0

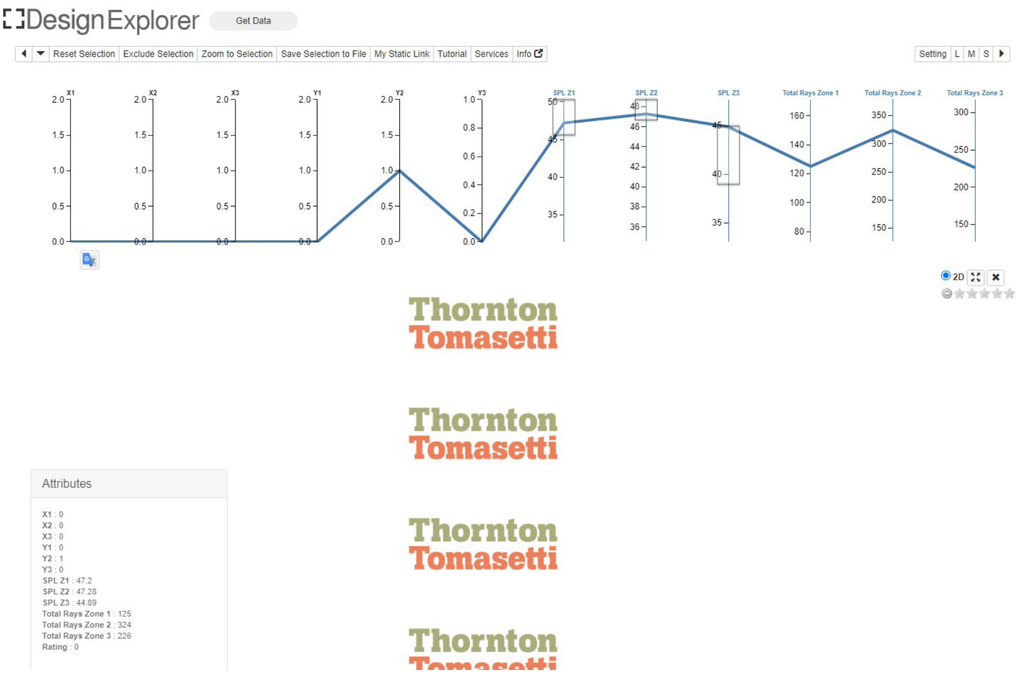
Acoustic Preference

SPL Z1 (bal) = 40.47 dB
SPL Z2 (bal) = 41.40 dB
SPL Z3 (bal) = 39.35 dB



Acoustic Preference

SPL Z1 (min) = 31.45 dB
SPL Z2 (min) = 34.94 dB
SPL Z3 (min) = 33.05 dB

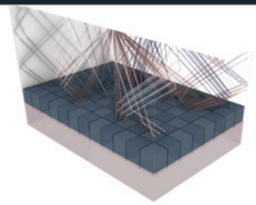
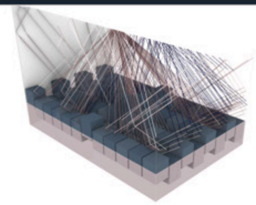
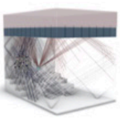
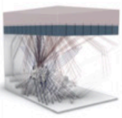
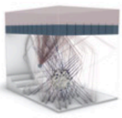
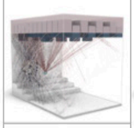
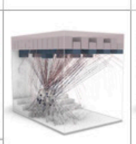
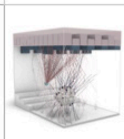
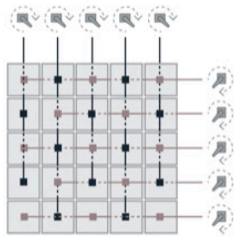


Acoustic Preference

SPL Z1 (max) = 47.20 dB
SPL Z2 (max) = 47.28 dB
SPL Z3 (bal) = 44.89 dB

RESULT SHEET — CLOSED ROOM

Test Case	SCENARIO 5
Design Type	ACUTE block | Quad Groote
Block Size - l x w x h (m)	0.6 x 0.6 x 0.8
Source Position	A3
Source Height	1.8 meters
Source Sound Pressure level	55 dB
Task	Zone 1: Balance; Zone 2: Balance; Zone 3: Balance

	INITIAL POSITION			OPTIMIZED POSITION			ACTUATOR DATA
Block Configuration							The numbers represent the angle that the respective actuator has to move to configure the blocks in the optimized position. The data is based on the preset algorithms created based on the acoustic simulations. The algorithms can be tweaked in order to achieve customized results.
Zone Number	Receiver - Zone 1	Receiver - Zone 2	Receiver - Zone 3	Receiver - Zone 1	Receiver - Zone 2	Receiver - Zone 3	
Ray Tracing Diagram							
Order of Incidence 1	0	0	0	0	0	0	
Order of Incidence 2	13	12	12	11	5	8	
Order of Incidence 3	12	17	32	27	16	27	
Order of Incidence 4	13	22	19	32	14	24	
Order of Incidence 5	32	20	12	37	21	6	
Order of Incidence 6	16	12	14	23	18	10	
Total number of rays	86	92	76	130	83	69	X axis: | 1 | 0 | 2 | 1 |
Sound Pressure Level (dB)	50.28	48.70	47.70	40.47	41.40	39.35	Y axis: | 0 | 0 | 1 | 0 | 2 | 1 |

SCENARIO II — CLOSED ROOM | 55 dB

	SPL (dB)			Number of Rays		
	INITIAL	OPTIMIZED	CHANGE	INITIAL	OPTIMIZE	CHANGE
Zone 1	50.28	40.47	▼ 9.81	86	130	▲ -44
Zone 2	48.70	41.40	▼ 7.30	92	83	▼ 9
Zone 3	47.70	39.35	▼ 8.35	76	69	▼ 7

End of Report.

TARANG GUPTA

TU Delft BK Bouwkunde