3D printed mycelium-bound bio-based sound absorbing panels

Graduation Report Daphne de Bruin

“There’s a brilliant chemistry to mushrooms, and endless possibilities. We’re just at the beginning of understanding them.”
– Michael Pollan

Titlepage

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Preface

Before I started the master Building Technology at the TU Delft, I worked at an architectural firm where I was given the opportunity to search for existing circular and bio-based building products. By doing this I saw there were not that many options and a lot of products which claim that they are circular are not that circular at all, which triggered me to investigate further. During my master Building Technology my passion for bio-based building materials grew even more, since in this master bio-based and circular building products are a point of interest. Along the road I have done some experiments with salt bricks and bioplastics. Because of this I quickly made the choice that I wanted to research a biobased building material for my graduation.

Another subject I'm interested in is Design Informatics. Because of this subject more and more possibilities are discovered and lots of opportunities lays ahead. For my graduation I want to combine these fields, so create a biobased building product in which Design Informatics plays a significant role. I also love working on hands-on projects so for this research I focus on a material which can be made at home. I am glad I have been given the opportunity to do this research together with Serdar Asut and Martin Tenpierik and I would like to thank them both for the tutoring along this journey.

Abstract

The built environment contributes in a large extend to the global greenhouse gas emissions. With a growing demand for new buildings another view on building products is required. This thesis focusses on creating a biobased sound absorbing panel made from a mycelium bound biomaterial derived from urban waste. The production method for this panel is 3D printing, since with this production method changing demands can be met.
In this thesis six experiments are executed regarding the development of a printable material from urban waste, the sound absorbing properties of the designed panel and 3D printing. To create a printable paste from urban waste, a couple of urban waste materials have been reviewed. Brewery's grain came out as the most promising growth medium for mycelium. This material is mixed with flour and water to create a printable paste.
The impedance tube B&K 4206 is used to discover the acoustic properties. For the 3D printing a UR5 robot in combination with a LDM WASP extruder 3.0 XL is used. To control the robot movement, Rhino with Grasshopper in combination with the plug-in Robots is used. For understanding the acoustic behavior of the panels, multiple variables regarding printing and design parameters have been tested.
The final product of this research is a 3D printed panel which can be made with a mixture of brewery's grain, all-purposes flour, water, and mycelium from the Pleurotus. The sound absorption class is class D, with a peak around 1800Hz at an absorption coefficient around 0.8, which will lower afterward and stabilizes around 0.3.

Keywords: *mycelium, biomaterial, building material, 3D printing, acoustic panel, sound absorption, additive manufacturing.*

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01. Introduction

1.1 Problem statement

The built environment contributes with 55% to the global greenhouse gas emissions. 33% of this finds its origin in the category buildings and 22% in the category infrastructure (United Nation Environment Programme, 2022). With the growing demand for buildings, action must be taken. To decrease the greenhouse gas emissions, shifting to a circular economy might be necessary. The Ellen MacArthur Foundation defines a circular economy based on three principles (n.d.):

- Eliminate waste and pollution
- Circulate products and materials (at their highest levels)
- Regenerate nature

In a circular economy, all products and materials are reused and recycled at the highest level. If virgin materials are required, preference is given to inexhaustible resources.

According to Brand, buildings can be divided into six layers (1995). In a building these layers have different rates of change which results in tearing itself apart. The six layer he describes are the site, which refers to the ground on which the building is situated, the structure, which are the load bearing elements and the foundation, the skin, which includes the exterior surface, the services, in this category electrical devices, pumping, and sprinkler systems are located, and space plan, in which indoor walls, doors, ceilings and floors are situated, and lastly the stuff, which includes furniture and kitchen devices. In figure 1 for all layers a life span is given, which shows after what time the elements usually start to change.

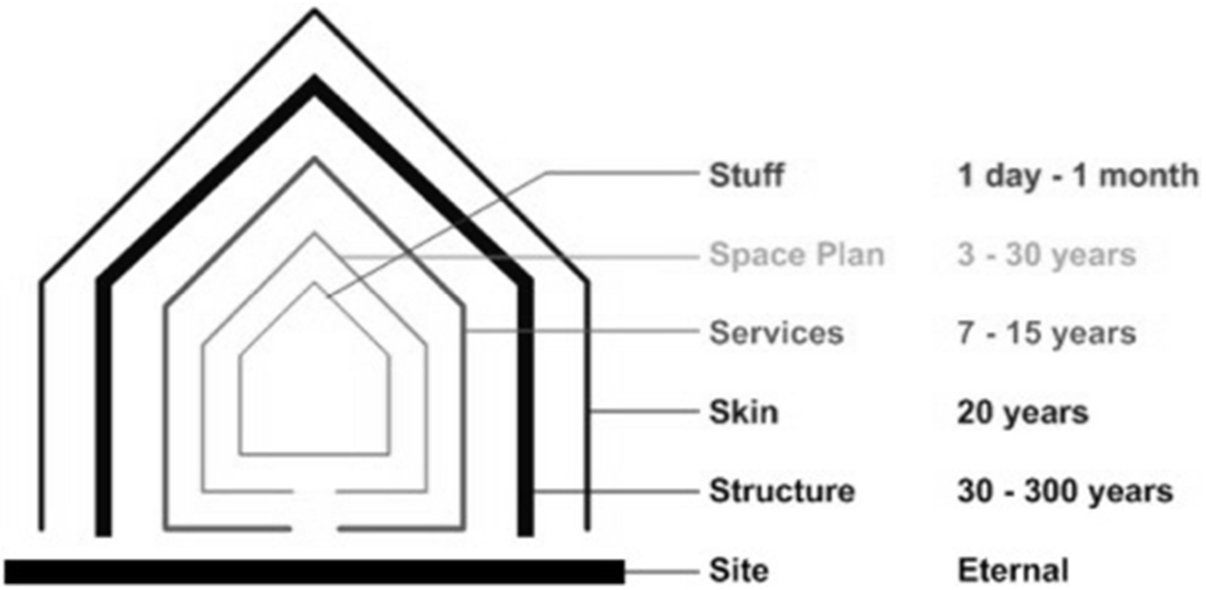


Figure 1 Shearing Layers of Change (Brand, 1995)

To create the biggest impact with this research, an element from the layer stuff will be researched. In this layer, multiple problems can be studied which have a

close relation to human well-being. According to Colenberg et al., the six features influencing human well-being in offices are: layout, furniture, light, greenery, controls, and noise (2020). This research will focus on noise and specifically room acoustics.
There are several elements which contributes to improved room acoustics. Examples of that are wall panels, ceiling panels and furniture. For this thesis wall panels will be taken into account.

To meet the requirements of a circular economy waste products in combination with bio-based materials will be used. In the build environment, a variety of bio-based materials are present, such as Hemp, Bamboo, and Straw. In recent years, living bio-based materials have been added to this list, like algae, seaweed, and mycelium. For those living bio-based materials, not all possibilities are discovered yet. In this research the acoustic properties of mycelium will be researched. One of the main advantages of Mycelium compared to other living materials, is that it grows on various by- and waste products of agriculture and forestry (Meyer et al., 2020). To create a circular product, urban waste products will be investigated as a growth medium for the mycelium.

3D printing will be investigated as the production method. 3D printing is a method in which several layers are placed on top of each other based on a pre-made 3D model (El-Sayegh et al, 2020).
As shown in the figure below, 3D printing can lower the production time, create less waste, eco-friendly structures can be formed, and the productivity can be improved.

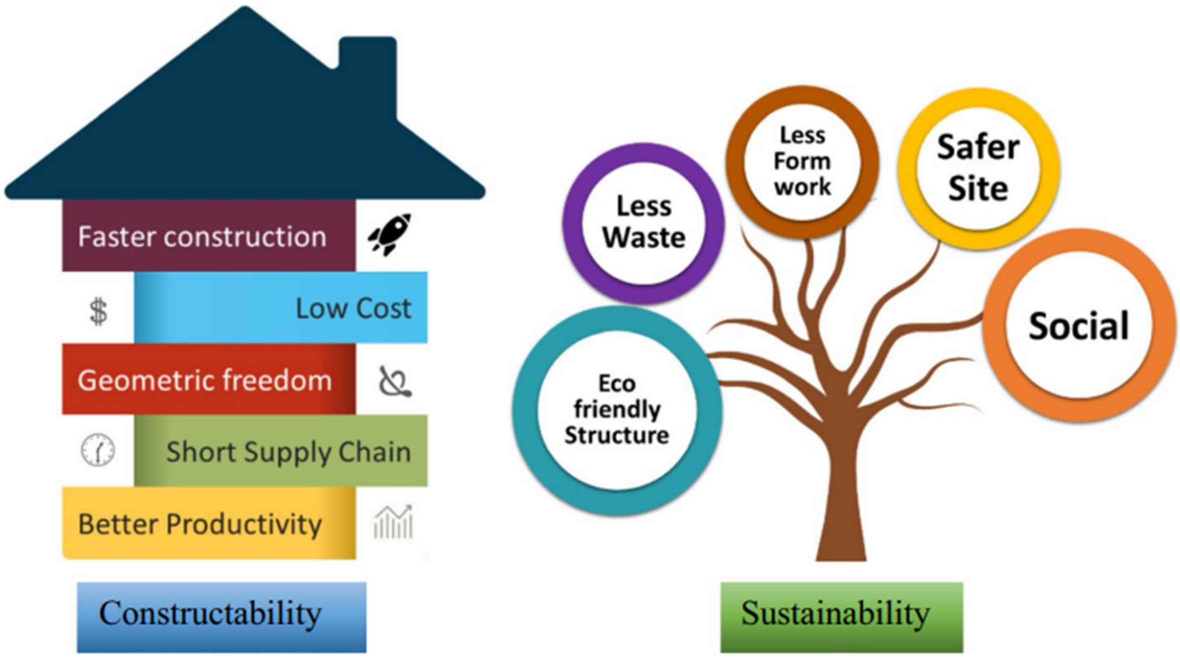


Figure 2 Benefits of 3D printing (El-Sayegh et al, 2020)

In most mycelium-based products, molding is used as the production method. In this research additive manufacturing in the form of 3D printing will be investigated to explore new design possibilities. It is not yet known if 3D printing with mycelium is something which can easily be done. Also, the influence of 3D printing parameters on the acoustic properties have not been researched yet.

1.2 Objective

The main objective for this research is to create a bio-based sound absorbing panel made from mycelium with 3D printing as the production method. The final product is going to be a 3D printed sound absorbing panel made from a mycelium bound biomaterial which includes urban waste. For this, the research can be divided into three subcategories: the material, the acoustic panel, and 3D printing.

The material

In the category of the material, multiple materials and mixtures are tested. The focus for the material lays on urban waste products. The goal for this is to create a paste based on urban waste on which mycelium can grow.
The boundary conditions in this category are:

- Common urban waste will be used
- Store and market bought fungi will be used
- All materials need to be non-toxic

Acoustic panel

To understand the acoustic properties of the material, multiple variations on the product will be made focusing on print and design parameters. The goal for this category is to determine what variable influences the sound absorbing properties and to what extent.
The boundary conditions in this category are:

- Sound absorbing panels for indoor use will be used
- The final product will be tested on sound absorbing performances, other material properties will be omitted
- The impedance tube B&K 4206 will be used
- The aim for the absorption coefficient is class C according to the NEN-EN-ISO 11654:1997 en

3D printing

The production method for the panels will be 3D printing. For this a robot will be used in combination with a paste extruder. Before the material with be 3D printed with the robot, hand extrusion and electrical extrusion will be explored. The goal in this category is to print prototypes which can be tested on the sound absorbing properties
Boundary conditions in this category are:

- The UR5 Robot will be used
- The LDM WASP Extruder XL 3.0 will be used

1.3 Research questions

The main research question for this thesis is:

How can a sound absorbing panel for indoor use be 3D printed with a mycelium bound biomaterial which finds its origin in urban waste?

Sub-questions:

- On which type of commonly available urban waste can mycelium grow?
- How can a mycelium bound bio-product be 3D printed?
- How do 3D printing parameters influence the acoustic properties?
- How do the type of substrate, the thickness, and the growth time of mycelium influence the acoustic performances?
- What are the design possibilities and constraints by using 3D printing as a production method for the developed material?

Background questions

- What is mycelium?
- What reference projects are done with this material and production method?
- How can biobased materials be turned into a 3D printable paste?
- How can the acoustic properties of a material be measured?
- How does cold 3D extrusion printing work?
- How can a robot be programmed by using offline programming applications?

1.4 Approach and methodology

This thesis consists of theoretical framework, six different experiments and a final design. The research set-up is as followed:

Theoretical framework

What is mycelium?
What reference projects are done with this material and production method?

Experiment 1: Mycelium growth

Can mycelium grow on urban waste?

Experiment 2: Extrudability

How can biobased materials be turned into a 3D printable paste?

Experiment 3: 3D printing with syringe

How can a mycelium bound bio-product be 3D printed?

Experiment 4: 3D printing with paste extruder

How can a mycelium bound bio-product be 3D printed?

Experiment 5: Acoustic properties

What are the acoustic properties of the developed material?

Experiment 6: Influences acoustic properties

How do 3D printing parameters influence the acoustic properties?
How do the type of substrate, the thickness, and the growth time of mycelium influence the acoustic performances?

Panel design

What are the design possibilities by using 3D printing as a production method for a sound absorbing panel made of mycelium?

For each experiment, the following layout will used:

1. Introduction
2. Methodology
3. Results
4. Discussion and conclusion

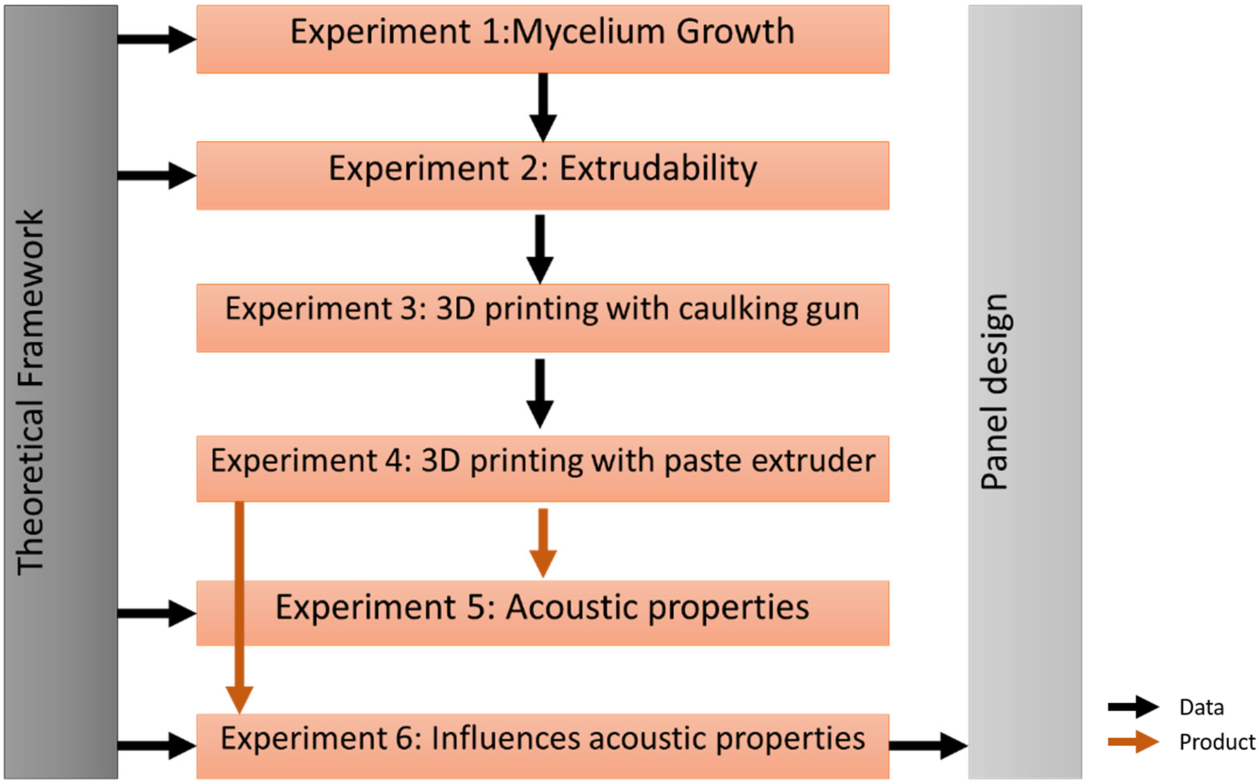


Figure 3 Methodology

The research and experiments on the different topics will be executed in a linear workflow since information of the previous experiment is an input for the following experiment. As shown in the figure above, experiment 1, 2, and 3 and 5 provide information for the following experiments, while experiment 4 provides physical material for experiment 5 and 6.

To execute these experiments some equipment is required:

- HBM Electric Kit Syringe 18 Volt
- UR5 Robot arm, with the LDM WASP Extruder XL 3.0
- Impedance tube B&K 4206

1.5 Planning and organization

In the figure below an overall planning, starting from P2, is given.

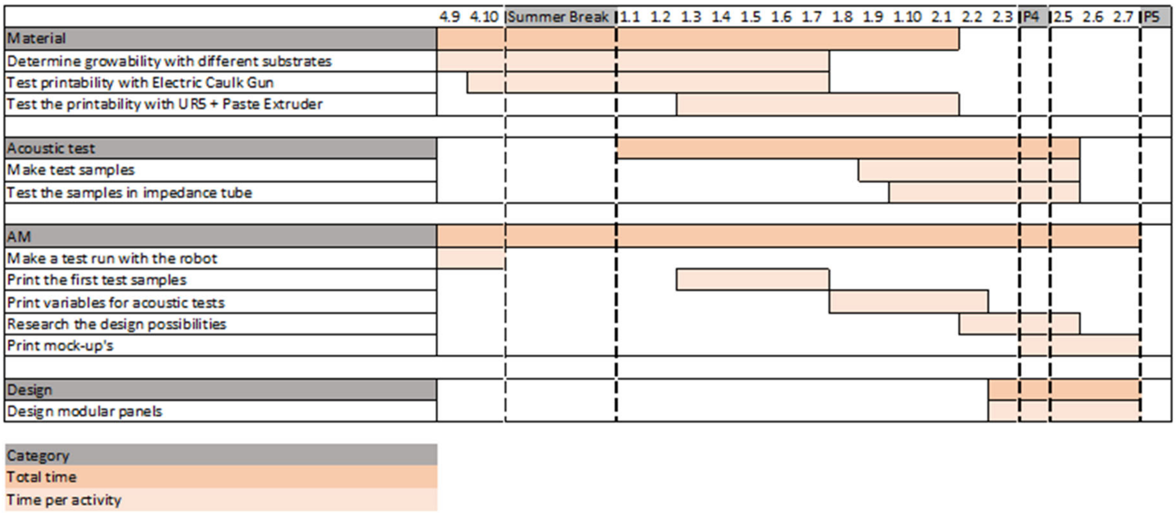


Figure 4 Planning starting from P2

This research will be executed commissioned by the TU Delft. The thesis is part of the master track Building Technology within the master Architecture, Urbanism and Building sciences. Within the master track, multiple research fields can be chosen. For this specific thesis, Design Informatics and Climate Design are chosen as main research field. Because of that, the research will be done with guidance from experts in these fields. The guiding experts are Serdar Asut from the chair of Design Informatics, and Martin Tenpierik from the chair of Climate Design.

1.6 Relevance

Material scarcity is a growing problem, and the CO2 emissions becomes a bigger discussion point. By using traditional building materials with high CO2 emissions those problems will increase. To look at bio-based alternatives for current building products, an example can be giving on how to work with those materials. People will see the possibilities, which might boost the development of new bio-based products. On the scientific framework, this research can contribute to both material research on mycelium, of which not all properties are known/captured, and on the knowledge of how design informatics, in specific 3D printing, can contribute to the process of creating new bio-based building products.

02. Theoretical framework

In this chapter the objectives of this research will be further discussed. This will be done by literature and reference study. The research is divided into three main subjects which are Mycelium, Acoustics, and Digital Fabrication.

Mycelium
In this paragraph the main material used for this thesis will be described by answering the following questions:

What is mycelium?
How does mycelium grow?
What type of mycelium can be used best?

This paragraph also discusses the different types of mycelia which can be used in this research and gives an overview of the urban waste which is easily accessible inside Dutch cities.

Acoustics
This paragraph will discuss the basic acoustics principles, the different types of acoustic absorbers and the factors which influence the acoustic properties. The chapter also helps answering the question:

What reference projects are done with this material and production method?

This will be done by projecting some reference projects related to the type of material and the specific function.

Digital Fabrication
In this paragraph an introduction will be given to digital fabrication by answering the question:

What reference projects are done with this material and production method?

2.1 Mycelium

2.1.1 What is mycelium?

Merlin Sheldrake described in his book '*ENTANGLED LIFE How fungi make our worlds, change our minds & shape our futures*' that mycelium is everywhere around us and that we cannot live without it. It makes plants be able to grow, helps digest the death and grows into eatable mushrooms (Sheldrake, 2021). Mycelium is the vegetative part and the root structure of fungi (Islam et al, 2017). The roots can become kilometers long and are able to feed on a variety of materials which they find on their journey. Mycelium is a fast-growing biomaterial.

To understand how mycelium works, a deeper knowledge on the life cycle of fungi is required. Fungi are fruiting bodies of fungal mycelium. As shown in the figure below, the fruiting body, also known as fungi, produces spores. These spores grow into longer hyphae. Hyphae grows in one direction but has the ability to branch and cluster with other hyphae. Once the branching and clustering has happened, a mycelium network has formed. Out of this network new fungi are grown, after which the cycle starts again (Meyer et al., 2020).

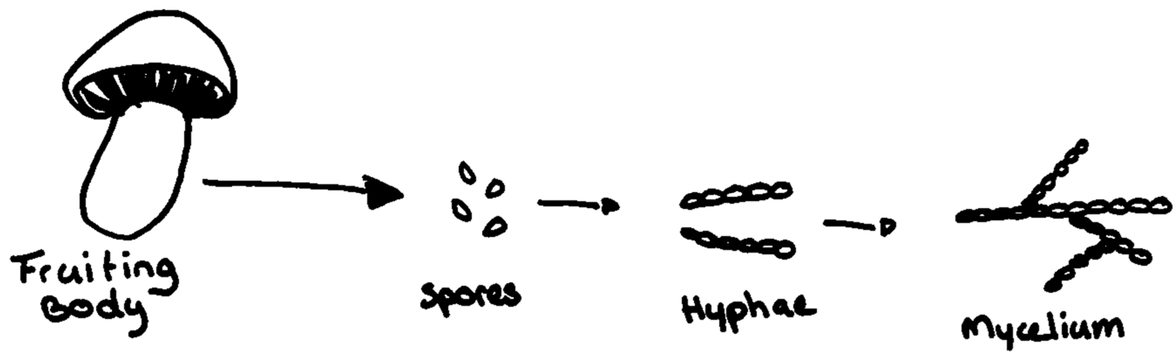


Figure 5 Fungal mycelium (Author)

In recent product developments mycelium is being used as a binder, as packaging, and for acoustic panels (Shakir et al., 2020) (Abhijith et al., 2018)(Pelletier, 2013). Another example of how mycelium can be used is the Loop Cocoon from Loop Biotech B.V. They made a coffin from mycelium, which will be placed under ground, after which the material will turn into fungi again by digesting the human body and the coffin itself (*Loop Cocoon | Levende Doodskist | Bob Hendrikx*, n.d.).

2.1.2 Different types of fungi

There is a wide variety of fungi all over the world. Each type of fungus creates their own unique mycelium, with their own growing speed, preferred temperature, and medium they grow on best. In the figure below, a list of most common fungi is shown in the Dutch name, Latin name, the growing speed, the growing medium and the temperatures in which they grow best.

Dutch name	Latin name	Growing speed	Growing medium	Growth temperature
Shiitake	Lentinula edodes	35-80	Hardwood	21-27
Grijze Oesterzwam	Pleurotus ostreatus	12-21	Variety	24
Roze Oesterzwam	Pleurotus Djamor	7-10	Variety	24-30
Blauwe Oesterzwam	Pleurotus ostreatus var. columbi	12-21	Variety	24
Gele Oesterzwam	Pleurotus cornucopiae var. Citrir	10-14	Variety	21-29
Nebrodensis Oesterzwam	Pleurotus Nebrodensis	10-15	Hardwood	12-15
Bleke Oesterzwam	Pleurotus pulmonarius	8-14	Variety	24-29
Iepoesterzwam	Hypsizygus ulmarius	14-21	Hardwood	21-27
Konings Oesterzwam	Pleurotus Eryngii	12-16	Variety	24
Tarragon Oesterzwam	Pleurotus euosmus	7-14	Variety	21-27
Loin's Mane	Hericium erinaceus	10-14	Hardwood	21-24
Stammetjesstekelzwam	Bankeraceae	10-14	Hardwood	21-24
Reishi Rood	Ganoderma lingzhi	10-20	Hardwood	21-27
Reishi Zwart	Ganoderma neo-japonicum	10-20	Hardwood	21-27
Cordyceps	Cordyceps	10-14	Rye, Brown Rice, Flour	21-24
Chaga	Inonotus obliquus	-	-	-
Fluweelpootje	Flammulina velutipes	14-18	Variety	21-24
Beukenzwam	Hypsizygus marmoreus	30-45	Hardwood and softwood	21-24
Bundelzwam	Pholiota nameko	14	Hardwood	24-29
Melkwitte paddenstoel	Calocybe Indica	10-14	Variety with vermiculite and coco coir	24-30
Eikzwam	Buna Shimeji	14-30	Hardwood and softwood	21-24
Gewoon Elfenbankje	Trametes versicolor	14-21	Variety	24-29
Zwavelzwam	Laetiporus sulphureus	25-35	Hardwood	24-27
Witte zwavelzwam	Laetiporus cincinnatus	25-35	hardwood	24-27
Cantharel	Cantharellus cibarius	-	-	-

Figure 6 Overview fungi mycelium based on Tuintje van Adam (2022)

The research will be done in a period of three semesters, which requires a fungus with a short mycelium growth time. The growth medium used for this experiment consists of urban waste, which can be grouped under variety of the growth medium in figure 6. The ideal fungus for this experiment will have a fast mycelium growing speed and can grow on a variety of growing mediums. The fungus that meets the requirements are a variety of Pleurotus (Oesterzwam), Flamming Velutipes (Fluweelpootje), and Trametes Versicolor (Gewoon Elfenbankje).

