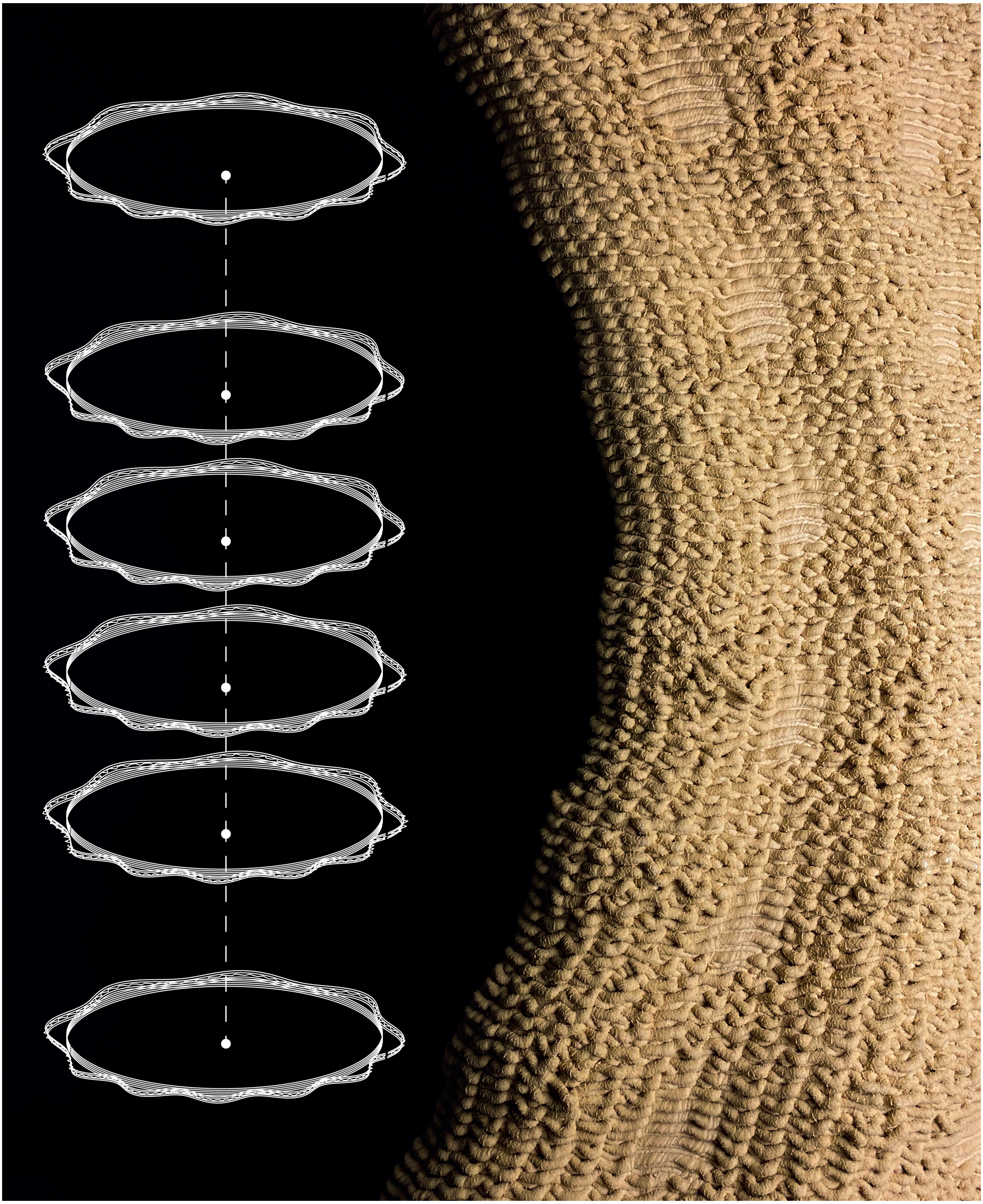

Sound over Matter

Shaping Architectural Acoustics Through 3D Printing

Chalmers School of Architecture - Department of Architecture and Civil Engineering - Markus Kempe

Year of graduation and publication: 2025 - Supervisor: Jonas Lundberg - Examiner: Jonas Lundberg

Thanks to...

Jonas, for your invaluable supervision, insightful ideas, and the inspiring references of architecture, literature, and design that have helped in shaping this work.

Samuel, for granting me access to the robotic lab, generously dedicating your time to the project, and providing enthusiastic supervision throughout.

Richard, for patiently listening to my rants, helping me stay grounded, and guiding me through the intricacies of acoustics.

Mom & Dad, the love and support is factually endless.

Sound over Matter

Shaping Architectural Acoustics Through 3D Printing

Student: Markus Kempe

Examiner - Jonas Lundberg

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Chalmers School of Architecture

Department of Architecture and Civil Engineering

Architectural Experimentation

Master's Programme of Architecture and Urban Design (MPARC)

Graduation and publication year: 2025

Abstract

When tasked with designing a space for acoustic performances, shouldn't the sound of that space be considered as carefully as its form? This question has been central to architectural acoustics since the early 1900s, when physicist Wallace Clement Sabine revolutionized the design of the Boston Music Hall through quantitative acoustic calculations, which led to the hall being one of North America's most acoustically respected venues (Petersen et al., 1998).

Today, acoustic considerations have spread to offices, museums, transport infrastructure, and even restaurants. But in many cases, the acoustic performance is rather expected to solve for the architectural vision, not to shape it. With exceptions such as Hamburg's orchestra hall, the Elbphilharmonie, where architectural acoustic plays the primary role within its design. This thesis argues that with current technologies like acoustic simulation and robotic fabrication, we now have the tools to put the relationship between the acoustics and the architecture in better balance. Designing with acoustics in mind from the beginning could open new creative possibilities for architects. By integrating such intent early in the design process, this thesis suggests that sound and form can enhance one another and thereby benefit an overall spatial experience.

To contextualize the findings, the thesis proposes an acoustic redesign of the building locally know as Palladium, a former cinema (now retail establishment) in central Gothenburg, Sweden. The intervention envisions how custom developed 3D-printed acoustic panels could transform such a venue, while simultaneously, reviving its original function towards an entertainment-focused program.

The research traces a design process that includes spatially acoustic-oriented building interventions, exploration of three-dimensional surface patterns and how to robotically fabricate such geometries, to prototyping and site-specific applications of acoustic panels in the shape of diffusers and reflectors.
Through computational design, acoustic analysis of three dimensional surface geometries and space, robotic fabrication and utilization of alternative sustainable materials, this thesis aims to contribute to the discourse on future technologies and -sustainability and performative architecture.

Keywords:
Performative architecture, Architectural acoustics, Acoustic analysis, 3D printing, Digital design, Robotic fabrication

"Interiors are like large instruments, collecting sound, amplifying it, transmitting it elsewhere. That has to do with the shape peculiar to each room and with the surface of the materials they contain, and the way those materials have been applied"

~ Peter Zumthor

(Zumthor, 2006, p. 28)

2019 - 2022 Chalmers University of Technology

Architecture and Engineering - Bachelor.

2022 - 2023 Internship at Cundall

Structural engineering internship in London, United Kingdom.

2023 - 2025 Chalmers University of Technology

Architecture and Urban design - Masters.

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- How can computational acoustic simulations inform both the transformation of a building into a venue for entertainment and dining, and the design of robotically fabricated acoustic diffusers and reflectors that enhance that venues spatial and acoustic qualities?

Aim

The aim of this thesis has been to learn about robotic fabrication and architectural acoustics and to investigate how those topics can be intertwined to be utilized in shaping the architecture and performance of sound within a space of entertainment.

Target Audience

This master thesis is written for those interested in acoustics, future technologies, material efficiency, material life cycles, material research, parametric design and sustainable architectural solutions.

This thesis delves into research on acoustics, alternative materials and fabrication technologies. Neither am I an acoustician, a chemist or a robotic engineer, so this thesis distances itself from certain areas within those fields and instead, it emphasizes how one as an architect can engage with and contribute to these fields beyond traditional consultation.

This is explained further for each field below.

Acoustics

This thesis does not include detailed acoustical calculations or simulations. Instead, it showcases general strategies and design adjustments to achieve acoustical qualities suited for the specified interior environments. The emphasis is on conceptual and geometrical explorations, rather than precise numerical analysis, aiming to provide a qualitative understanding of how architectural elements can influence architectural acoustic performances.

The visualizations and illustrations shown in this thesis, is either based on theory extracted from the literature presented in the text or produced via the acoustical design tool pachyderm which is a plug in for Rhinoceros and Grasshopper. The tool is not recommended to use for detailed acoustical calculations, but rather, to use as a tool to generate rough visuals dependent on the geometry implemented design.

An additional aim of this thesis has been to consulate people on the department of Sound and Vibration at the university to set up tests to learn about the acoustic properties of the prototypes designed, but so far it has be unsuccessful.

Material

The thesis wont go into depth in how the working material is made or it’s chemical properties. However, the thesis will explain what the material contains, and how it can contribute to a more sustainable material approach within architecture.

Fabrication

The thesis will not explain any code regarding the fabrication. All design is done through digital 3D modelling, which then is transformed into a tool path via a grasshopper script I’ve been handed by Samuel Norberg. The specific fabrication process which this thesis utilizes is called Fused Filament fabrication (FFF), but there are also other ways to use robots in fabrication towards similar results.

Personal motivation

A fascination for 3D-printing in architecture began during a university course called Material and Technique, where I together with two colleagues designed a degradable pavilion for the Botanical Garden in Gothenburg. The project combined biomimicry, sustainable materials, and digital tools like AI generated imagery, Rhino, and Grasshopper, which sparked my interest in innovative, future-oriented design methods.

Earlier in 2022, during my internship as a structural engineer in London, I contributed to projects involving stage structures, pavilions, and public artworks. There, I saw how my love for music and live performance could intersect with architecture, especially through temporary forms that prioritize materiality, atmosphere, and experimentation.

Drawing from both these experiences, this thesis aims to push fabrication boundaries and explore alternative applications of 3D-printing through a focus on materiality, concept, and spatial atmosphere.

Sustainable motives

3D printing is an alternative manufacturing process within architecture that continues to develop each year. However, concerns regarding the environmental impact of plastic and energy usage have started to emerge. Efforts to improve environmental and durable characteristics of the materials used are being heavily investigated by researchers and stakeholders worldwide. Bio-based fillers, such as wood waste products paired with biodegradable polymers, are currently of particular interest among researchers (Di Salvo, 2024).

According to Ramaux et al. (2024), while 3D printing shows promise, further research is still needed to improve product life cycles and increase loading capacity. Similarly, Le Duigou et al. (2016) highlight that the hygroscopic properties of 3D-printed biocomposites are still lacking. These limitations, when considered in relation to the demands of structural materials, makes 3D Printing still unreliable for architects as a structural alternative.

When these potentially sustainable materials and fabrication processes emerge, the question of how and where to apply them arises. As designers and architects, it should be within our deepest interest to experiment and explore these possibilities. Not only to push the research forward but also to challenge ourselves and advance our field, ensuring that our industry evolves alongside new technologies. Acoustically supportive elements could be one of many potential solutions. A direction I feel enthusiastic about investigating.

Listening and hearing

I've always held an appreciation for sound, and I know that you do too. Because sound can be beautiful, it can be ugly. It can be soft and warm, yet it can also be sharp and cold.

Sound is information, which hearing constantly prompts for us to translate and react upon, even when we don't intend to.

If we truly listen, sound can tell us about the weather. It can tell us about the matter around us, the size of the room or whether the room exists at all.

Sound can be delicate, but it can also be violent. It can fill you with disgust, but it can also make you fall in love.

I believe we should listen more, and stop hearing so much.

"Hearing is a physiological phenomenon; listening is a psychological act"
~ Roland Barthes
(Barthes, 1982, p. 245)

Architectural acoustics

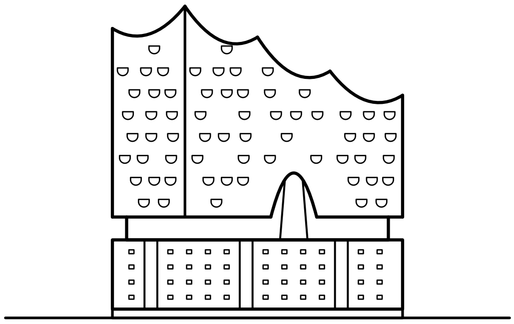
Acoustics and architecture have always been closely related, although researching and optimizing the two fields in parallel is a relatively new design practice.

Physicist Wallace Clement Sabine, who operated during the end of the 1800s and beginning of the 1900s, is often mentioned as the founder of architectural acoustics. His most famous work, the Boston's Musical Hall, was the first concert hall where quantitative acoustics played a role within the design process. Sabine perfected the acoustics of the auditorium by implying proportions and materials even before the architects had set their pen on the paper for the hall. His ideas was based on calculations in regard to both reverberation and material absorption, something which at time was completely new (Petersen et al., 1998).

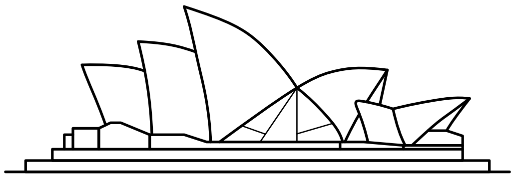
Even though Sabine revolutionized the way auditoriums could be designed using a more theoretical and calculated approach, spaces dedicated to both visual and acoustic experiences had been integral to architectural language long before his time. A clear example is the many amphitheatres built during the Roman Empire.

Today, concert halls are often found among the most recognizable monuments in cities worldwide, which suggests that such structures capture public interest even beyond those with a specific passion for architecture or the performances themselves held within those buildings. Orchestra halls, theatres, and opera houses are now typical examples of structures where fabrication processes and geometric expressions have pushed previous limits. Which is particularly notable when considering that architectural acoustic theory remains relatively underdeveloped compared to other architectural fields (Cox & D'Antonio, 2016) such as structural engineering.

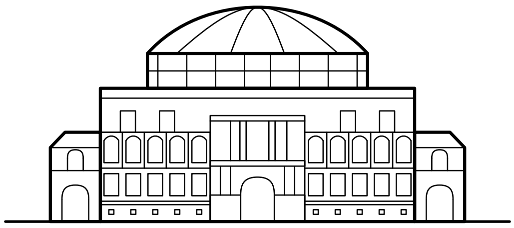
However, there has been significant progress in recent years regarding the science surrounding architectural acoustics, especially with the introduction of new technologies such as artificial intelligence and machine learning. For example, engineers at ARUP development consultancy have developed a tool called SoundLab, which uses these technologies to simulate how projects would actually sound in specific scenarios, such as at different seat locations in an orchestra hall, inside a tube station during an announcement, or within a residence located next to a railway (SoundLab, 2025).



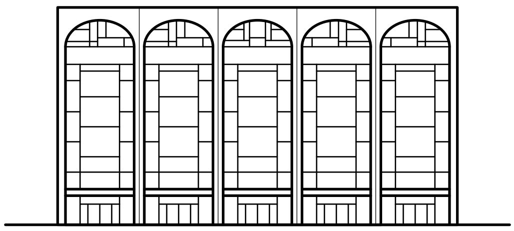
Elbphilharmonie - Hamburg



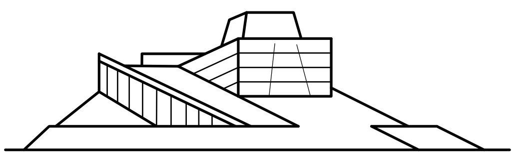
Sidney Opera House



Royal Albert Hall - London



Metropolitan Opera house - New York



The Norwegian Opera & Ballet - Oslo

Interesting Times Gang

Interesting Times Gang (ITG) is a Stockholm based design group with a commitment to circular design and sustainable innovation, using 3D printing to fabricate sustainable products from waste materials of different origin.

The Kelp Collection contains 3D printed furniture made from recycled fishing nets and wood fiber, sourced from the sawmill industry in Sweden. The bio-composite allows their furniture to be fully recyclable, thereby enabling a closed-loop design. Originally, the set was designed for Black Milk Sushi, a Michelin-starred restaurant in Stockholm (Interesting Times Gang - Kelp Collection, 2022).

The "wall-as-furniture" concept, ITG developed together with OBOS introduces two sets of modular acoustic grid-like panels / partitions made from degradable materials. LOOM, crafted from mycelium, and JUGOSO, 3D-printed from orange peel rinds.

Both collections aim to reduce waste in the design industry, by replaceability and recyclable materials, extending the product's lifecycle (Interesting Times Gang - Jugoso & Loom, 2023).

New Delft Blue by Studio RAP

New Delft Blue, designed by Studio RAP, is a contemporary reinterpretation of the city of Delft's iconic blue porcelain. The project spotlights two large entry gates, framing a public staircase that leads to a courtyard. The result is a sublime blend between historic Dutch design elements and modern fabrication technology. Reflecting Delft's history as a medieval trading city while embracing modern aesthetics.

3,000 unique 3D-printed ceramic tiles were designed by using algorithmic processes that take certain manufacturing constraints into account. The tiles feature a complex biomimetic pattern, finished with a blue glaze. This glaze, together with the dynamic wave-like pattern, creates sparkling hues of blue, similar of the traditional Delft Blue colour palette historically produced by the city (Ibrahim, 2023).

Through this project, Studio RAP created a piece of architecture which holds historical symbolization, while also, pushing the boundaries of architectural design through modern fabrication.

Figure 1 - The Kelp Collection by ITG (left). (Örterström, 2022). Reproduced with permission.
Figure 2 - Jugoso by ITG and OBOS (right). (Frendberg, 2023). Reproduced with permission.

Figure 3 - 3D-Printed clay fused with artisanal glazing (De-Vecchi, 2023). Reproduced with permission.

Elbphilharmonie by Herzog & de Meuron's, Yasuhisa Toyota and One to One

The concert hall of Elbphilharmonie in Hamburg, Germany which first opened in January of 2017, is regarded as one of the biggest achievements in not only modern acoustics but in efficient engineering as well.

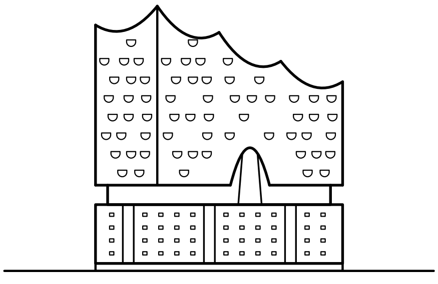
It's crown jewel, the grand orchestra hall, developed by Herzog & de Meuron, showcases a perfect collaboration between architects, the acoustician Yasuhisa Toyota and computational engineer Ben Koren of One to one (Architizer Editors, 2018).

The halls interior surfaces host no less than 10,000 individual, custom developed acoustic gypsum panels. Each one, fabricated with a CLC technique, which applies a three-dimensional diffusing pattern, with a unique outcome for each piece. All pieces where able to be fit together around the whole auditoria with an impressively low error rate of only 0.2% (Architizer Editors, 2018).

This project showcases the huge potential of how robotic fabrication tools can effectively be applied to a certain task within architecture, while elevating the result towards a level of precision out of reach of the human hand without an iterative journey of adjustments to a space. For Elbphilharmonie, the architecture was created with the acoustics in the highest value of regards, and the result was tremendously effectful (Architizer Editors, 2018).

Robotic fabrication is sometimes dismissed by craftsmen and art enthusiasts who place greater value in traditional, hands-on craftsmanship, a perspective I can partly understand. In some cases, robotic methods simply replicate or mimic hand-made work, and in doing so, the nuance and skill of the original process can feel lost.

However, in examples like the Elbphilharmonie, the sheer quantity, scale, and precision of the fabrication elevates the work beyond what could be done by hand. In such cases, it becomes difficult for even the most skeptical critic to argue that robotic fabrication lacks artistic merit.



Elbphilharmonie - Hamburg

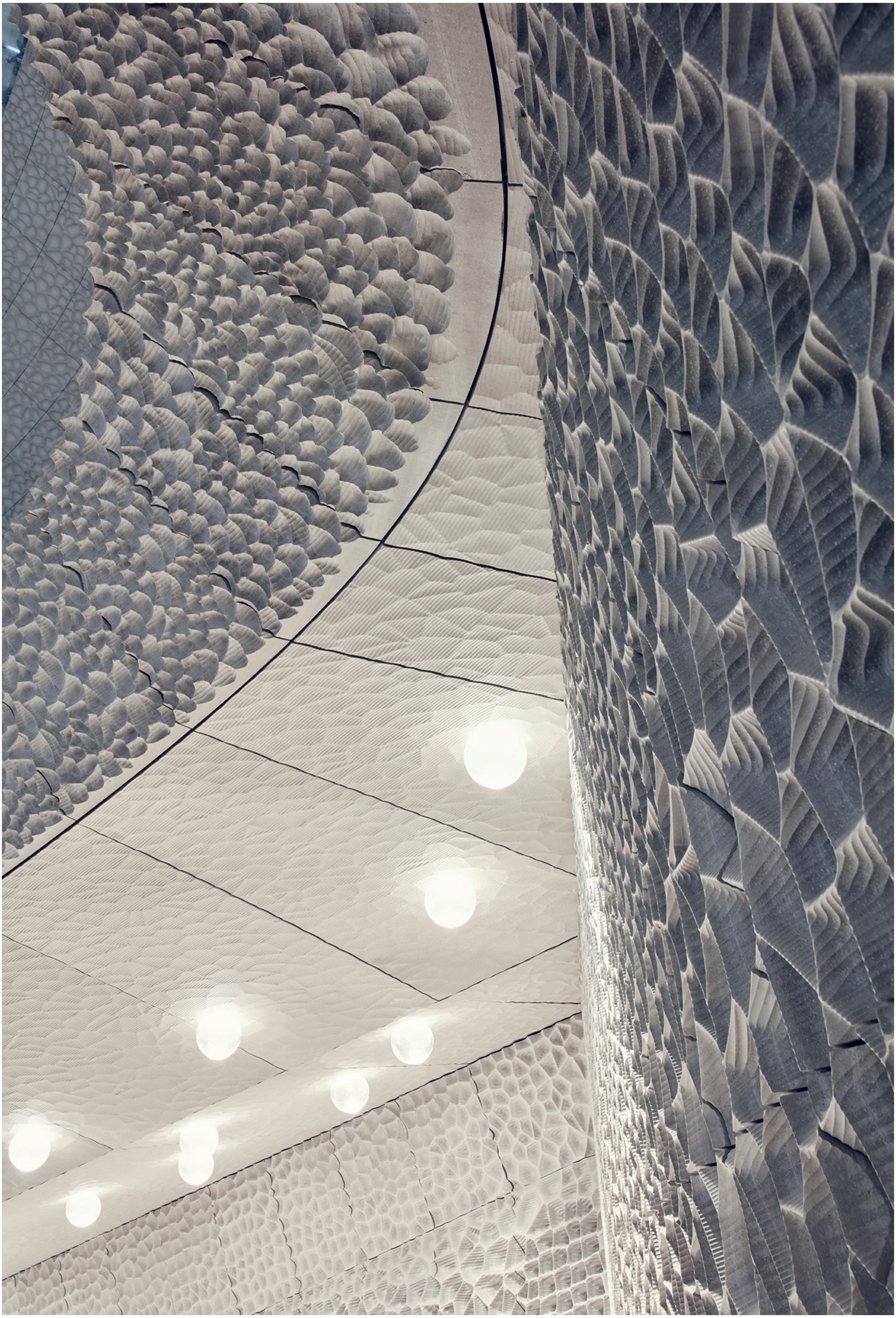


Figure 4 - Photograph of custom developed gypsum panels (Schulz, 2023). Reproduced with permission.

Theoretical framework

Literature study

To support the design choices relating to spatial design of the venue, patterns, fabrication and formation of acoustical treatment elements; literature studies about architectural acoustics, acoustic diffusers and absorbers, additive manufacturing and wooden polymer composites, and restaurants and auditoriums is made.

Pre studies toward a design foundation

Acoustic analysis

Through the work of this thesis, spatial adaptations and patterns to 3D-print are explored and evaluated with the help of the digital tools of *Rhinoceros* and *Grasshopper* and another supporting plug-in called *Pachyderm*.

Surveying and adaptations of the concept venue

The site which I from here on call the concept venue serves as a hypothetical performance hub for the prototypes, while also, being the canvas which suggest how the material and fabrication process can help future designers to adapt existing interiors towards such spaces where a functional soundscape is of large importance to its visitors. Adaptations made to the space are done to suit the program proposed, and as well, based on prior spatial expressions of the venue.

Pattern exploration and small scale prototyping

Patterns which are applied to the acoustic panels have different inspirations from nature, mathematics, the site, and existing products of acoustic panel systems. The goal is to find patterns which is feasible to print and supports the acoustics in different ways, while also suggesting a visual concept.

Since access to the larger 3D-printer at the university is limited, a smaller printer available on campus is used for small scale prototyping. This printer only prints with plastic, so during this stage, the aim is to develop concepts of printable patterns which suggest different kinds of acoustical treatment.

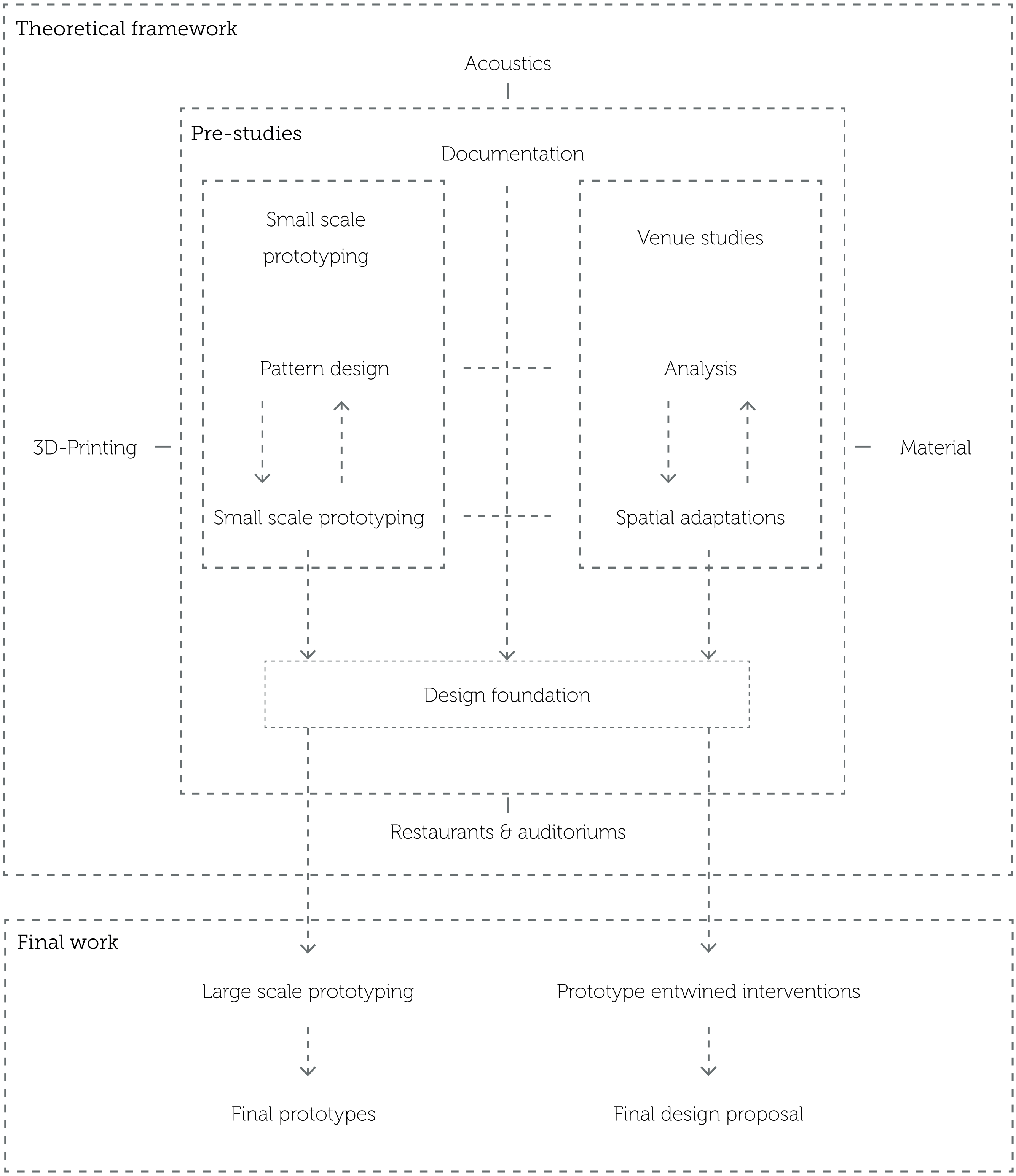
Final design work upon the design foundation

Large scale prototyping

Continuing from the knowledge acquired during the pattern exploration, large scale prototypes for showcasing the venue-specific design are developed and printed.