To be able to execute multiple experiments, the Pleurotus will be used for this research. The Pleurotus is a fungus which can be bought in supermarkets, which makes it easy to obtain. For the experiment the spores directly form the fungi will be used.

2.1.3 Urban Waste

As mentioned in the previous paragraph, mycelium can use a lot of materials as food source ranging from wood to dead animals to vegetables. In this paragraph the available urban waste products will be discussed. In a future experiment for this urban waste products research will be done on the potential to grow mycelium.

Urban life creates a lot of different waste streams which are not all circular. There are multiple initiatives going on already making urban life more sustainable. Some work in collaboration with restaurants, hotels, and supermarket to reduce the food waste. To not interrupt in these initiatives, food waste will be left out of the research.

Looking at the main businesses present in cities; five categories can be formed:

- Catering industry
- Shops
- Building industry
- Production industry
- Offices

Catering industry:
The catering industry is one of the biggest sectors in Urban life, varying from restaurants, bars and bakeries to coffee bars and sandwich shops. In this sector the biggest waste streams are plastic, cardboard, food leftovers, squeezed oranges, and grinded coffee.

Since the aimed material needs to be biodegradable, plastic from the catering industry will be left out of the research since not all plastic is biodegradable. Also, food leftovers not considered. From this industry, cardboard, squeezed oranges, and grinded coffee will be used as potential growth medium.

Shops:
Shops produce lots of waste, mainly originated from packaging, which consist of both plastic and cardboard. Cardboard will be used from this industry.

Building industry:
The building industry is an industry which involves a lot of waste, from both packaging and product leftovers. In this industry most materials are not bio-based, which results in the decision that no waste products from the building industry will be used.

Production industry:
Since recent years, food and beverages are valued more when produced locally. One of the shifts from big factories to local small scale production lines is in the field of beer brewery. A growing amount of beer breweries are rising in cities. In Leiden alone there are three active breweries. Breweries have as a waste product a big amount of brewery's grain. This is a mixture of all the grains used to produce the beer. Since mycelium can grow on grains, this product might be promising to include in the research.

Offices:
The waste products of offices are mainly used coffee, coffee cups, paper, and cardboard. Paper is one of the products with a closed recycle circle. Used coffee, coffee cups, and carboard will be used for this research.

To conclude the following waste products will be used to experiment with:

Figure 7 Waste products: Squeezed oranges, Grinded coffee, Cardboard, Brewery's grain

Carboard already has a well-developed recycling process, which may conclude in leaving this product out of the research.

2.2 Acoustics

This research focusses on acoustic panels. The term acoustics includes lots of aspects varying from indoors to outdoors and room separation to room based. For this study, room based interior panels will be used.

2.2.1 Acoustic principles

Before the acoustic properties of a new material can be determined, it is important to understand some acoustic principles.

In general, there are four ways sound interacts with materials (B. Akoestische theorie, n.d).

Figure 8 Interaction with sound: 1. Transmission, 2. Absorption, 3. Reflection, 4. Diffusion (Author)

1. Transmission
   When sound is transmitted, it means that the sound has travelled through a surface and comes out of the other side. An example for this is the sound cars outside produce which can be perceived inside. Also, in a building itself transmission can take place from one room to the other.

2. Absorption
   Sound is completely absorbed when incoming sound it not leaving the material anymore. In practice sound is almost never completely absorbed, except in the anechoic room at TU Delft.

3. Reflection
   Sound which reaches a surface and does not get absorbed or transmitted by the material of the surface will be reflected.

4. Diffusion
   Diffusion is when sound is reflected in different directions, which lowers the intensity.

The four ways of how sound interacts with a material never happen on their own. Acoustic products, like acoustic panels, ceilings, floors, carpets, and acoustic insulation consists of multiple values according to determine their acoustic properties. Those properties are transmission coefficient, absorption coefficient, reflection coefficient, and scatter coefficient. This report focusses on the absorption coefficient.

Absorption coefficient:

The absorption coefficient is a value which varies from 0 to 1. At 1 the sound is completely absorbed and at 0 no sound is absorbed, which means that the sound is completely reflected. The absorption coefficient is different for each frequency [Hz].

There are different types of sound absorbing panels (City Soundproofing, n.d.):

- **Porous absorbers**
  Examples of porous absorbers are carpets, fibrous mineral wool, and glass fibers.
- **Membrane absorbers**
  An example for this type of absorber is a plasterboard wall.
- **Resonance absorbers**
  Examples of this are Helmholtz absorbers and micro perforated panels.

2.2.2 Factors influencing sound absorption

The sound absorbing properties of a porous material are influenced by several factors, these factors are the fiber size, the thickness, the density, the porosity, the tortuosity, the resistance of air flow, the thermal characteristic length, and the viscous characteristic length (Kalauni & Pawar, 2019). This research focusses on the fiber size, the thickness, and the density.

2.2.3 Reference projects

In this paragraph, several references will be described with their acoustic properties.

Walter & Gürsoy

Walter and Gürsoy (2022) did an evaluation study about the acoustic properties of panels made from mycelium which was grown on agricultural waste products. In Figure 9 and Figure 10, the overall sound absorption coefficient is shown for several combinations. Since uneven mycelium growth was present in the samples, the samples were split in two categories: low to medium frequencies and high frequencies. To address the combinations, abbreviations were used, which stand for: FC: Fine Cardboard Samples, SC: Shredded Cardboard, FP: Fine Paper, EM: Ecovative Mixture, SN: Shredded Newsprint. The L and H in the abbreviations stands for Low and High frequency.

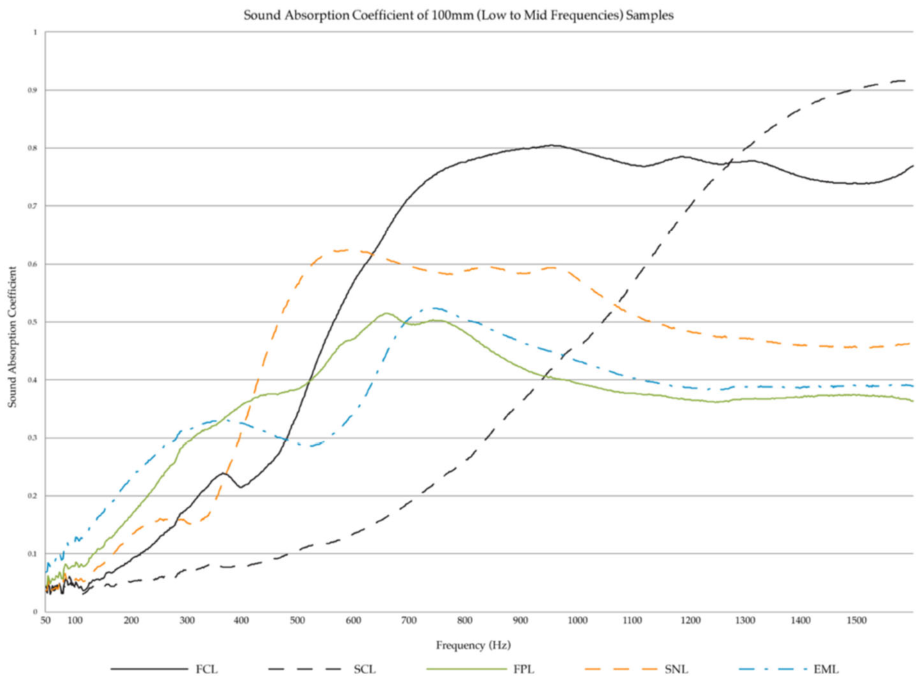


Figure 9 Sound Absorption Low to Mid Frequency Samples (Walter & Gürsoy, 2022)

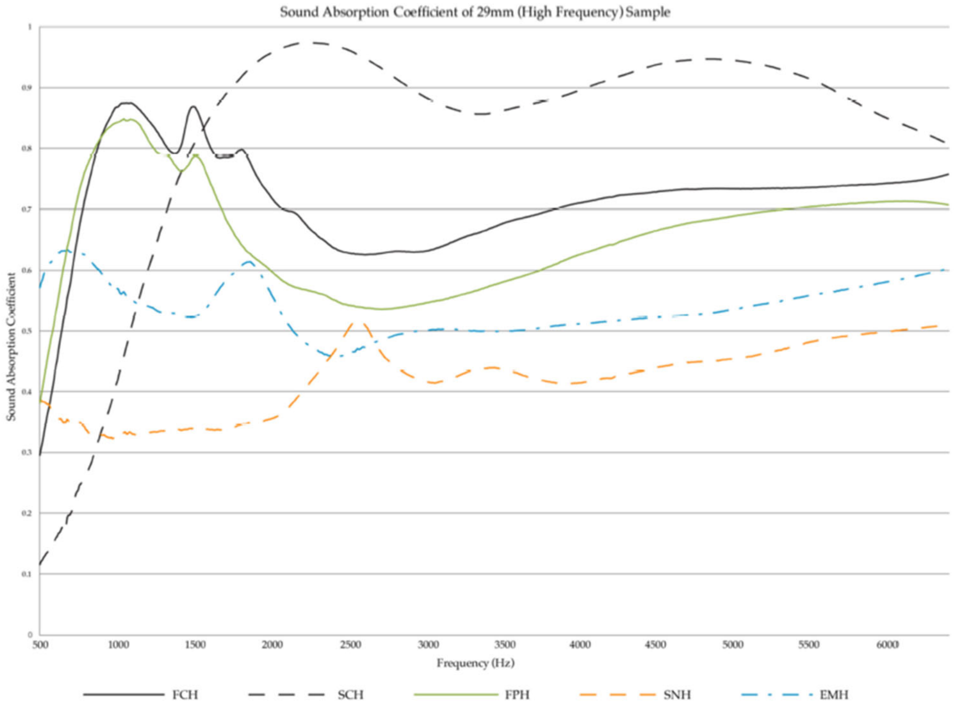
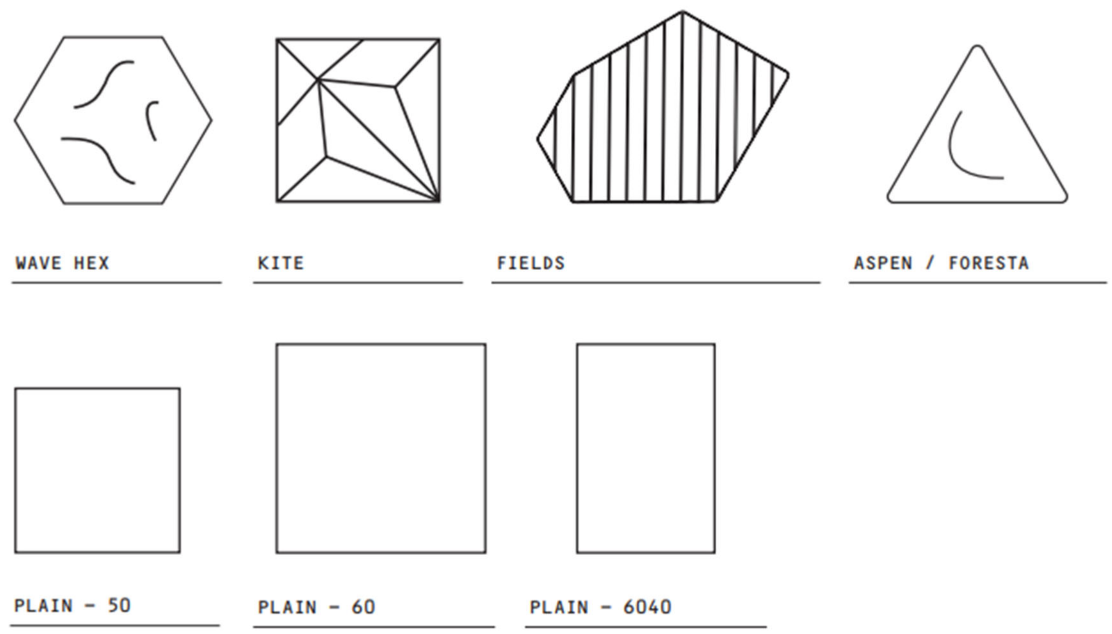


Figure 10 Sound Absorption High Frequency Samples (Walter & Gürsoy, 2022)

The figures show that the samples with a high growth frequency experience a shifting in the peak at the low frequencies. It also shows an overall better sound absorption in the higher frequencies. Because of this, the conclusion can be made that mycelium growth has a positive influence on the sound absorption coefficient.

Mogu

At Mogu (Mogu.bio, 2022), they created acoustic panels with different properties made from mycelium. Their production method is molding. In the graphs below, the acoustic properties are shown. The names given are the types of panels. The panels have different surface patterns and shapes. For these tests, except for the ASPEN, the Impedance Tube is used as a measuring tool. The ASPEN panel is measured using the Foresta set-up.



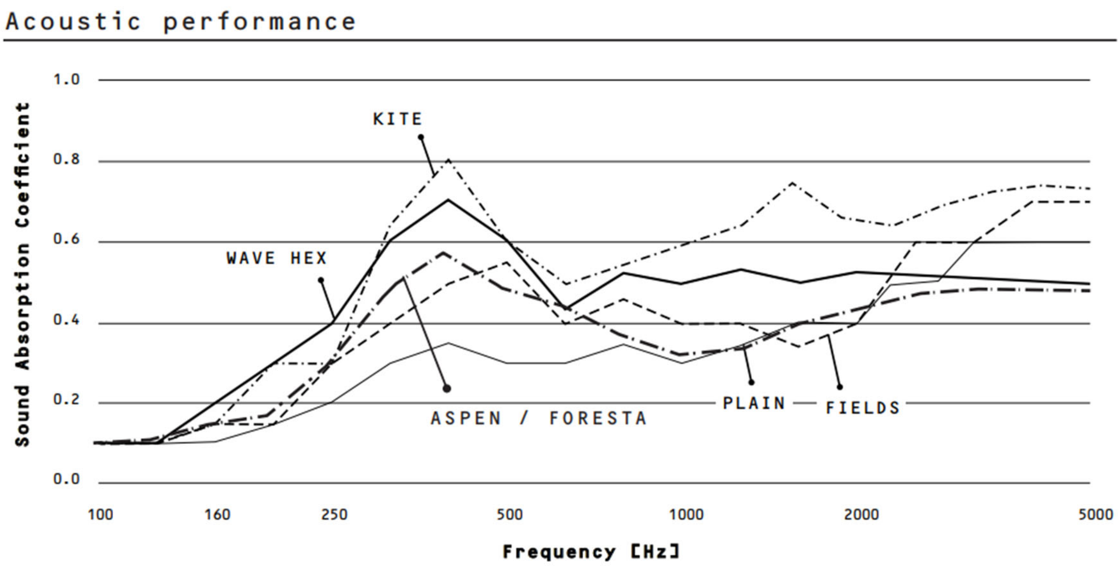


Figure 11 Datasheet Mogu Acoustic Panels (Mogu.bio, 2022)

This graph presents the Kite as the best sound absorber. This can be caused by the surface pattern, which create diffusion, or because of the varying thickness.

Previous Master Thesis

In a previous master thesis, Jurjen Vos researched the acoustic properties of mycelium grown on different substrates (Vos, 2020). To test the acoustic properties the impedance tube is used with samples with a thickness of 4cm. In the figure below the results of these tests are shown with on the side an index with the used substrates.

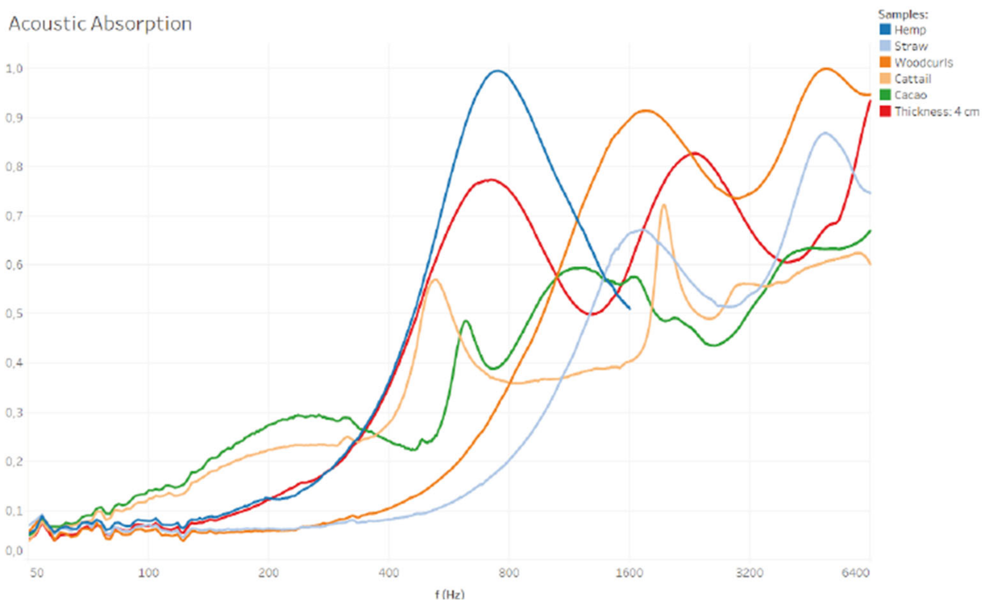


Figure 12 Acoustic Absorption for Different Growth media (Vos, 2020)

The substrate performing best at lower frequencies is Hemp, unfortunately this measurement stops at a frequency of 1600Hz, which does not show the acoustic performances on the higher frequencies. At the higher frequencies Wood Curls perform best.

2.3 Digital Fabrication

In this paragraph reference projects regarding 3D printing with mycelium are described.

2.3.1 Reference projects

Blast Studio

Biological Laboratory of Architecture and Sensitive Technology, Blast Studio (n.d.) made a product named Mycelium Column. This column is made from a 3D printed mixture which is bound by mycelium. For the mixture they used already used coffee cups, which they shredded, boiled, added water to it and finally added mycelium. They transformed it into an extrudable paste after which they used cold extrusion 3D printing to print it into a column. After the print was made, they stored the pieces in a dark room, where the mycelium was able to grow. The column was made from six different elements which they put together after the mycelium had grown. The mycelium on its turn connected the different parts.

Figure 13 Lovely Trash Column (Tree Column, n.d.)

Studio Klarenbeek & Dros
At studio Klarenbeek & Dros (2013), multiple projects with mycelium are executed. They focused on printing an outer shell which they filled with substrate and mycelium, after which the mycelium gave strength to the printed piece. The 3D printed chair is one of their projects and has won a couple of awards.

Figure 14 Mycelium Chair (Fairs, 2013)

HBBE Lecture
HBBE had a series of lectures on the topic of mycelium. One of these lectures was about 3D printing with mycelium (HBBE, 2021). In this lecture three different speakers form three different companies gave a short lecture about how they used mycelium in their 3D printing project. The presentations were given by Natalie Alima from BIOLAB/ Rmit, Claudia Colmo from CITA, and Ana Goidae from BioDitigal matter lab.

Claudia Colmo showed how they used different recipes to create a double walled object which was infused by mycelium at CITA. Inside the walls they placed a growing medium to see how the mycelium would respond. They stored the object in a glass box to observe what happened. The object started to produce mycelium and eventually, with some adjustment of the environmental values, formed fruiting bodies. For this research the same robotic set-up, available at TU Delft, is used.

3D printing using Bamboo
Soh et al. (2020) developed an extrudable material by using bamboo as a main source. They combined the Bamboo with chitosan and mycelium. For this experiment a syringe is used for extrusion. They concluded that this mixture can be promising for creating building materials because of its mechanical properties and its buildability.

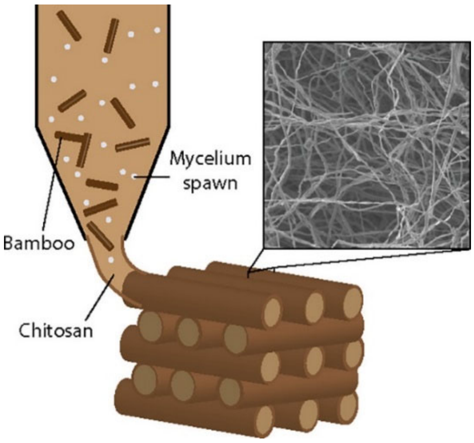


Figure 15 3D printing with bamboo (Soh et all, 2020)

PULP Faction
In this project Goidea et al. from Lund Universiy explored the ability of mycelium to repolace thermosetting plastics or synthetic binders. The mixture used exists of lignocellulosic biomass. For the fabrication a Vormvrij Lutum v4 is based on air pressure and rotation (Goidea et al., 2020).


Figure 16 PULP Faction (Goidea et al., 2020)

03. Mycelium Growth

Experiment 1: Mycelium Growth

1.1 Introduction

In this experiment several urban waste products and materials found at home will be used as a source to gain a better understanding on how mycelium grows. This experiment answers to the question:

On which type of commonly available urban waste can mycelium grow?

1.2 Methodology:

The Urban Waste products researched in this experiment are:

- Squeezed Orange
- Cardboard
- Brewery's Grain
- Grinded Coffee

Instead of using squeezed oranges, in this experiment mandarin peel will be used. Next to that cotton and wood chips are added.

For the mycelium, store bought biological Oyster Mushrooms are used.

Execution plan

First, all the different substrates are being boiled to ensure a sterile environment. Secondly, the spores of Oyster Mushrooms are collected. This is done by removing the hyphae and spores from the stems and underneath the cap of the mushrooms by using a disinfected knife.
Thirdly, the containers in which the mixtures are stored are sterilized by using boiling water.

Once the substrate is sterilized, the substrate is placed in the disinfected containers. On top of this, the removed hyphae and spores are placed. To make sure no bacteria will enter the container, the containers are covered with an airtight lid.

The boxes are placed in a dark space since literature shows that this has a positive effect on the growth (Weitz et al., 2001). To make sure enough oxygen is present, the containers will be opened once every day.

Measures taken

The measures taken from this research are:

- The visual growth: For this, pictures are taken every day at 5 o'clock with an iPhone camera to visually assess the growth and speed of growth of the mycelium
- The smell: For this, every day the containers are opened at 5 o'clock and the smell is assessed by using a human nose
- The presence of other molds: For this, every day at 5 o'clock visual inspection is done of the presence of other mold on the substrate

1.3 Results of the measurements

Experiment A: Mandarin peel

For this experiment mandarin peel is cut in smaller pieces.

Figure 17 Experiment A: Day 4, 5, 8

Experiment B: Wood chips and Cotton

For this experiment wooden sticks are cut in smaller pieces and cotton pads are soaked in cold water, after which they are wringed and ripped apart.

Figure 18 Experiment B: Day 1, 3 and 5

Experiment C: Cardboard

For this experiment carboard from packaging is used.

Figure 19 Experiment C: Day 1

Experiment D: Brewery's Grain

For this experiment brewery's Grain from Pronck Brewery in Leiden is used.

Figure 20 Experiment D: Day 1, 2 and 4

Experiment E: Brewery's Grain grinded

For this experiment also Brewery's Grain from Pronck Brewery in Leiden is used but the difference between experiment D is that the grains are boiled before grinding.

Figure 21 Experiment E: Day 1, 2 and 4

Experiment F: Grinded coffee

For this experiment grinded coffee received from the espresso bar at the faculty of Architecture, TU Delft is used.

Figure 22 Experiment F: Day 1, 2 and 4

1.4 Discussion of the results

Analysis

Experiment	Mycelium growth	Smell	Other molds present
A: Mandarin Peel	Present	An extreme mandarin smell, which smell rotten	Present
B: Wood Chips and Cotton	Present	No smell present	Not present
C: Cardboard	Not present	Smells like wet paper, not unpleasant	Present
D: Brewery's Grain	Present	Smells like old milk	Not present
E: Brewery's Grain Grinded	Present	Smells like old milk	Not present
F: Grinded Coffee	Present	Smell like coffee, not unpleasant	Present

Looking at the analysis, some conclusions can be made:

- Mandarin might be a good growth medium but comes with the risk of creating other molds.
- Mandarin produces a strong smell.
- Cotton and woodchips can grow mycelium without forming other molds.
- Cardboard, in this setting is not able to grow mycelium or any other molds.
- Brewery's grain is able to produce mycelium without forming other molds.
- When brewery's grain is grinded, more, and faster mycelium growth is visible, without forming other molds.
- Grinded coffee can grow mycelium but comes with the risk of growing other molds.

Limitations

- Only visual inspections are taken for the mycelium growth.
- Oyster Mushroom is the only source of spores/hyphae used for the research
- No measures are taken on the moisture inside the containers

Conclusion

The conclusion of this experiment is that wood chips and cotton, and brewery's grain are the only materials which are able to grow mycelium without creating other molds. Since wood chips and cotton were only used to form a better understanding of the mycelium growth, these materials will not be further researched. Looking at the type of produced mold, grinded coffee forms cobweb mold, which is created by a too wet environment. This material will be further researched in the next experiments with moisture as a point of interest.

04. Extrudability

Experiment 2: Extrudability

4.1 Introduction

To understand which additive might work best for 3D printing purposes, this experiment examines different additives on their ability to create a paste. For this, additives which find their origin in food binding purposes will be used. As a result of the previous experiment, brewery's grain and grinded coffee will be used for further research. This experiment limits to brewery's grain since the focus is on the additives and not on the main ingredient. The experiment gives an answer to the research question:

How can mycelium be turned into a 3D printable paste?

4.2 Methodology:

Materials

Brewery's grain:

For this experiment brewer's grain from Brewery Pronck is used. The grains are first dried in the oven for a couple of hours to kill the egg white bacteria which created the strong smell in the previous experiment. After that, the grains are grinded by using a coffee grinder to create an extrudable fiber size.

Figure 23 Dried and grinded brewery's grain

For this experiment the following binding agents are used:

- Self-rising flour
- Baking soda
- Whole grain buckwheat flour
- Wheat flour
- Potato starch
- Patent flour
- Cornstarch

Others:

- Tap water
- Ceramic bowls
- Metal spoon
- Plastic syringe

Experiment set-up

This experiment took place on a kitchen worktop. Bowls are used to mix the materials in, and a metal spoon is mixed to determine the ratio and to mix the material. A plastic syringe is used to extrude the paste.

Figure 24 Experiment set-up

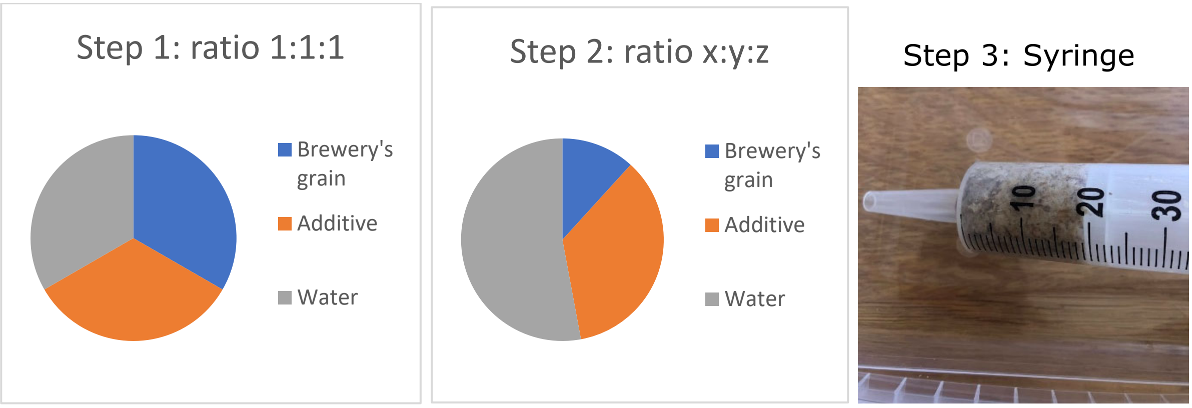


Figure 25 Steps Experiment 2

4.3 Results of the measurements

The first step of this experiment is to mix all the binders with water on a ratio of 1:1. The image below shows the test setup, together with the mixed substances.

Once the materials were mixed, the ratio was changed to see if the material was able to become a printable substance

Additive	Ratio Brewer's grain:additive:water
Self-rising flour	3:1.5:9
Baking soda	1:1:1
Whole grain buckwheat flour	1.5:1.5:4
Wheat flour	1.5:1.5:3
Potato starch	1:1:1
All-purposes flour	2.5:1.5:4
Cornstarch	3:1:1.5

Self-rising flour, all-purposes flour, wheat flour, and whole grain buckwheat flour are used in the next phase of the experiment.

Figure 26 Mixtures 1. All-purposes flour, 2. Wheat flour, 3. Whole grain buckwheat flour, 4. Self-rising flour

4.4 Discussion of the results

After mixing the materials at the first step in the experiment already two additives were eliminated. These were baking soda and potato starch since they created a mixture which formed a clustered material which does not allow to be extruded. When pressing a force on the material, only small drops of water were extruded.

During the second step, some materials formed an adhesive mixture, which is required for extrusion. Other materials created a crumbling substance in which the water was not able to merge.

The materials which were selected to enter the last phase of this experiment were All-purposes flour, wheat flour, whole grain buckwheat flour, and self-rising flour. At this final stage the adhesiveness of the material was tested.

As visible in figure 26, all-purposes flour and wheat flour create a thick sticky mixture which stays intact after extruding. The other two materials were difficult to extrude and created a layer of water around the print.

Limitations

- The ratio in which the materials have been mixed are determined by trial and error. Because of this, some materials might function better or worse in a different ratio.

The conclusion of this experiment is that all-purposes flour and wheat flour are most suitable for creating an extrudable paste and will be used in the next experiments.

05. 3D printing

Experiment 3: 3D printing with a syringe

Experiment 4: 3D printer with a paste extruder

5.1 Introduction

In the previous chapter, a printable paste has been formed. In this chapter two experiments regarding the printability of the paste will be described. The first experiment focusses on 3D printing with an electrical caulking gun, for the second experiment a paste extruder which is attached to a robot will be used. These experiments will answer the following research questions:

How does cold 3D extrusion printing work?
How can a mycelium bound bio-product be 3D printed?

Since in this chapter two experiments will be executed, this chapter is divided into two sub chapters:

- 3D printing with an electrical caulking gun
- 3D printing with a paste extruder

Both paragraphs will describe the methodology, the derived results, and discuss the results. At the end of this chapter an overall conclusion on both experiments will be given.

5.2 3D printing with a caulking gun

The first experiment of this chapter contains 3D printing with a caulking gun. For this experiment two different materials are used which are brewery’s grain and grinded coffee in combination with all-purposes flour.

5.2.1 Methodology

These experiments were done by using an electrical caulking gun. Two variations were made to see the growth process. For the first sample Brewery’s Grain is used, for the second sample Grinded Coffee is used. Both samples consist of flour, water, and mycelium from store bought Oyster Mushrooms.

To create a sterile environment, alcohol is used to clean the storage box and the container which is used to mix the ingredients. The samples were printed directly into the containers and were closed with an air-tight lid.

First the materials are mixed inside a bowl, after which the mixture will be transferred to the cartridge. This cartridge will be placed inside the caulking gun, which allows to extrude in a fluent way with a variable speed.

Figure 27 Caulking gun equipment

5.2.2 Results of the measurements

Sample 1
For this sample the mycelium is mixed with brewery's grain, flour and water in ratio 1:5:2:6. The pictures were taken on day 1, day 6 and day 12.

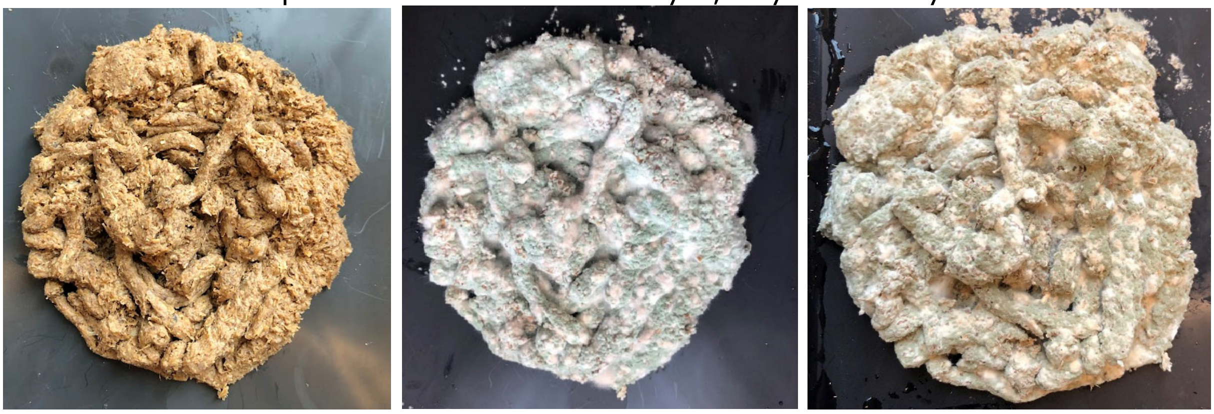


Figure 28 Sample 1, Brewery's Grain

Sample 2
For this sample the mycelium is mixed with grinded coffee, flour and water in ratio 1:5:2:3. The pictures were taken on day 1, day 6 and day 12

Figure 29 Sample 2, Grinded Coffee

5.2.3 Discussion

Both samples show both mycelium and green fungal growth. The mycelium on the coffee sample is more spreading in the environment while the sample with brewery's grain is staying in place.

Looking at the two samples, the conclusion can be made that with coffee the amount of mold creation is larger than the one with brewery's grain. To understand if this was a coincidence or if this is one of the material properties of coffee, multiple experiments are done with this material. In the image below a small overview of some of the experiments are shown, in which a lot of molds are visible. In general, there are three categories of mold: Trichoderma, Bacteria, and Cobweb Mold. All of them were present on the samples. Several cleaning experiments were done by using hydrogen peroxide and vinegar. Both of the attempts did not solve the problem.

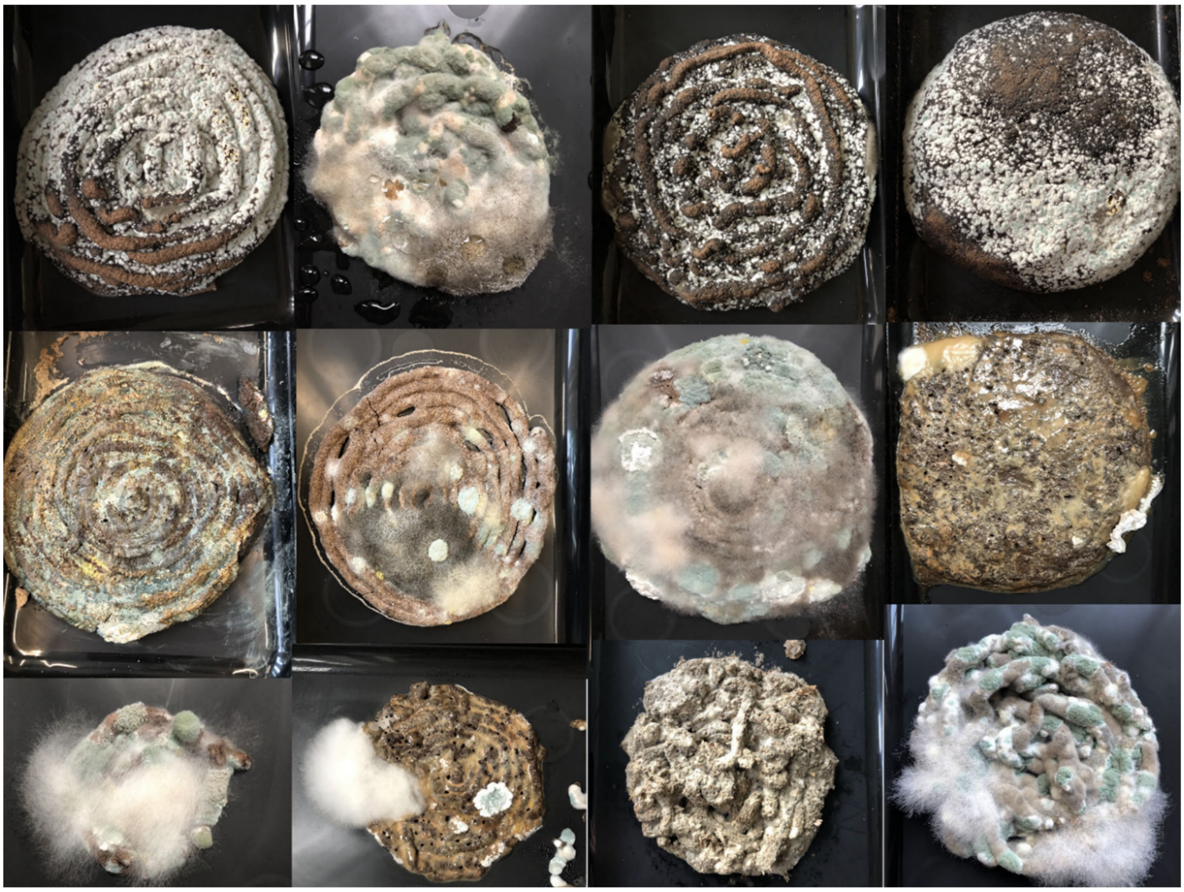


Figure 30 Follow-up experiments with coffee

The conclusion which can be made based on this experiment are:

- More water is needed compared to the previous experiment to be able to print the paste with a caulking gun
- The samples made with coffee create a lot of molds
- Both mixtures are able to grow mycelium
- Brewery's grain will be used in the next experiments since coffee creates molds under all tested circumstances.

5.3 3D printing with the UR5

5.3.1 Methodology

For this experiment multiple steps need to be taken before the official experiment can be conducted. 2 electrical devises need to be controlled:

1. The Robot
2. The Paste Extruder

The Robot

To be able to extrude the developed paste into a specific shape, a robot is used. This robot will be programmed to follow the path determined by a 3D shape.
In this experiment the UR5 robot is used since this robot is present at the faculty of Architecture at the TU Delft.
The robot has the following properties:

- It can carry 5kg
- Is has a reach of 850mm
- It has an accuracy of 0.1mm
- It can rotate 360 degrees with six joints
- A variety of tools can be installed on the it

Figure 31 UR5 Robot

Multiple options are present to program the robot:

- Using the teaching pendant, which is directly connected to the robot
- Insert a G-code by USB
- Sent a script via offline programming applications

For this experiment the choice has been made to make use of offline programming applications, since this allows the user to create a printing script offline before running it on the robot.

The programming application used is a combination from Rhino and Grasshopper. Rhino is a 3D modelling program, which in this case is used to create the desired design. To create a toolpath with a required script/code, Grasshopper is used. Grasshopper is a plugin for Rhino which allows to create, among others, generative designs. In this project, Grasshopper is used to create a custom code which will be sent to the Robot.

Inside the Grasshopper program a plug-in called Robots is used to create a robot simulation and when approved, send the program to the physical robot.

Paste Extruder

For extruding the paste, a paste extruder from WASP is installed on the robot. In the set-up available at the university the extruder does not have a direct connection to the robot. Because of this the extruder needs to be controlled manually. For this, a connection with the extruder needs to be connected via a program which is able to send a code. In this case the program being used is Simplify3D.

Paste extruder

The tool which will be installed on the UR5 is a paste extruder, which will be used for cold 3D printing. This tool needs to be installed on the robot with a wooden frame. In the figure below the different components are shown.

Figure 32 Overview extruder components

Simplify 3D

The paste extruder functions on a G-code. To generate and send this code Simplify3D is used. This program connects the extruder to the computer by using a USB-port. Once the connection is made, a G-code can be sent. The G-code sent to the extruder can for example be G0 E100.000 F1700, in which:

G0: Run the motor

E: The amount of rotations

F: The speed the rotations

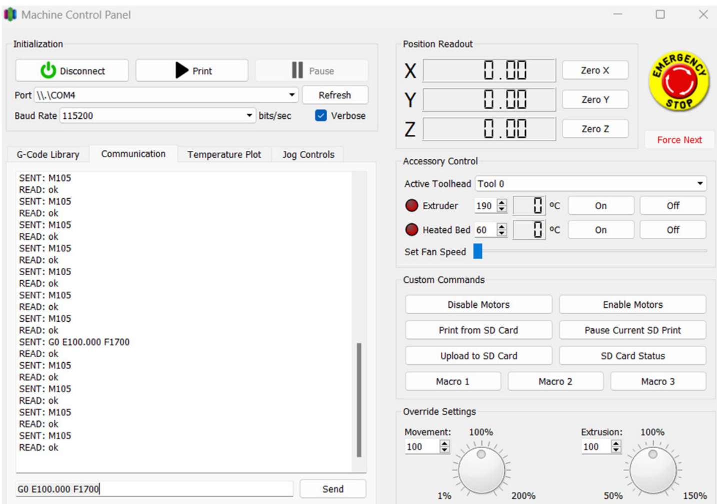


Figure 33 Simplify3D interface

Print pattern

To create the g-code which can be sent to the robot, the plug-in Robots is used in Grasshopper. This program will use points and movement types to create a code. The plugin has one limitation which influences the possible designs: it only contains linear and joint movements. Therefore, the robot is not able to move in circular movements, which means the printing script needs to be made with points which are connected with a linear movement. The first idea was to print circular samples, which could directly be used for the acoustic tests, since for these tests circular samples are needed.

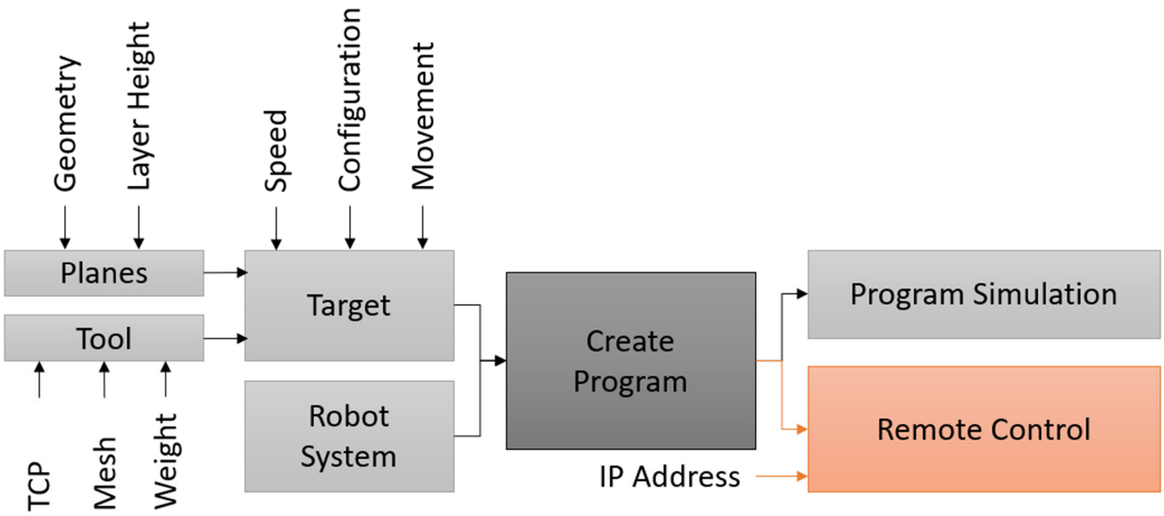


Figure 34 Workflow Grasshopper

In appendix 1 a detailed description on how to create the program is given. Appendix 2 contains an example of the created G-code which will be sent to the robot.

5.3.2 Results

Test 1:

Figure 35 Test 1 Before and after growth

Test 2:

Figure 36 Test 2 Before and after growth

Test 3:

Figure 37 Test 3 Before and after growth

5.3.3 Discussion of the results

In contradiction to the experiment with the caulking gun, this method uses air pressure to press the paste out of the cartridge. Because of this the proportions of the mixture needed to be changed, because with the mixture of the previous experiment, a hole was found inside the mixture which allowed the air to find a direct way to the outside. To prevent this to happen, more water was added to the mixture.

To create a printed sample, several parameters must be aligned within the printing conditions and the material properties.

Print parameters:

- Layer height
- Speed of the extrusion
- Speed of the robot movement
- Space between the lines

Material parameters:

- Viscosity of the paste
- Amount of paste in the cartridge

To conclude:

- More water is needed to create an extrudable paste compared to the experiments with the electrical caulking gun
- The height and the speed are in close relation with the chance of success for the print

5.4 Conclusion

The conclusion of these two experiments is that brewery's grain in combination with wheat flour or all-purposes flour creates a good mixture for a printable paste. For printing with the caulk extruder, more water needs to be added to the mixture compared to the previous experiment. For printing with the paste extruder even more water is needed because the paste extruder uses air pressure to press the material out of the cartridge. For this is it important to create a sticky paste which is firm enough to be pressed out in once by air pressure. Another conclusion which can be made is that the height of the layers and the speed of the extrusion important parameters for creating a print.

06. Acoustic mycelium

Experiment 5: Acoustic properties

6.1 Introduction

To understand the acoustic properties of the material, the different samples, created in the previous experiment, will be tested in the impedance tube. This experiment answers the research question:

What are the acoustic properties of the developed material?

6.2 Methodology:

For this experiment, an impedance tube B&K 4206 is used. This tube consists of two measurement tools which both will be used. One tool measures the absorption coefficient for sounds from 50Hz to 1600Hz, the other one has a reach from 500Hz to 6400Hz. For the tool which measures the low frequencies a circular sample with a diameter of 10cm is used, for the tool measuring the high frequencies a circular sample with a diameter of 2.9cm is used. The measures take place according to NEN-EN-ISO 10534-2 en (NEN-EN-ISO 10534-2:2001 en., 2001).

Impedance tube

The impedance tube is a measuring tool which is based on the Transfer-Function-Method. In this method sound with different frequencies is sent in a linear movement towards the sample. The tool measures the reflected sound, after which it determines the sound absorption coefficient. The low frequency tool will be used to measurements from 50Hz to 800Hz, since from this frequency the high frequency tool is more reliable.

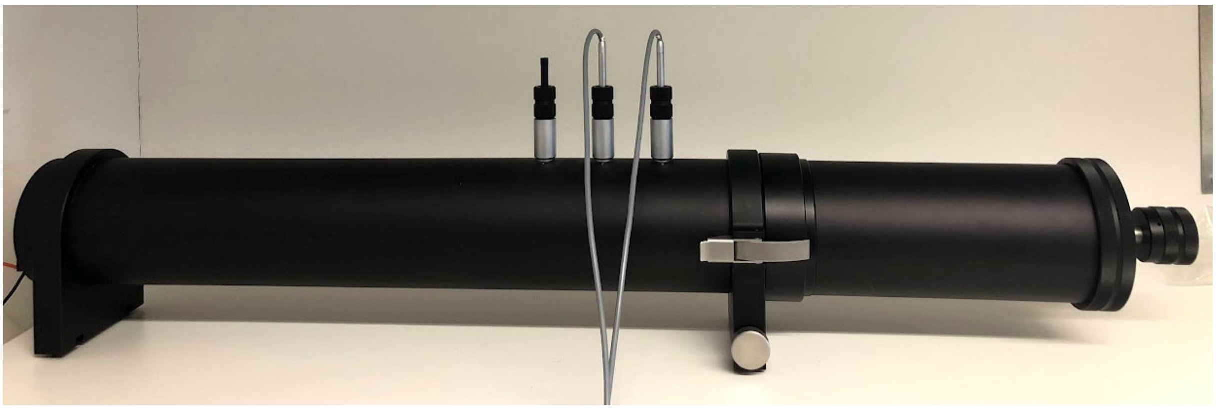


Figure 38 Impedance tube with the low frequency tool

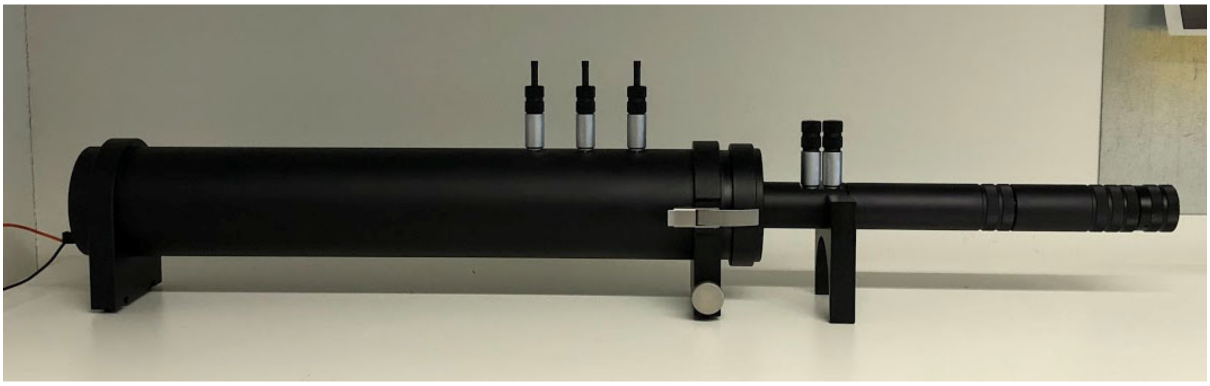


Figure 39 Impedance tube with the high frequency tool

Before the samples can be tested, the growth process of the mycelium will be stopped. This is done by drying the samples for multiple hours, depending on the thickness, in a drying oven. The drying oven used for this is the ProfiCook DR 1218. This oven has a temperature scope from 30 to 75 degrees Celsius and a timer up to 24 hours with 30 minutes intervals.

Figure 40 Before and after drying

When the samples are dry, circular samples with a diameter of 10cm and a diameter of 2.9cm will be cut out. For this a sharp knife is used with circular products as a reference.

In figure 41 a flowchart is given of the experiment.

1. The materials are collected
2. The materials are transformed into a paste
3. The paste will be extruded into a 3D shape
4. The print is stored in a dark place in a closed container
5. After the mycelium has grown the box is opened
6. The grown sample is dried in the oven to stop the mycelium growth
7. Circular samples with a diameter of 10cm are cut out of the bigger sample
8. The sample are tested with the low frequency tool
9. Circular samples with a diameter of 2.9cm are cut out of the circle from 10cm
10. The small samples are tested with the high frequency tool

After this, the program will collect the data which can be transported into an excel file.

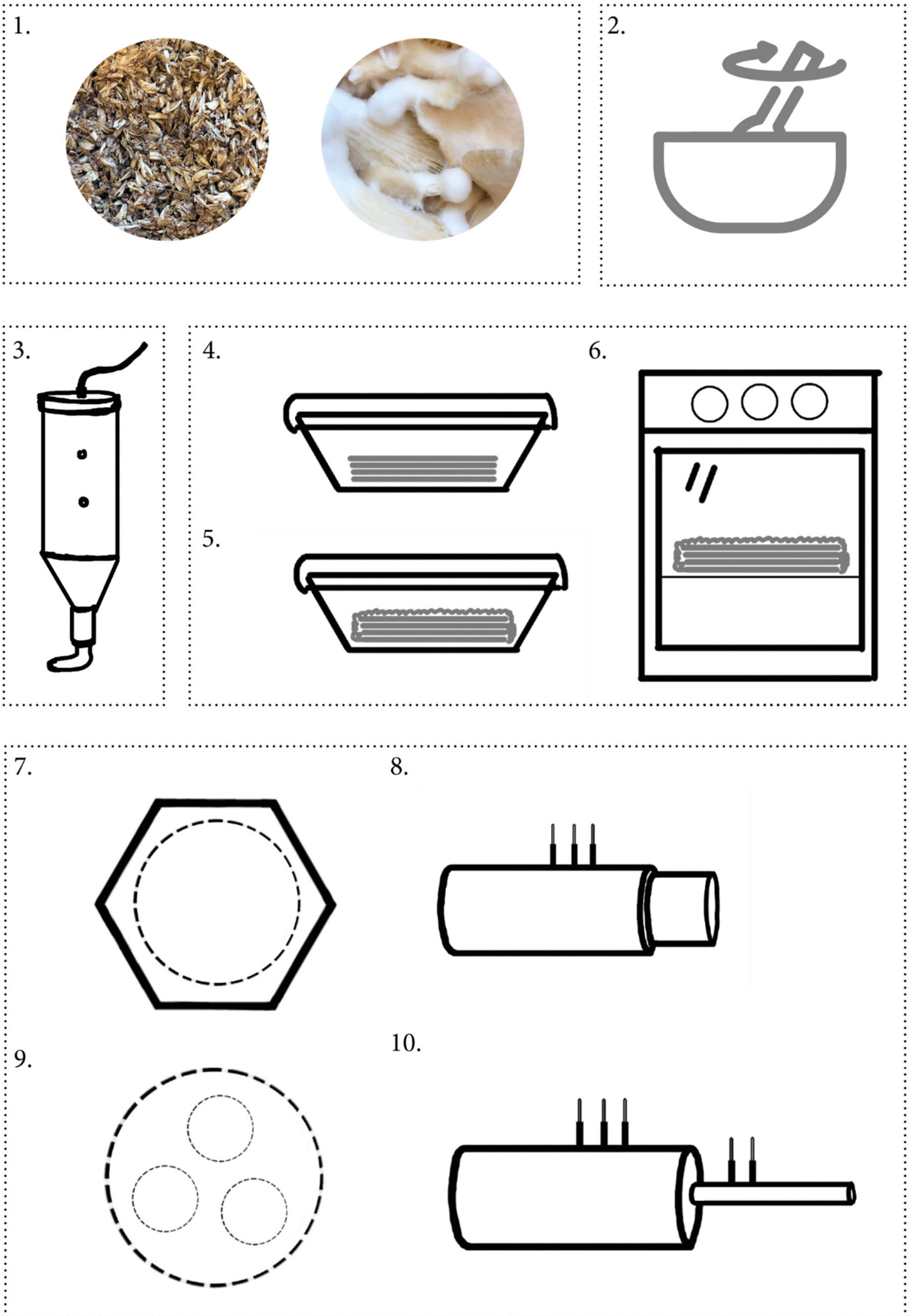


Figure 41 Flowchart acoustic tests

6.3 Results of the measurements

In this paragraph the samples derived from the previous experiment will be tested in the impedance tube. Three samples will be tested, sample 1: fully grown on an uneven surface, sample 2: grown longer on an uneven surface, sample 3: 3D printed and grown for too long.