Design proposal

The concept venue is illustrated as a restaurant and a hall of live music performances, with applied acoustic treatment. For the mentioned purposes, the acoustical treatment is designed according to print-ability and the knowledge acquired from the pre studies, while also aiming towards a visually intriguing design.


Theoretical framework
Acoustics
Pre-studies
Documentation
Small scale
prototyping
Venue studies
Pattern design
Analysis
3D-Printing
Material
Small scale prototyping
Spatial adaptations
Design foundation
Restaurants & auditoriums
Final work
Large scale prototyping
Prototype entwined interventions
Final prototypes
Final design proposal

Wooden polymer composite

A composite is a mixture of at least two materials, in the one which I'm working with, the defining material is wooden sawdust, and the complementary one is a thermoplastic. The wood acts as the filler -, and the thermoplastic as the binder within the material. Additionally, water and a kind of lubricant is often added to smooth the blend between the materials. In 2021, Huang, Löschke, and Proust tested 3D printed wooden composites using varying filler-to-binder ratios, specifically 30%/70% and 40%/60% (Huang et al., 2021).

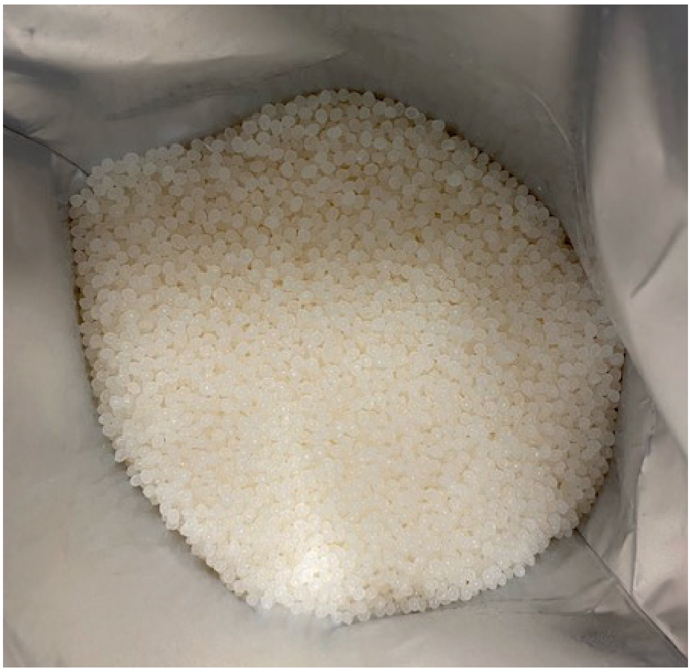
For 3D-printing, these components are minced together into pellet-shaped pieces, which then can be melted and thereby extruded to produce various shapes and forms.

With Sweden being one of the world's leading producers of timber, forestry has well established itself as one of the countries most important resources. Wood has always been a big part of Scandinavian architecture, especially within the housing sector.

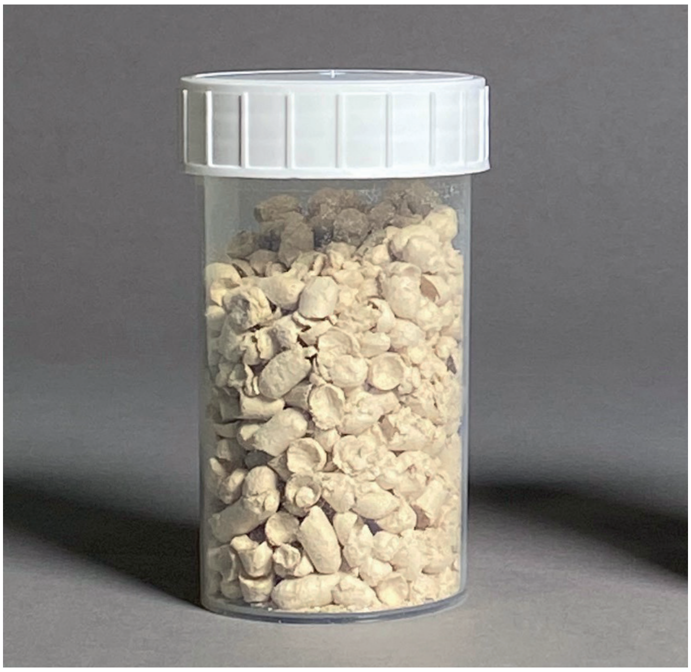
However, statistics from Naturvårdsverket in 2021 reveal that only about 22% of felled trees in Sweden were used for long-term products, while nearly 75% were used for short-term products, where 50% went towards the production of bio-energy (Hansson, 2021). There is also many reports from Sweden's forestry agency of ongoing disturbances and significant damage caused by the bark beetle since an outbreak began in 2018 (Carlén et al., 2024). Resulting in a large amount of wood being unable to contribute to the building industry in first place.

In conclusion, most of the trees cut down in Sweden are being thrown to the production of energy, which all together, means most of the Swedish forest is used as fuel.

By exploiting sawdust or other biomaterials for 3D printing of novel architectural elements, more opportunities of sustainable solutions emerge within not only the architecture industry, but as well the industry of waste management and product design in general.





Photographs taken by author - top right PLA marble - top right wooden spill - middle left lubricant - middle right pellet mill - bottom two samples of different samples produce by students of the chemistry department at the university

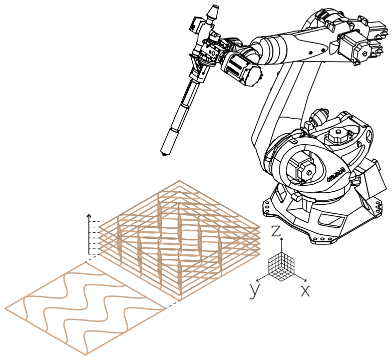
Robotic fused filament fabrication (FFF)

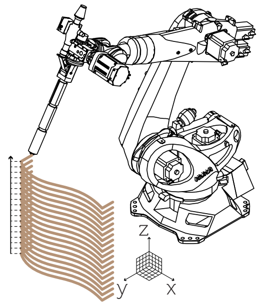
Through the project, the designs made are done to specifically fit a fabrication method called robotic fused filament fabrication, which is often times shortened to FFF, or FF fabrication.

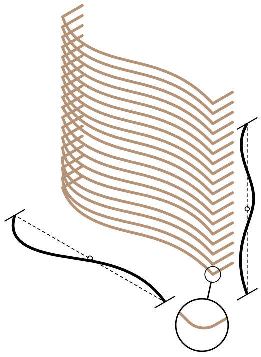
The robot which conducts the fabrications of proto-types is a KUKA Quantec KR90-KR270 R2700 Robot available here at the university. This kind of robot is a typical industrial robot which can be utilized in many different ways, a common application of the kind is within the assembling belt for fabrication of cars. At the end of the arm for this robot, there’s a heating extruder mounted with a pressurised suction hose attached in the back of the extruder. Through the house, the print-ing material is sucked in and then melted and extruded though via an 8 mm nozzle at the end of the extruder.

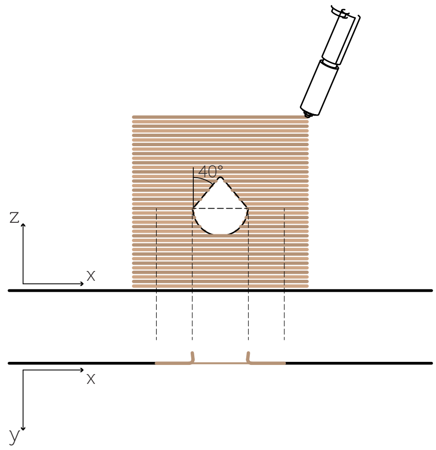
When designing for large-scale FF fabrication, several challenges arise in comparison to small-scale 3D print-ing with a typical commercial printer. Most of these challenges are related to the relative weight and size of the print. However, some also stem from the complex-ity of translating 3D geometry from modelling software into code that defines the tool path, meaning the path the robot follows with the extruding nozzle.

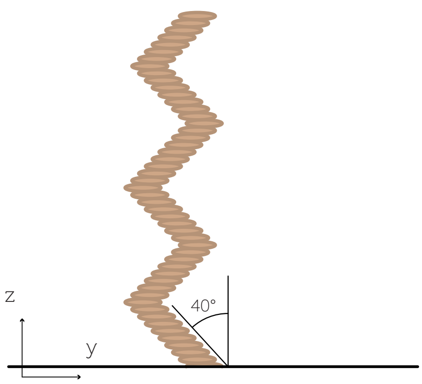
In terms of geometry, large-scale FF fabrication is most effective when producing hollow forms without a top cap. This approach helps to optimize print time. Addi-tionally, since the extruded filament is approximately 1 cm thick and takes around one minute to solidify, it is not possible to print into thin air, each layer must be supported by the one below. Layers can be gradually shifted outward to form smooth, curved geometries in a variety of configurations, as long as the outward angle does not exceed approximately 40 degrees. As a result, holes and recesses must be designed with these constraints in mind.

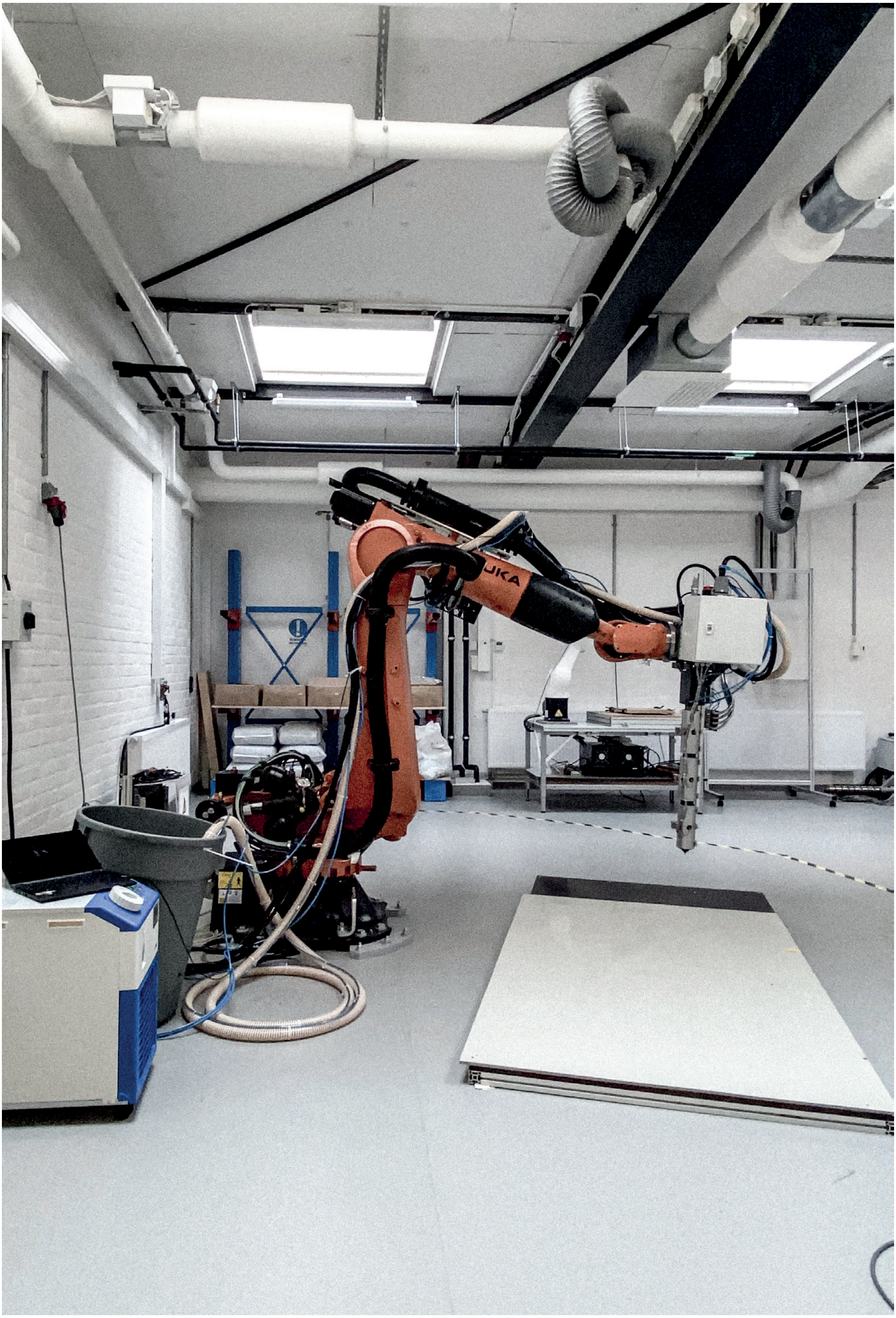












Photograph of the robotic arm taken by author

Waves of sound

A sound wave is a repetition of disturbance when energy travels through a medium. Typically for us humans, this medium is (of course) air, but sound waves do travel just as fine through any solid, liquid or gas.

When waves hit a new medium 2 things happen to a relative extent depending on the two mediums involved. Some of the wave's energy is absorbed by the receiving material, and some is reflected through the transmitting material.

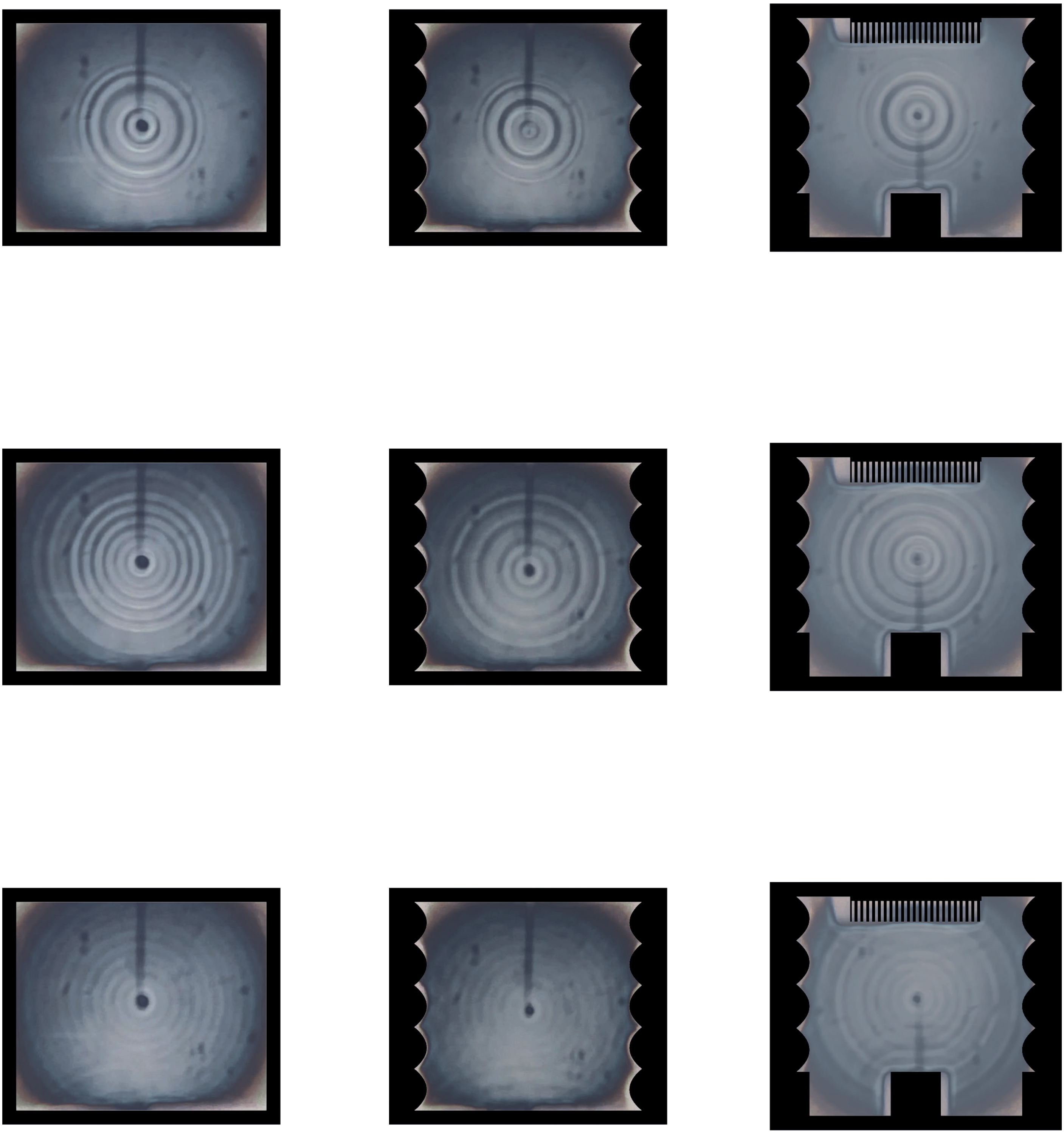
So, to put this in context within architecture; this means that the surfaces which we use to define our spaces not only define our understanding of the space visually, but as well through how it sounds.

Surfaces of different materials, geometries and textures and as well the objects, all effect the soundscape of a space in different ways. In an untreated room, with parallel flat walls, floors and ceilings, the reflections produced when sound waves hit the surfaces interfere with each other. This can lead to some wave frequencies cancelling each other out, which translates to an overall bad sound quality.

When a room instead is treated with, for example, convex surface panels, the reflections are now much more unevenly distributed, which tends to lead to a more even soundscape, since the interference patterns are much more subtle, instead we in a sense have sound "everywhere" within the room.

So as an architect, by designing with this in mind in the early stages of a design, one can help with shaping the acoustics of space while simultaneously reach an aesthetically pleasing result.

Untreated room | Treated room - convex panels | Treated conference room



Water simulation of how waves behave toward different surface geometries, performed during the early stages for this thesis.

Acoustic panels

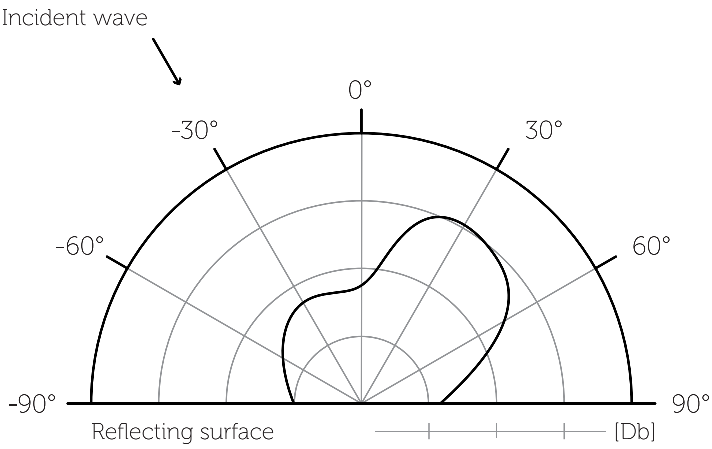
In principle, there are three kinds of acoustic panels to treat a room with: reflectors, diffusers and absorbers.

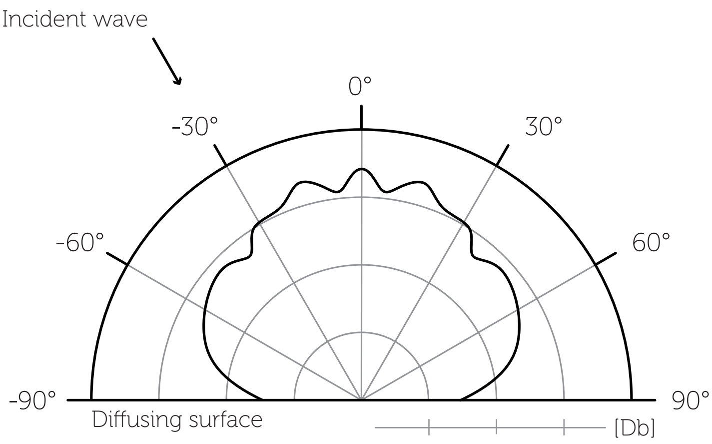
Reflecting surfaces are smooth, often such surfaces are simply the result of an acoustically untreated wall. When such surfaces are hit with a wave of sound, the reflecting wave is close to equal to the one which travelled towards it, the reflection is also perpendicular to the wave of incident, which leads to such surfaces being well suited for controlling the direction which the reflecting sound waves travel.

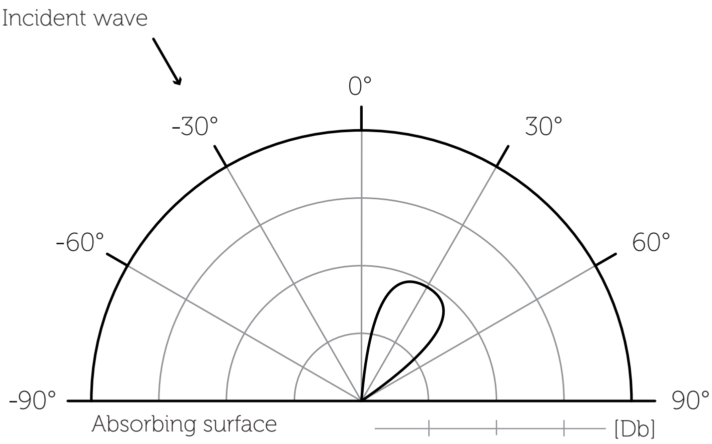
Diffusing surfaces reflect sound waves in a disperse manner, which in principle leads to a more even and thereby more equal experience of the sounds within the room at all locations.

Absorbing surfaces helps with reducing the sound levels within the room. The absorbing properties of these surfaces mostly comes from the surface material and not the surface geometry. Most often, the common choice for these kinds of surfaces is either of porous materials or textile curtains (Cox & D'Antonio, 2016).

To the right this is roughly explained graphically, but there are infinitely many ways geometries and materials can be arranged to create different kinds of acoustic panels which reflects, diffuse and absorb sounds to different extents.


Incident wave
0°
-30°
30°
-60°
60°
-90°
90°
Reflecting surface
[Db]


Incident wave
0°
-30°
30°
-60°
60°
-90°
90°
Diffusing surface
[Db]


Incident wave
0°
-30°
30°
-60°
60°
-90°
90°
Absorbing surface
[Db]

Characteristics of treatment for different acoustical spaces

The interior soundscapes we experience are in almost every case the result of the active direct sound sources and indirect sound reflections of surfaces and objects produced by those sources combined. This means, that for well-functioning room acoustics, the treatment of walls, floors and ceilings is dependent on the amount and characteristics of sound which is expected in the room. Which again, depends on not only the sources, but also the rooms shape and volume.

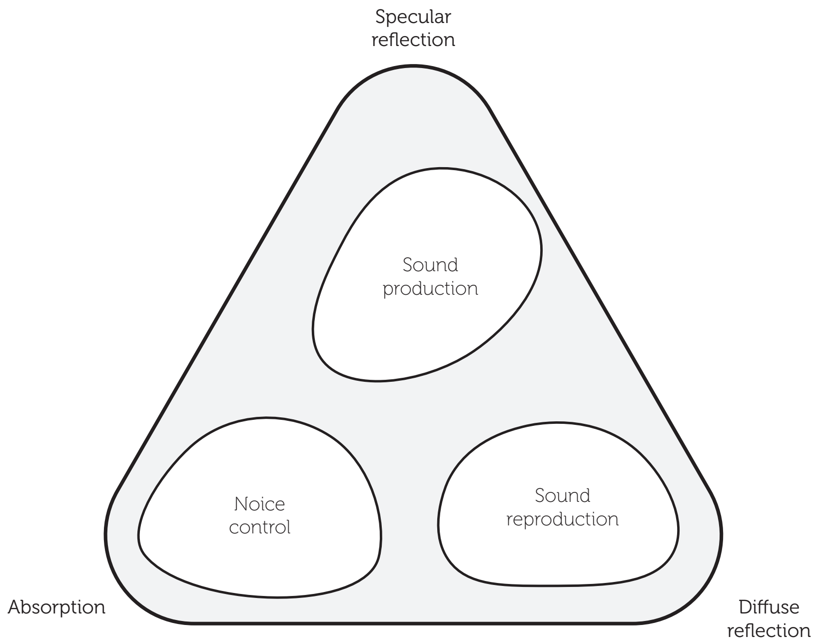
Loosely divided, there are often three different kinds of acoustical spaces: Spaces of Sound reproduction, sound production and noise control.

Spaces of sound reproduction are spaces where the soundscape aimed for is neutral. Usually, spaces defined as such are for example recording studios, home theatres and listening rooms.

Spaces of sound production are most often those spaces where some kind of sound dependent performance is taking place, such as theatres, conference halls, lecture halls and worship places.

Spaces of noise control are spaces in which the soundscape needs to be adjusted, usually towards crowds of people in different sizes. These are spaces like swimming pools, libraries, restaurants, atrias, lounges and train stations, many people having separate conversions can result in large energies of sound inside the space, which makes it unpleasant for people to stay in such areas, if not treated with care (Cox & D'Antonio, 2016).

In this project, I'm focusing on treating spaces towards rooms of sound production, with a slight aim towards both noise control and sound reproduction.


Specular
reflection
Sound
production
Noice
control
Sound
reproduction
Absorption
Diffuse
reflection

Acoustic treatment for restaurants

Dining on a restaurant is typically a social experience shared between two or many people, where the quality of the conversion takes a big part in shaping people's reception of the overall atmosphere and experience of the food. Most of us has probably been to at least one restaurants where the whole evening is done through slow and load pronunciations, making our best effort in clearly communicating our speech through the noise and echoes produced by every-body else doing the same thing. The problem with these spaces is not neces-sarily that they are filled with too many guests, but instead, this is often times due to reverberation (Wøhni, 2018). When talking about the acoustic qualities of a space, people tend to talk about perceiving a room as either "lively" or "dead". Usually, this refers to their perception of the occurring reverberance, which within the principle's of acoustics, means it neither has to do with any loudness or absence of sound (Cox & D'Antonio, 2016).

Reverberation refers to the lasting noise of decay, once the source of sound has stopped producing (Cox & D'Antonio, 2016). It is usually an appreciated acoustic quality in spaces of worship, like large cathedrals and mosques, where the vol-ume of the rooms tends be large and out of hard surfaces. This makes sounding preaches and gospels echo around long after they where initially produced.

For restaurants, since gatherings often times are subconsciously fighting over each other's sound of speech, it is important to treat the environment toward a mixture between energetic vibrancy and absorption of sound energy, so that people both can feel the liveliness of the space but also be able to clearly com-municate with each other. This is achieved by strategically placing absorbing surfaces on the walls, the ceiling and the floor, depending on how much you want to reduce the reverberation and from what surface areas of the room. Since eating may be a rather filth-producing activity, cleanability of surfaces close to diners are important as well. Since absorbers tend to be made out soft materials, the ceiling and high up enough on walls to be out of diner's reach are the most suitable areas (Cox & D'Antonio, 2016).

Acoustic treatment for auditoriums

In performance halls, a common acoustic treatment involves installing overhanging reflective canopies above the audience. These canopies are often diffusive to ensure a more uniform sound distribution for spectators.