Sample 1

Figure 42 Sample 1

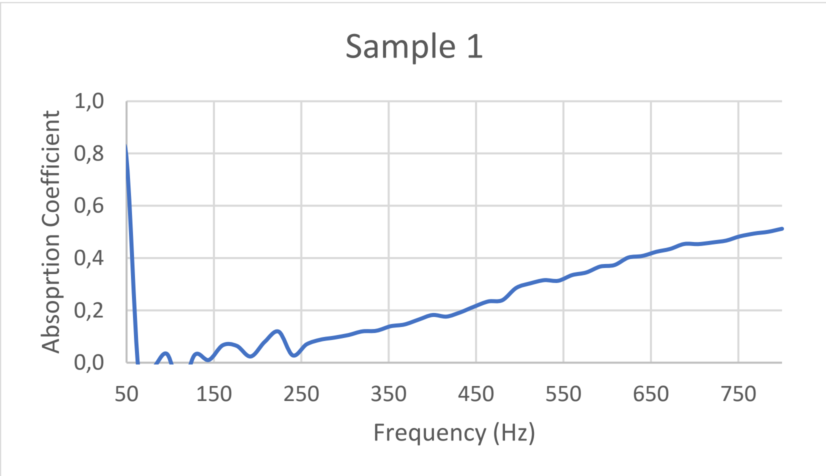


Figure 43 Sample 1, Low frequency measurements

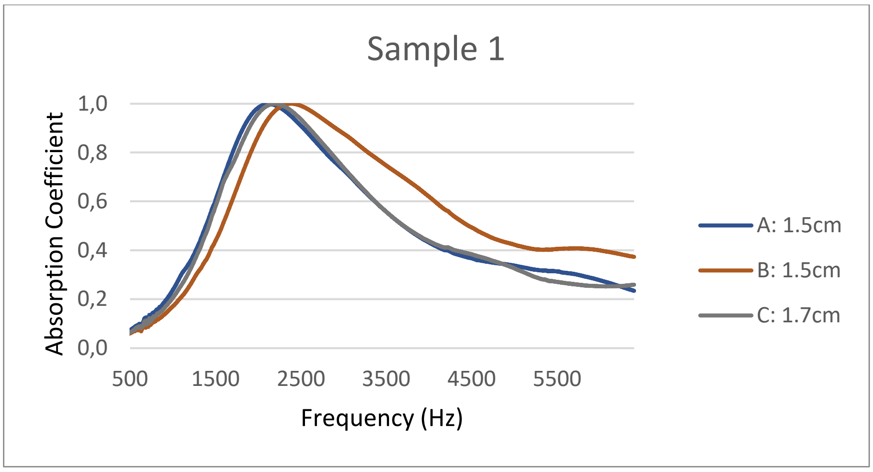


Figure 44 Sample 1, High frequency measurements

Sample 2

Figure 45 Sample 2

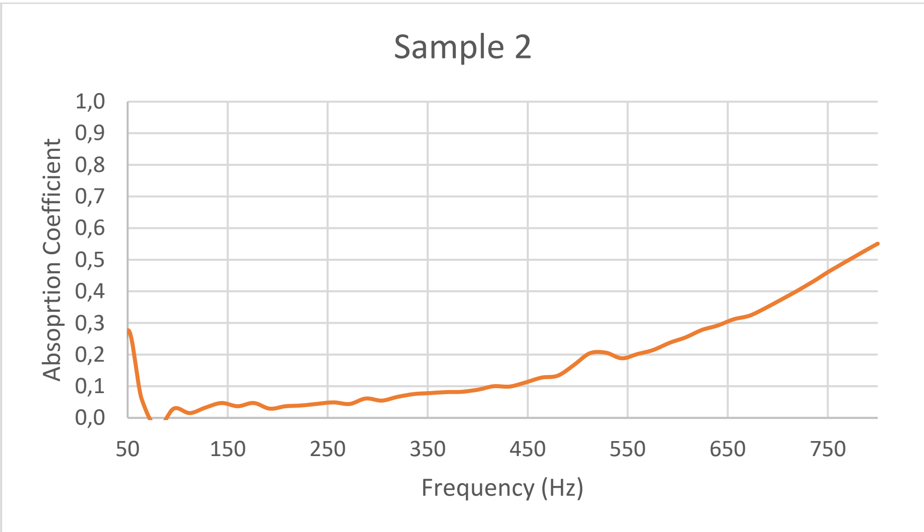


Figure 46 Sample 2, Low frequency measurements

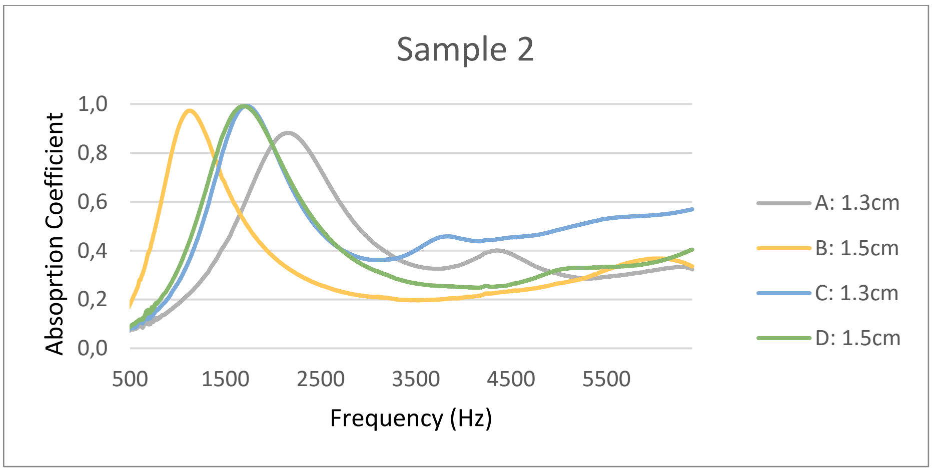


Figure 47 Sample 2, High frequency measurements

Sample 3

Figure 48 Sample 3

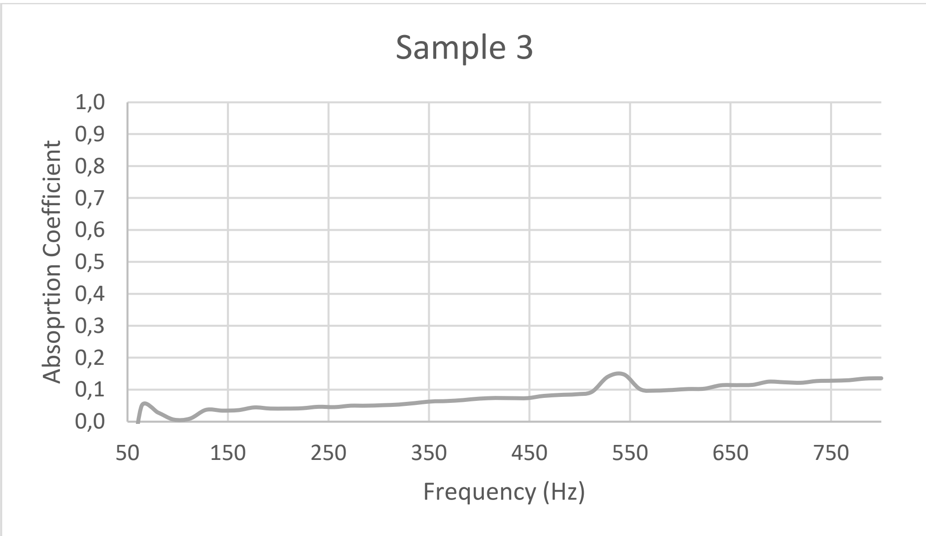


Figure 49 Sample 3, Low frequency measurements

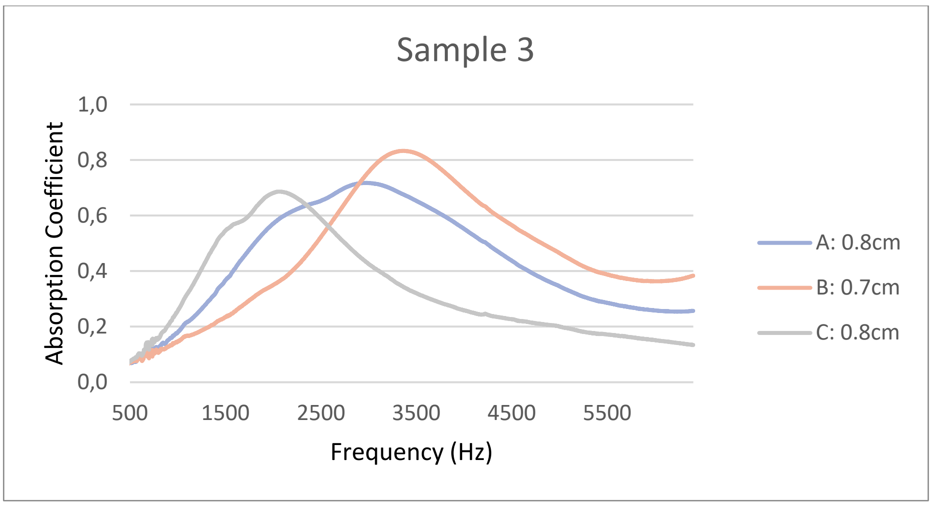


Figure 50 Sample 3, High frequency measurements

6.4 Discussion of the results

This experiment shows that the created paste might have decent sound absorbing properties. Although the samples are very different from each other, comparable behavior is present. The lines show a peak after which the value decreases again, stabilizing above 0.1α.

Another conclusion which can be made is that the measurements with the low frequency tool are not showing much information. Therefore, in the next experiments only the tool with the high frequencies will be used.

This study comes with some limitations:

- Since these tests are based on cylinders of the material which are put in the impedance tube, it is very important that the entire diameter of the tube is filled. Since the materials are dried in the oven, some of them are very brittle. The results might be slightly affected by these imperfections.

- The impedance tube measures a wide range of frequencies which results in some imperfections in the highest and lowest values.

- The usage of samples for the high and low frequency test set-ups are slightly different. This is because the samples used for this, are cut out of bigger samples. Since the growth of the mycelium is not evenly spread, the values might be slightly different per sample.

- The mycelium growth might not be in its perfect phase. Further research must be done on this variable.

07. Acoustic parameters

Experiment 6: Influences acoustic properties

7.1 Introduction

As described in the theoretical framework, the acoustic properties are mainly determined by fiber size, the thickness, and the density. To determine the best properties for this specific material, different variables will be taken into consideration, answering the following questions:

How do 3D printing parameters influence the acoustic properties?

How do the type of substrate, the thickness, and the growth time of mycelium influence the acoustic performances?

These questions can be split into subcategories:

3D printing parameters

3D printing is used as a production method. To measure whether this production method has a positive effect on the acoustic properties, it will be compared to sculpting. This production method is chosen as a comparison since in both methods the top surface is exposed to the environment.

With 3D printing as a production method, the distance between the printed lines can be varied, which influences the density. Also, because mycelium is a living material, the space between the lines can have an influence on the mycelium growth.

The density of the material might be influenced by the used nozzle. To test this, prints made with two different nozzle sizes will be measured.

Type of substrate

As a result of the experiment 'Extrudability' two substrates will be tested. The different substrates vary in fiber size.

Thickness

The thickness is one of the main properties of a product which influences the acoustic properties. Therefore, multiple thicknesses will be tested.

Growth time of mycelium

Mycelium is a living material which means that during time the properties of the material will change. With this parameter the influence of the mycelium growth on the acoustic properties will be measured.

7.2 Methodology

The method for this experiment will be the same method as the previous experiment.

- The impedance tube will be used
- The samples will be cut out of a bigger sample.

The previous experiment has shown that the absorption coefficient of the samples is not rising significantly before 500Hz, the extension for the impedance tube with the low frequencies and the big sample diameter will be left out of this experiment. For this experiment the preference has been given to increase the number of samples being tested in the extension for the high frequencies with the small sample diameter.

Variables:

1. Printed vs not printed
2. Nozzle size
3. Type of flour
4. Line distance
5. Thickness
6. Growth time

To investigate the function of the mycelium film, which grows on top of the samples, an extra variable: not printed, without mycelium, is added.

To test these variables, 10 samples have been made:

	Nozzle size (Big: 8mm, Small: 4mm)	Type of flour	Layers	Line distance (mm)	Thickness (cm)	Growth time (days)
1	Big nozzle	Wheat flour	4	4	2	9
2	Not printed	Wheat flour	-	-	2	9
3	Not printed, whithout mycelium	All-purposes flour			3.7, 1.5, 1.5	
4	Small nozzle	All-purposes flour	5	4	2	13
5	Big nozzle	All-purposes flour	4	8	2	13
6	Small nozzle	All-purposes flour	5	4	1.5	12
7	Small nozzle	All-purposes flour	5	4	1.5	13
8	Big nozzle	All-purposes flour	6	8	2.8 - 3	12
9	Big nozzle	All-purposes flour	5	8	2.5	13
10	Big nozzle	All-purposes flour	4	10	2	12

Figure 51 Printed Samples

7.3 Results of the measurements

In this paragraph the comparisons of different variables are shown. For this, average measures of the samples are used. The graphs of all measures are shown in 'Appendix 4: Acoustic Measures'.

1. Printed vs not printed

Sample 1: Printed
Sample 2: Not Printed

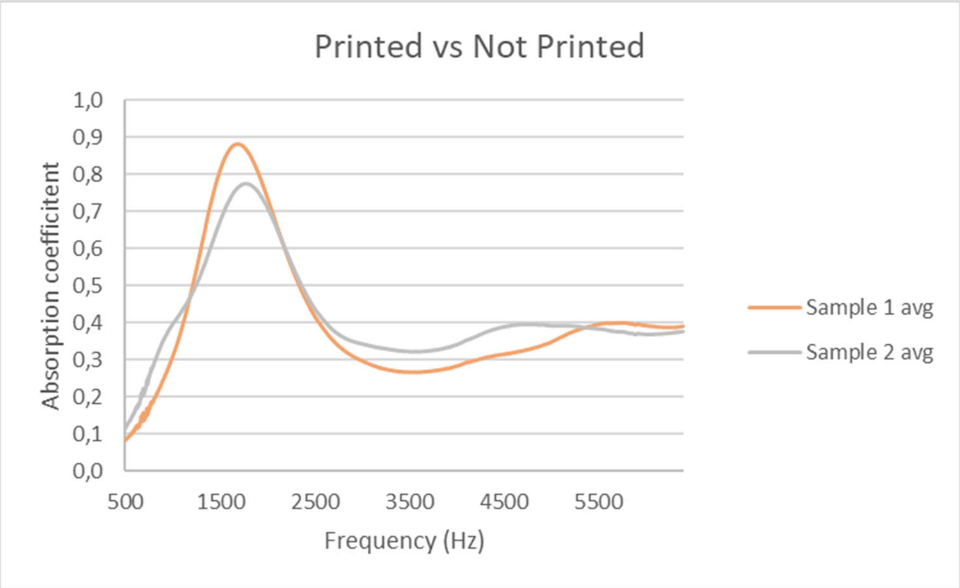


Figure 52 Printed vs Not Printed

2. Line distance

Sample 5: Line distance of 8mm
Sample 10: Line distance of 10mm

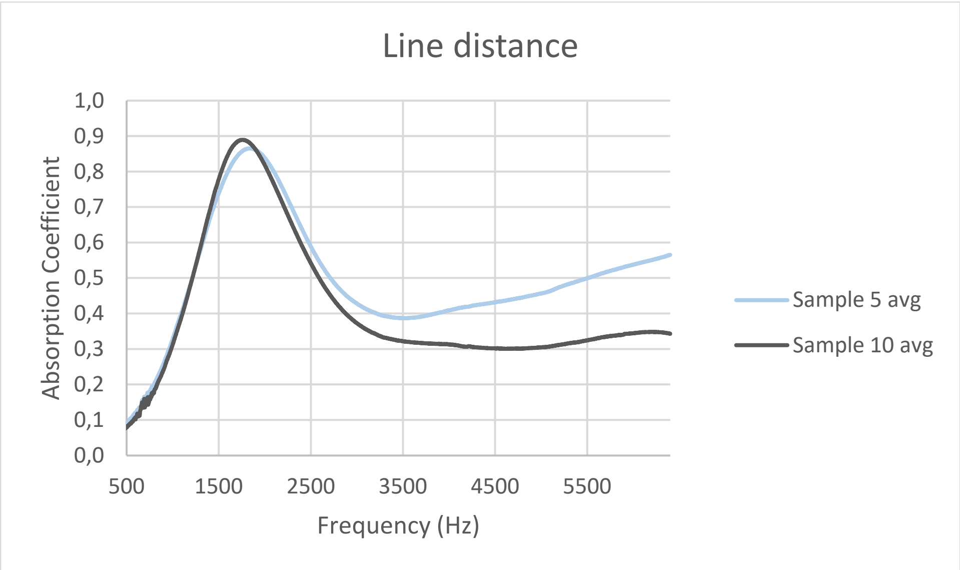


Figure 53 Line distance

3. Nozzle size

Sample 4: Small nozzle, 4mm.
Sample 10: Big nozzle, 8mm.

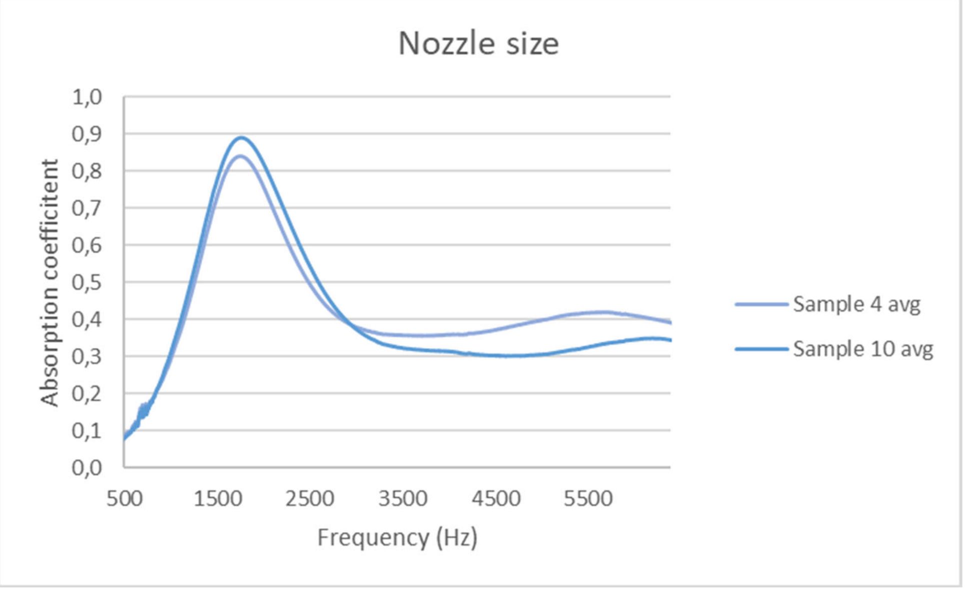


Figure 54 Nozzle size

4. Type of flour

Sample 1: Wheat Flour.
Sample 10: All-purposes Flour.

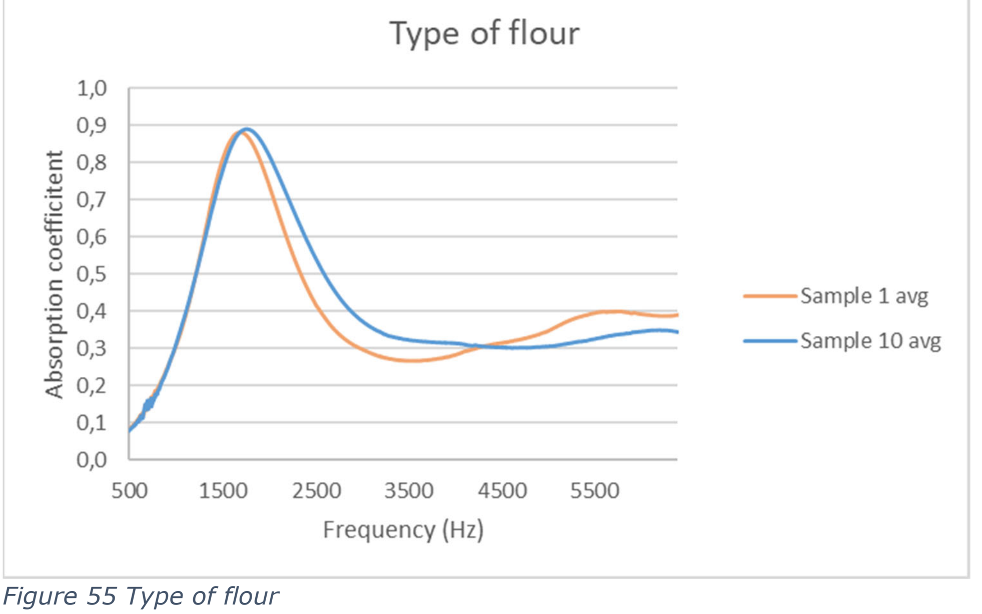


Figure 55 Type of flour

5. Growth time

Sample 6: Growth time of 12 days.
Sample 7: Growth time of 13 days.

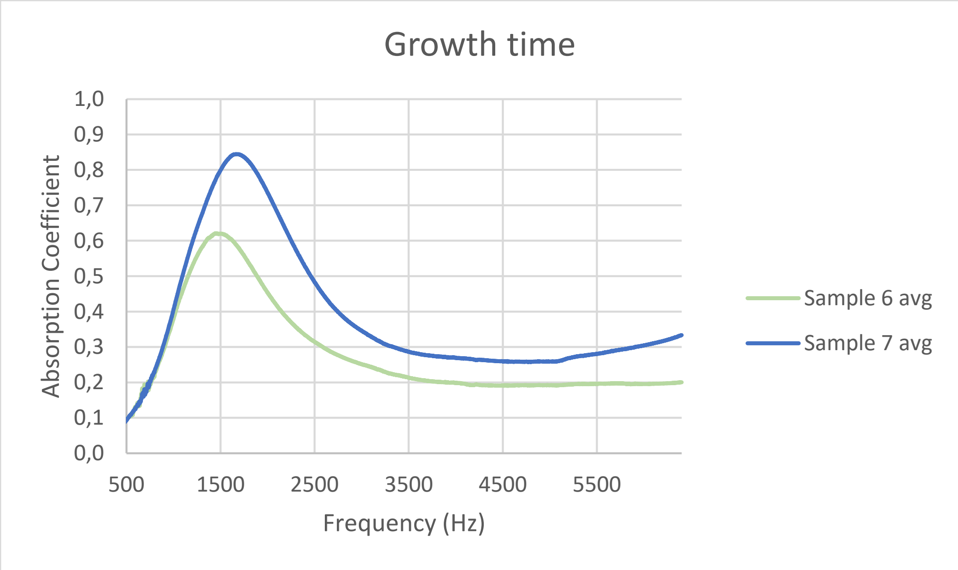


Figure 56 Growth time

6. Thickness

Sample 4: 2cm.
Sample 6: 1.5cm.
Sample 8: 2.9cm.

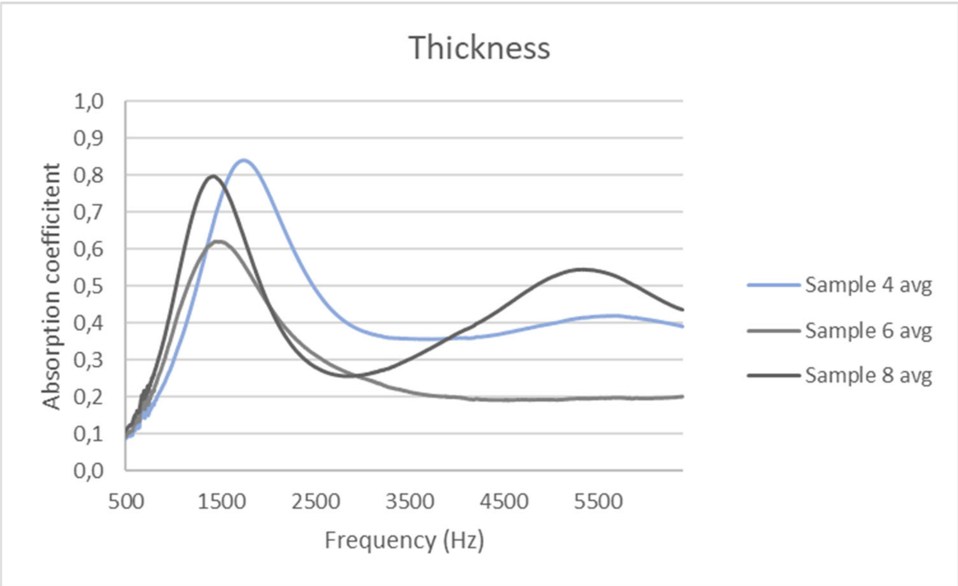


Figure 57 Thickness

7.4 Analysis of the results

The expectation of the experiment was that multiple variables have an influence on the acoustic properties. Looking at the results, conclusions can be made whether all the variables have an effect or not.

01. Printed vs not printed

Looking at the graph with the two average lines, with sample 1 as printed and sample 2 as not printed, no significant differences are visible. The printed sample performs a bit better in the low frequencies, and the not printed sample performs a bit better in the middle/high frequencies. The conclusion can be made that this variable does not have a significant influence on the acoustic performances.

02. Line distance

Comparing sample 5 with a small line distance with sample 10 with a large line distance, the conclusion can be made that printing with a small line distance has a small positive effect on the acoustic properties. Sample 5 performs better at high frequencies.