A key consideration in auditorium acoustics is the audience itself, which acts as a significant sound-absorbing element. However, there are occasions in which the hall is empty and this absorption is lost. This alters the room's acoustic behaviour. To some extent, this is not a problem, since when there are no people present, well... there are no people who can complain about the sound experience. However, this means that the room acts differently in regard to sound for the performers during rehearsals. This leads to complications and affects the overall quality of the performance once it takes place. To tackle this issue, designers often tune the seating design to mimic human absorption when unoccupied. Another solution is to use temporary textile curtains to cover key surfaces during rehearsals or smaller events.

Areas of interest to focus the acoustic treatment around commonly include the flanking walls and the rear wall. But importantly, auditoriums which include balconies as well need to take the design of not only the underneath of the balconies, but the railing facing the stage as well, since it can act as reflecting surface which creates early echoes for the performers on stage. Adding diffusing treatment to these areas causes sound to more evenly bounce around all surfaces within the auditorium, which commonly result in a more even soundscape.

Then we have the stage enclosure. This area is where the main sounds within the room should source from. Here, sounds need to be reflected out towards the audience. This is usually done by having the sides in an angle, so that the bounces of sound are aimed outwards, and not across the performers on stage. Another common element surrounding the stage design is the addition of hanging canopies simply above the stage, these are usually not designed towards diffusion, but rather they are smooth and flat to guide the sounds well towards the audience, especially those observing from above balconies.
In some cases, absorbing surfaces are applied around the performers to reduce the sound energy so that there is a reasonable loudness occurring during the performance (Cox & D'Antonio, 2016).

Palladium

Address: Lilla Nygatan 2, Gothenburg, Sweden

Former Operation: Cinema 1919-2008

Current Operation: Clothing store 2012-2025

Tenant: Collection of Style (COS)

Main building adjustments timeline / seating capacity:

1919 - *Conversion to cinema / 1028*

1954 - *Alteration of balcony / 850*

1975 - *First floor foyer altered into smaller cinema (Little Palladium) / 805 (69)*

1990 - *Unspecified / 770*

2010 - *Conversion to business premisses / 0*

From the 1850s onward, the building at the intersection of Lilla Nygatan and Östra Larmgatan in Gothenburg, Sweden, served solely as a residential space. In 1917, the premises were taken over by brothers Anton and Fred Kanold, also known as the "Caramel Brothers" due to their success in industrializing candy production in Sweden. That same year, they had expanded into real estate. With their newly established company, Fastighets AB Orion, this building became one of their earliest investments (Svensson, 2017). A fourth floor was added, apartments were converted into offices, and the Palladium cinema was constructed towards the central courtyard of the property.

Through AB Orion, the Kanold brothers developed a large network of cinemas across Gothenburg (Bjelkendal, 2009). Many of these, including Palladium, have since been repurposed for commercial retail.

During its time as a cinema, Palladium was one of the most popular film venues in Gothenburg. With 1,028 seats, it had the largest cinema capacity in the city and, until the early 1950s, it was the second-largest cinema in Sweden (Furberg, 2000). When Palladium opened, positive reviews fell in, praising not only the overall atmosphere but also the experience of watching all six acts of the film with only a single intermission. However, one critic pointed out the lack of seat-side hooks for hats. A minor yet notable grievance in the 1910s (Bjelkendal, 2009).

In the early 20th century, going to the movies was a vastly different experience from today. A typical screening program featured live musical preludes, several short films, and a main feature (Bjelkendal, 2009).

Figure 5 - Photograph of exterior taken in 1920 (unknown) . Public domain

Figure 6 - Photograph of the cinema saloon (Lidén & Nyman f.d. Karnell). Reproduced with permission of photograph holder.

By the 1920s, live music had become a central aspect of Palladium's programming. The auditorium was highly regarded as a concert hall in Gothenburg, with the venue also having its own orchestra, which performed regularly for film screenings and accompanied guest performers, including celebrated artists of the time, such as Mischa Elman, Martin Öhman, and Naima Wifstrand (Bjelkendal, 2009).

In 2007, Svensk Filmindustri (SF), who were the current operators of the cinema, decided to shut down the projectors for good (Engström, 2009). Their final viewing was of the Tim Burton horror classic Sweeny Todd, with Johnny Depp in the leading role (Tollesson, 2012). SF had noticed how their costumers seemed to prefer to go to their new-built multi-saloon of Bergakungen instead of the singular cinema found at Kungsportplatsen (Engström, 2009).

Almost reaching 100 years of service, the customers had eventually turned on this once cherished location for film and music. Speaking with people about the former cinema, many of those who remembers it lights up, and continues with explaining how beautiful they remember the setting was.

Palladium today

After its closure, in the years surrounding of the 2010s, the estate owners evaluated what could be done to the piece to solve a new tenant. Eventually, they landed in converting the space into multiple residencies for commercial retail (Domellöf-Wik, 2008; Löfgren, 2012).

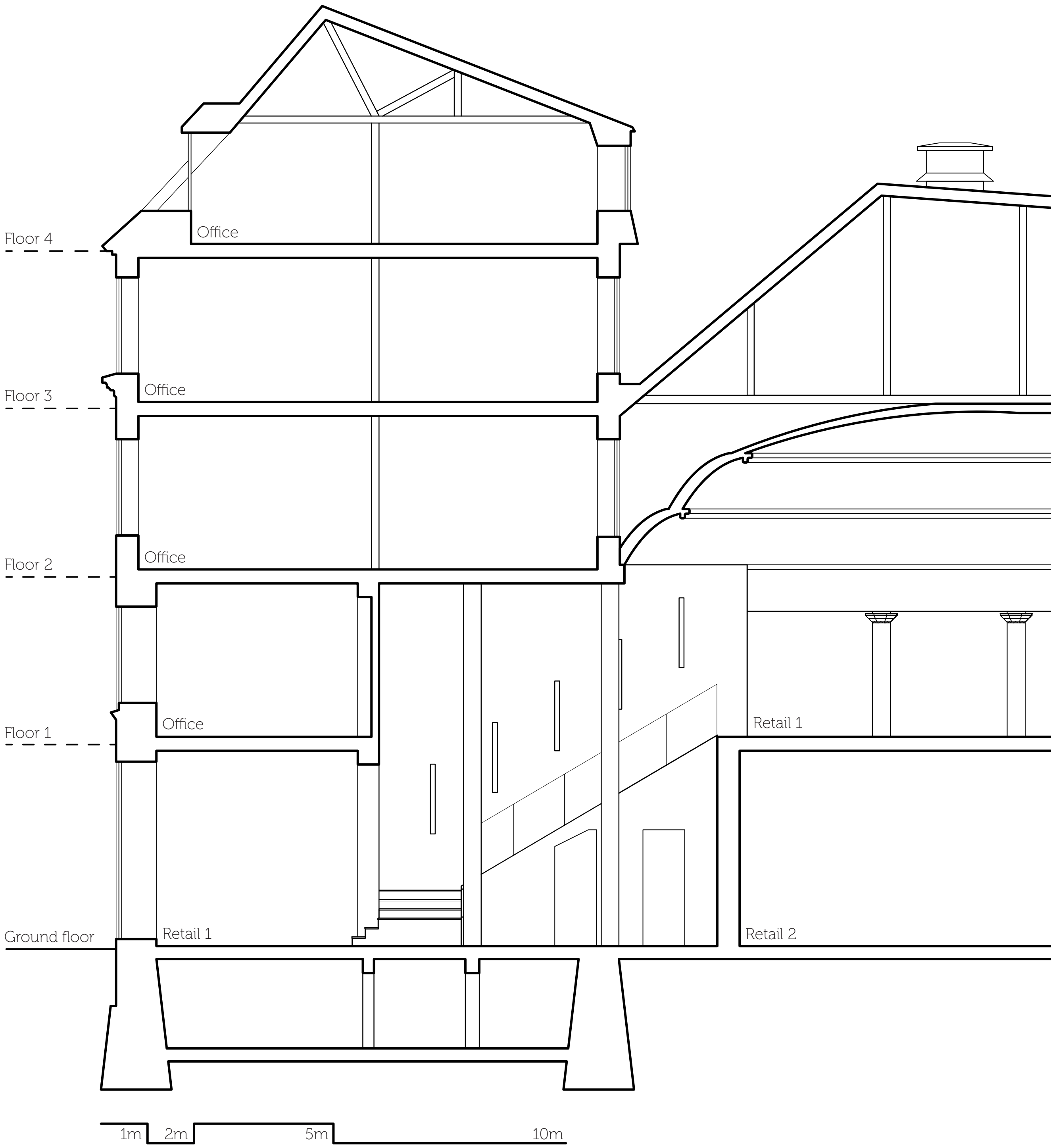
The auditorium was thereby split in to two floors, with the top one displaying the whole former auditorium area and the preserved ceiling, while the ground floor was divided into multiple residencies with entrances facing the street of Lilla nygatan.

Several brands are today established within these retail spaces, with the clothing brand of COS as the current tenant of the main space which hold the large room on floor-1 of the former cinema hall.

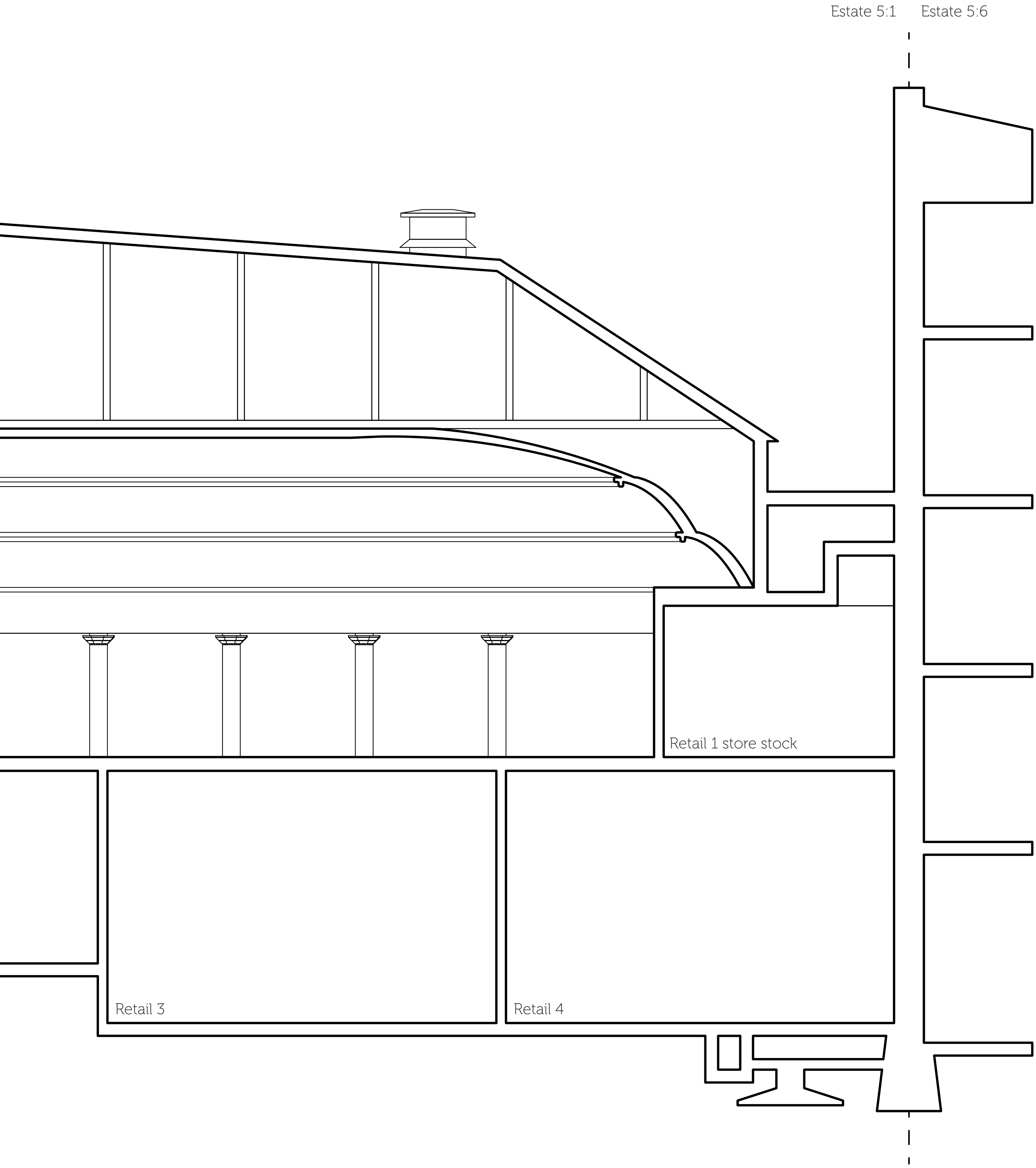
The unimplemented proposal from 2010

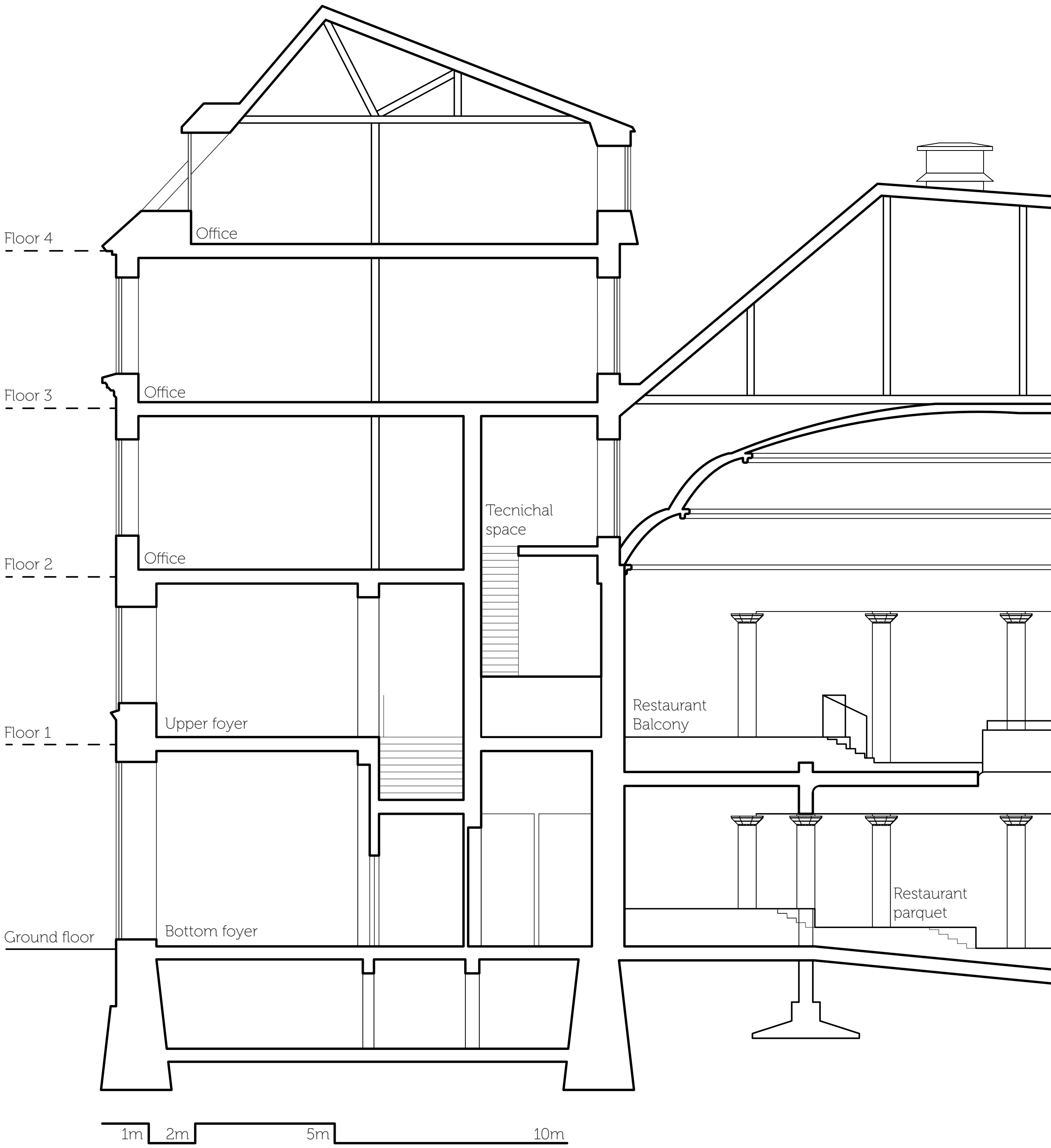
However, a building permit from 2010 confirms that ideas of converting the space into an entertainment establishment, were far in development. The accompanied drawings suggests that the cinema auditorium where to be refurbished into a large restaurant, with servings both on the balconies and the parquet seating, with a performance stage fronting the serving. Additionally, an extension covering parts of the courtyard suggest the location for a new kitchen, dressing room for performers and additional offices. The question of if this would had been a smoother transition from the buildings original purpose arises.

Photograph of the current outlook of the former cinema hall taken by author

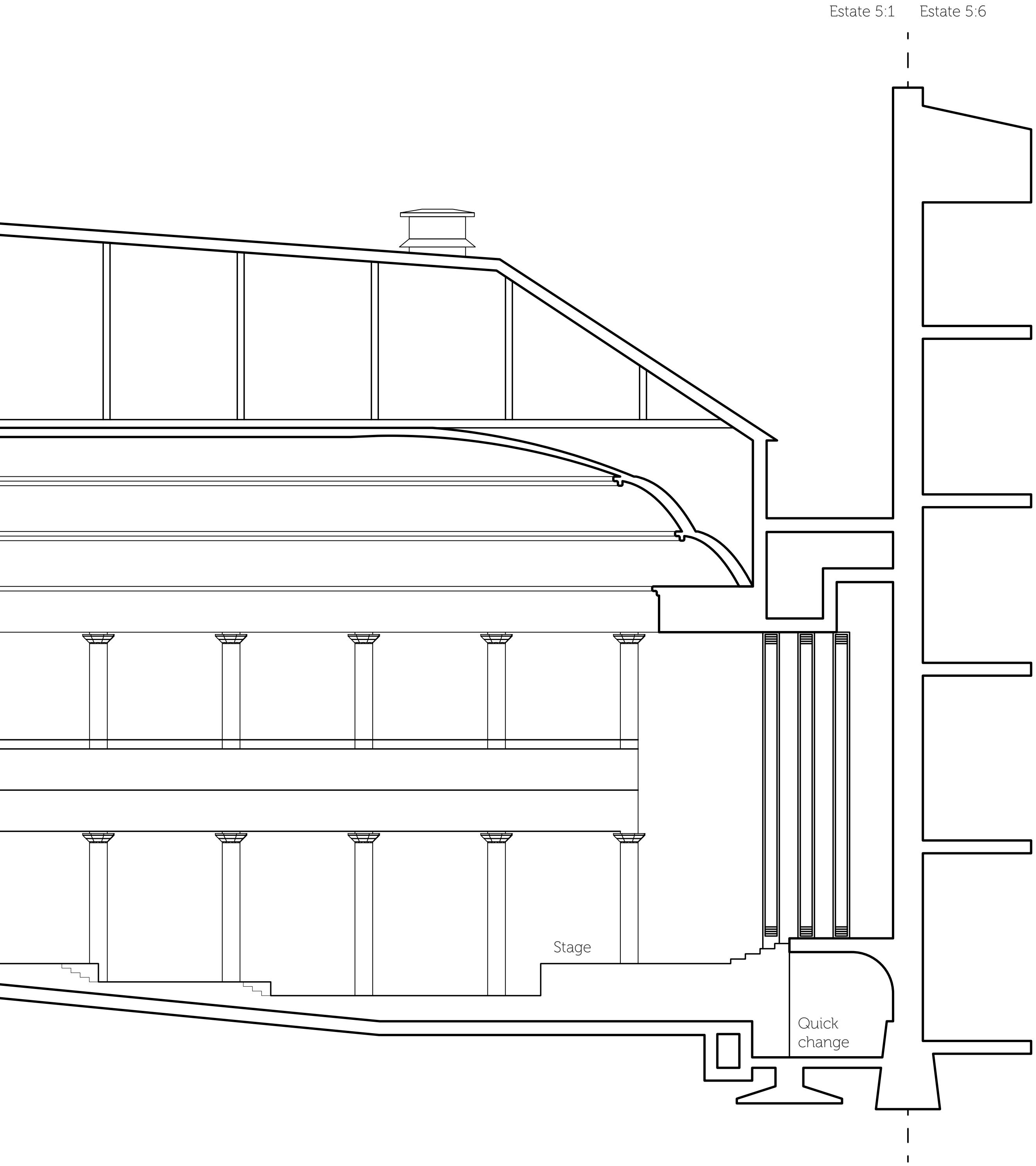


Section drawing of Palladium today traced from archive drawings sent by Stadsbyggnadsförvaltningen Göteborg and according to my own on-site observations


Estate 5:1
Estate 5:6
Retail 1 store stock
Retail 3
Retail 4



Section drawing of the unimplemented proposal from 2010 traced from archive drawings sent by Stadsbyggnadsförvaltningen Göteborg


Estate 5:1
Estate 5:6
Stage
Quick
change

The ceiling

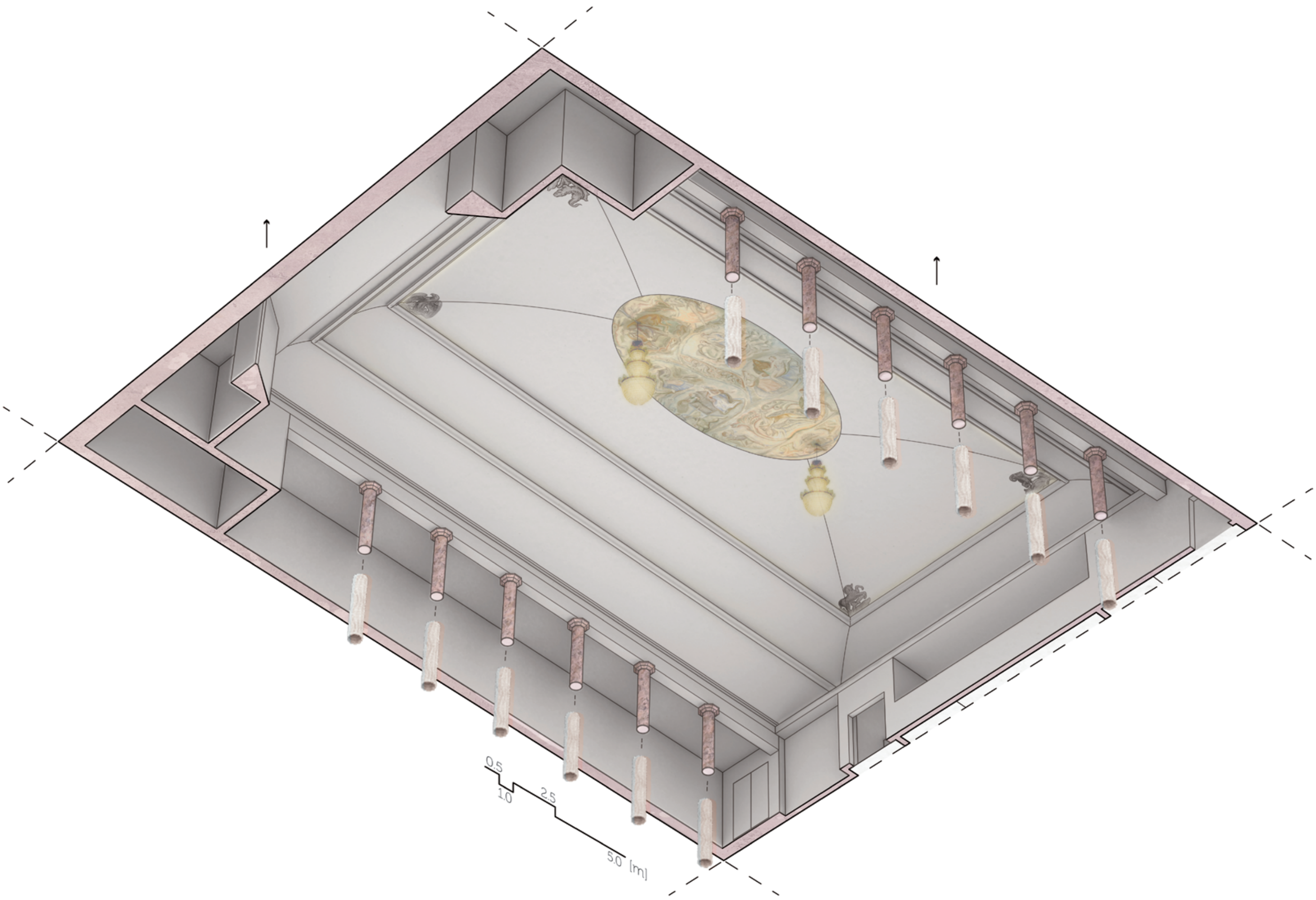
When Palladium was repurposed into retail establishments, some special elements of the cinema hall were carefully preserved, particularly ones which relates to the ceiling.

The original ceiling paintings, hand-drawn on site before the cinema's grand opening by painter Gunnar Ström (Bjelkendal, 2009), were retained along with the full vaulted form of the inner ceiling itself, which is supported by the flanking pillars that once stood upon the former balcony.

Since these elements hold significant historical value, and are already beautiful as they are, I am choosing not to intervene with any 3D printing around the paintings that would visually disturb their appearance, while the pillars may be kept, but wrapped with additional geometry to support the overall design language of the space.

By keeping the pillars positioning and structurally supporting function of the ceiling, they thereby guide my spatial adaptations toward a performance hall once again.

Photographs of original paintings done by Gunnar Ström and one of the flanking pillars taken by the author.


0.5
1.0
2.5
5.0 [m]

From retail to venue

When developing the new layout for the two affected floors of the re-adapted venue, both the existing plans and the unimplemented designs were studied of Palladium. By tracing the plans and layering them on top of each other, an understanding of how the venue might once again serve a program centred in entertainment was formed.

Some of the current load-bearing pillars align with those from the unimplemented plans, but many do not, which suggests that significant structural alterations were made when the building was adapted for retail use.

Attempts were made to gain full access to the building on site, but none of the retail tenants permitted any entry to their back-spaces or office spaces. The large retail unit in the top-right corner of the ground floor (marked in blue) has also remained inaccessible throughout the whole duration of this project.

Due to these limitations, many of the internal spaces were considered either demolished or significantly altered, and thus the new layout primarily reflects the current state of the building rather than its original or proposed configurations.

On the following page, the redesigned floors are illustrated in more detail. The retail units along the long side of the building are shortened and fragmented to make room for a kitchen. The entrance space currently occupied by COS is transformed back into a foyer, with its staircase retained to lead up to the new balconies. The large area on the first floor is opened up to reintroduce the spatial experience of the former auditorium, with seated service on the ground floor (parquet) and standing service on the balconies.

Current layout

Ground floor

Floor 1

Unimplemented proposal layout

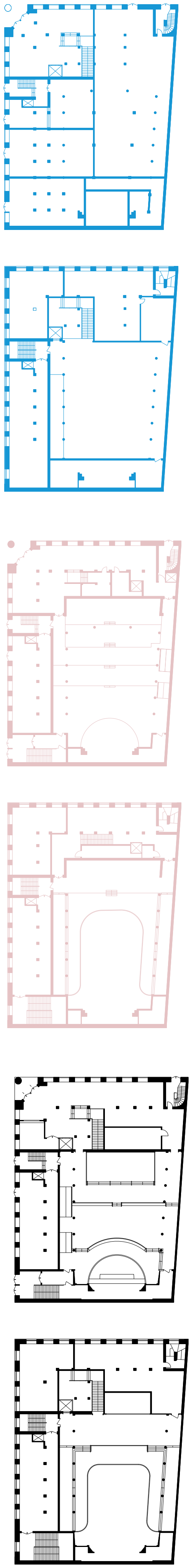
Ground floor

Floor 1

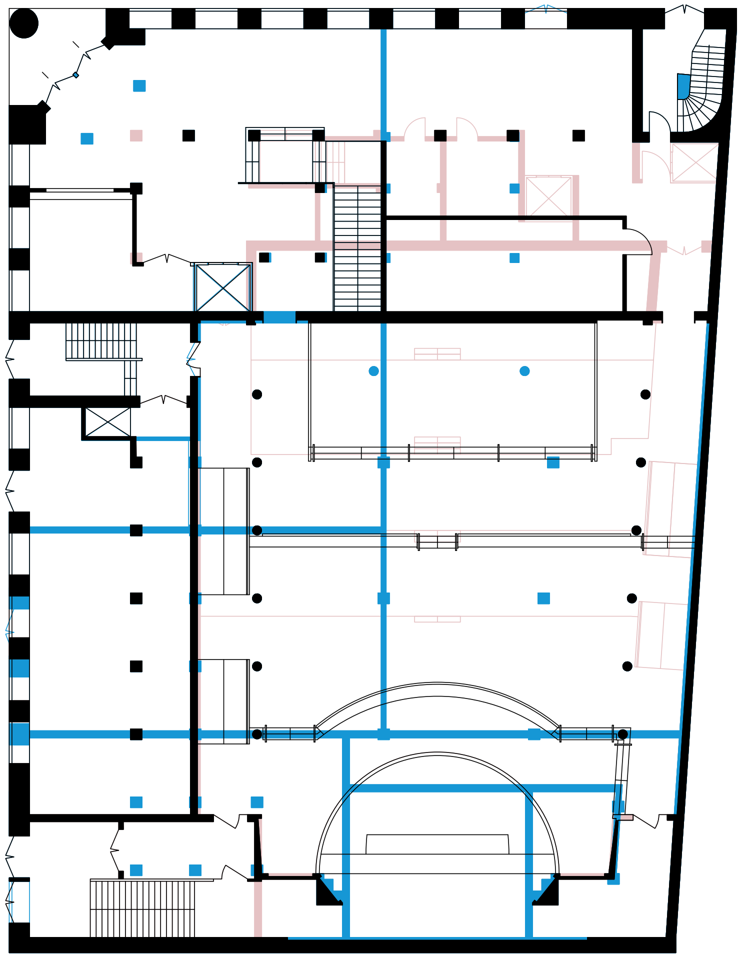
Altered layout

Ground floor

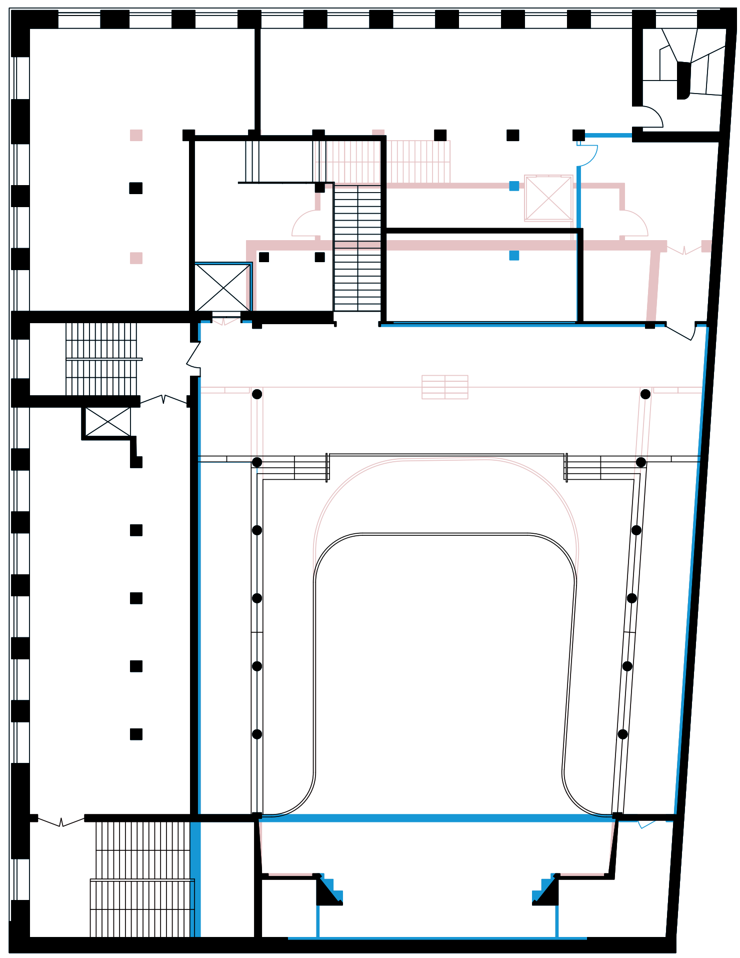
Floor 1



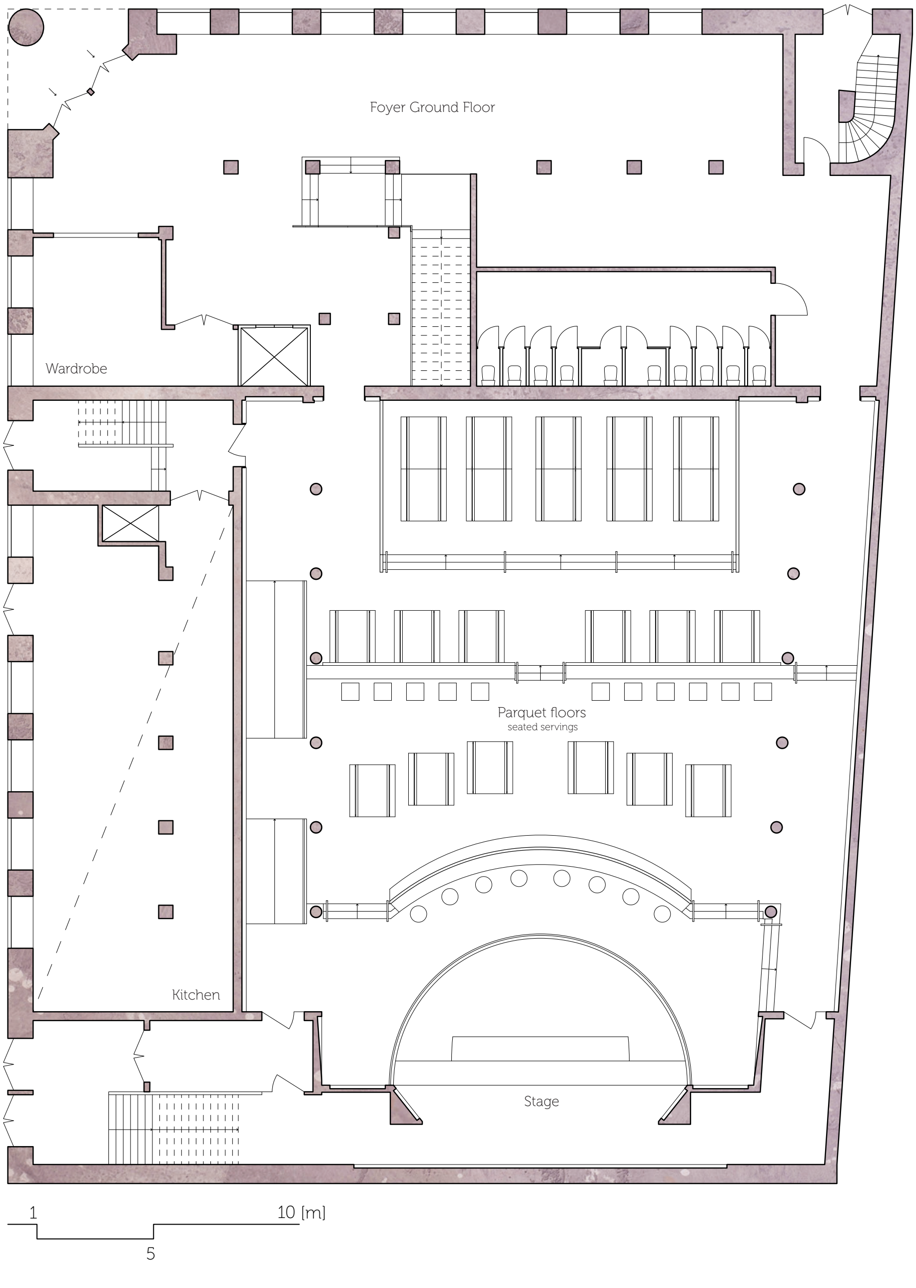
Ground floor



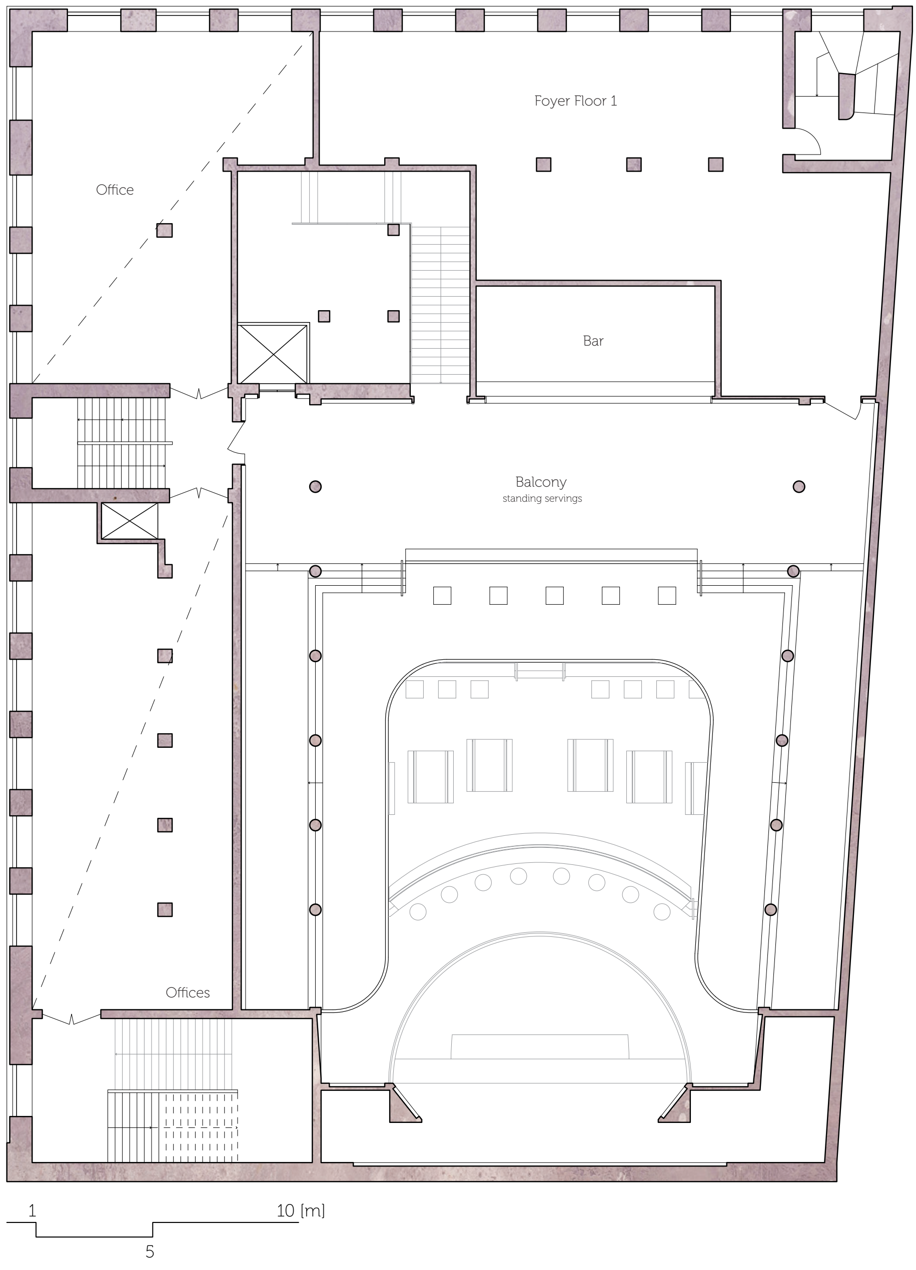
Floor 1



Different plans layered



Plan drawing - ground floor - New layout.



Plan drawing - floor 1 - New layout.

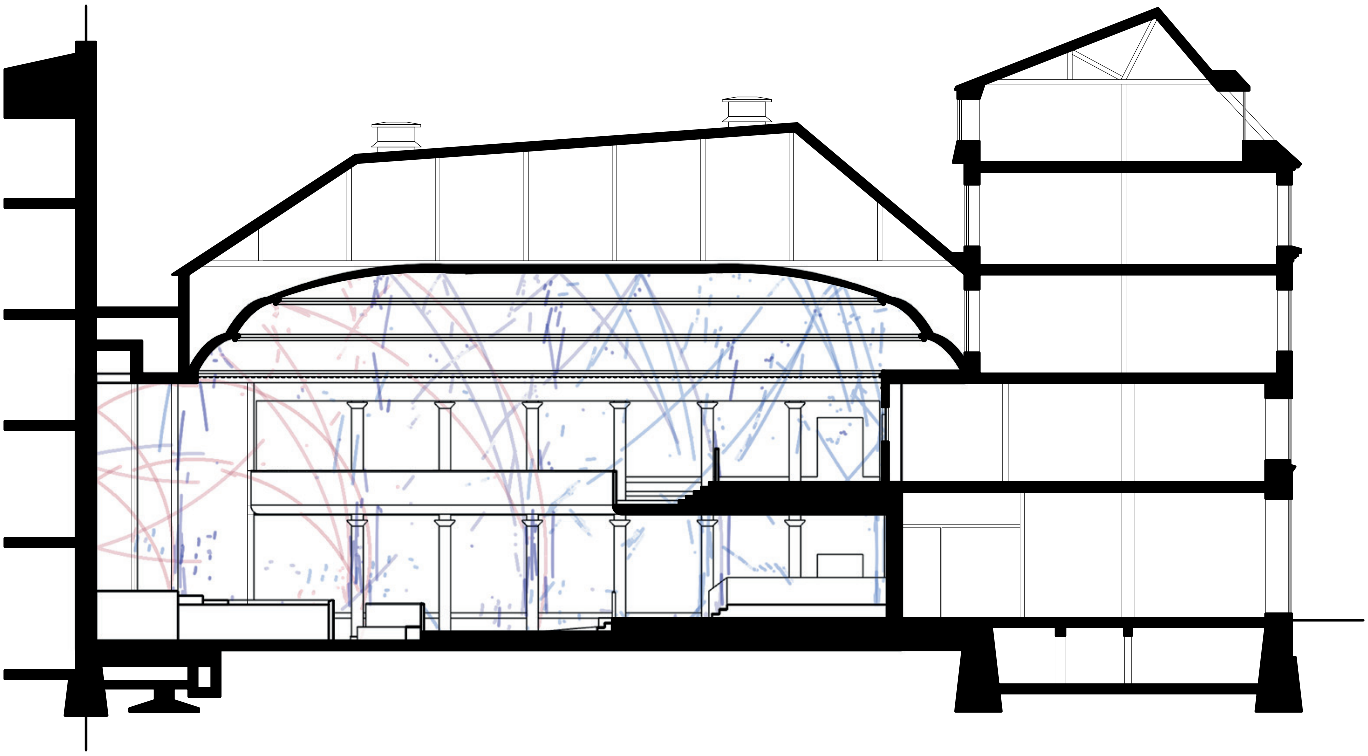
Spatial acoustic analysis of the altered venue

When accurately analysing acoustics with digital tools, engineers typically take into account the materials and dimensions of the geometry, the people within the space, and the properties and characteristics of the sources of sound (Cox & D'Antonio, 2016). But since this is within the early stages of an design processes, these simulations are very simplified into two dimensional sections of the space, with only the most defining spatial geometry in consideration.

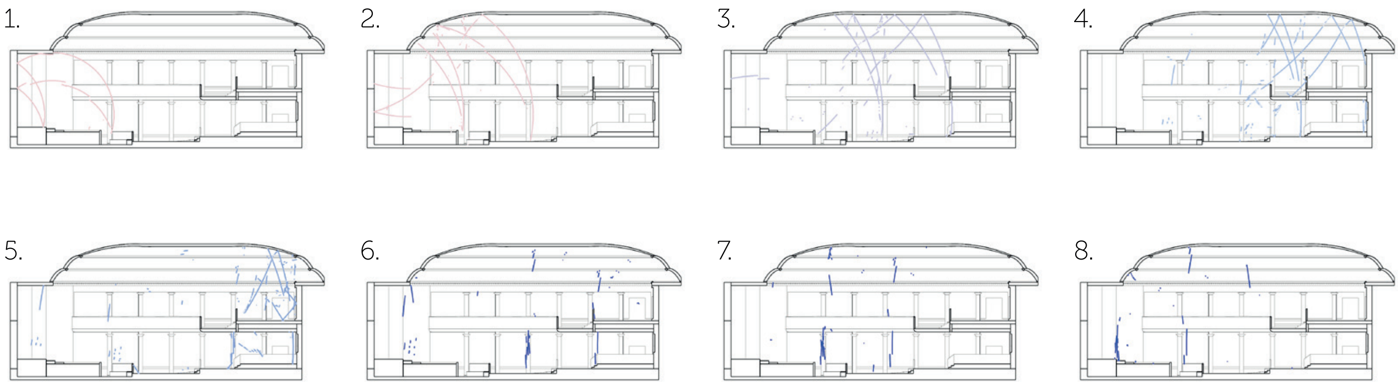
The purpose of these simulations is to gain an understanding of where to introduce acoustic panels. They are performed using the 3D modelling software of Rhinoceros in combination with Grasshopper and an acoustic analysis plug in called Pachyderm. These tools in collaboration, generates visuals that indicate how waves of sound would bounce around the auditorium. The output consists of ray-traced curves that simulate how sound reflects within the space. I then evaluate all these curves simultaneously by tracking a single point along their length. Which let's me produce images which tracks how these points moves around the space similar to how sound would.

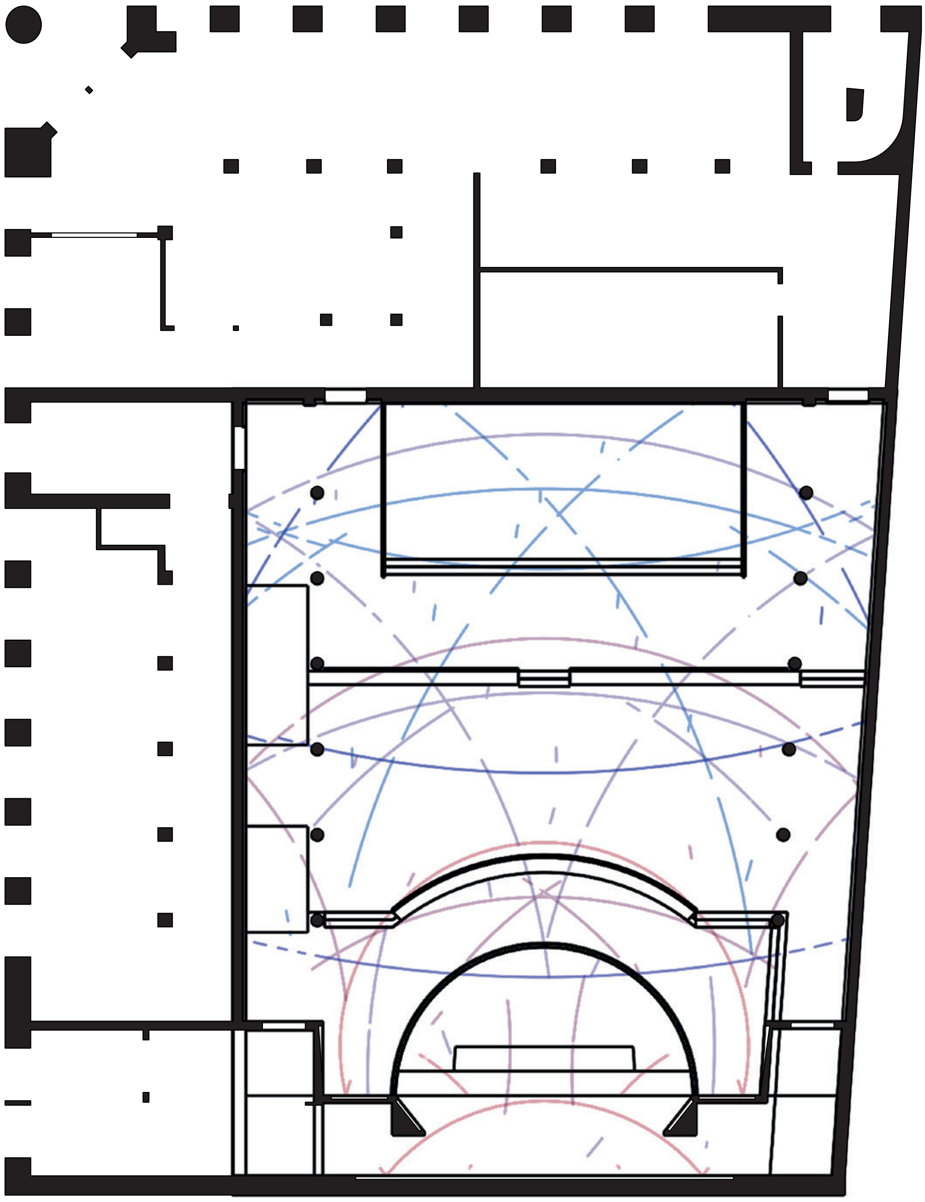
Elevation section

Looking at this simulation of how sound moves in section around the adapted auditorium, I can conclude that the already existing sloping roof seem to help with transferring sound waves across the room towards an audience standing at the balconies, especially in the far end [2. to 4.]. There are some vertical echoes going on across the stage which is not preferable, this could be solved by suspending some convex canopies above the stage, which instead would reflect the sound waves outward [1. & 2.]. Lastly, there are clear strong echoes reflecting from the rear wall below the balcony [6. to 8.]. With an audience, such echoes would be reduced to some extent, especially the ones which bounces back between the floor and the underneath of the balcony, but absorbing or diffusing panels at the rear wall could be beneficial.

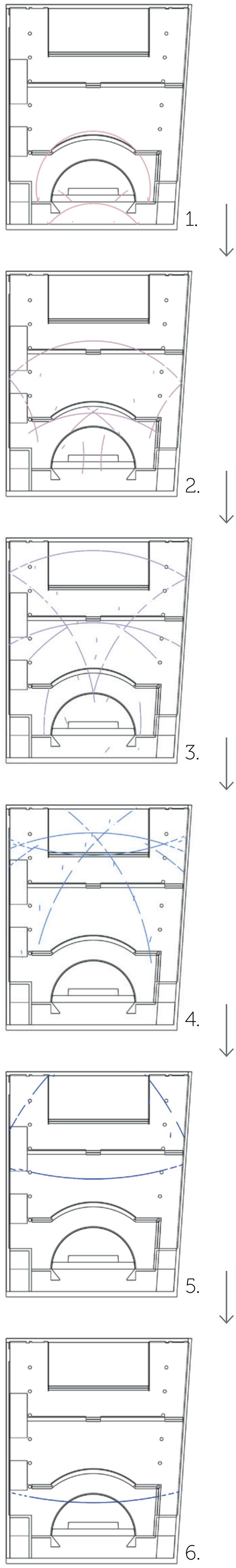


Acoustic ray tracing simulation performed with Pachyderm for Grasshopper - Section elevation



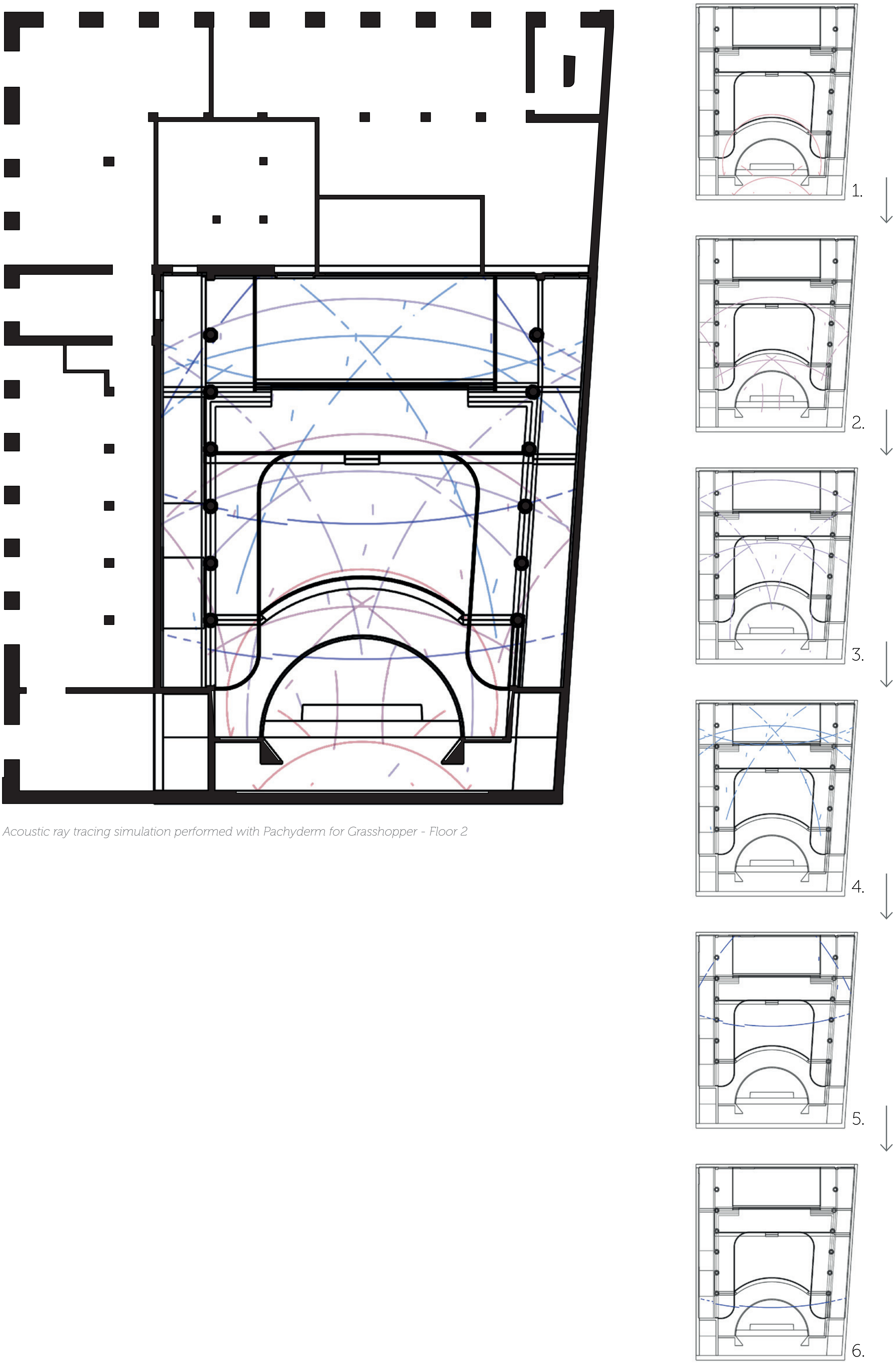


Acoustic ray tracing simulation performed with Pachyderm for Grasshopper - Floor 1