03. Nozzle size

Looking at the graph of the different nozzle sizes, again some small differences are visible. These differences are within the margins, which results in no significant influence.

04. Type of flour

For this experiment all-purposes flour and wheat flour have been compared. For the sample with wheat flour more water was required to create an extrudable paste. Regarding the acoustic properties a small difference is visible at the higher frequencies. The wheat flour has a valley at 3500Hz on 2.7, and a peak at 5500Hz on 4, while the all-purposes flour has a more stable line in the middle of this.

05. Growth time

By looking at the growth time, with sample 6 grown one day shorter than sample 7, the conclusion can be made that the growth time of the mycelium has a big influence on the absorption coefficient. Especially for this comparison the two samples are identical. They were printed with the same cartridge and have been stored together in one big box. Because of this, the growth conditions have not been different for both samples, except their growth time. The graph shows that growing the mycelium one day longer on this specific sample, creates a higher absorption coefficient with a peak at a difference of 0.2. With this, the conclusion can be made that the growth time has an influence on the absorption coefficient.

06. Thickness

Looking at the graph the conclusion can be made that the thickness has a significant influence on the absorption coefficient. For this, three different thicknesses have been compared: sample 4 2cm, sample 6 1.5cm, and sample 8 2.8-3cm. Comparing sample 4 and sample 6, a shifting of the entire line upwards is visible. Comparing sample 4 and sample 8, the line acts different. In this case, the line forms a second peak. Also, the peak moves a bit to the lower frequencies and becomes a bit lower. Looking closely to sample 4, the peak is already visible but much less extensive.

To conclude, the variables with the largest influence on the acoustic properties are growth time and the thickness. The line distance and the nozzle size have a small influence on the properties. And printing and the type of flour used are not having a significant influence. Concluding in a print with a small line distance, small nozzle, a growth time 13 days, which might vary under different growth properties, and a thickness of 2.5cm.

To understand how the mycelium film functions, a sample without mycelium growth has been tested. In the figure below, the test results are shown. In this the same behavior of the material is present. Sample 3.1 is thicker than all other examples and shows a second peak, comparable to sample 8. The reason for this can be that because of the dried sample also creates a film on the top and the bottom of the sample, comparable to the mycelium samples.

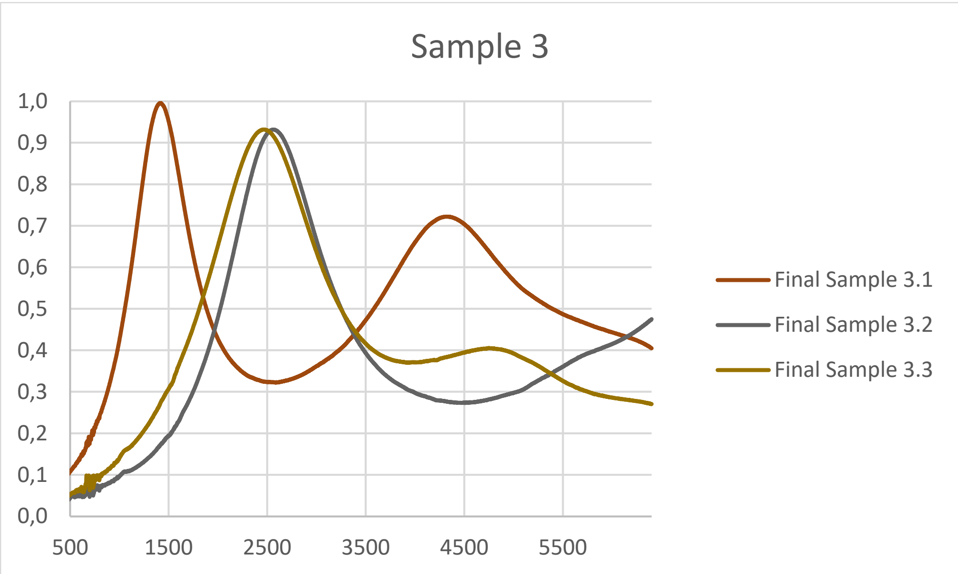


Figure 58 Without mycelium

During this experiment multiple other material properties were discovered.

First, the temperature has a huge influence on the mycelium growth. This has been experienced by storing the samples in the LAMA Lab during a weekend in which the temperatures reached below 6 degrees. The expectations were that the mycelium has grown during the weekend and the samples were ready to be tested. However, no mycelium growth was visible at all. Because of this, the samples were stored next to a drying oven, which was turned on to create more substrate, after which the mycelium started to grow. Because the oven creates radiant heat, the samples might be affected differently by the warmth, which might have had an influence on the mycelium growth over time.

Another material property, discovered during this experiment, is that the samples which were printed with a large nozzle size started to fall apart. In the samples with a bigger line distance, the material spread, which resulted in intact lines. In the samples with a close line distance, the samples cracked open, which created holes. Because of the collapsing, the height of the samples was influenced, which resulted in lower height differences in the big nozzle sized samples.
Possible type of acoustic absorber

As described in the theoretical framework, there are different types of absorbers: porous absorbers, membrane absorbers, and resonance absorbers. Comparing the derived data with literature, one of the possible absorber types might be a micro perforated panel. In the image below a reference of this panel is given.

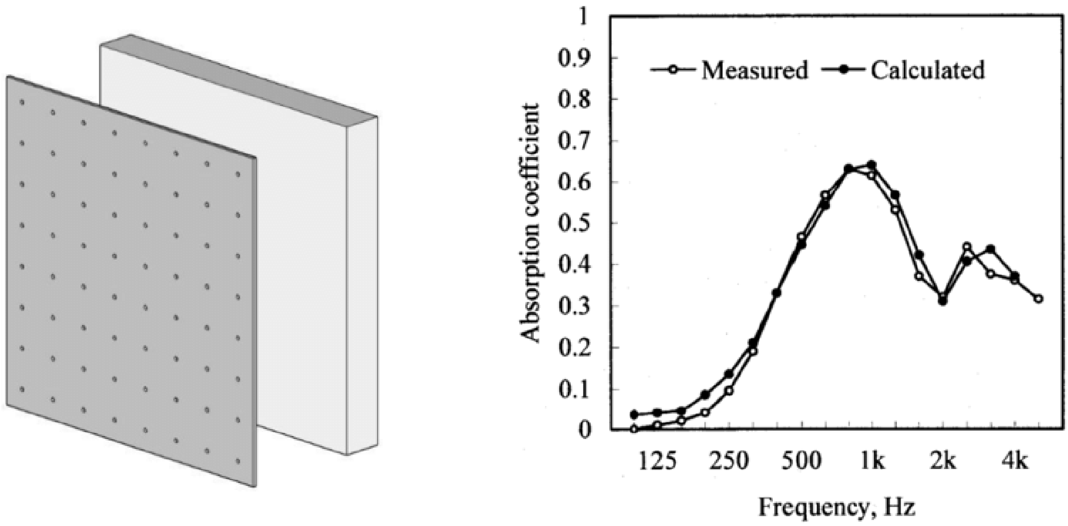


Figure 59 Example micro-perforated panel (Sakagami & Okuzono, in press)

To evaluate if this panel type might be a possibility, microscopic images have been made of a couple of samples. The images below show the mycelium network on two different samples. For this the digital microscope VHX-7000 is used, which can zoom up to 200 times. The left image has been zoomed in 200 times, and the right image has been zoomed in 100 times. In both images, the network shows that micro perforations are present, which may contribute to the assumption of a micro perforated panel.

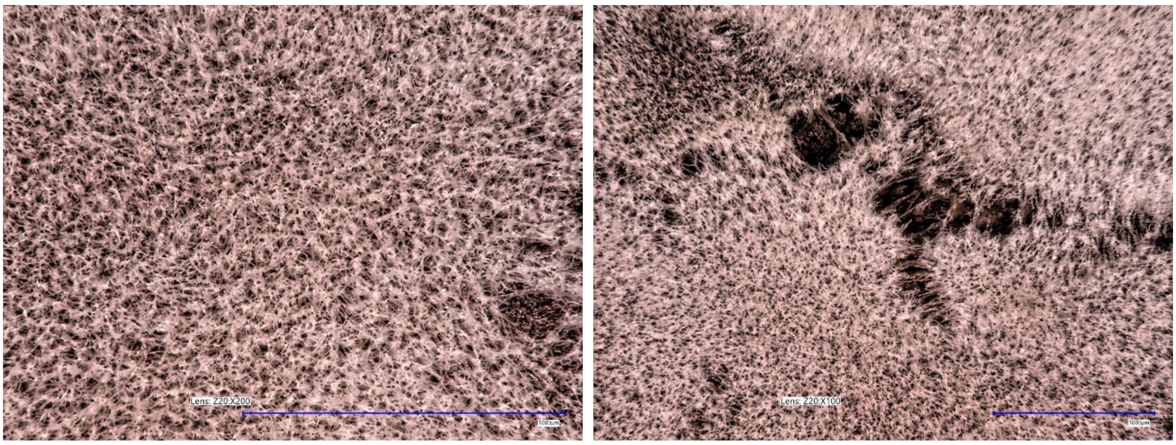


Figure 60 Microscopic images mycelium samples (Left: x200 zoom, right: x100 zoom)

To be certain whether the mycelium bound acoustic panels function as a micro perforated panel, more research must be done with this outcome as a hypothesis.

Another explanation might be that the panel functions as two porous absorbers on top of each other. Because of the density differences a standing wave occur inside the panel, which might explain the second peak.

7.5 Acoustic simulation
The derived data of the acoustic properties of the panels make it possible to simulate the acoustic behavior in a room. In appendix 7 a simulation of a classroom shows the added value of the panels in relation to the reverberation time.

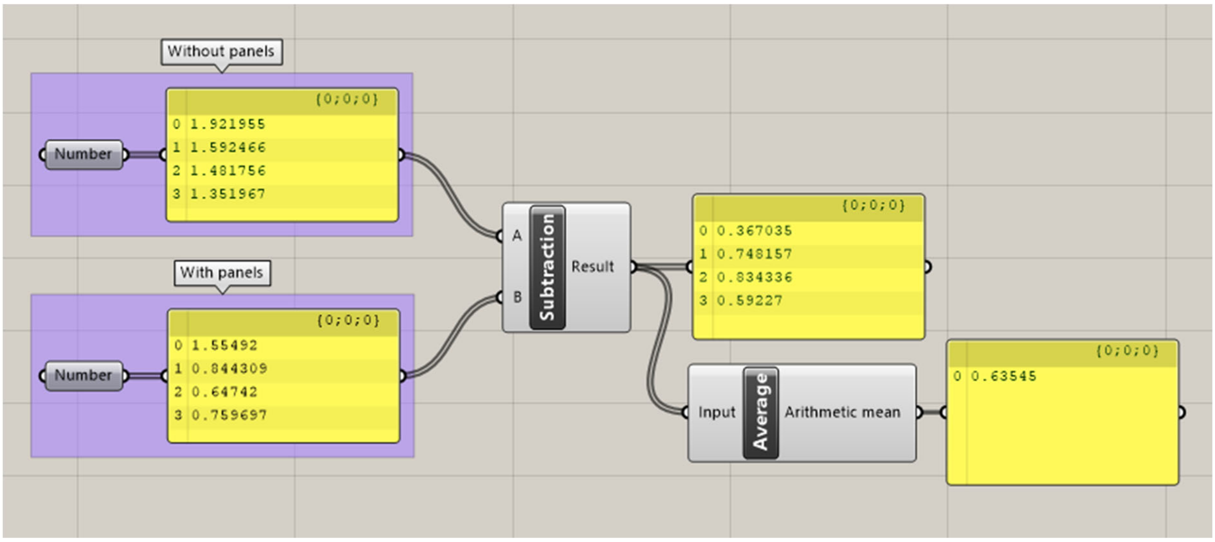


Figure 61 Reverberation time with and without acoustic panels

In the image above, a simulation of two different setups is shown. One is without acoustic panels, while the other has acoustic panels, with the acoustic properties based on the sample 9. The first numbers, highlighted in purple, show the reverberation time in seconds for four different frequencies: 500 Hz, 1kHz, 2kHz and 4Khz. By subtracting them, the reduction of the reverberation time caused by the acoustic panels is visible. For this specific set-up the panels show an average reduction of reverberation time of 0.6 seconds, with the highest differences between 1kHz and 2kHz. Further research regarding the simulation might improve the results.

08. Design

Acoustic panel design

8.1 Introduction

Using 3D printing as a production method comes with both possibilities and constrains. This chapter will give answer to the following question:

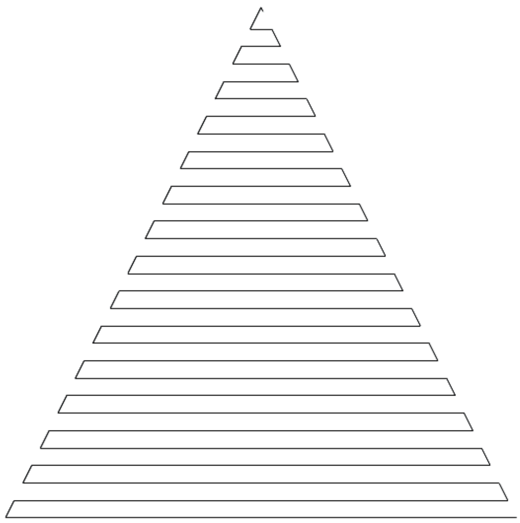
What are the design possibilities when using 3D printing in combination with grasshopper as a production method for the developed material?

To answer this question, three design methods will be discussed.

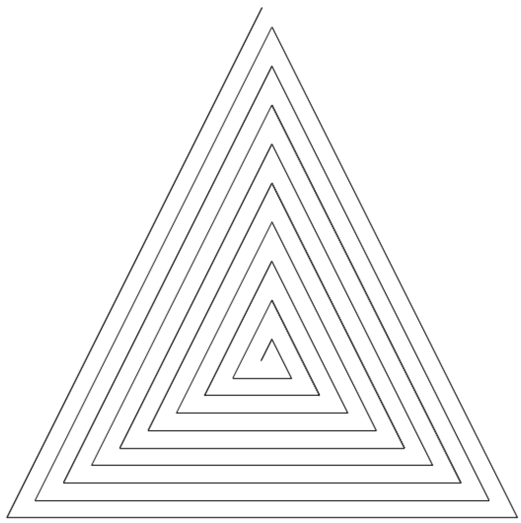
8.2 Customizable design

The final design of the panels is going to be a hexagonal base with on top a variety of designs. The hexagons have a maximum size, based on the drying oven, of 30x28cm. For the designs on top of this multiple options are available. Since Grasshopper in combination with Robots is used, the constraint for the design is that the points need to connect in a linear movement.

There are two ways to create an infill for a design with a linear movement.
These two ways are:



Zigzag pattern



Spiral pattern

The images below show the 3D printed patterns. For this the mixture derived from the previous experiments is used.

Figure 62 Zigzag pattern

Figure 63 Spiral pattern

Because 3D printing is used as the production method, a variety of designs a possible. Figure 64 show some possible designs. In figure 65 a prototype has been made with a hexagon for the base and a smaller hexagon on top for the surface design.

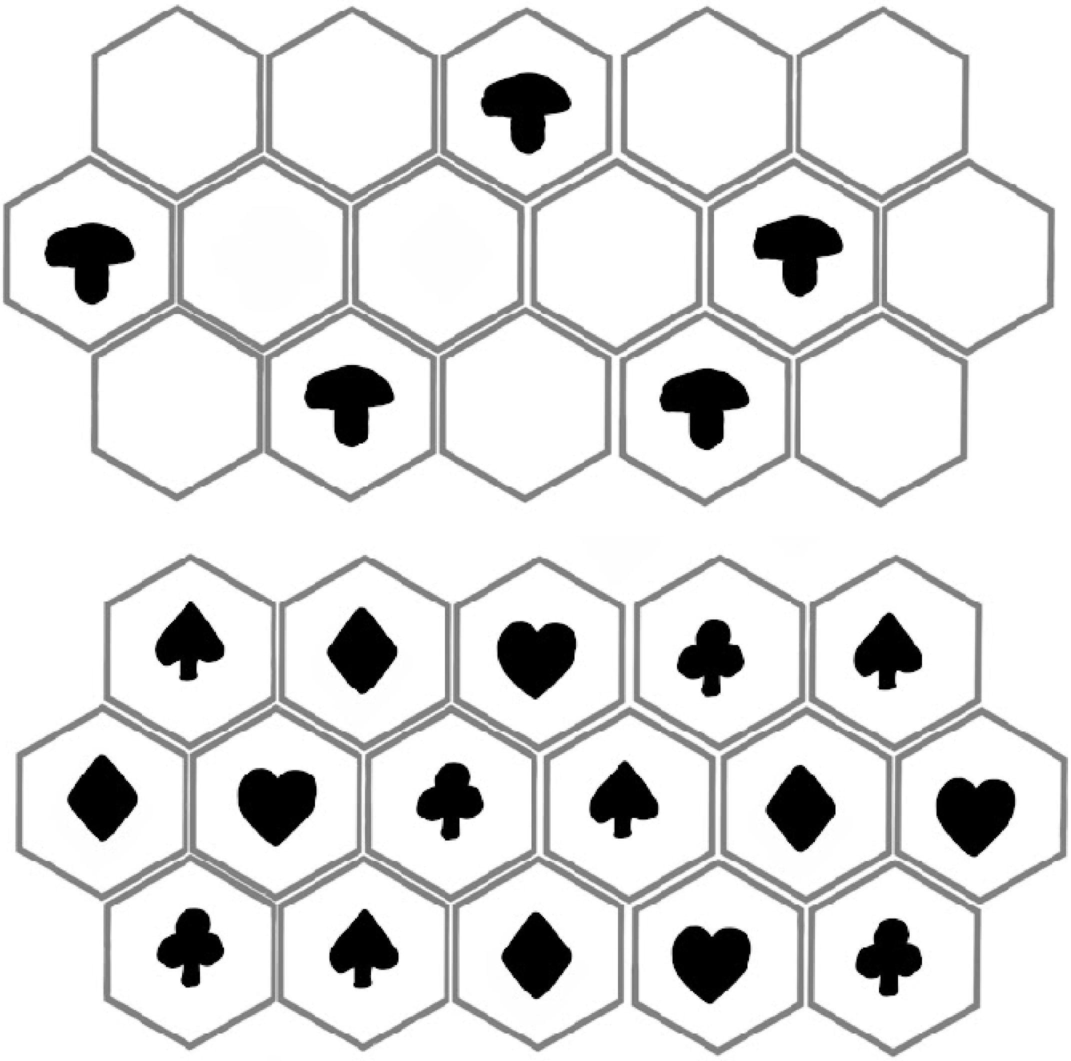


Figure 64 Possible designs

Figure 65 Acoustic panel with custom design on top

8.3 Parametric design

The developed product functions as a sound absorbing panel. In general sound absorbing panels function best when soundwaves enter the panel within a scope of 0 to 45 degrees. To improve the sound absorbing properties of the panels, the surface pattern of panels could be optimized.

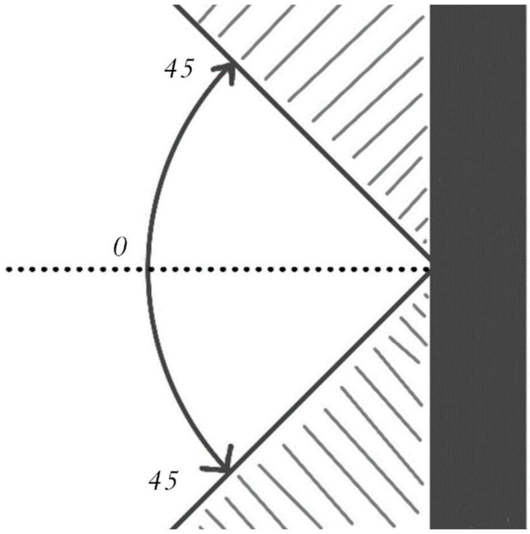


Figure 66 Optimal angle incoming sound absorption

To design these panels, Rhino in combination with Grasshopper is used. The first step is to create a surface, which will determine the size of the panel, and a point, which indicates the origin of the soundwave.

In this paragraph a quick overview of the steps will be given. In appendix 7 an extensive explanation will be given.

- Step 1. Create surface and point
- Step 2. Create multiple spheres around point.
- Step 3. Find intersection point spheres and surface
- Step 4. Create lines at intersection points
- Step 5. Distribute points along the intersection lines
- Step 6. Create grid of points on surface
- Step 7. Move points on intersection line towards point
- Step 8. Find closest points related to points on surface
- Step 9. Replace points by moved intersection points
- Step 10. Create surface from derived points
- Step 11. Loft the created surface with the initial surface

The images below show two possible generated designs.

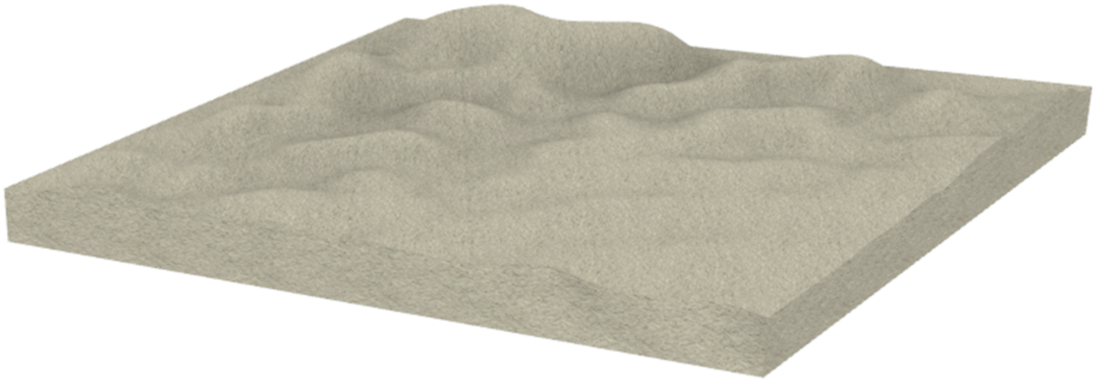


Figure 67 Variant a, generated design

Figure 68 Variant b, generated design

8.4 Object Design

Although 3D printing might not always be the most effective production method for acoustic panel, 3D printing gives other freedom. Since the acoustic properties of the material is determined by the growth time of the mycelium and the thickness of the panel, lots of other objects could be formed. With 3D printing the possibilities are endless. Directions in which the objects could be found are lamps, vases and candle holders, and fine arts. On the next page some mycelium or 3D printed examples are shown.

Colored lamps (Blast Studio, 2022) (top left)
Candle holders by Blast Studio (Beall, 2020) (top right)
Suede-like lamps (Krejci, 2017) (middle)
Hypnerotomachia Naturae by Stefan Maier and Giacomo Pala (Jamie D, 2021) (bottom)





09. Product overview

MYCELIUM BASED SOUND ABSORBING PANELS

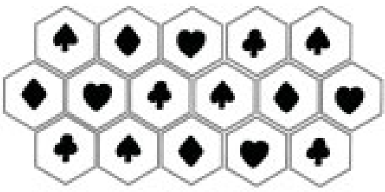
Ingredients

Oyster Mushroom (1)

Brewery's Grain (2)

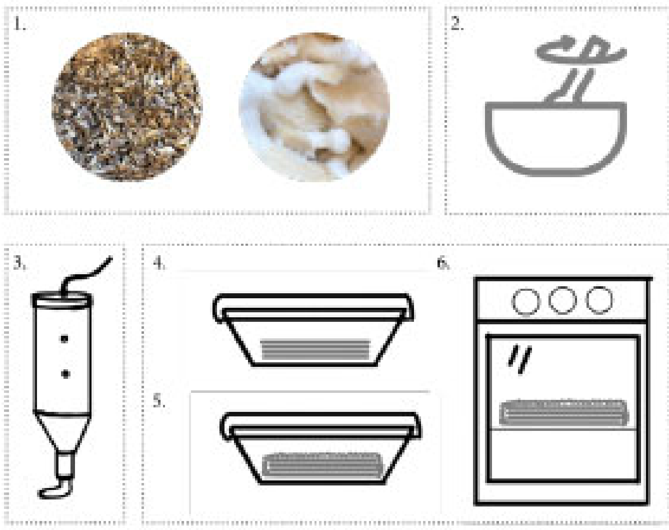
All-Purposes Flour (3)

Design possibilities



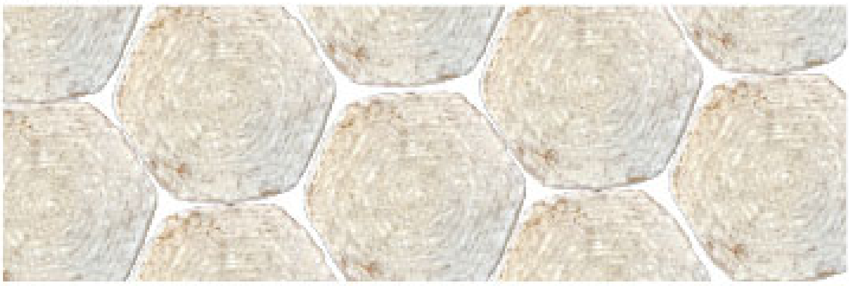
(4)

Production



1. The materials are collected 2. The materials are transformed into a paste 3. The paste will be extruded into a 3D shape 4. The print is stored in a dark place in a closed container 5. After the mycelium has grown the box is opened 6.The grown sample is dried in the oven to stop the mycelium growth

Prototype



100% biobased

1. (Kirow, n.d.) 2. (Upcycledfoods, n.d.) 3. (Dietitians of Canada, 2022) 4. (Krejci, 2017)

10. Conclusion

Conclusion
This thesis aims to answer the research question: How can a sound absorbing panel for indoor use be 3D printed with a mycelium bound biomaterial? This research showed that a sound absorbing panel made from mycelium in combination with urban waste products can be 3D printed by using a robot arm with a paste extruder. The mixture for these panels consists of brewery's grain in combination with flour into which mycelium particles are mixed. This mixture is used to 3D print the panels, after which the panels will be stored in an air-tight, warm, dark environment which allows the mycelium to grow. When the mycelium is grown into the desired stage, the samples are dried in the oven to stop the mycelium growth and create a firm product.

To answer this question six experiments have been executed with a focus on mycelium growth, acoustic properties and 3D printing. These experiments were: 1. Mycelium Growth, 2. Extrudability, 3. 3D printing with a syringe, 4. 3D printing with a paste extruder, 5. Acoustic properties, 6. Influences on the acoustic properties. To conduct these experiments acoustic measurement equipment, the impedance tube with a small tube attached to it, and the UR5 robot in combination with a WASP paste extruder have been used. To make the robot and the paste extruder work, Rhino in combination with Grasshopper with the add-in Robots, and Simplify3D were used.