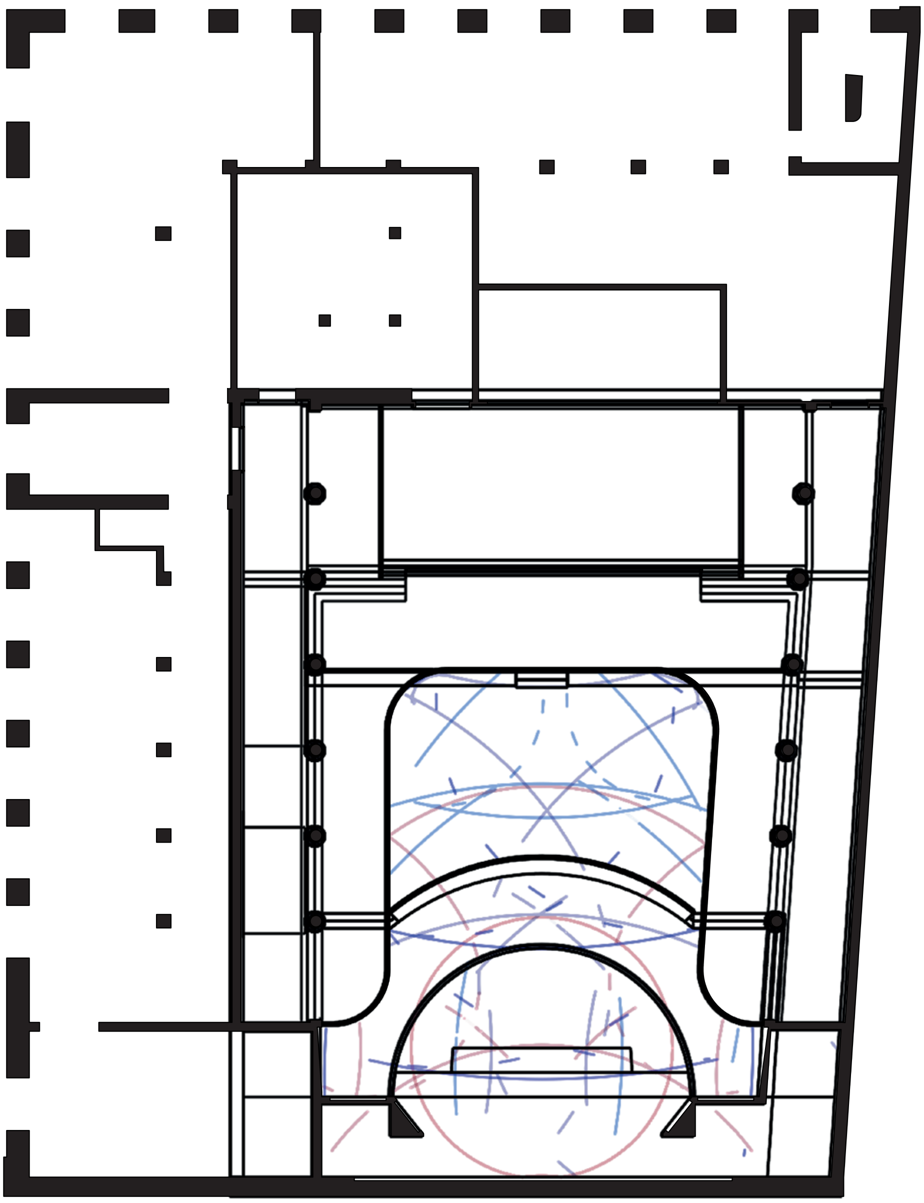


Plan section - Floor 1 & 2

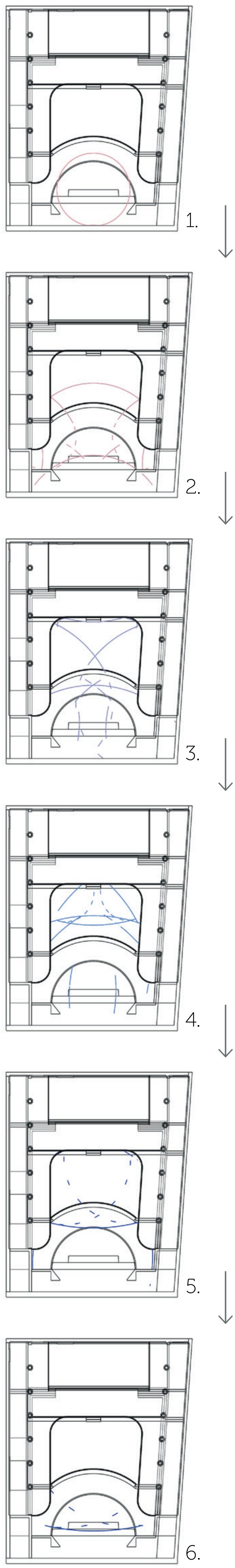
With the adapted auditorium being of a shoe-box kind (a common description of rectangular auditoriums with parallel walls), we can see through a ray tracing simulation in the horizontal plane that this space has in general very clear interference patterns occurring when being completely acoustically untreated. The pillars offers some sound diffusion, but with them having a relatively small diameter, it's not much [3.]. Most importantly we can see how late reflection from the rear walls clearly reaches back to the performing stage [5. & 6.], which could result in a tough time for performers to clearly understand what is going on. The angled walls in the back of the stage helps with reflecting sound across the audience [1.], there are some flutter echoes (fast echo across a small distance) across the stage from the side walls, which could be disturbing for performers, but this could be slightly adjusted with diffusing panels which spreads the sounds across the audience to some extent [2].



Acoustic ray tracing simulation performed with Pachyderm for Grasshopper - Floor 2



Acoustic ray tracing simulation performed with Pachyderm for Grasshopper - Floor 2 - Balcony cross section



Plan section - Floor 2 / Balcony

Looking at a simulation of a horizontal cross section which cuts the balcony, we see that this element, if untreated, creates early reflection back towards the stage. The curved corners in the front are acoustically favourable since they break up the incident waves by its' convex geometry [2.]. However, we instead get focal reflections in rear corners of the balcony because of the curvature the being of the concave kind instead [3. & 4]. By applying a diffusing panels to the stage outfacing side of the balcony, the acoustics of the auditorium could be improved.

Conclusions

After evaluating the simulations its concluded that:

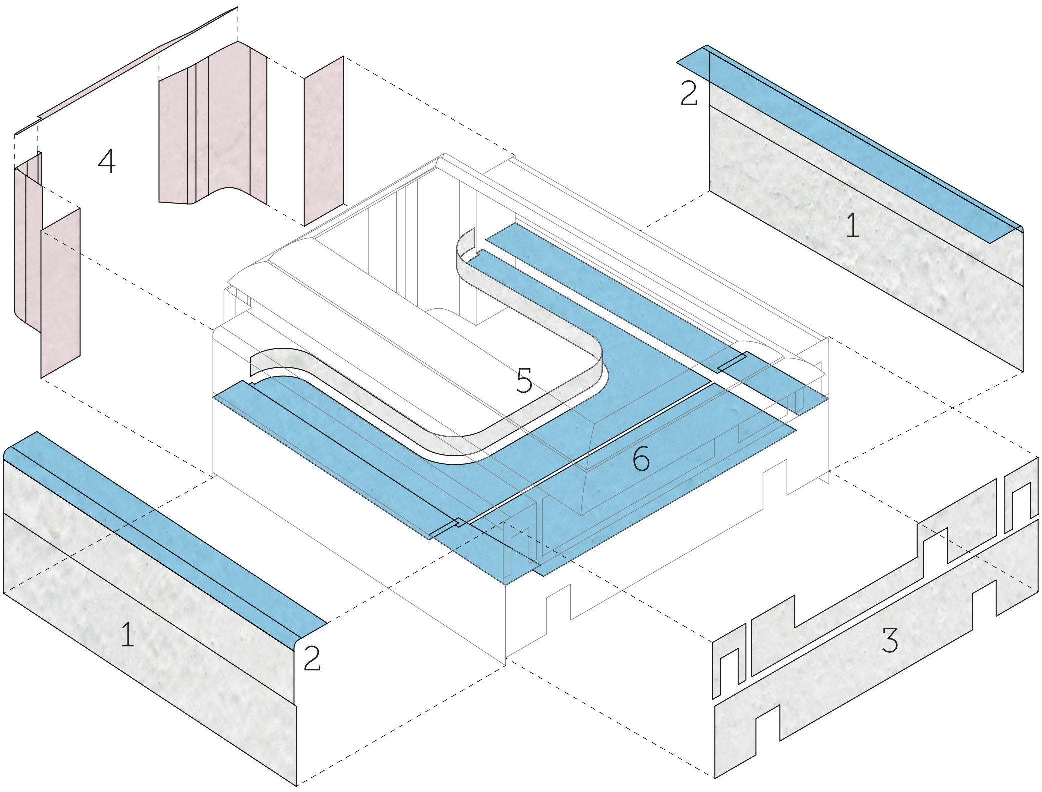
- The existing ceiling is arguably well functioning as it is in regard to the acoustic context of a stage performance.
- Canopies should be suspended above the stage.
- Diffusing panels should be applied to the rear walls to reduce clear echoing reflections toward performers on stage.
- Diffusing panels should be applied along the flanking walls to obtain a more even soundscape across the auditorium.
- Claying the pillars could benefit the soundscape within the space, but since the have a relatively small surface area in relation to overall space, it could be argued it wouldn't have a huge effect. However, it could speak better with design language of final design.
- Diffusing panels should be applied to the balconies in the outward direction.
- Absorbing materials could be applied to the ceiling surfaces underneath the balconies and beside the flanking walls.

1: Flanks
2: Flank ceilings
3: Rear wall
4: Stage
5: Balcony railing
6: Balcony underneath

Reflect

Diffuse

Absorb



Spectrum of function

With 3D printing enabling new possibilities around shape and form, I find it deeply necessary to explore those possibilities in relation to function. As mentioned in the theory, there are mainly three types of acoustic panels used to treat an acoustic environment: diffusers, absorbers, and reflectors. By using patterns, it is possible to smoothly transition between these treatments, allowing the design to be guided by function rather than aimless aesthetics. However, absorption mostly comes from the porosity of the panel material itself, not the geometry. By designing the panels with some kind of hollowness, they may gain some absorbing properties, but to what extent would need to be tested in a lab using precise acoustic evaluation methods.

Any line, curve or shape repeated enough can be perceived as a pattern, since the very definition itself of a pattern is the result of a repetition of any element or motif. When working with patterns, spacing and proportions is often times preferred over complexity (Proctor, 1990). I myself, believe there is value to be found in readability when it comes to well designed patterns, since there is some kind of satisfaction one can experience when a pattern can be understood, both in terms of function, and in terms of how it is structured.

In architecture, patterns often emerge naturally, shaped by materials, structure, or aesthetics. They may be inherent to the building material, like a rhythmic grid of offset bricks, or reflect the structure, such as the skeletons of Gothic cathedrals or the steel frameworks of modern skyscrapers. They can also serve a decorative purpose, reflecting the culture or architectural trends of a particular era.

One could easily dedicate an entire thesis to patterns, simply given the endless possibilities of the three dimensions. By setting specific parameters, I'm exploring how smoother patterns reflect sound, sharper ones diffuse it, and hollow forms help absorb it.

Evaluation method

To gain a visual understanding of how sound waves are affected by the patterns I design, two dimensional simulations are conducted in a similar manner to the ones done during the spatial acoustic analysis.

For each pattern, a 5x5 room environment within the 3D modelling software of Rhinoceros together with *Grasshopper* and *Pachyderm* is modelled. A sound source is placed at the centre of the modelled room as a point. From this point, the tools generates ray-traced curves that simulate how waves (in this case sound) bounces within the space. I then evaluate all these curves simultaneously by tracking a single point along their length. This method allows me to visualize how a particle moves through the ray-traced paths and, in turn, understand how the designed patterns influence the behaviour of sound waves.

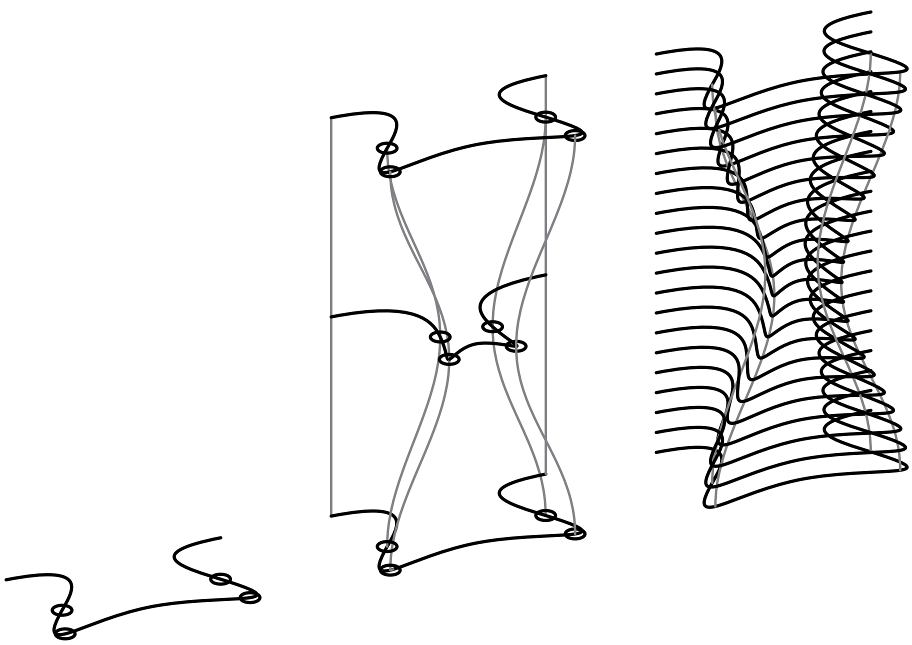
The forever pattern

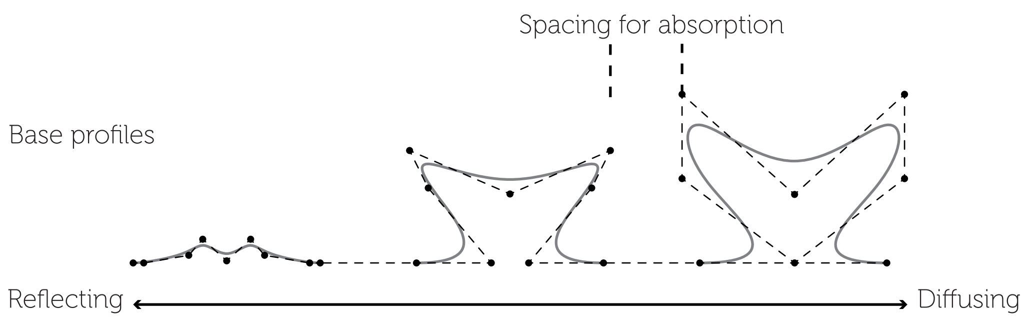
The first set of patterns explored is based on the ogee shape, a common structure of curves found within multiple fields of design such as architecture and fabric design. In general, these patterns are constructed by two parallel S shaped curves narrowing and widening in unison, which results in a scale-like layout which in principle can be expanded infinitely. (McLaughlin, 2020).

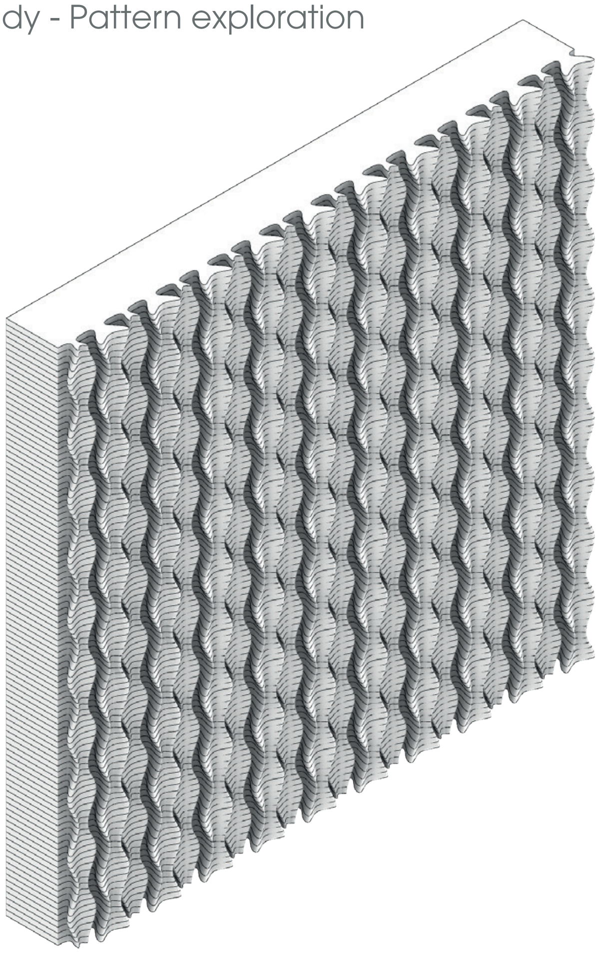
This shape is in relation to 3D printing favourable. Because of it having a very natural vertical directionality, the pattern does not depend on any horizontal crossings when using the spaces between the curves, since they always meet in the same vertical tangent.

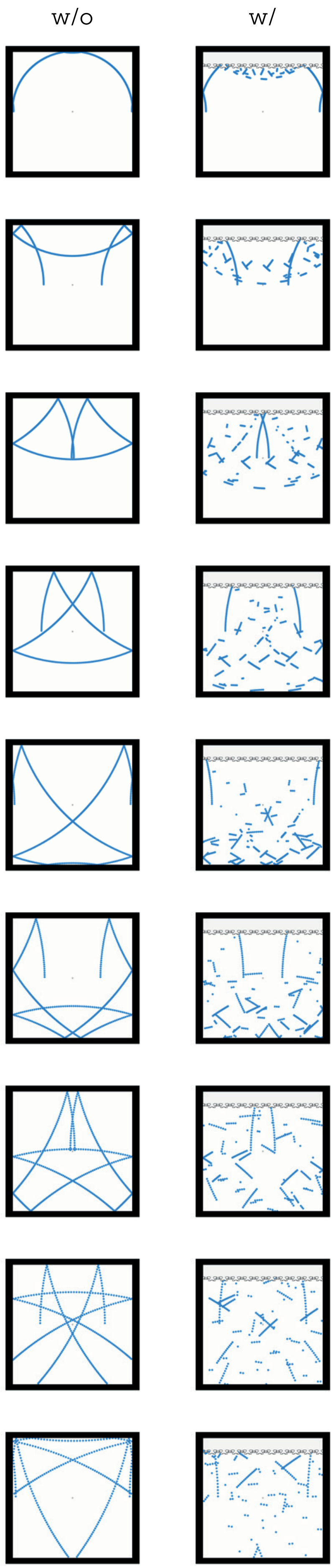
By arraying a base curve in the vertical direction which deforms on certain control points according to a sinus curve, the ogee pattern can be constructed with a three dimensional profile.

Additionally, by controlling the depth of the profile, the pattern can appear more smoothly or more sharp, while still suggesting the very nature of the ogee pattern. This way, the surface can suggest reflecting, diffusing and absorbing solutions.





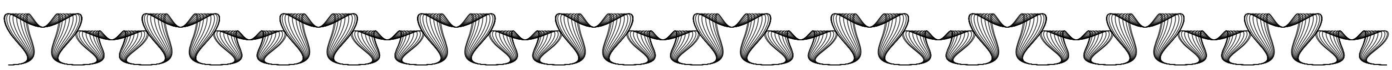


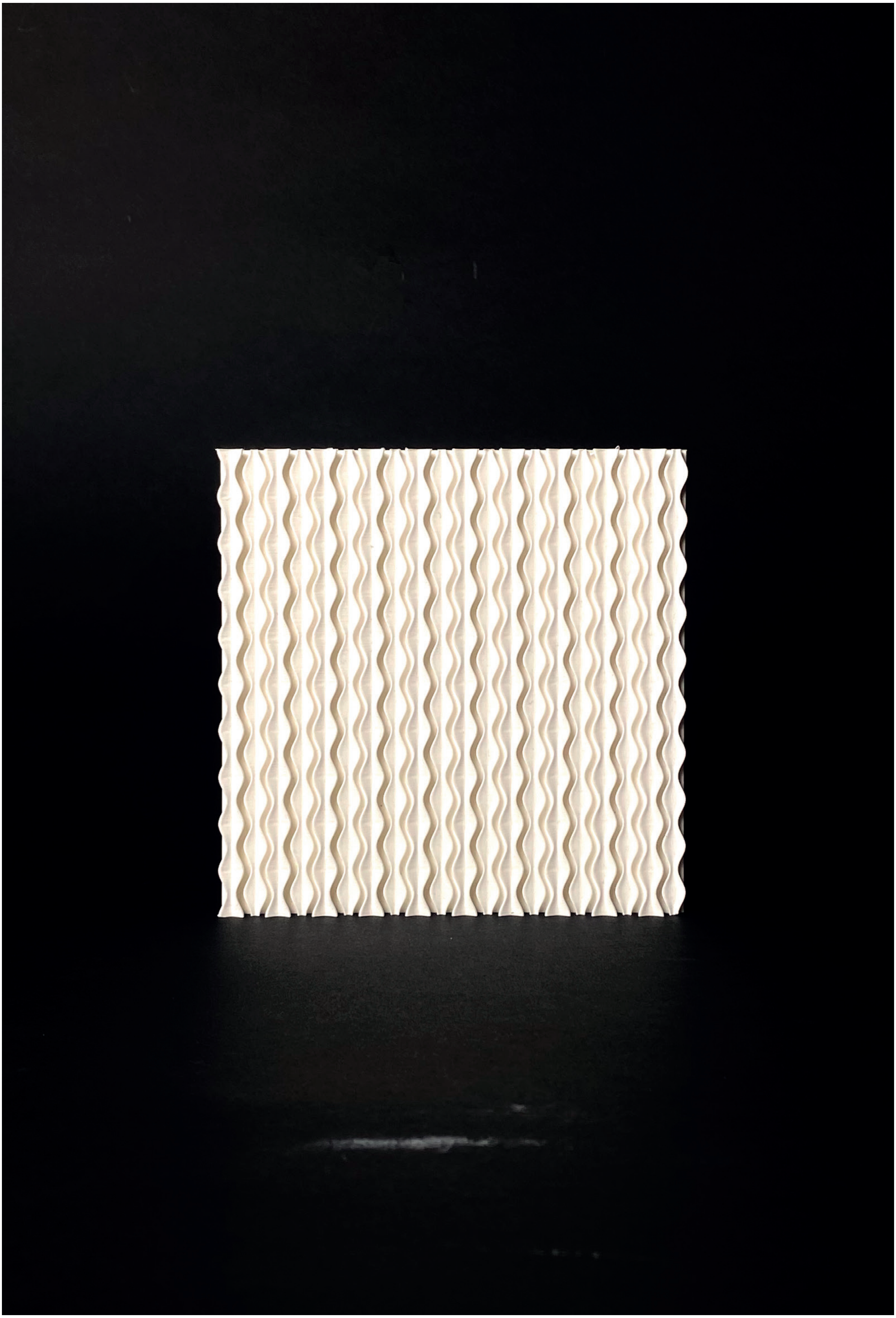


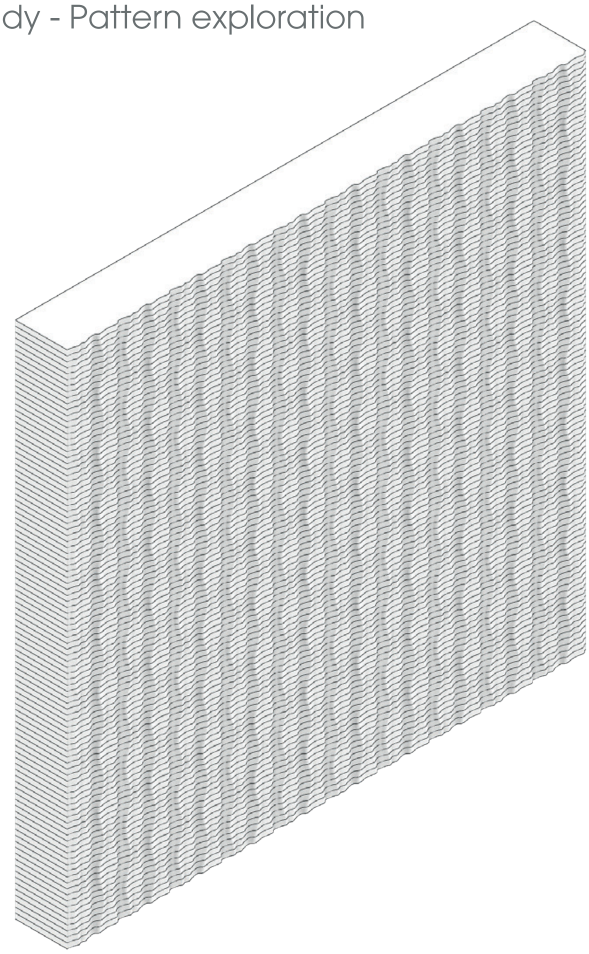
Ogee 1 uses two profiles with different depths placed next to each other. Both profiles flow in unison relative to the shape next to each one, creating a consistent gap between them throughout the pattern. This gap could be an ideal place to incorporate a light source, such as an LED strip.

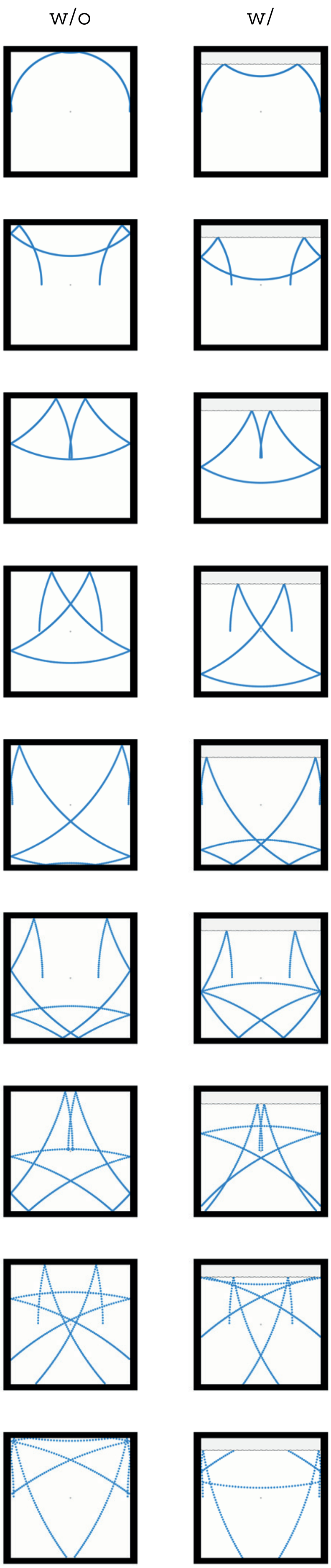
Using 2D particle ray-traced simulation, we can observe that the pattern disrupts the incident wave and creates clusters of focal reflections. This behaviour could potentially be adjusted by using a more convex base shape that faces the incoming waves, rather than a concave one.

However, I personally find the concave shape aesthetically pleasing, and the results still show promising potential for effective wave diffusion. We can all notice how towards the end of the simulation, the particles are slightly focused toward the right, this probably due to the pattern not being completely symmetrical as you can see below.



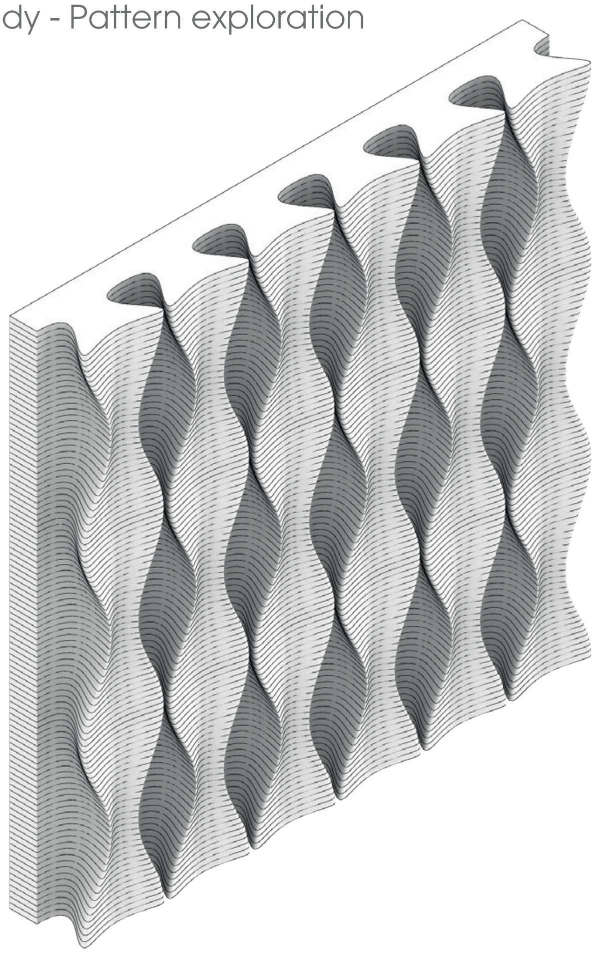


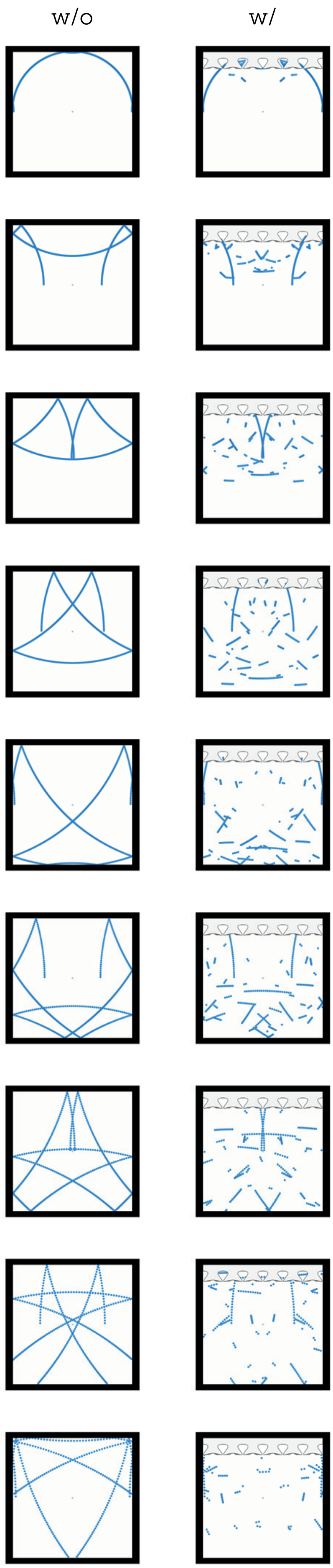




Ogee 2 reduces the depth of the profiles until the gap occurring in ogee 1 disappears. This results in a smoother surface, with the ogee remaining only subtly visible.

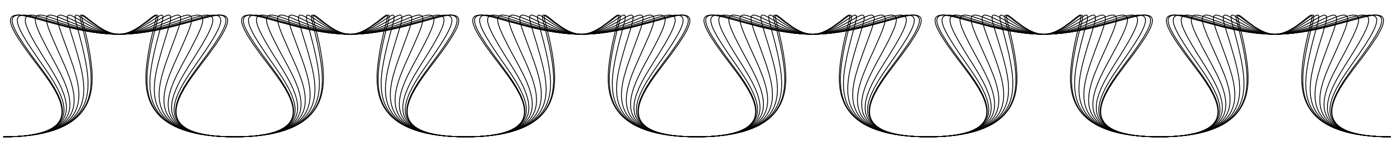
The simulation shows that this version largely behaves like a flat surface, producing undisturbed, perpendicular reflections. This approach works well for surface areas where clear and strong reflections are desired, such as around the stage, so that sound is effectively projected toward the audience.

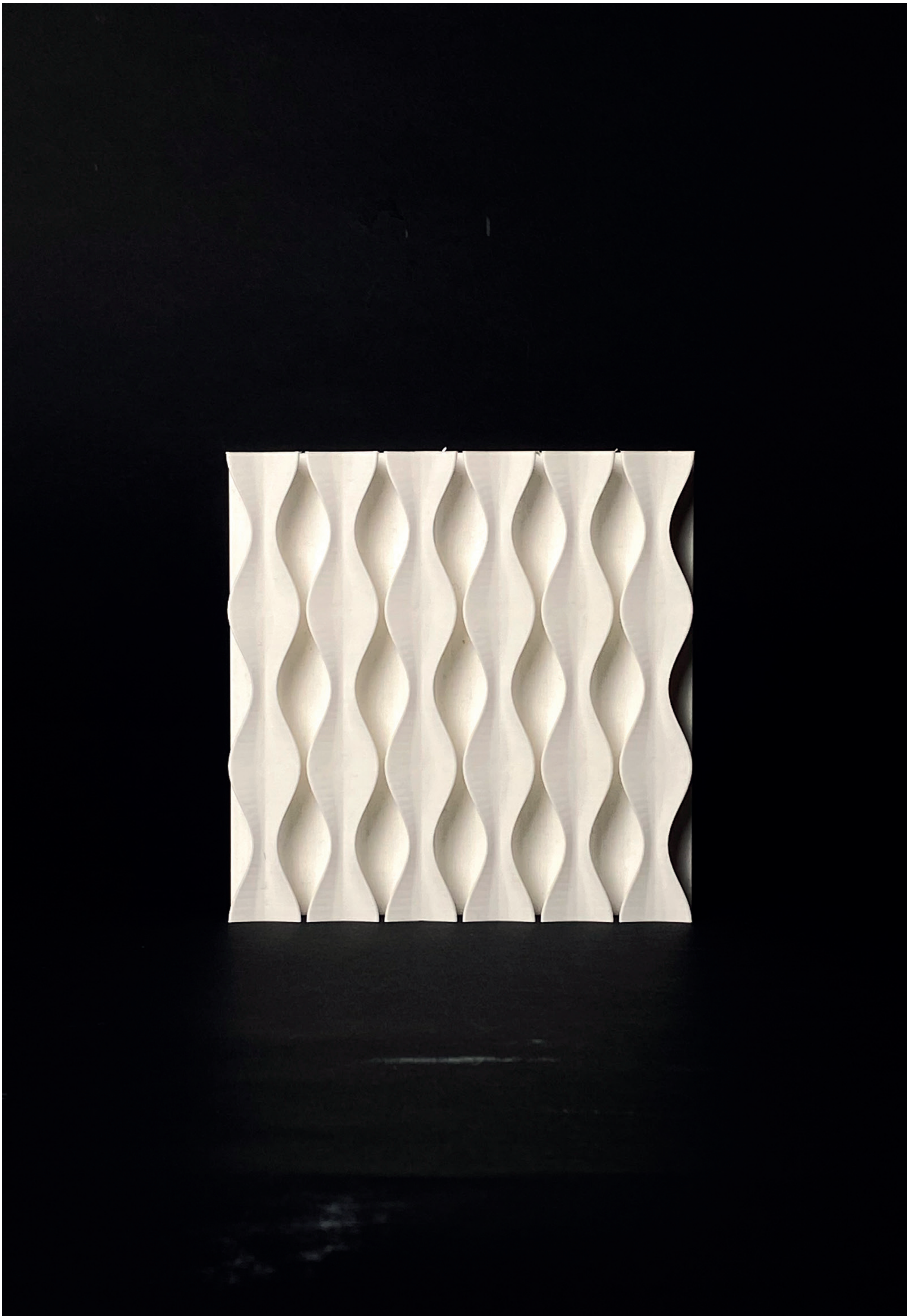




Ogee 3, the depth of each profile next to each other is extended equally, the scale of the pattern is also as heavily increased to see how the focal reflections compare to the ogee 1. Additionally, each base profile this time set to flow equally to the ones next to each other, which leads to gaps showcasing a similar shape as the printed geometry, these gaps could be well suited to host an additional absorbing material. Either far back in the gap, or as thin textile at rim of the cavity.

The simulation showcases a similar outcome to ogee 1, but interestingly, particles get stuck within the gaps, which means that some rays of the simulation bounce back and forth within the cavities.





Velumventis

My second pattern concept explores a way of introducing random properties to the design, while still maintaining a visible structure which is easy for spectators to read. Inspired by my knowledge of this space as a former cinema, I decided to try to create a surface which stems from a simulation of a suspended curtain. A classic feature within the architectural elements of a cinema.

Through the use the plug-in *Kangaroo* for *Grasshopper* and *Rhinoceros*, a curtain can be simulated as a mesh through a form finding process set towards certain parameters.

By applying a horizontal force to either a set of random points or to points arranged in a pattern, the curtain's form can be manipulated in various ways. The process is relatively soft, meaning each iteration results in slightly different outcomes. However, it do create very smooth meshes which is easy to work with for me personally, and later, the meshes can be transformed into tool paths for 3D-printing.

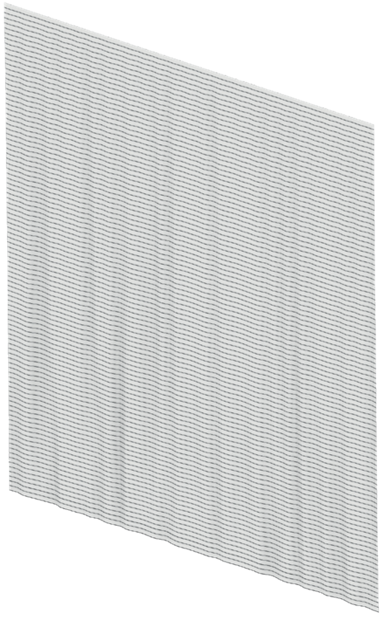
Velumventis can be loosely translated from Latin as "Curtain in the wind."

1: *Without any horizontal forces applied, the geometry simply illustrates a hanging curtain.*

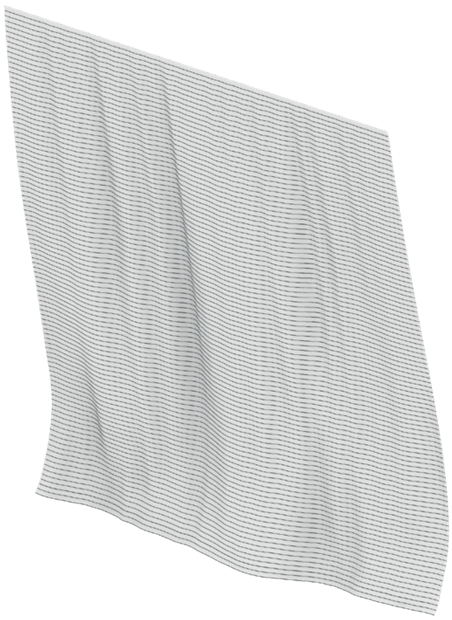
2: With horizontal forces applied at a random set of points, the geometry starts look like curtain which "sways" in the wind

3: *With horizontal forces applied on a set of points arranged toward a pattern, that pattern can appear within the rules set for the curtain simulation.*

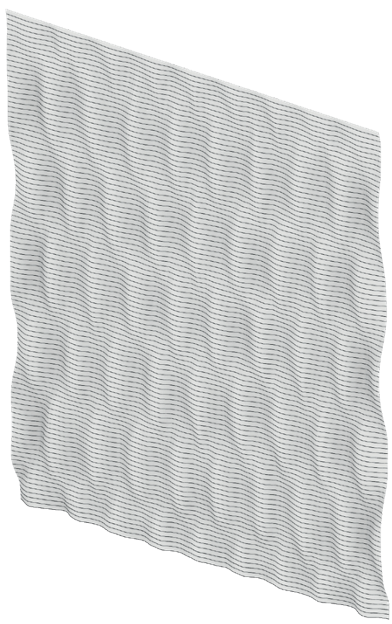
1.

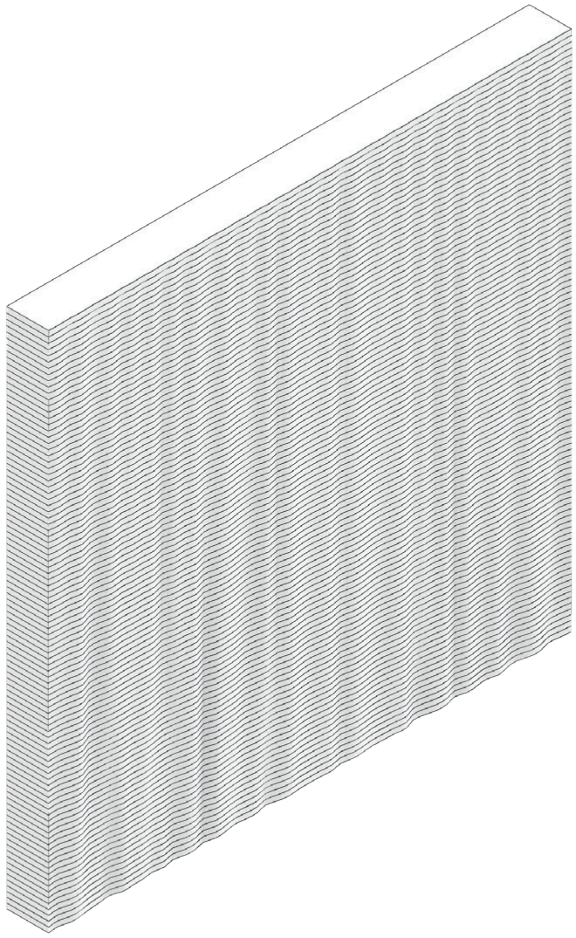


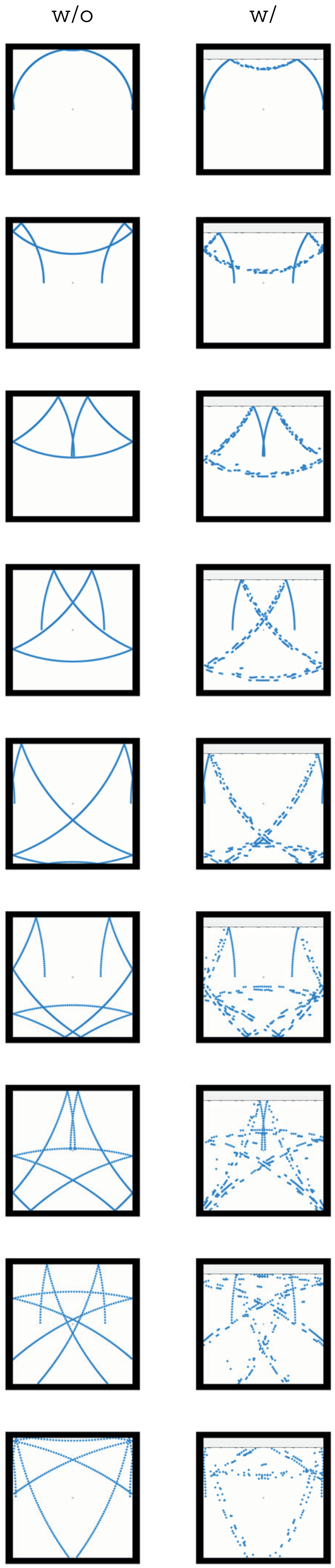
2.



3.

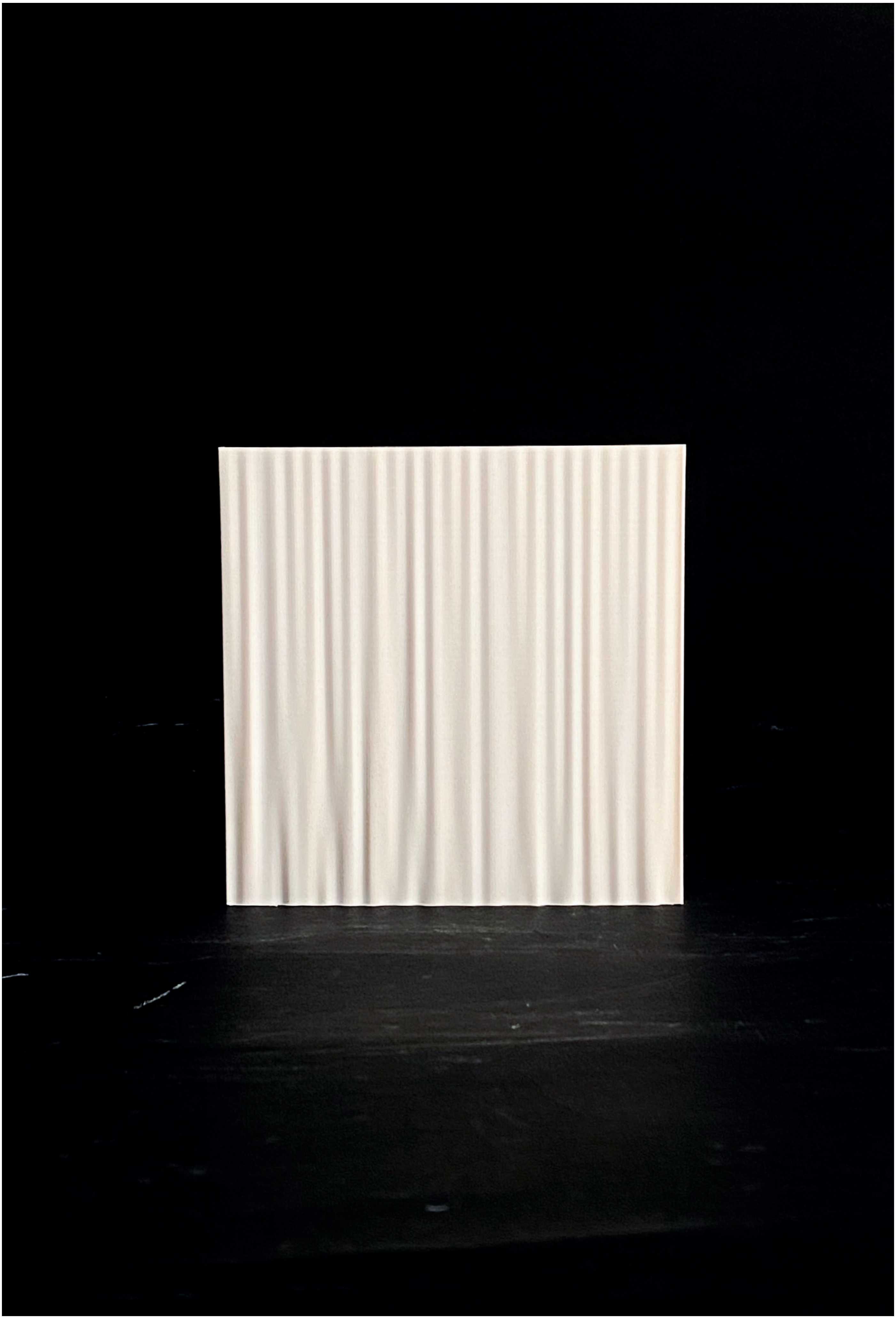


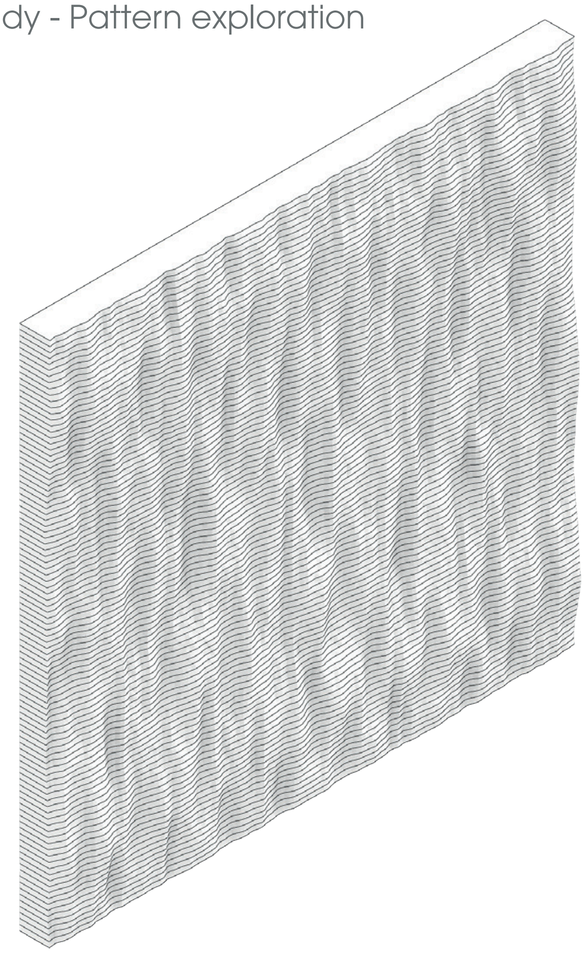


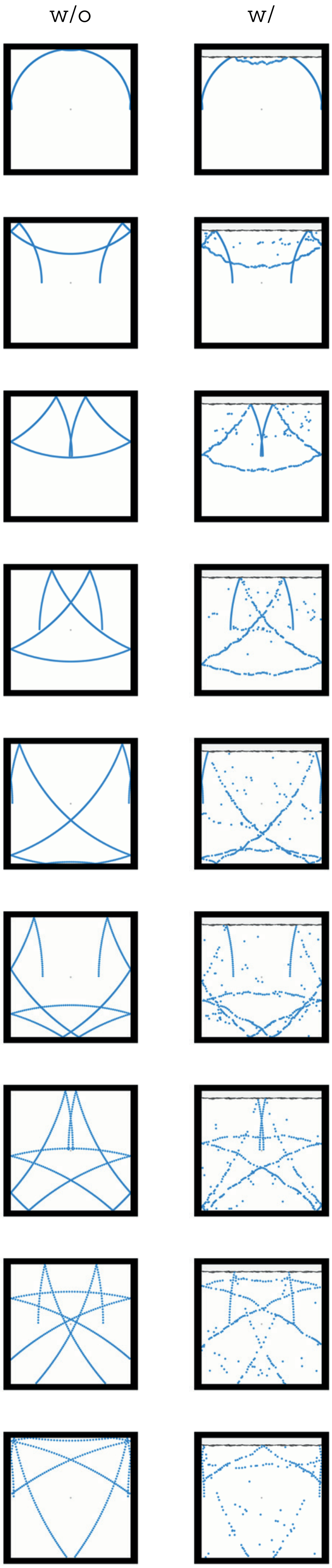


Velumventis 1 is produced by simulating a hanging curtain. By disrupting it with horizontal forces, but then letting the simulation keep going until the curtain is just almost back at its normal suspended state and then freeze the simulation, I get a block which could be divided into multiple pieces and when put together, they would illustrate the curtain shape.

The acoustic simulation showcase that this iteration do have some scattering properties, but in general, the result mostly suggest quite similar results to a fully reflecting wall.

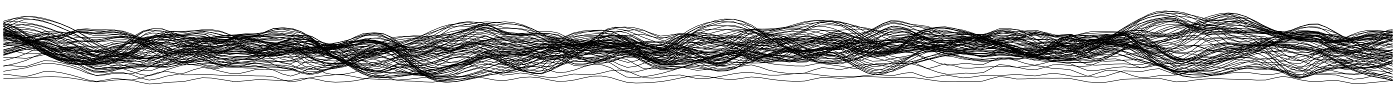


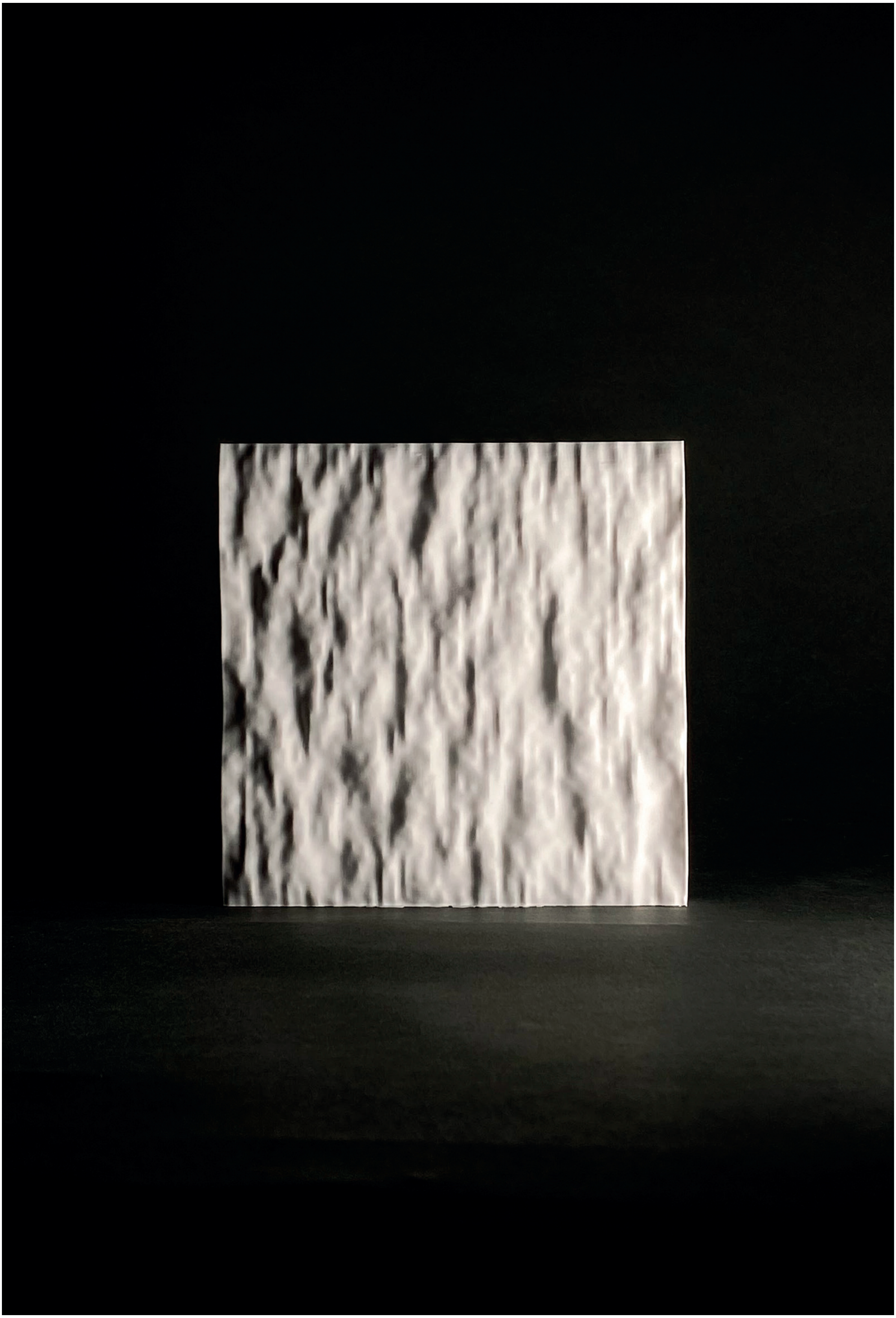


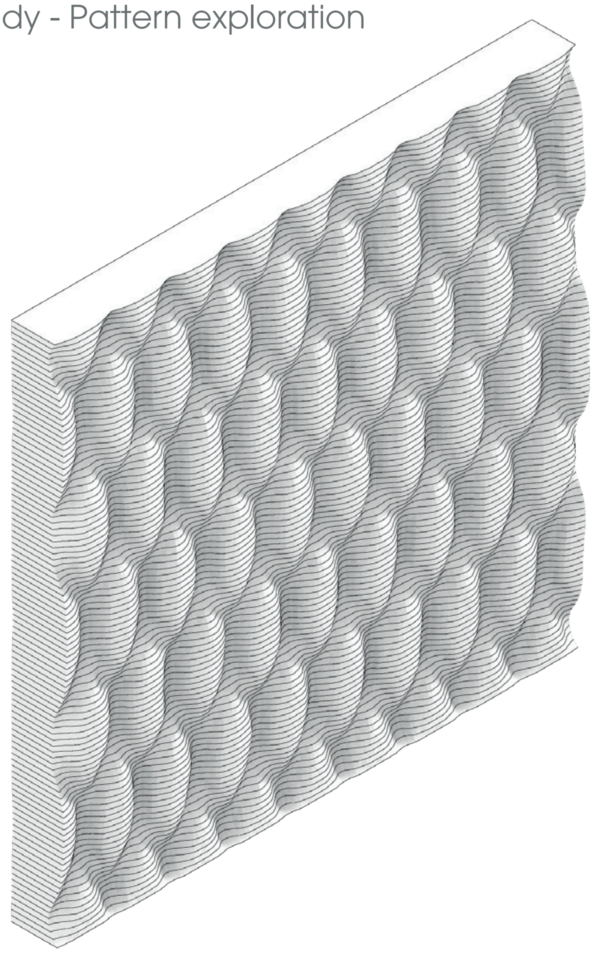


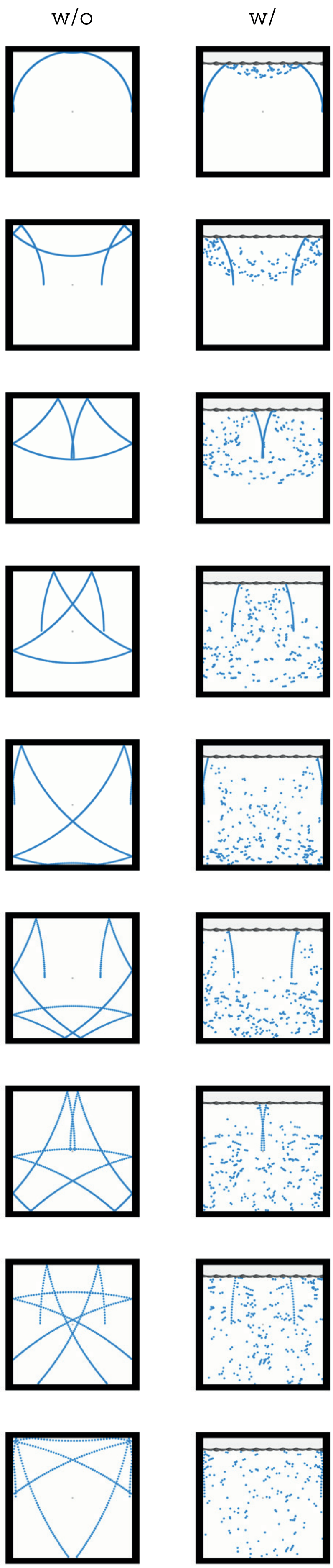
Velumventis 2 is produced by simulating a hanging curtain which gets disrupted by perpendicular wind forces at random points along the geometry, the result illustrates a random freeze frame of a drape in the wind, which would be well suited for 3D-printing particularity, since if a design like this would be split into multiple pieces of similar size, each piece would be completely unique.