To create a printable paste, the urban waste product 'Brewery's Grain' has been used in combination with a food thickening product. For this, multiple products have been researched which concluded in all-purposes flour and wheat flour as the best paste maker. These products are mixed with grinded mycelium and water in a ratio of 24:24:3:35, (brewery's grain:flour:mycelium:water).

To find the best composition for the panels, variations in thickness, growth time, printing parameters and substrate have been tested, resulting in an acoustic panel printed with a small nozzle to reach shape stability, a thickness of 2.5cm, a growth time of 13 days, which might differ at different storage temperatures, and a small line distance as a best practice. The material can be printed both with wheat flour and all-purposes flour since no significant differences are measured.

In the final stage 3D designs have been made to understand the possibilities by using 3D printing as a production method. This concluded in three types of designs which could be made: a customizable design, a parametric design, and printing object instead of panels.

To conclude, this research has shown that it is possible to create a biobased 3D printing material with which customizable acoustic panels can be 3D printed with a paste extruder. It shows how biomaterials can be transformed into a printable paste, how acoustic properties can be measured, and which variables influence the acoustic properties.

This thesis includes experiments, multiple of those experiments include the growth of living material. Since the growth of living materials is influenced by their environment, other environmental properties might have resulted in slightly different outcomes. Also, since the experiments did not take place in a sterile environment other living materials might have entered the product.

Reflection

Strengths	Developed a printable material Determined the variables which influence the sound absorbing properties Being able to use a robot, create a printing script and print useful samples.
Weaknesses	No perfectly grown panel is produced No specific result on the behavior of the mycelium is present Worked on a material which did not meet the required outcome for too long
Opportunities	Future research on the estimation of the mycelium behavior Use the produced material for other products Research mycelium with a microscope for a better understanding
Treats	No data on the end-of-life scenario, when will it dissolve The mycelium growth time is influenced by a variety of environmental conditions A possible leak of supply of the brewery's grain

Future research
As a result of this research a couple of future research topics can be formulated:

Finding waste products which are able to create an extrudable paste to replace the flour. For this research all-purposes flour is used, which is also used in kitchens to produce food. To find a replacement for this, ideally from waste products, the food chain is not affected.

Determine the best growth conditions for the developed material. In this research the growth conditions were limited affected, research on this topic might have a positive effect on the mycelium development.

Research the behavior of the mycelium film which is formed on the surface. This research describes a micro perforated panel as a possible explanation for the mycelium behavior. Research focused on this outcome might confirm or deny this explanation.

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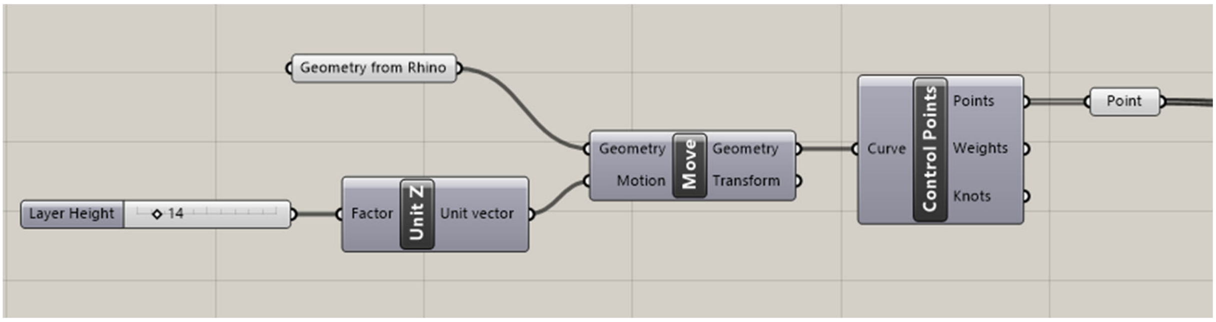
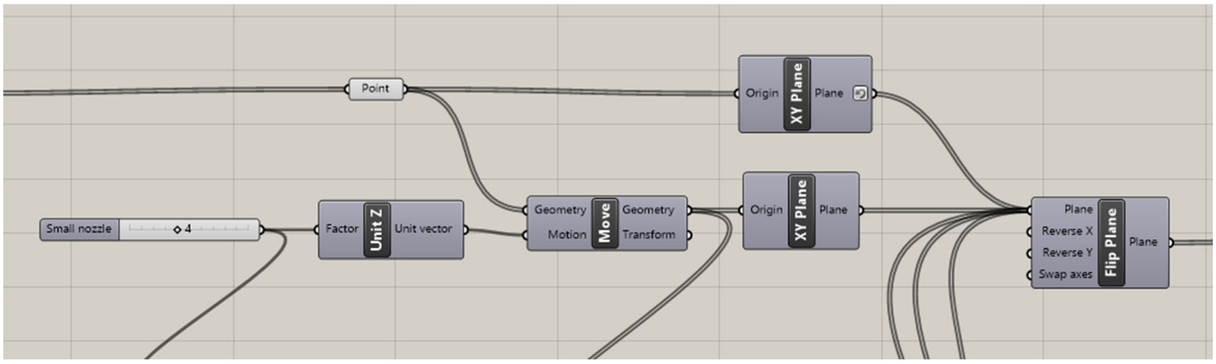
Appendix 1: Grasshopper script

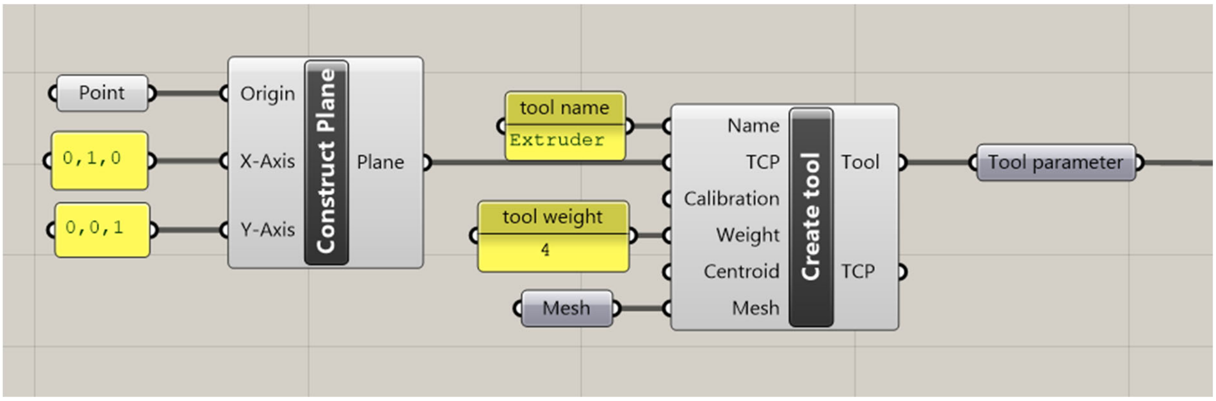
Grasshopper script
Step 1: Insert geometry from rhino, move to required layer height, and create points in the corners of the geometry.
In the first step, a line, created in rhino 7, will be inserted in grasshopper by using a geometry component. This geometry will be moved in the z-direction for the extruder to extrude at a higher level. From this elevated curve, the control points will be extracted, which will be used to create a path for the Robot.



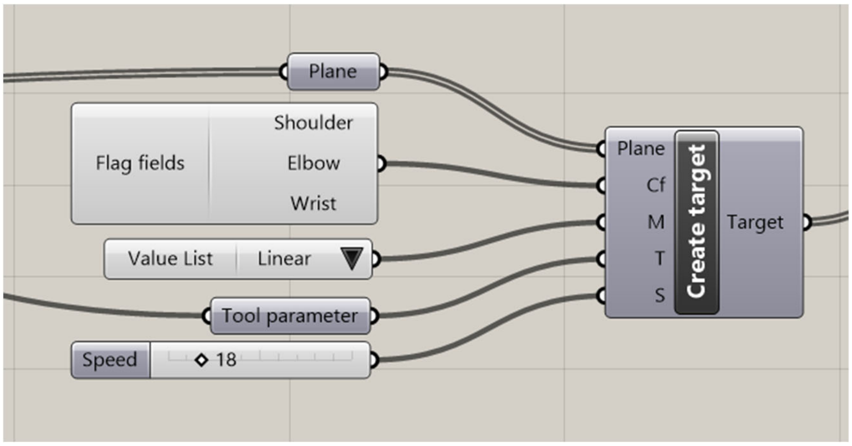
Step 2: Create higher levels
For the levels above the base layer, the same points will be used, which will be lifted in the z-direction. In this step it is important to look at the list of points to know whether the robot will start on the start or end of the curve. To make a fluent path, it is important that the points start conversely for each layer.



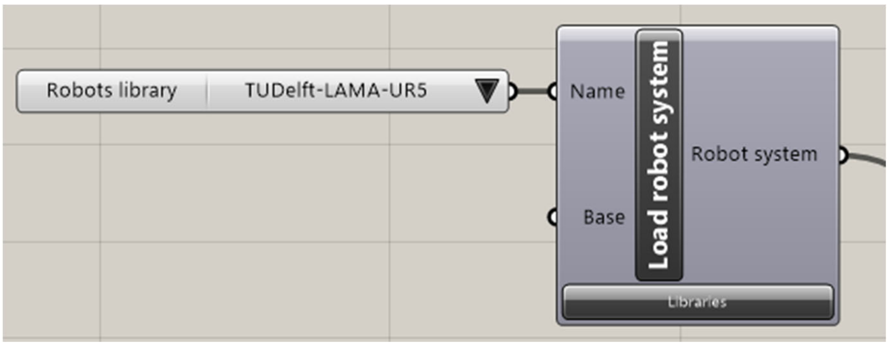
Step 3: Create Tool
For the robot to know how high above the table the path needs to start the tool, in this case the extruder, needs to be programmed. To create a tool, a name, a TCP, which determines the direction and the location of the tool, the weight, and optional a mesh with a model of the tool need to be inserted. With these inputs, a tool is created.



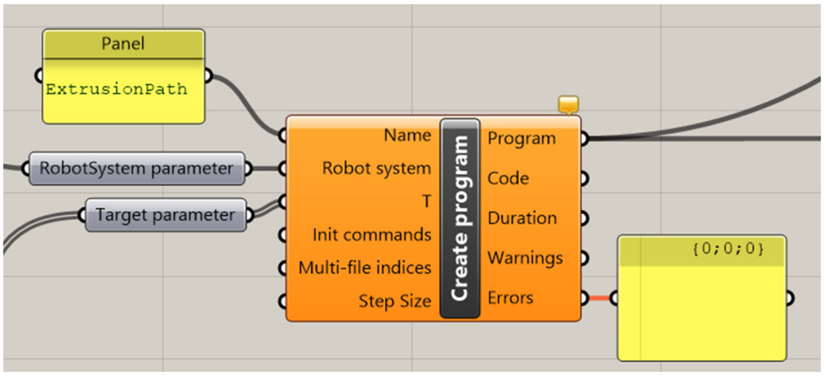
Step 4: Create Target
After the tool is created, a target can be made. For this all the points, created in step 2, are needed as an input, together will the tool parameter. Next to that, the configuration of the robot itself can be done by positioning the Shoulder, Elbow, and Wrist of the Robot. This parameter will be used to be able to help the Robot by shifting the position in case of collisions inside the program. The motion component sets the way the robot moves from one point to another. In this case the Linear motion type is used, since straight lines are required. Lastly, the speed in which to Robot will move from point a to point b can be inserted, which is in mm/s.



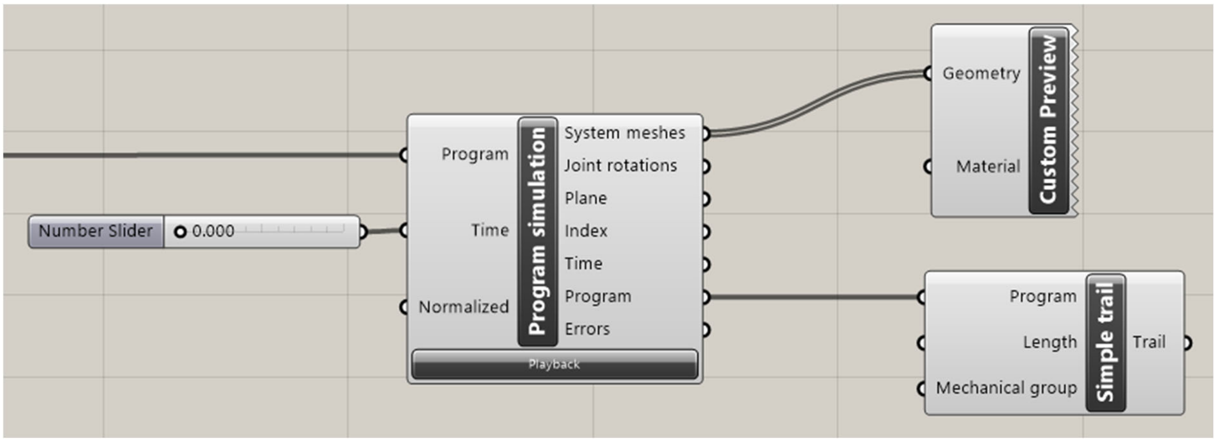
Step 5: Load robot system
To make a script, the data of the specific Robot needs to be inserted. Here fore, a library is present, in which most of the robot types are located. In this case the UR5 will be selected.



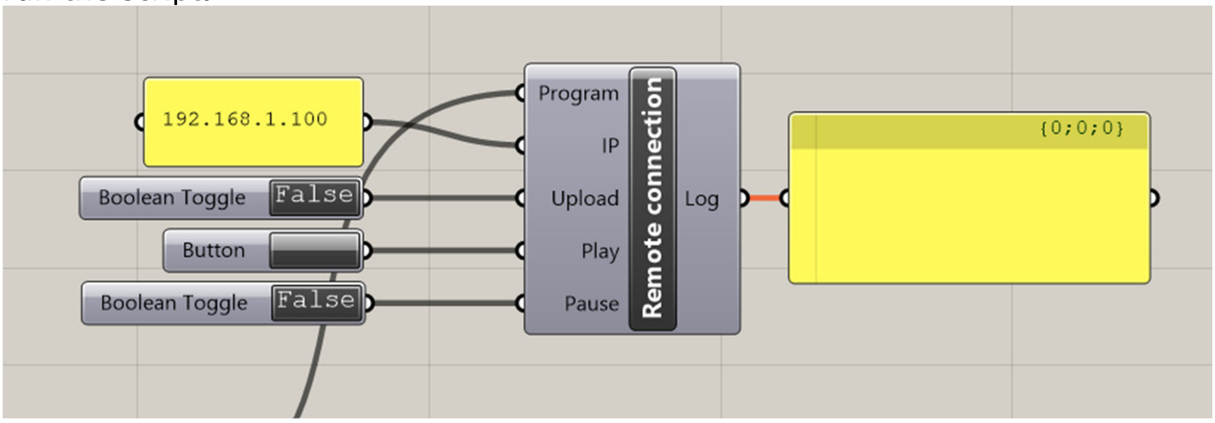
Step 6: Create program
This is the step in which everything comes together. The program which the robot needs to run will be created. For this the Robot system needs to be inserted, together with the target parameter. This program creates a program which can be sent to the robot directly by using a remote connection, and a code which can be used to inset in the robot by using a USB card. In this case, preference is given to the remote connection, since in this case changes can easily be made while running the program to see the effect.



Step 7: Program Simulation
Before the robot will execute the program, it is recommended to execute the program simulation. With this component a virtual simulation of the program will be made in the rhino file. This step is present to be able to perceive whether the program will cause collisions, after which changes in the configurations can be made.



Step 8: Remote connection
The final step, after whether is it clear that the program does not cause any collisions, the program can be uploaded to the robot after which the robot will run the script.



Appendix 2: G-code

```
def Program():
  ExtruderTcp = p[0, 0.13467, 0.05681, 0, 2.22144, 2.22144]
  ExtruderWeight = 4
  ExtruderCog = [0, 0.13467, 0.05681]
  Speed000 = 0.018
  DefaultZone = 0
  set_tcp(ExtruderTcp)
  set_payload(ExtruderWeight, ExtruderCog)
  movej([1.3076, -1.1376, 1.7723, -0.6347, -0.2632, 3.1416], a=3.1416,
v=0.0565, r=DefaultZone)
  movel(p[0.11761, -0.50196, 0.01393, 2.22144, 2.22144, 0], a=1,
v=Speed000, r=DefaultZone)
  movel(p[0.11987, -0.50589, 0.01393, 2.22144, 2.22144, 0], a=1,
v=Speed000, r=DefaultZone)
  movel(p[0.11758, -0.50985, 0.01393, 2.22144, 2.22144, 0], a=1,
v=Speed000, r=DefaultZone)
  ……

 movel(p[0.1753, -0.50589, 0.02993, 2.22144, 2.22144, 0], a=1, v=Speed000,
r=DefaultZone)
  movel(p[0.1453, -0.55785, 0.02993, 2.22144, 2.22144, 0], a=1, v=Speed000,
r=DefaultZone)
  movel(p[0.0853, -0.55785, 0.02993, 2.22144, 2.22144, 0], a=1, v=Speed000,
r=DefaultZone)
  movel(p[0.0553, -0.50589, 0.02993, 2.22144, 2.22144, 0], a=1, v=Speed000,
r=DefaultZone)
  movel(p[0.0853, -0.45393, 0.02993, 2.22144, 2.22144, 0], a=1, v=Speed000,
r=DefaultZone)
end
```

Appendix 3: Samples Experiment 6

Sample 1

Sample 2

Sample 3

Sample 4

Sample 5

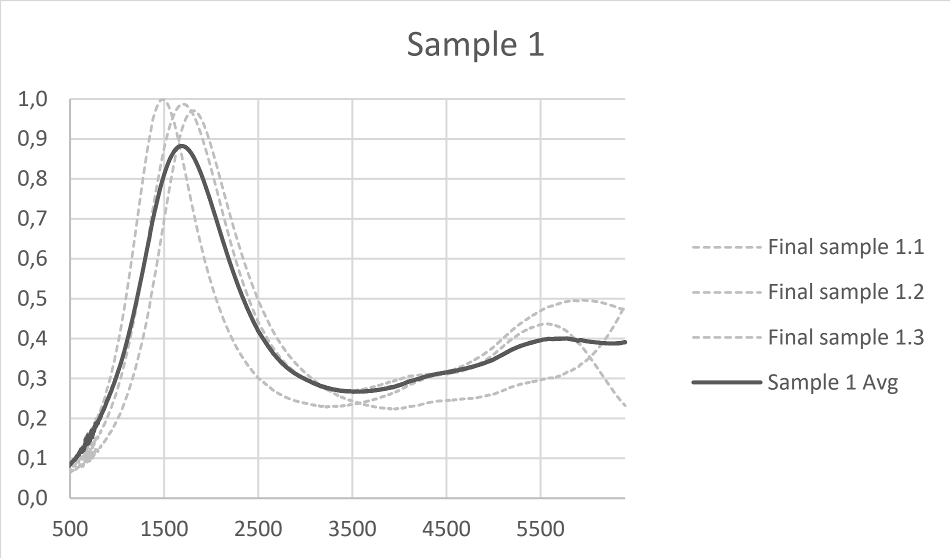
Sample 8

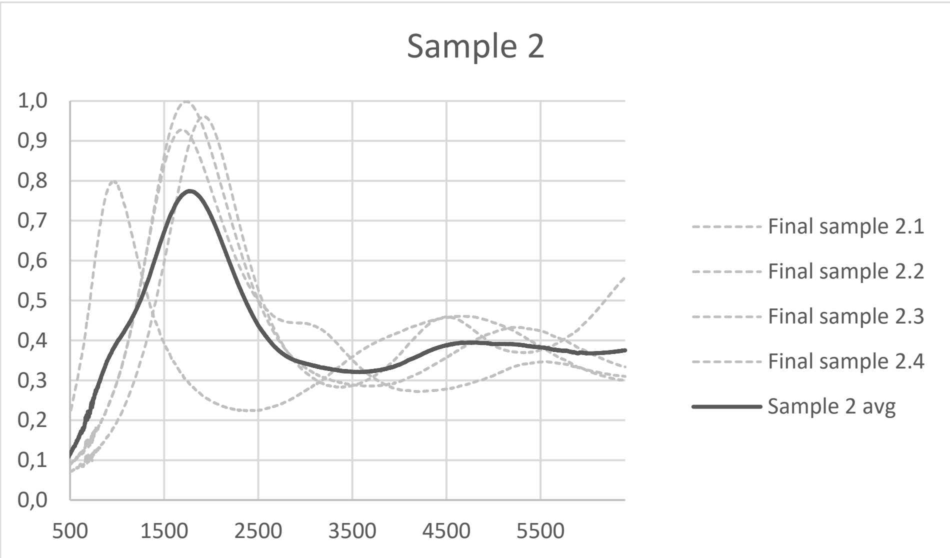
Sample 6 and 7

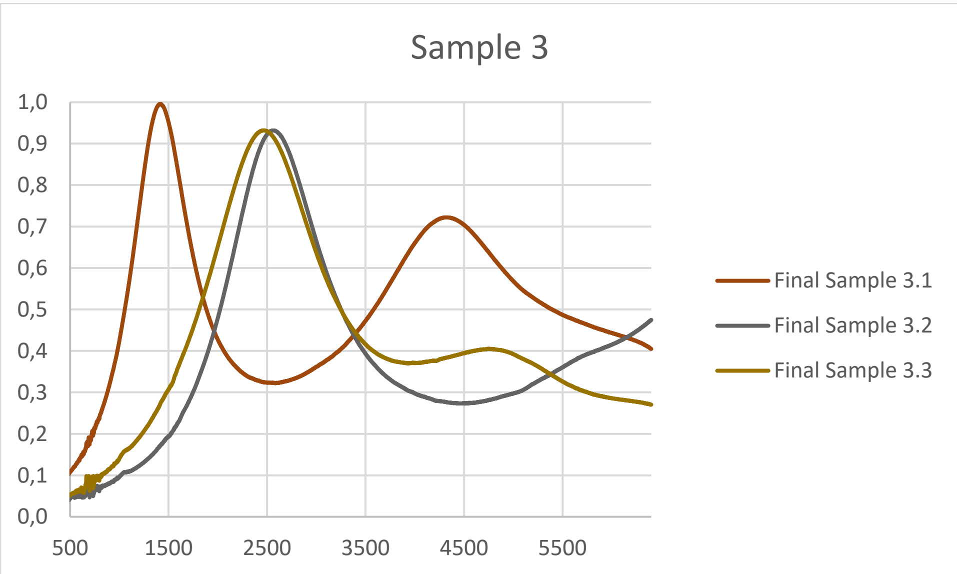
Sample 9

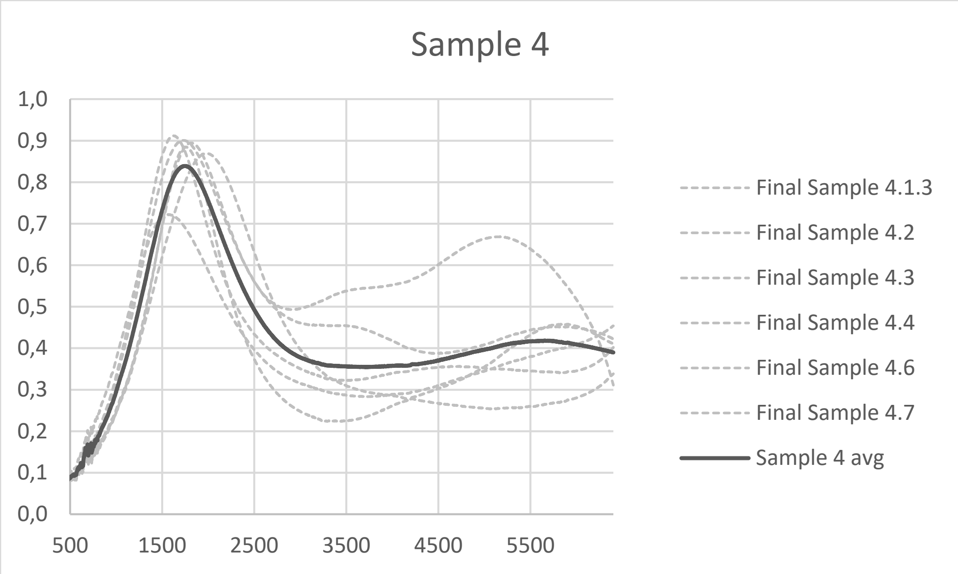
Sample 10

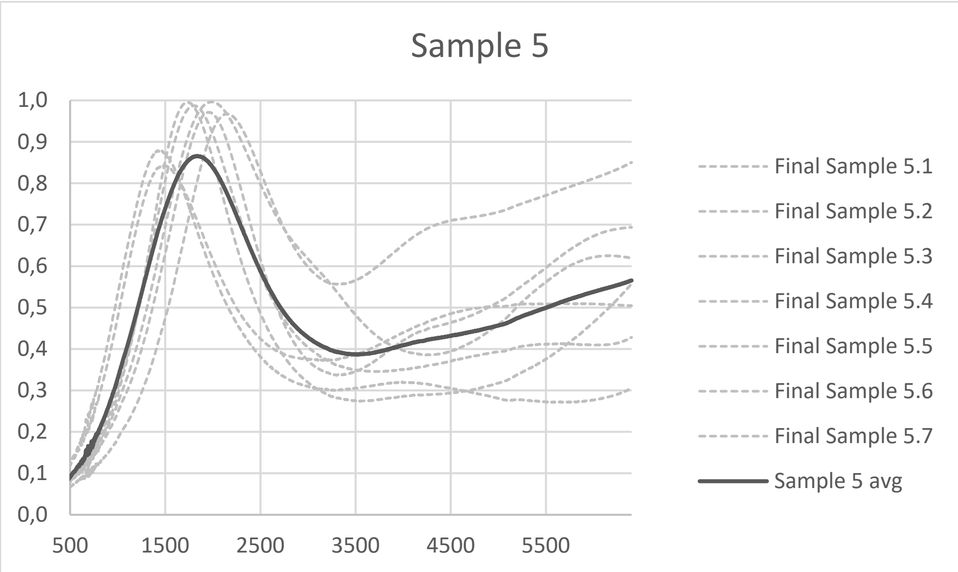
Appendix 4: Acoustic Measures

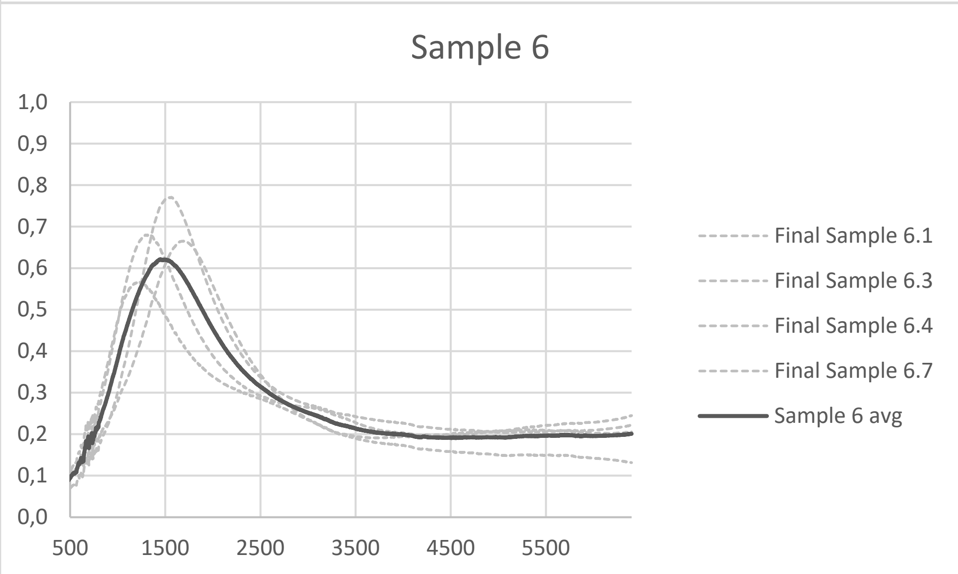

Sample 1
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
500
1500
2500
3500
4500
5500
Final sample 1.1
Final sample 1.2
Final sample 1.3
Sample 1 Avg