The simulation shows disrupted reflections, but ones that are still similar to the ones within the untreated example. Obviously, a more disrupted surface would produce a more diffused result, but in this iteration, the panel is working more as reflector.



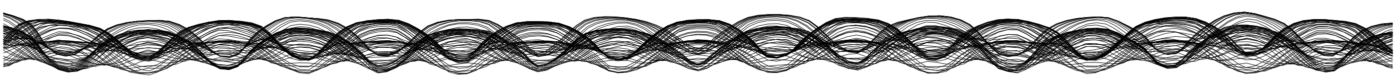


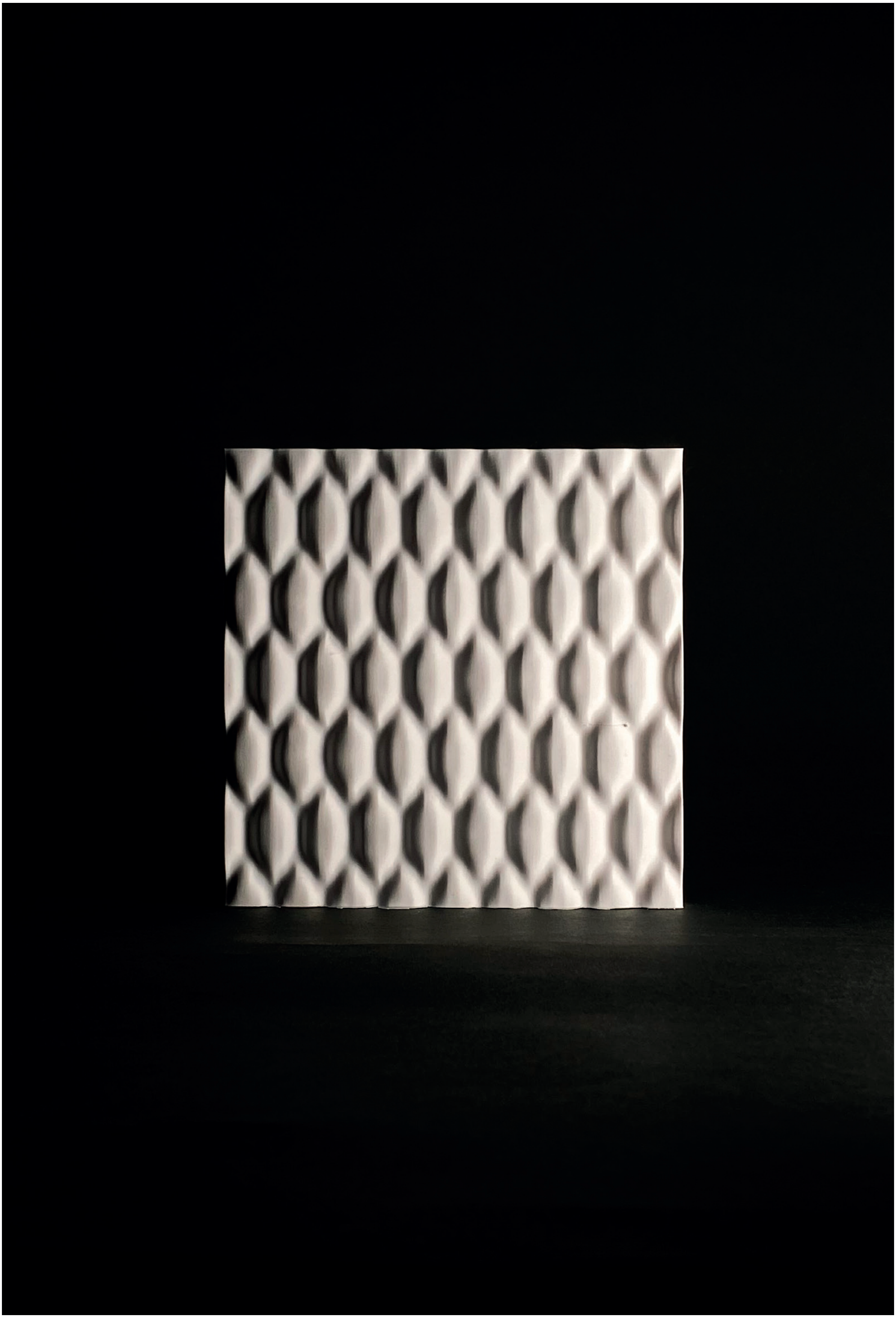




Velumventis 3 is modelled in a similar manner as 1 and 2, even though it's expression is very different. Here, the forces applied in the curtain simulation are applied on a set of points which follow the ogee pattern, but in the opposite direction compared to 1 and 2. This results in surface which almost looks inflated, with convex pillow like boils.

The simulation shows very promising results in regard to diffusion. Reflections are instantly from the first bounce well distributed around the space. This shows how convex geometries can better scatter the sound waves in a room compared concave ones. Important to note, is that the reason particles seem to fall behind right after the first bounce, is because they are reflected in diagonally upwards, and downwards





Conclusion

To be able to manage the time for applying these pattern to the auditorium in a concise manner, I'm choosing to only continue with 2 of them; Ogee 1 and Velumventis 2.

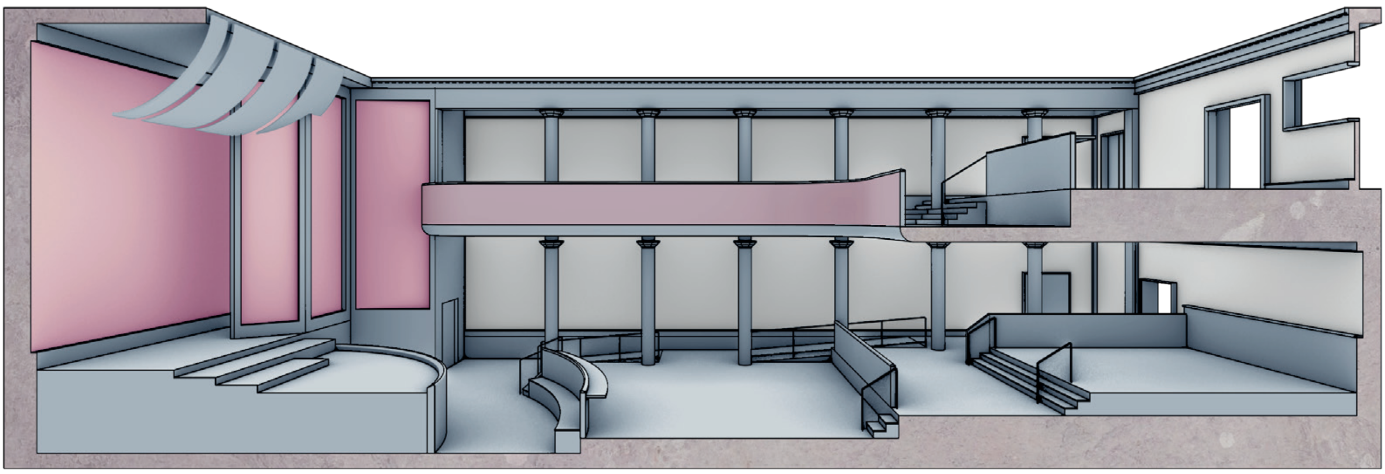
Ogee 1, because of its promising results in regards of scattering sound while also, suggesting a quite uniform surface area compared to Ogee 3 for example, which has quite wide welds which I don't find particularly pleasing in regard to aesthetics. Ogee 1 has a clearer directionality which I also find better suiting for casting a wall with. Ogee 2 is a bit too subtle and looks a bit too much like flat surface. I believe it will be well suited for the flanks and the rear wall.

When continuing with this pattern, there needs to be some orders of parameters added to the script which makes it so that when I later divide the whole wall cladding into individual pieces, each piece is it's unique thing. This could be done via random attractor points which deforms the whole piece in different ways.

Velumventis 2 is good and easy to work with since it seems to scatter sound less then Ogee 1, but it also gives me completely individual pieces right away. It could be applied to the stage to reflect sound, by making the dents a bit subtle, while it can also be applied to the balcony with deeper dents to scatter sound more.

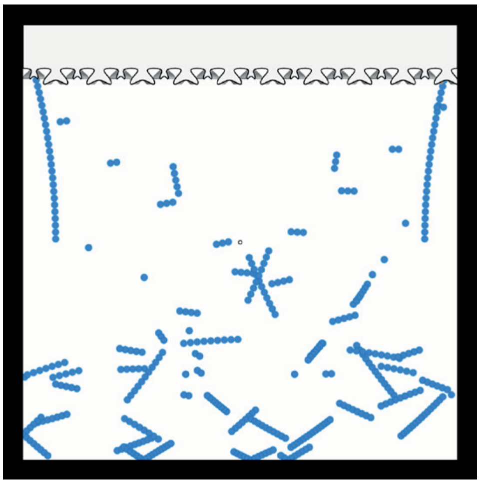
Ogee 1

Velumventis 2

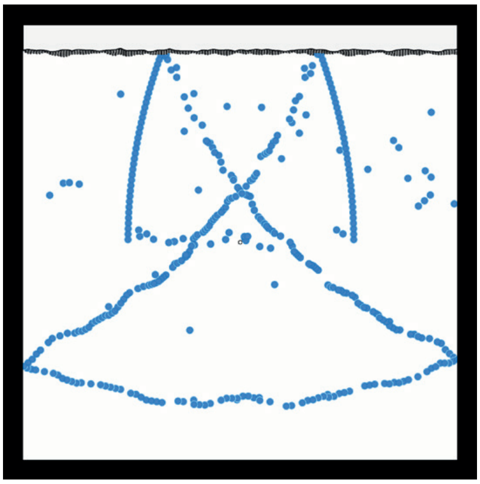


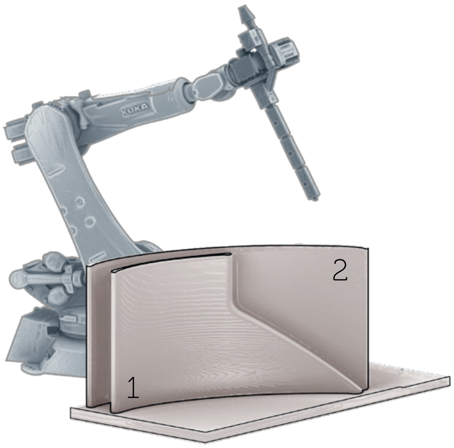
Section diagram showcasing where the two patterns are applied.

Ogee 1



Velumventis 2





Canopies

1 Quantity: 2

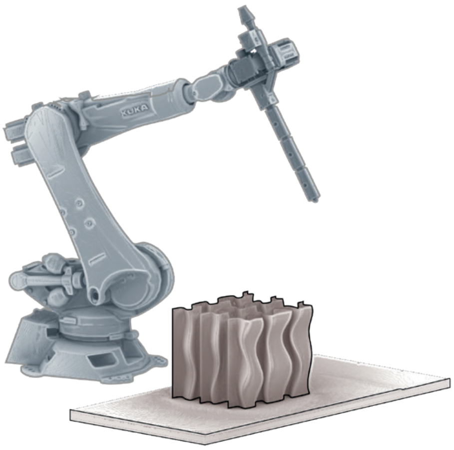
1 Approx. print time / piece: 5 h

2 Quantity: 5

2 Approx. print time / piece: 8h

Total time: ~50h (2 full days) -(6.25 8h work days) w/ 1 Robot.

The canopies are designed as simple arcs to be suspended above the stage, there is no particular pattern implemented to them, to make sure they produce strong reflections out across the space.



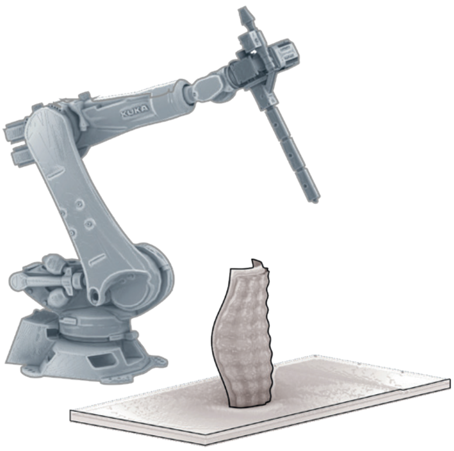
Flank- and rear wall diffusers

Quantity: 910

Approx. print time / piece: 1h-2h

Total print time: ~1592h (66 full days) - (199 8h work days) w/ 1 Robot

The panels which are applied for the walls utilizes the ogee 1 pattern which was further developed to generate different orders of change along the walls which the cover. This means that every single piece is it's an original piece, which would disrupt the flow of the pattern if displaced.



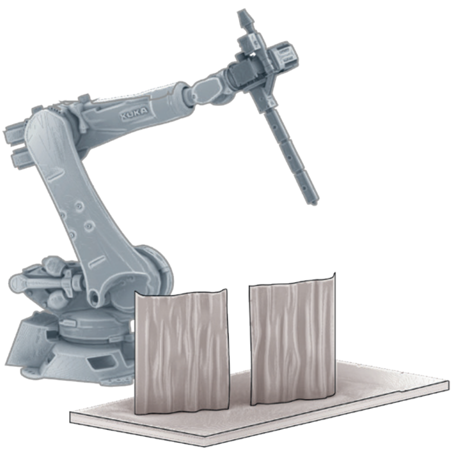
Pillar cover piece 1

Quantity: 156

Approx. print time / piece: 2.5-3h

Total print time:~429h (18 full days) - (54 8h work days) w/ 1 Robot

The pillars are covered with sweeping pieces which are defined by the amplitude and frequency of sinus waves in many different orders. Similar to how sound work in principle. The closer one would travel to the stage, the more the pillars will seem to be deformed.



Stage and balcony reflectors and diffusers

Quantity: 105

Approx. print time / piece: 2-4h

Total print time: ~315 (13 full days) - (39 8h work days) w/ 1 Robot

Behind and beside the stage floor, there are panels of velumventis 2 with intent to reflect sound toward the audience. These pieces are also found along the balcony railing.

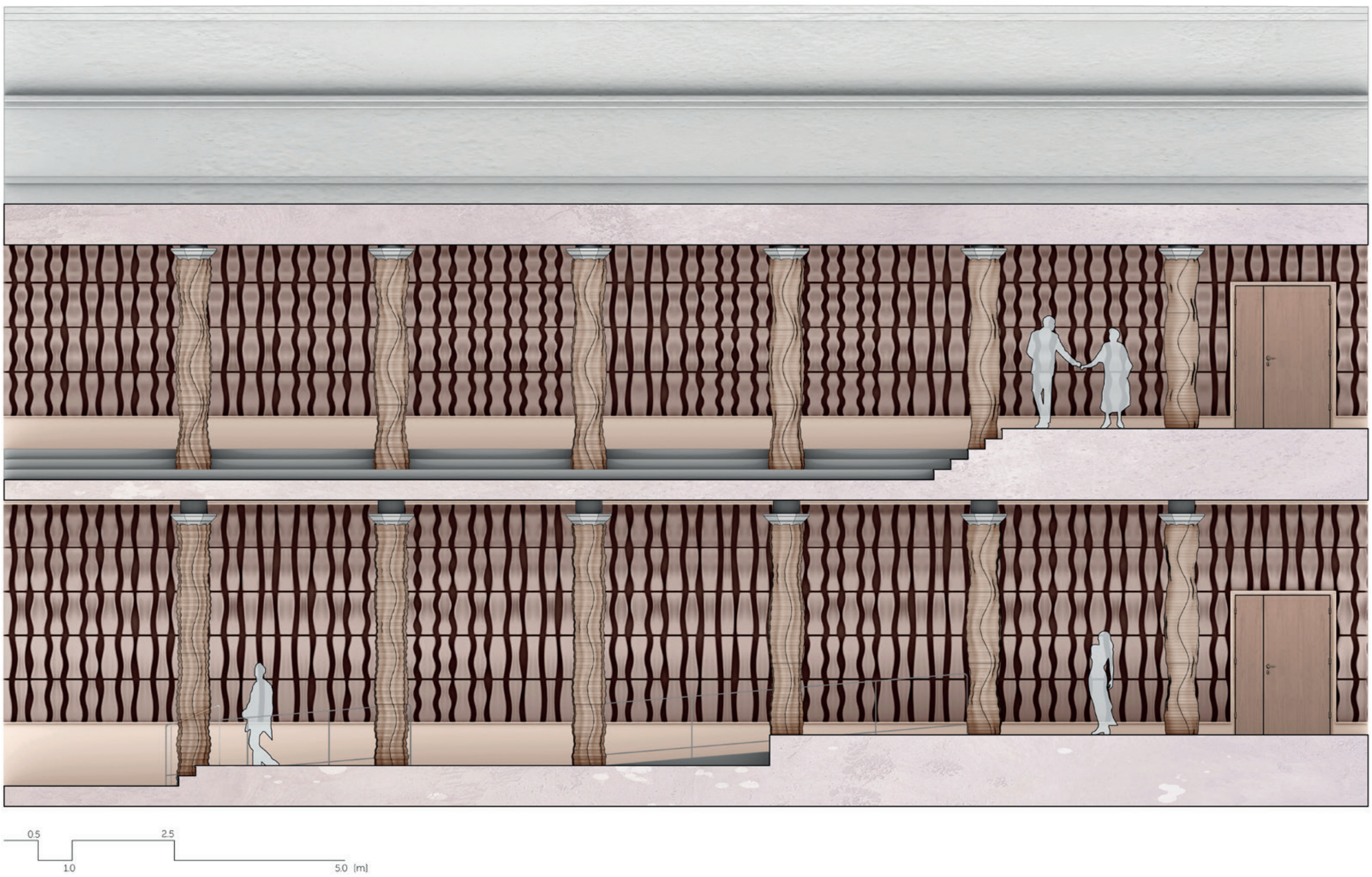
Fabrication efficiency

To support and enhance the auditorium's sound toward a program for entertainment and dining, close to the whole auditorium is covered with roughly 1,200 individual 3D-printed pieces.

Printing all the different pieces with a single robot would take at least 298 working days. Realistically, this time frame would likely exceed a full year when accounting for weekends, errors, and the time needed to move printed pieces and prepare for the next print.

However, using two robots could cut that time in half. Additionally, various programming techniques of the toolpaths can still improve the efficiency of the design, like printing continuous curves without seams, similar to a spring.

Even so, one year is relatively short when compared to the overall timeline of renovating the venue. If a sculptor were to craft all these pieces by hand, the process would take significantly longer.



Interior elevation showing 3D printed elements applied to the flank walls.

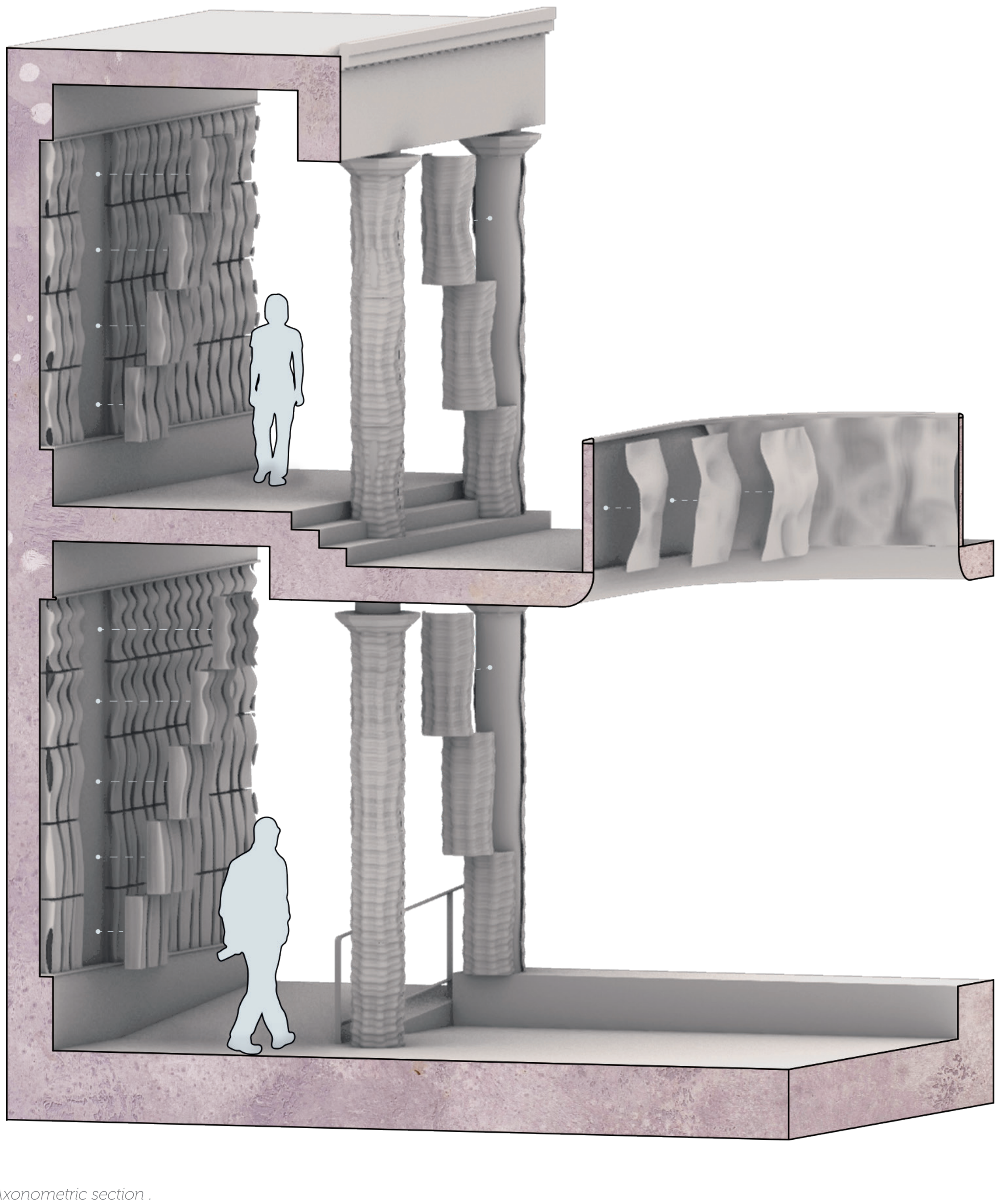
Final layout

Diffusing panels have been applied to the flanking walls, the balcony railing, and the rear walls on both levels.

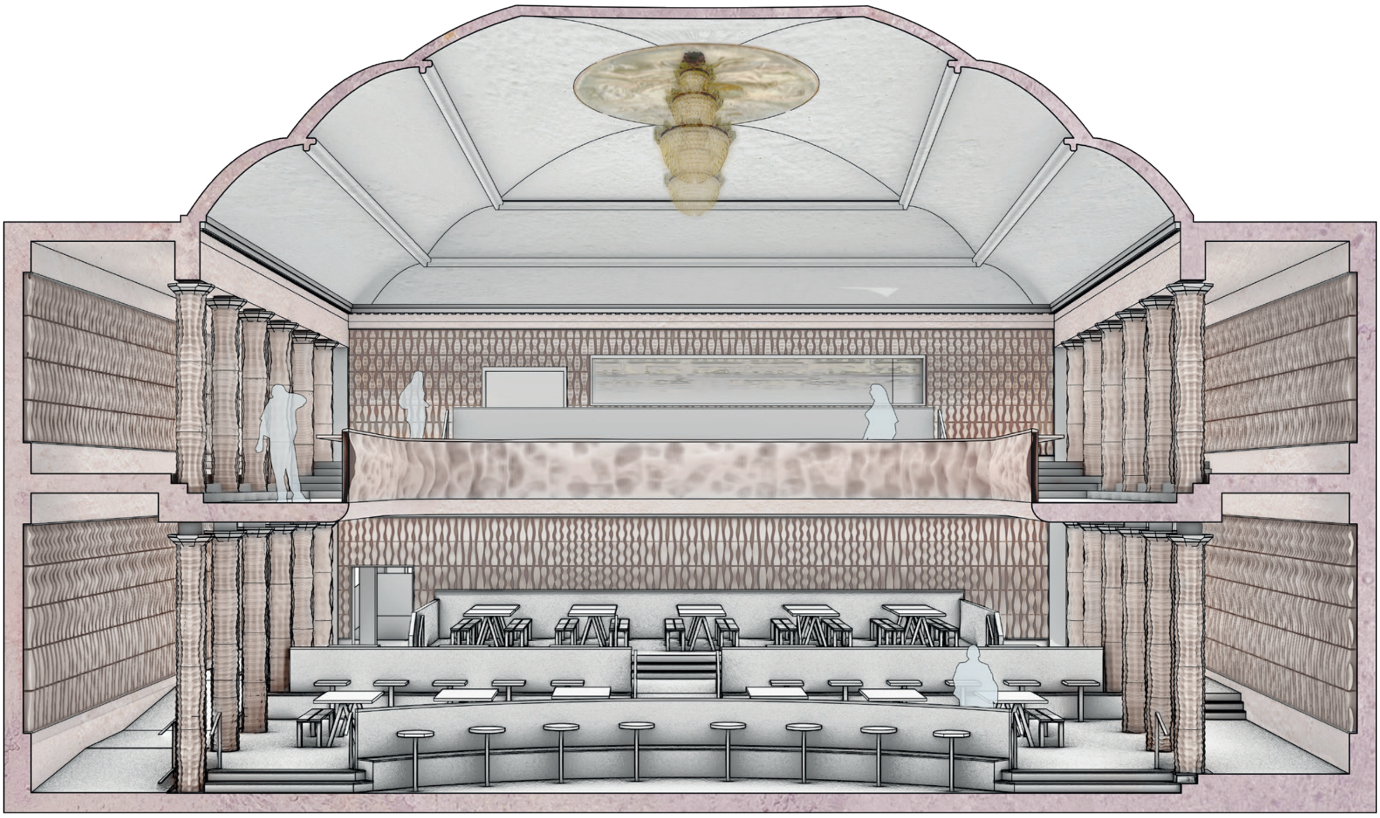
The stage features smoothly formed 3D-printed surfaces designed to reflect performers' sound clearly across the audience.

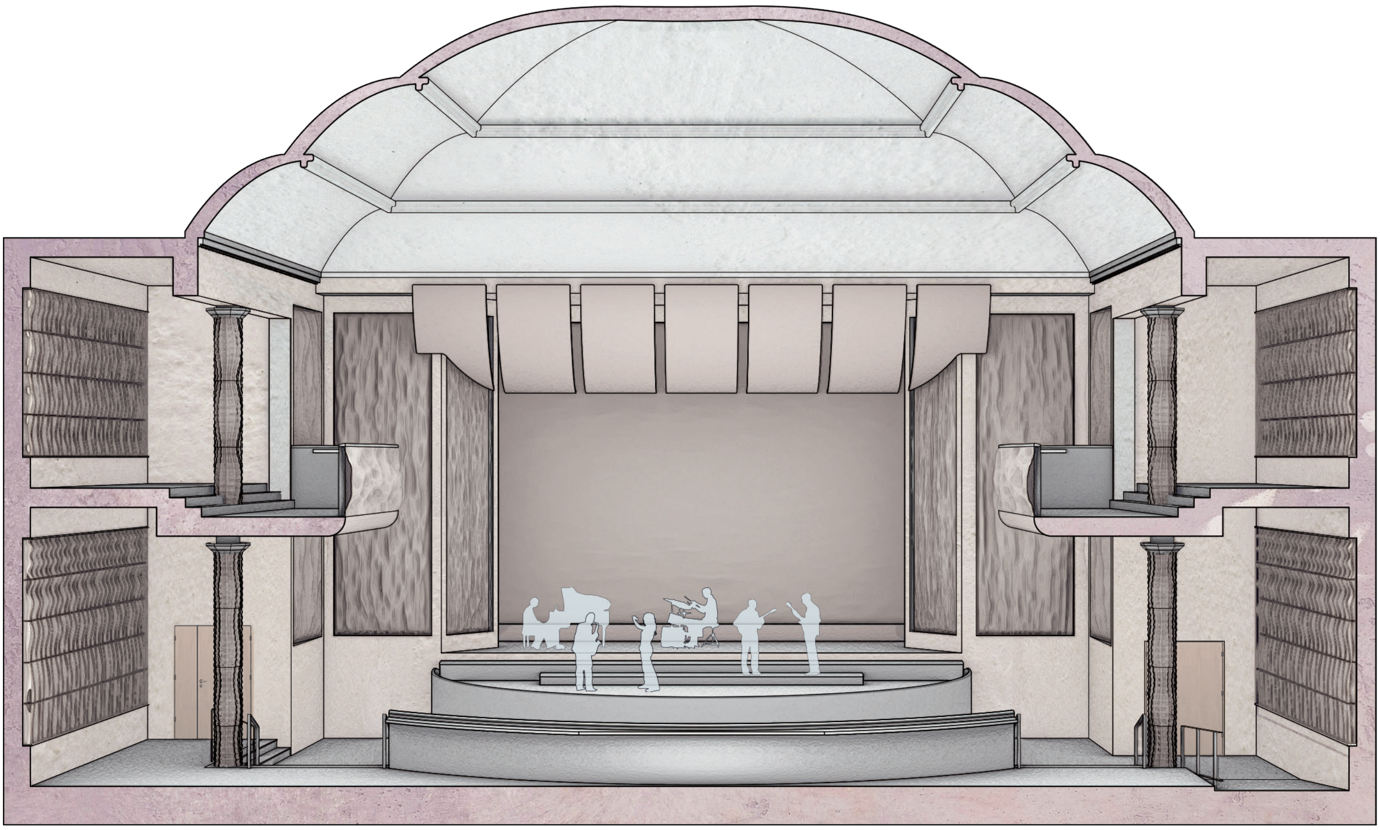
The ceiling, along with the chandeliers and paintings, has been fully preserved. Since the ceiling was good for carrying the sound across the room towards the back, no additional pieces are suspended from the ceiling. However, seven canopies are suspended above the stage area, to decrease vertical echoes across the stage.

The pillars are also clad with 3D-printed diffusing elements, both to align with the space's design language and to diffuse high-frequency direct sound.



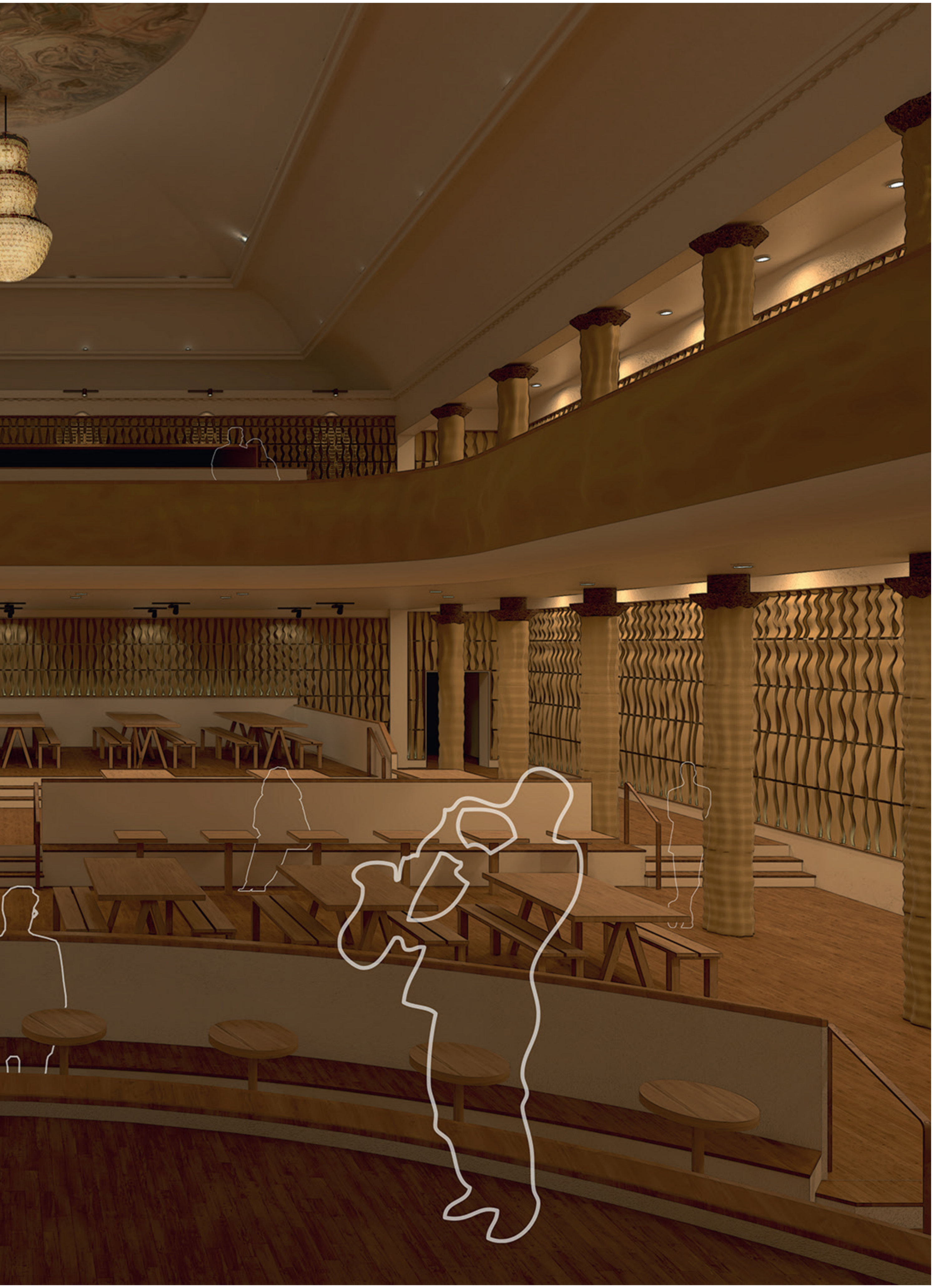
Axonometric section .



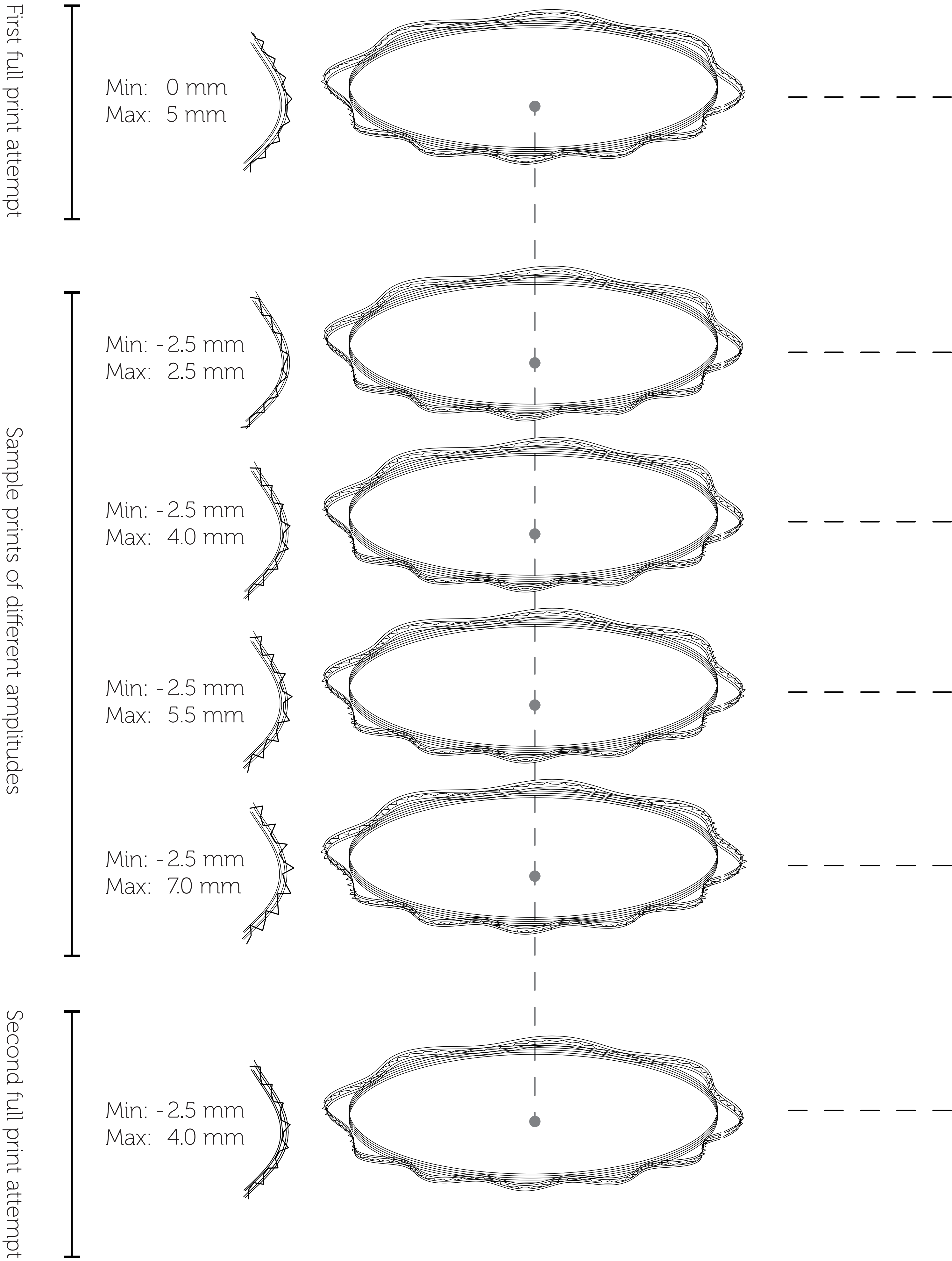


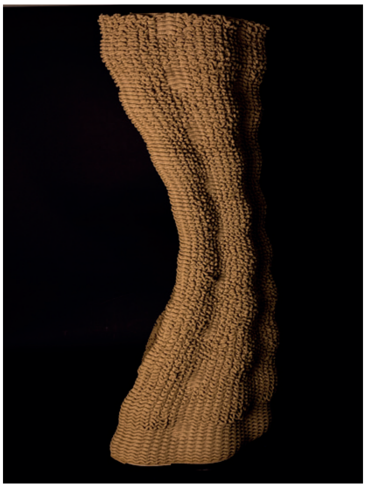
Two sections of the auditoriums with applied 3D-printed interventions.

Interior perspective from the stage.



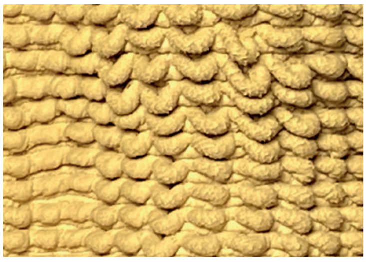
Sine amplitude domain





First full print attempt

During the first attempt at printing one of the pillar components, a texture was applied by printing every third layer in a zig-zag pattern. The zig-zag originates from a mathematically defined sine curve, but when translated into a toolpath for the robot, it appears angular due to the robot's straight-line movements between each point. The outcome was not entirely satisfactory: the layers began to separate early during session, although they held together well enough to complete the piece. The resulting surface had an organic appearance, but since the print didn't go as planned, we decided to iterate on the texture by printing small samples with varying amplitudes of the sine curve that defines it.



Sample prints of different amplitudes

The samples textures where then evaluated towards preferences of aesthetics, more specifically texture distinction, layer distinction and organic outlook.

All the prints seemed be able to continue without failure, but it may be possible that failure could apppear if the prints would had continued high enough, just as during the first attempt. But for these, the domain of the amplitude for the sine curve was changed to - 2.5 mm- x mm, instead of 0 - x, which may have made every layer to stack upon each other much better.

In the first sample, the texture is barely visible, which removes it as a candidate for the attempt for a full print.

The second sample, each layer is very distinct, while the organic nature of the texture is visible, but still not enough so that print looks jagged.

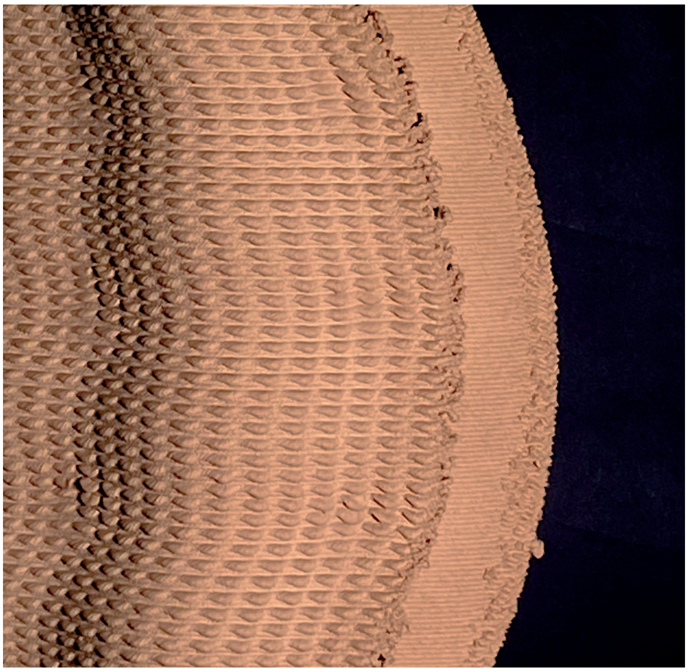
The third print has similar qualities as the second one, but the texture is bit organic

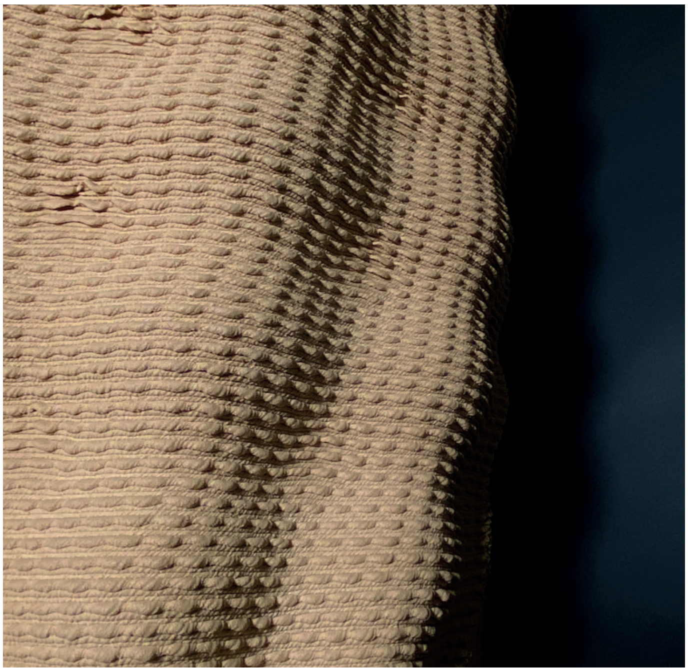
.

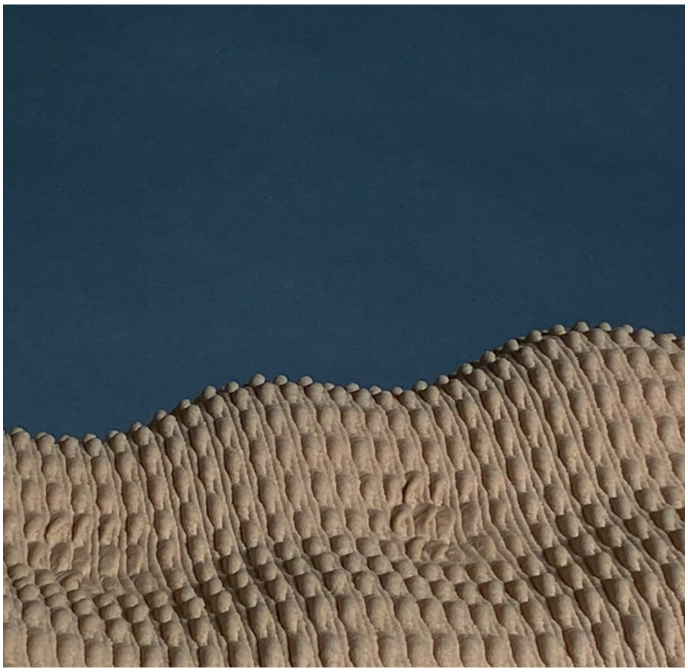
The last attempt the layers seem to start to fall over each other, which removes it as a candidate for the attempt for a full print.

Second full print attempt

The second full print came out as expected, successfully showcasing both the texture and overall form as intended. Fortunately, the margins set before any of the prints were conducted turned out to be sufficient, allowing the pieces to fit together well. By joining them, the intended purpose of wrapping the pillars has been successfully achieved.







This thesis set out to explore how architects can innovatively incorporate digital analytic tools, acoustic theory, digital design, and robotic manufacturing into a cohesive workflow toward a design of a concert hall. The aim was to show how such approaches can benefit the overall design outcome, both in regard to how it is shaped and sound.

It was initiated with the belief in my own ability to explore and connect two seemingly distinct fields: architectural acoustics and robotic fabrication, and letting that investigation guide me toward a united design outcome.

As the work unfolded, it became clear that both fields are niche and technically demanding disciplines that in practice require years of experience to master individually. Attempting to merge the two topics within the scope of a single thesis has been a challenge, but as well, an opportunity. It has pushed me to balance deep technical research and surveying with the architectural thinking I have developed throughout my education, which has led the work to embrace a more speculative and experimental approach of methods rather than precisely illustrate pragmatic architectural solutions.

Robotic manufacturing is a time-consuming process that demands frequent interaction with the robot, developing a conversant relationship between man and machine. The best results, in regard to form and geometry of the printed designs, are reached when one can iteratively test different orders of parameters which defines the final design outcome. Instead, due to limited access to the robot, many of the design choices made for the fabrication were based on prior knowledge from earlier coursework and references, rather than that hands-on experimentation during the work of this thesis. As a result, while the relationship with the robot was not explored to its full potential, the process still revealed significant potential for further development.

Thanks to the experience gained from prior work, well thought out preparations were still able to be made before each conducted session. As a result, the printed outcomes where efficiently produced within a highly precise manner, leading to the samples and prototypes obtaining significant values of both visual and evaluative qualities.

For the acoustic analyses and the simulations made to determine where and how to treat the spatially defining surfaces of the hall, as well as those for the panels themselves, it is important to note that the simplifications made limit the accuracy of the final presented result of design, in terms of achieving a perfectly balanced acoustic outcome for the intended program.

However, by iterating on the process and eventually introducing more precise analytical tools, along with conducting in-lab acoustic tests of the prototypes, a more refined and realistic result could eventually be reached. But this would require additional resources in terms of time and collaborative personnel, preferably with specialists within acoustics and industrial engineering.

An important aspect to highlight in this project is the challenge of handling large and complex data files. Due to the scale of the venue and the decision to design a geometric system that generates individual pieces for the entire auditorium, the project resulted in approximately 1,200 unique meshes. This made it clear that developing a well-functioning system to reduce computational load and minimize waiting times during script execution and simulations, where crucial in keeping the project moving forward within the pace necessary. However, building such a system is a time-consuming task in itself, especially when working with new tools and methods.

Still, since robotic fabrication was a core component of this project, I believe this was an essential challenge to engage with. Without the scale, quantity, and system behind it, one could argue that traditional craftsmanship would have been more suitable than the precision and productivity offered by robotic manufacturing. The system which was designed could however be developed further, particularly through the introduction of more accurately designed mounting solutions for the panels.

This project contributes to the broader discourse on future projects involving both newly built and re-adapted acoustic environments. For cities already having prominent concert halls. The methods exemplified in this thesis could be valuable when adjusting or enhancing the soundscape within such spaces, and by tuning down the volume of applied treatment, the prior visual intent of the architect could in special cases still be maintained.

Halls in need of such upgrades do occur, and efforts to address their acoustic shortcomings are ongoing. A relevant example is the recently completed acoustic refurbishment of Alvar Altos Finlandia Hall in Helsinki, Finland, which early in 2025 reopened after several works of restoration and as well, acoustic treatment (Kuusela, 2025).

Architizer Editors. (2018, February 22). Architectural Details: Herzog & de Meuron's Spectacular Elbphilharmonie - Architizer Journal. Journal. https://architizer.com/blog/inspiration/stories/architectural-details-herzog-de-meuron-elbphilharmonie/

Barthes, R. (1991). The Responsibility of Forms. Farrar, Straus and Giroux, Inc.

Bjelkendal, G. (2009). Göteborgs Alla Biografer—En resa i 100 år. Landsarkivet in Göteborg and Regionarkivet.

Carlén, M., Rolander, M., Gramner, T., & Svensson, L. (2024). Skogsskador i Sverige 2023. Skogsstyrelsen.

Cox, T., & D'Antonio, P. (2016). Acoustic Absorbers and Diffusers: Theory, Design and Application (3rd ed.). CRC Press. https://doi.org/10.1201/9781315369211

Di Salvo, S. (2024). Insights into New Trends and Contemporary Challenges in 3D Printing in Architectural Sector. Engineering Innovations, 8, 43–61. https://doi.org/10.4028/p-VPN0Le

Domellöf-Wik, M. (2007, November 6). Palladium är värdefull. Göteborgs-Posten. https://www.gp.se/palladium-ar-vardefull.5f8308c1-52e5-4a95-bc72-e8a6c30b9771

Engström, E. (2009, February 13). Stängningen av Palladium en ren förlustaffär. Göteborgs-Posten. https://www.gp.se/stangningen-av-palladium-en-ren-forlustaffar.f6214556-ee4e-412f-aedb-3912f8dc1f64

Furberg, K. (2000). Svenska Biografer. Bokförlaget Prisma.

Hansson, E. (2021, March 17). Svensk skog blir till 75 procent kortlivade produkter. Natursidan. https://www.natursidan.se/nyheter/svensk-skog-blir-till-75-procent-kortlivade-produkter/

Huang, Y., Löschke, S., & Proust, G. (2021). In the mix: The effect of wood composition on the 3D printability and mechanical performance of wood-plastic composites. Composites Part C: Open Access, 5, 100140. https://doi.org/10.1016/j.jcomc.2021.100140

Ibrahim, N. N. (2023, August 29). New Delft Blue by Studio RAP. AmazingArchitecture. https://amazingarchitecture.com/installations/new-delft-blue-by-studio-rap

Interesting Times Gang—Jugoso & Loom. (2023). ITG Studio. https://www.itg.studio/concepts/veggro

Kuusela, O. (2025, January 3). Renewed Finlandia Hall Opens to the Public. Finlandia-Talo. https://finlandiatalo.fi/en/news/renewed-finlandia-hall-opens-to-the-public/

Le Duigou, A., Castro, M., Bevan, R., & Martin, N. (2016). 3D printing of wood fibre biocomposites: From mechanical to actuation functionality. Materials & Design, 96, 106–114. https://doi.org/10.1016/j.matdes.2016.02.018

Löfgren, I. (2012, September 27). Palladium nytt modehus. Göteborgs-Posten. https://www.gp.se/ekonomi/palladium-nytt-modehus.c3b711ee-7064-48e2-9742-113d05c90dee

McLaughlin, B. W. (2020, February 3). Ogee Definition and Design. Design Pool. https://www.designpoolpatterns.com/ogee-definition-and-design/

McLaughlin, B. W. (2020, February 3). Ogee Definition and Design. Design Pool. https://www.designpoolpatterns.com/ogee-definition-and-design/

Petersen, G., Ledbetter, S., & Kimberly, S. (1998, July 22). NATIONAL HISTORIC LANDMARK NOMINATION.

Proctor, R. M. (1990). Principles of Pattern Design. Courier Corporation.

Ramaux, J., Ziegler-Devin, I., Besserer, A., & Nouvel, C. (2024). 3D Printing of Wood Composites: State of the Art and Opportunities. Polymers, 16(19), Article 19. https://doi.org/10.3390/polym16192827

SoundLab. (2025). ARUP. https://www.arup.com/services/digital-solutions-and-tools/soundlab/

Svensson, A. (2017, February 2). Bröderna Kanold. Göteborgs historia. https://gamlagoteborg.se/2017/02/02/broderna-kanold/

Tollesson, N. (2012, January 1). Nytt liv i det gamla biopalatset. Lokalnytt. https://www.lokalnytt.se/artiklar/799/nytt-liv-i-det-gamla-biopalatset

Wøhni, T. (2018). Method for classification of restaurant acoustics [Master thesis]. Norwegian University of Science and Technology. https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2564443/20129_FULLTEXT.pdf?sequence=1&isAllowed=

Zumthor, P. (2006). Atmospheres. Birkhäuser Verlag AG.

Figure 1: Örterström. L. (2022). The Kelp Collection by ITG [photograph]. Retrieved October 11, 2024, From Alexander Westerlund, Head of Design at Interesting Times Gang, via inquiry.

Figure 2: Frendberg, M. (2023). Jugoso by ITG and OBOS [photograph]. Retrieved October 11, 2024, From Alexander Westerlund of ITG via inquiry.

Figure 3: De-Vecchi, R. 3D-Printed clay fused with artisanal glazing [photograph]. (2023). Retrieved October 11, 2024, from https://riccardodevecchi.net/DelftPassage

Figure 4: Shculz. M. (2023). Photograph of custom developed gypsum panels [photograph]. Retrieved April 11, 2025, from https://www.elbphilharmonie.de/en/elbphilharmonie-hire#grand-hall

Figure 5 - Unkown. (1920). Photograp of exterior taken in 1920 [photograph]. Found 4 Mars 2025 at https://samlingar.goteborgsstadsmuseum.se/carlotta/web/object/385079

Figure 6 - Photograph of the cinema saloon [photograph] (Lidén & Nyman fd Karnell) Retrieved 6 Mars 2025, from Krister Collin of the Swedish Film institute via inquiry.

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Sound over Matter

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2025