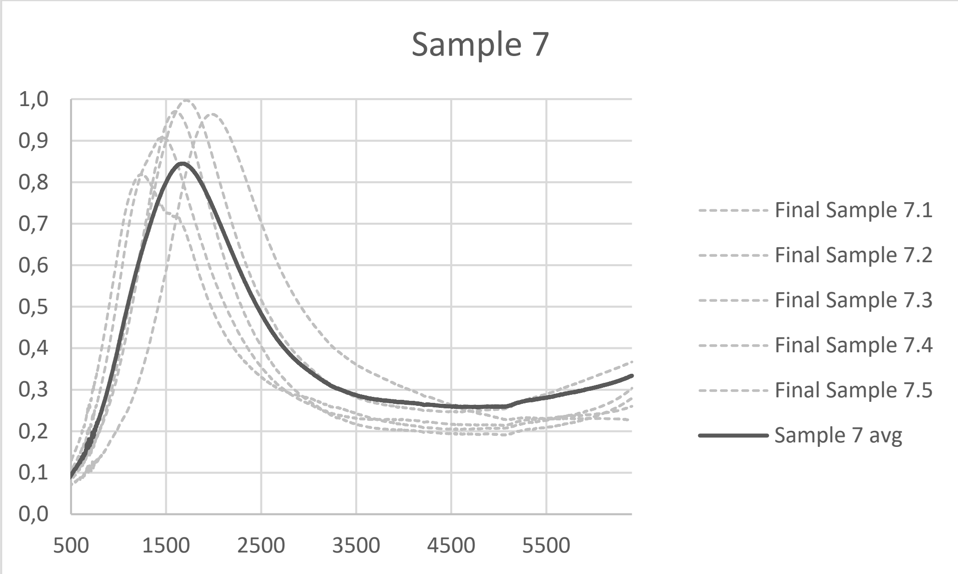

Sample 2
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
500
1500
2500
3500
4500
5500
Final sample 2.1
Final sample 2.2
Final sample 2.3
Final sample 2.4
Sample 2 avg

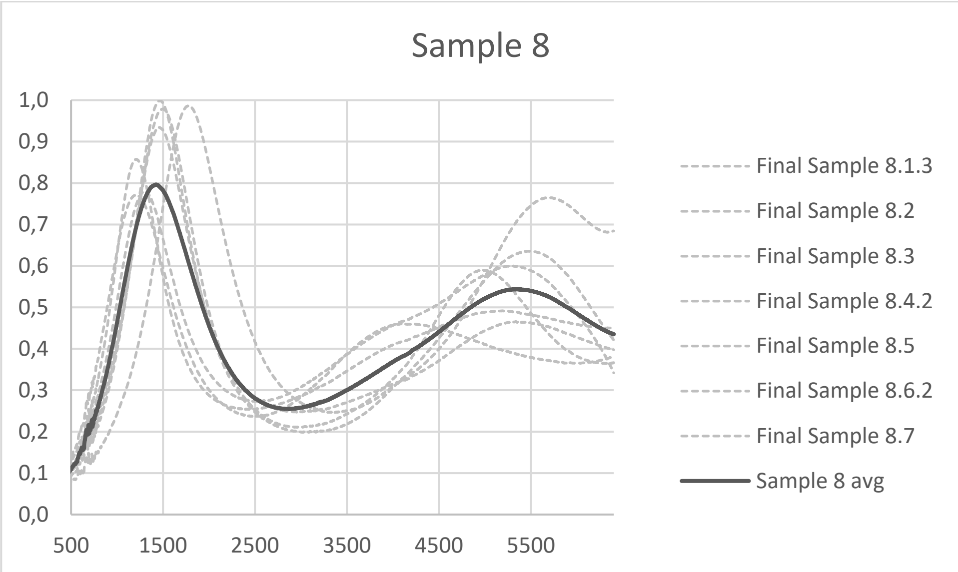

Sample 3
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
500
1500
2500
3500
4500
5500
Final Sample 3.1
Final Sample 3.2
Final Sample 3.3

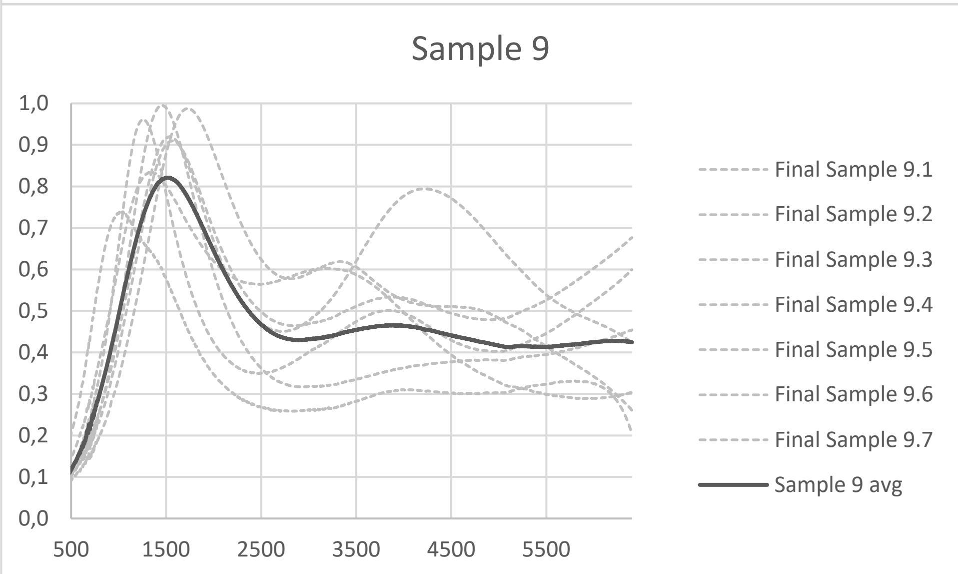

Sample 4
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
500
1500
2500
3500
4500
5500
Final Sample 4.1.3
Final Sample 4.2
Final Sample 4.3
Final Sample 4.4
Final Sample 4.6
Final Sample 4.7
Sample 4 avg

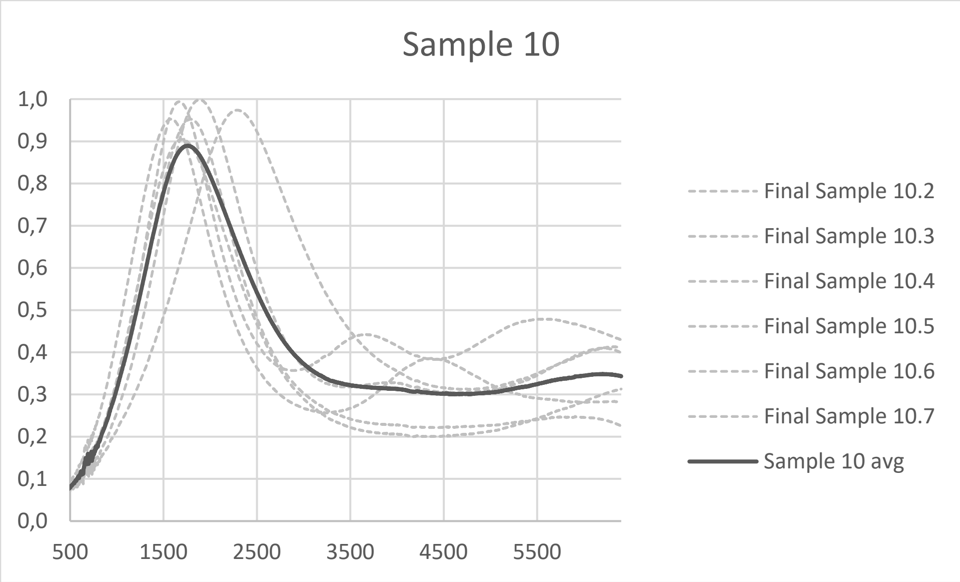

Sample 5
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
500
1500
2500
3500
4500
5500
Final Sample 5.1
Final Sample 5.2
Final Sample 5.3
Final Sample 5.4
Final Sample 5.5
Final Sample 5.6
Final Sample 5.7
Sample 5 avg


Sample 6
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
500
1500
2500
3500
4500
5500
Final Sample 6.1
Final Sample 6.3
Final Sample 6.4
Final Sample 6.7
Sample 6 avg


Sample 7
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
500
1500
2500
3500
4500
5500
Final Sample 7.1
Final Sample 7.2
Final Sample 7.3
Final Sample 7.4
Final Sample 7.5
Sample 7 avg

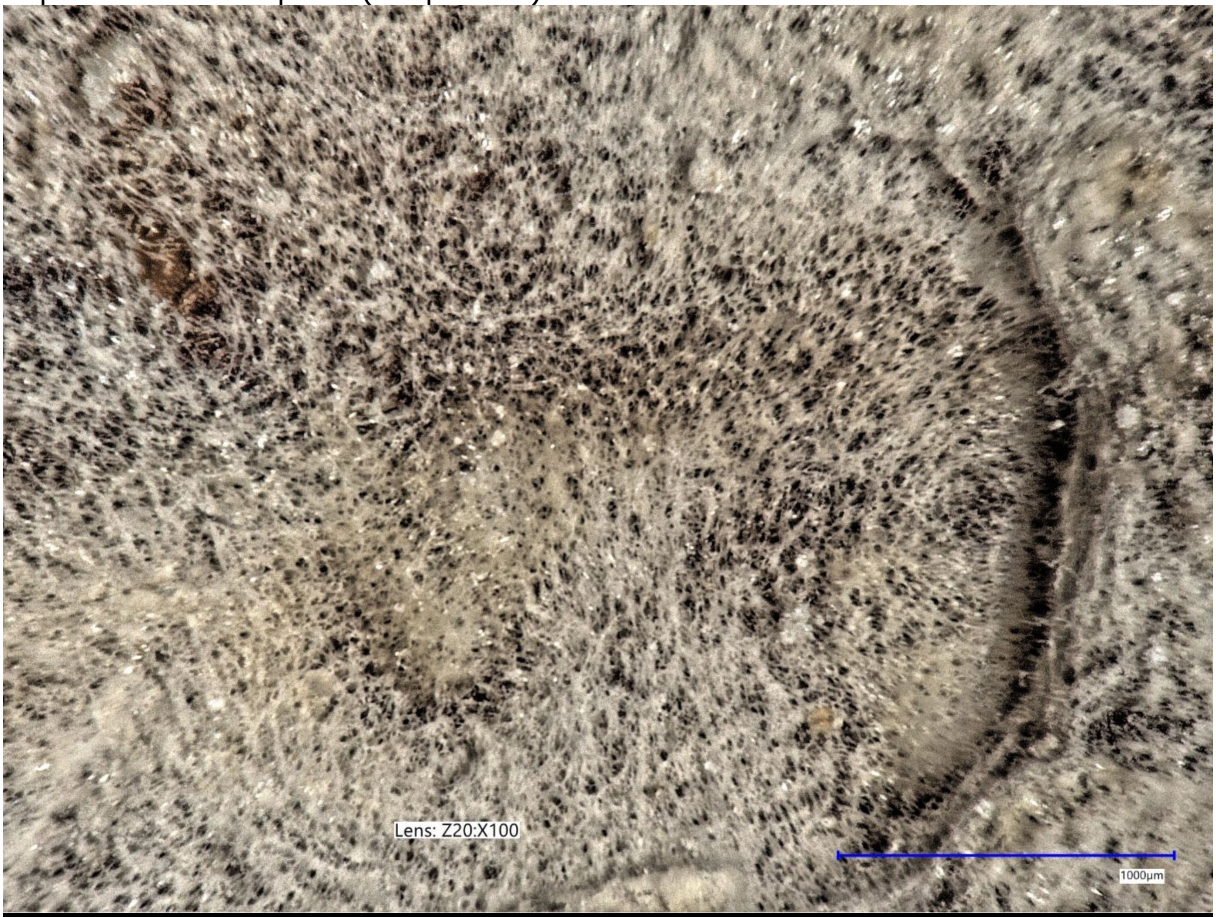

Sample 8
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
500
1500
2500
3500
4500
5500
Final Sample 8.1.3
Final Sample 8.2
Final Sample 8.3
Final Sample 8.4.2
Final Sample 8.5
Final Sample 8.6.2
Final Sample 8.7
Sample 8 avg

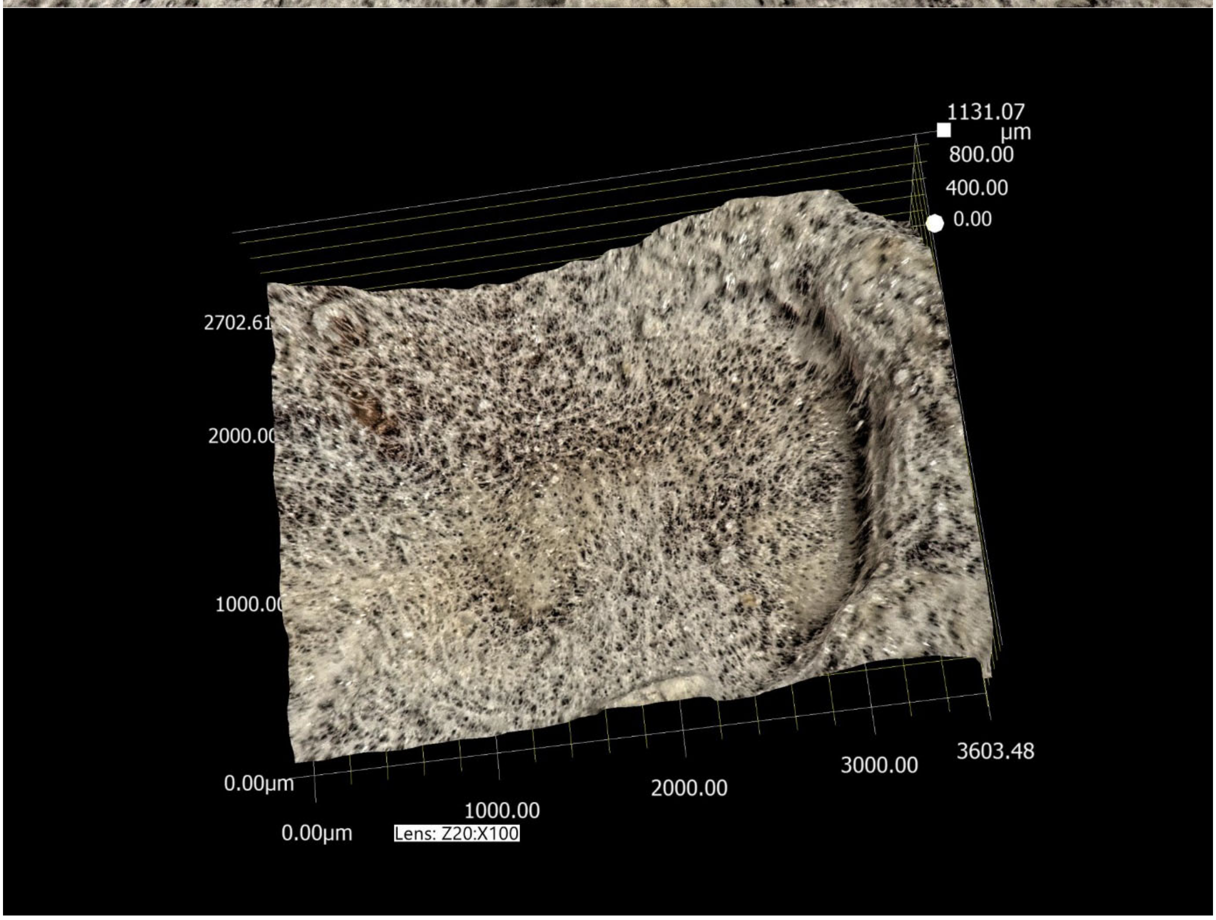

Sample 9
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
500
1500
2500
3500
4500
5500
Final Sample 9.1
Final Sample 9.2
Final Sample 9.3
Final Sample 9.4
Final Sample 9.5
Final Sample 9.6
Final Sample 9.7
Sample 9 avg


Sample 10
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
500
1500
2500
3500
4500
5500
Final Sample 10.2
Final Sample 10.3
Final Sample 10.4
Final Sample 10.5
Final Sample 10.6
Final Sample 10.7
Sample 10 avg

Appendix 5: Microscopic pictures

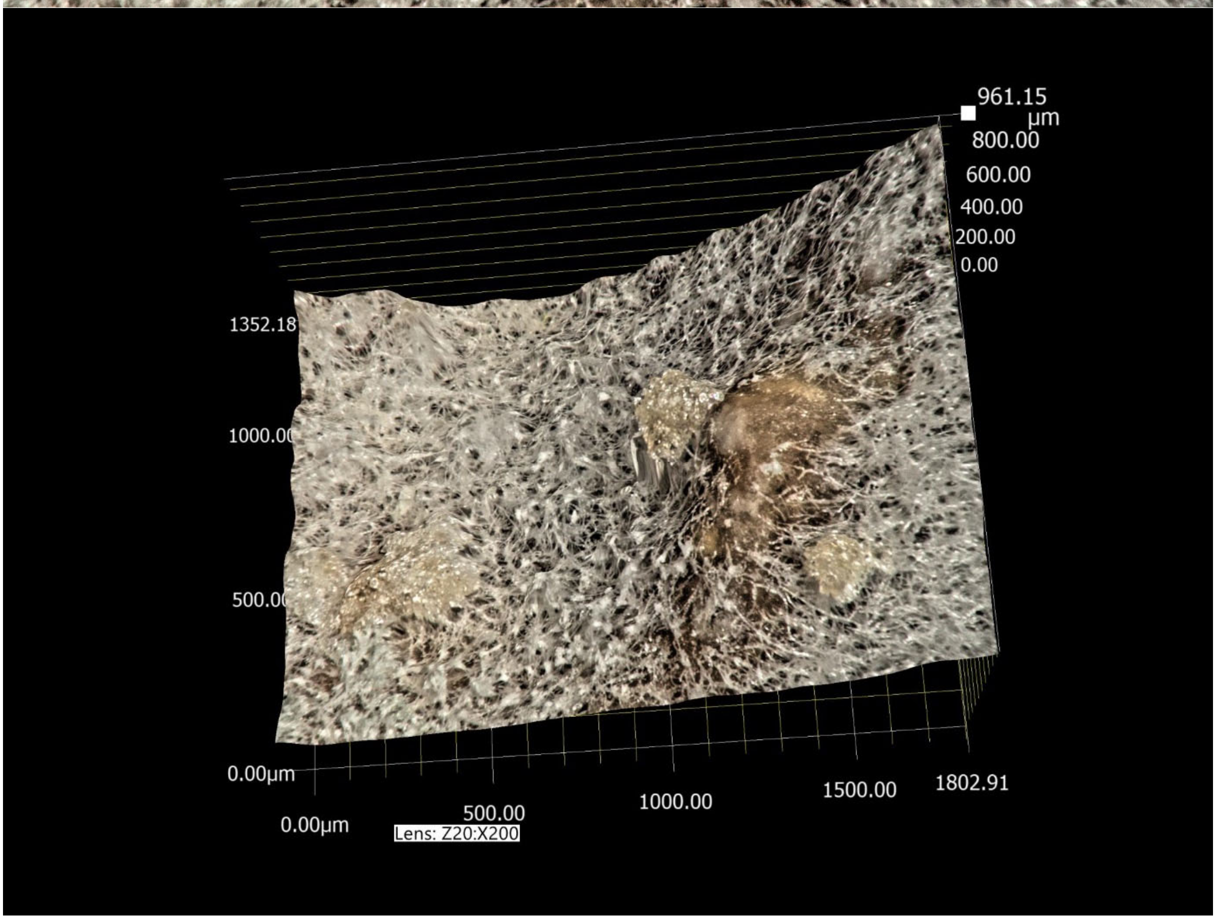
Experiment 1 Sample 3 (3D printed)



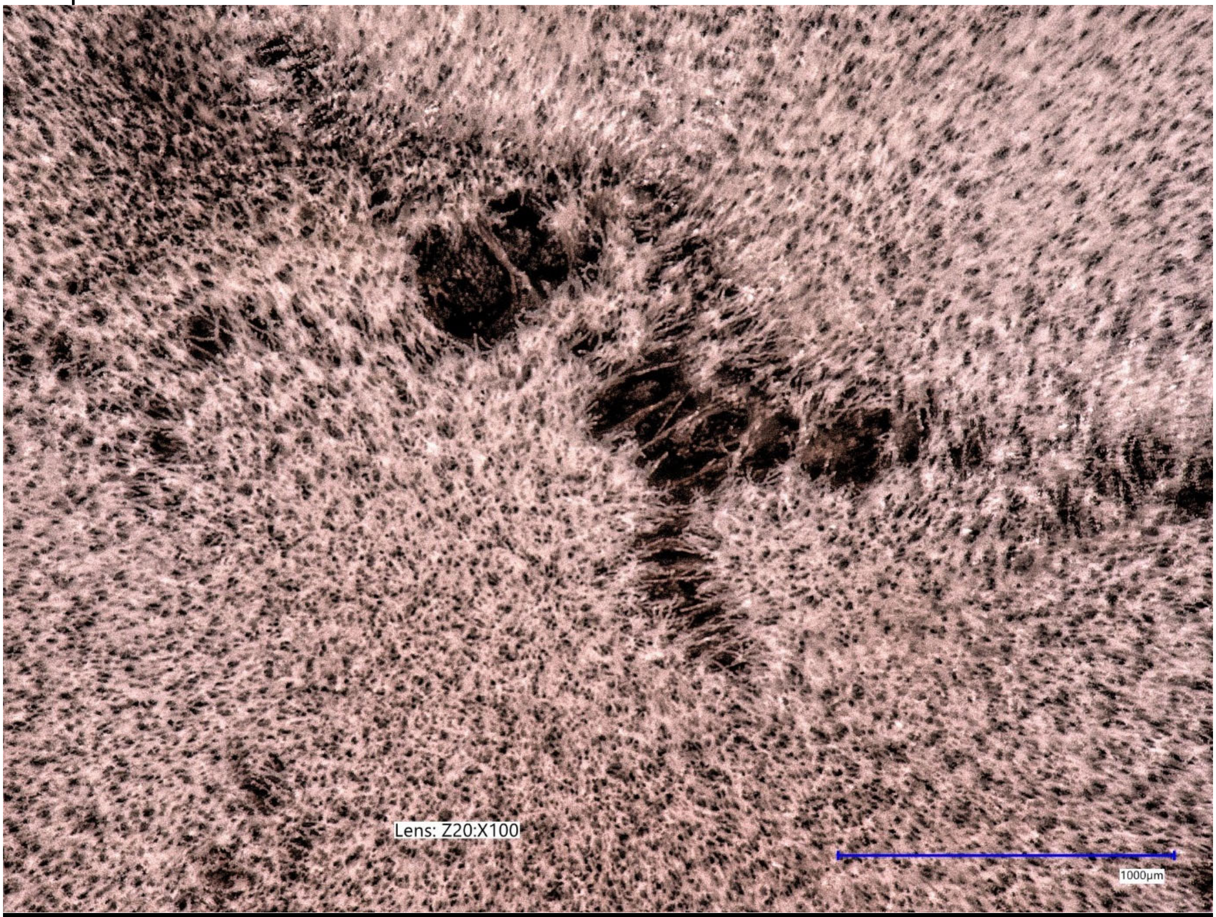


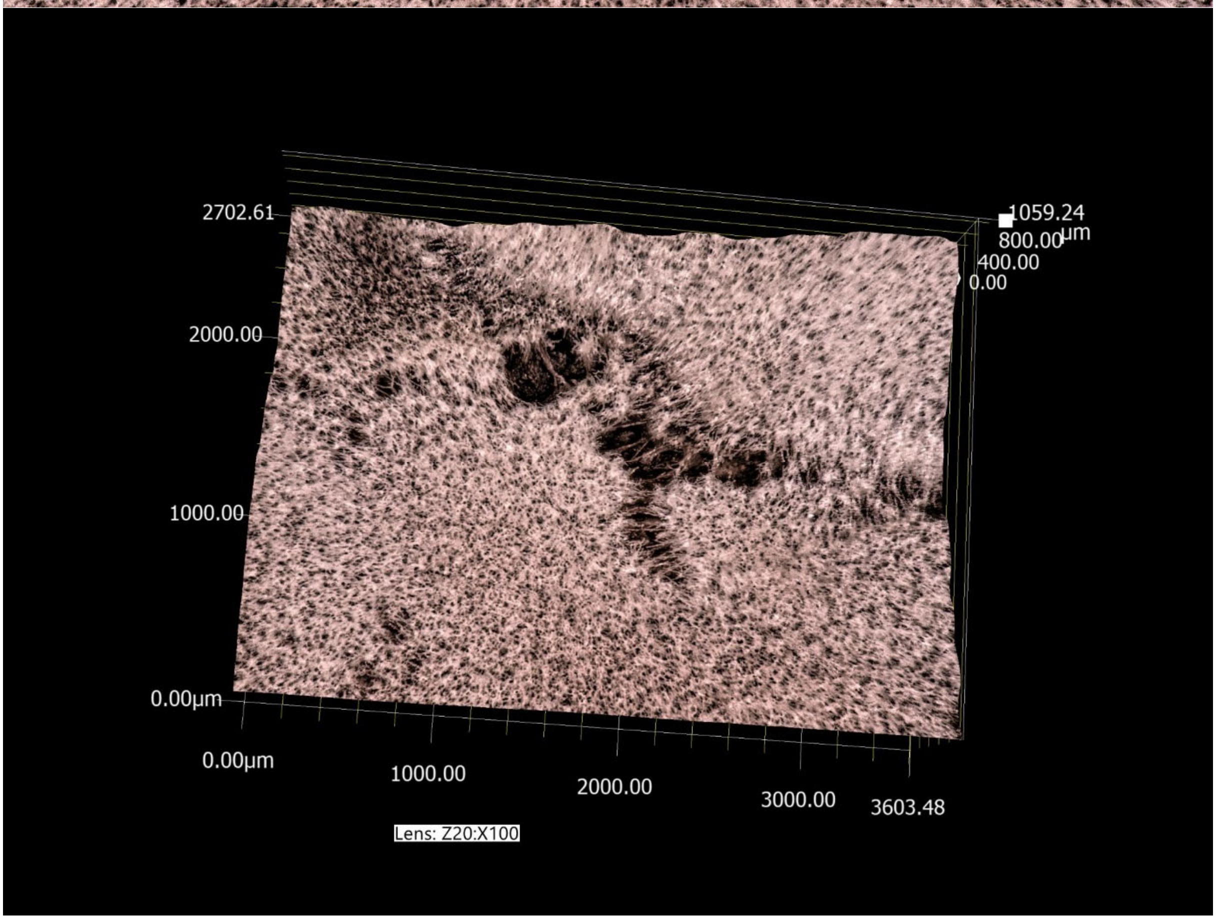
Sample 4


Lens: Z20:X200
1000μm

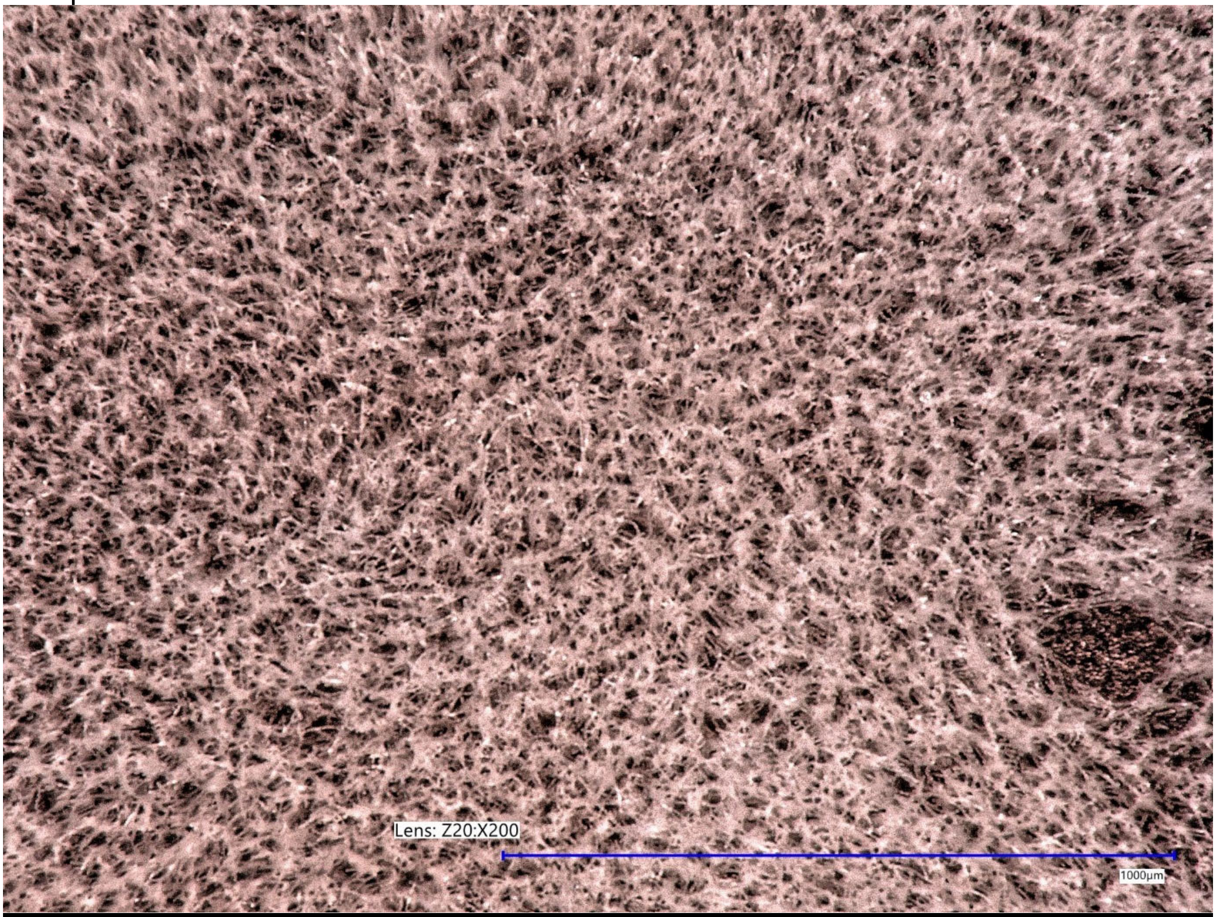

961.15
μm
800.00
600.00
400.00
200.00
0.00
1352.18
1000.00
500.00
0.00μm
0.00μm
500.00
1000.00
1500.00
1802.91
Lens: Z20:X200

Sample 7

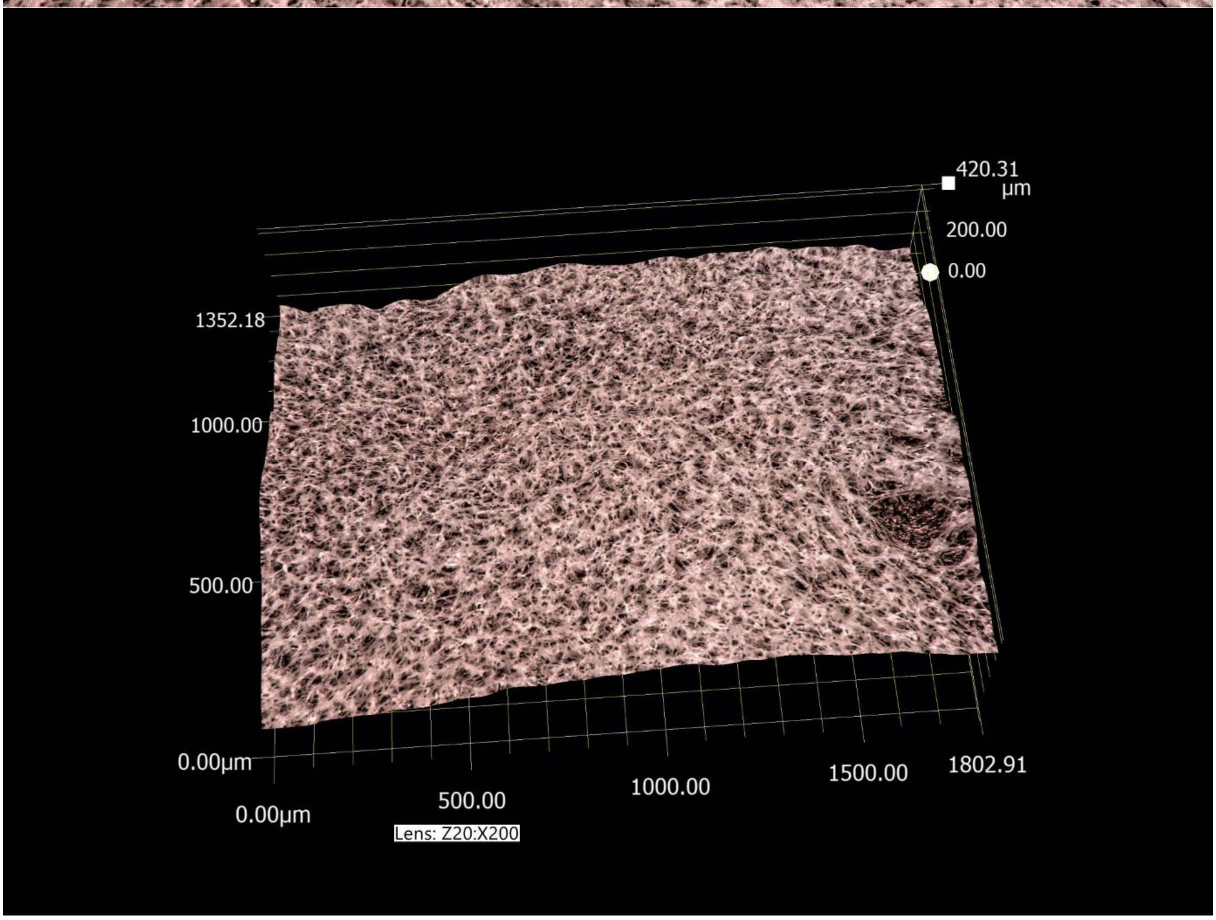

Lens: Z20:X100
1000μm


2702.61
2000.00
1000.00
0.00μm
0.00μm
1000.00
2000.00
3000.00
3603.48
1059.24
800.00
μm
400.00
0.00
Lens: Z20:X100

Sample 7 C



Lens: Z20:X200
1000µm



420.31
µm
200.00
0.00
1352.18
1000.00
500.00
0.00µm
0.00µm
500.00
1000.00
1500.00
1802.91
Lens: Z20:X200

Appendix 6: Acoustic simulation

Acoustic Simulation
For the acoustic simulations Rhino in combination with Grasshopper is used together whit the add-in PachyDerm. PachyDerm is an acoustic simulation add-in made by Arthur, which can be used to predict noise and visualize the propagation of sound. For this thesis, PachyDerm is used to calculate the reverberation time of the produced sound in the room.

To be able to run the simulation, multiple steps need to be done.

1. Create a closed room

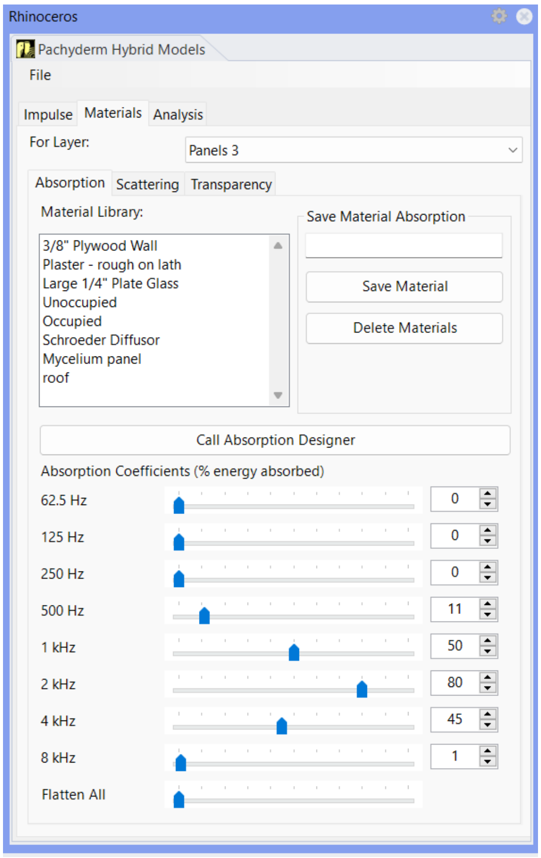
The first step is to create a closed room. This room needs to contain walls, a roof, and a floor.

2. Determine sending and receiving point

The simulation workst with a sending and a receiving point. The sending point will produce sound in different frequencies after which the simulation will determine how long the reverberation time is the receiving point.

3. Add the acoustic panels

Next to the closed room, the acoustic panels need to be modelled.



4. Create a custom material

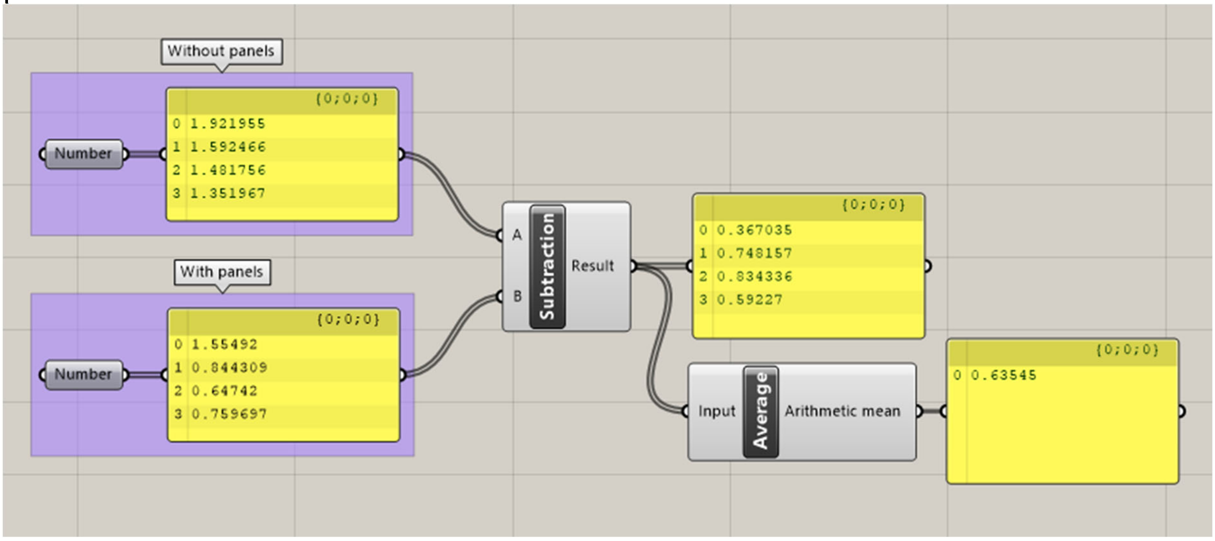
Since the acoustic panels, used for this simulation, are custom made, there is no data present in the database. Therefore, the derived data from the acoustic tests need to be inserted manually.

5. Add acoustic properties to all elements

Not only the acoustic panels, but all elements present in the room contain acoustic properties.

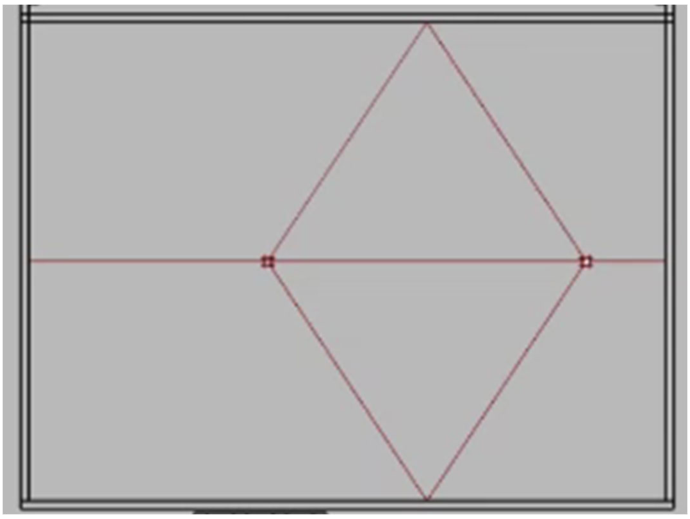
6. Run acoustic simulation

Once elements are connected to the correct data, the acoustic simulation can take place. The outcome of this simulation will be the reverberation time in the receiving point.



7. Adjust the location and the number of panels to meet the requirements

When the simulation is done and the required outcomes are not met yet, the number of panels and the location can be adjusted.

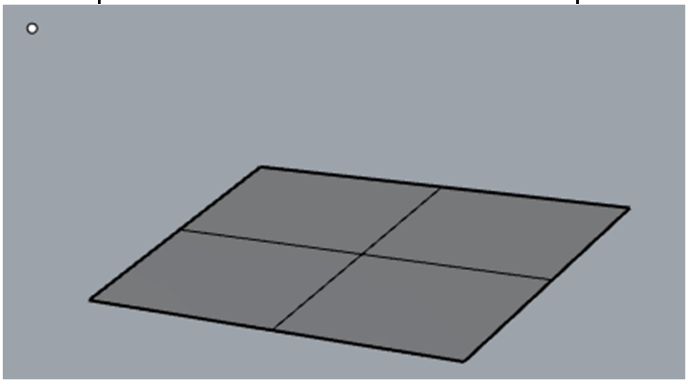


Appendix 7: Parametric panel design

Parametric panel design steps

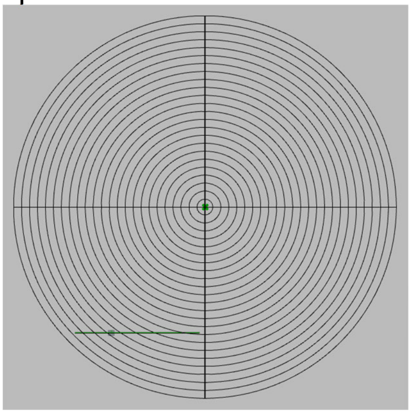
Step 1: Create surface and point

The first step is to create the surface of which the acoustic panel will be formed, and a point which indicates where the produced sound is coming from.

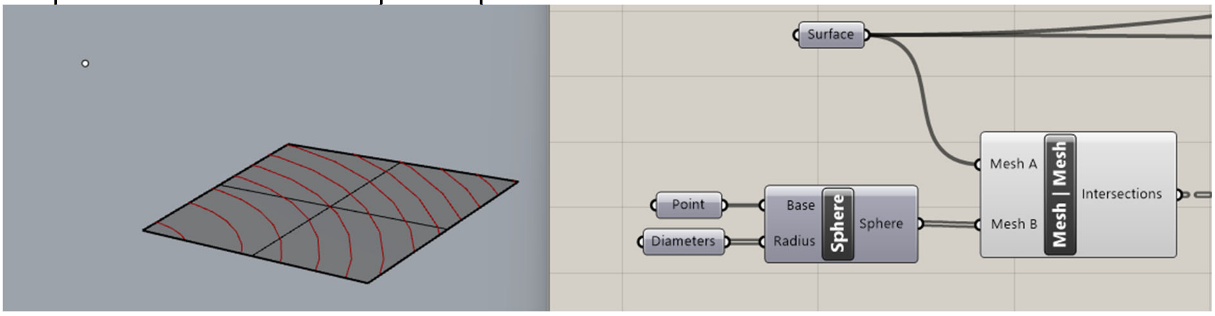


Step 2: Create multiple spheres around point.

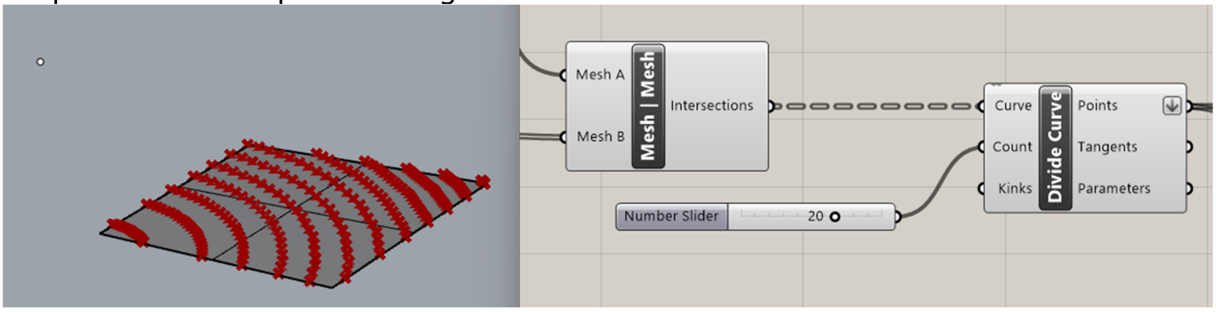
To find the intersection points between the soundwaves and the surface, multiple spheres with different diameters are formed around the created point.



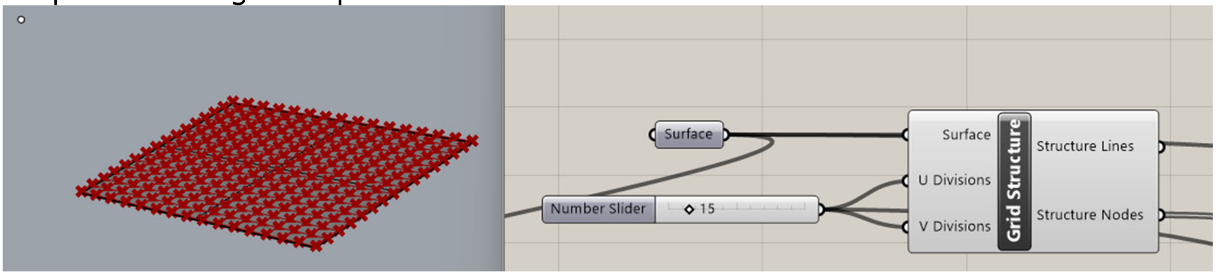
Step 3: Find intersection point spheres and surface and create lines



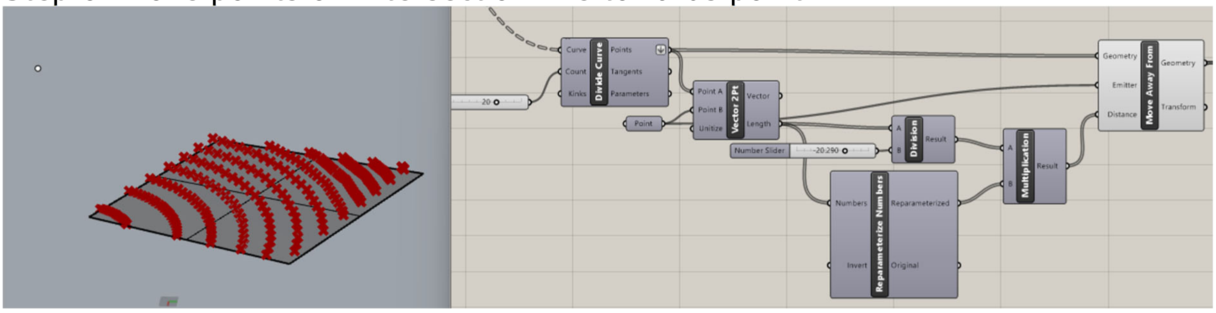
Step 4: Distribute points along the intersection lines



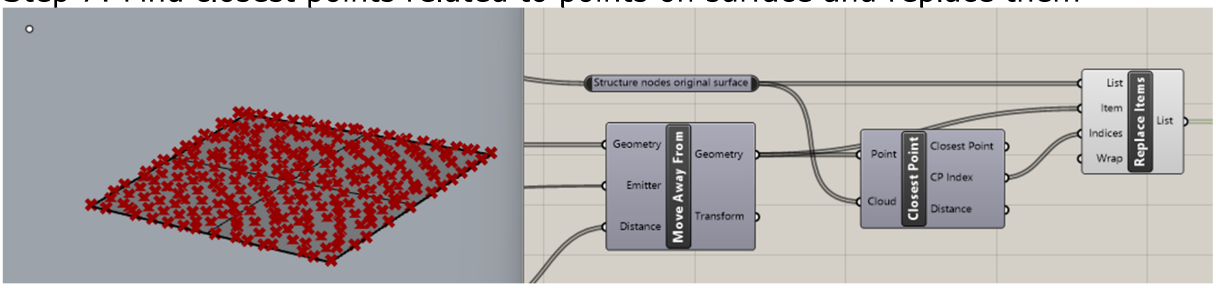
Step 5: Create grid of points on surface



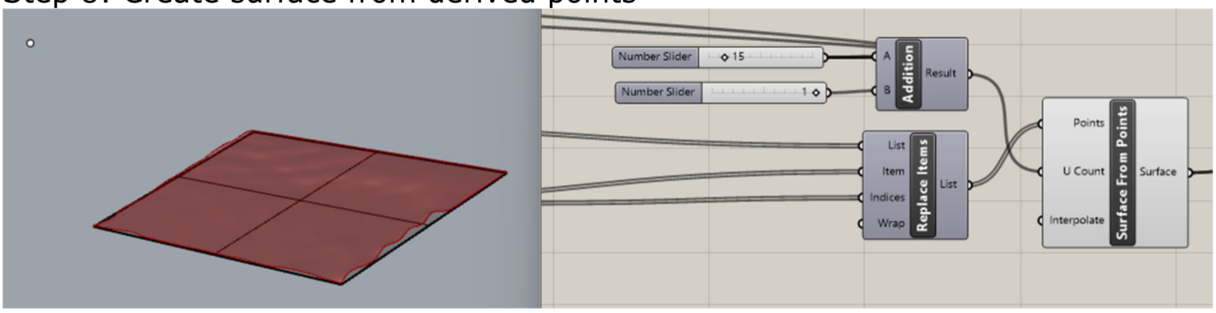
Step 6: Move points on intersection line towards point



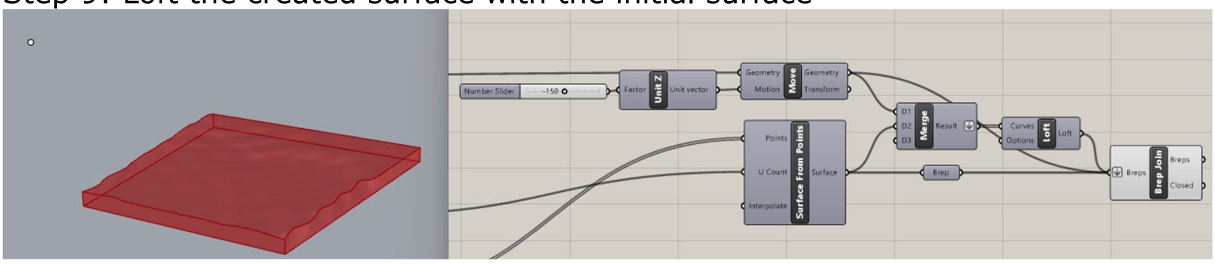
Step 7: Find closest points related to points on surface and replace them



Step 8: Create surface from derived points



Step 9: Loft the created surface with the initial surface



Step 10: Bake the panel