Exploring flexible structures in 3D-printed bio-based materials to closely mimic the properties of foam

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MASTER THESIS

Exploring flexible structures in 3D-printed bio-based materials to closely mimic the flexibility of foam

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Abstract

Plastic is used for an enormous number of products worldwide, one of these being conventional foam. This foam can be found in everything from an office chair to a sponge. To be able to move away from non-renewable sources in hope of protecting our planet we need to find alternatives materials and manufacturing methods for these products. This master thesis will focus on trying to replace conventional foam by using additive manufacturing methods and a bio-based plastic.

Inspiration for this master thesis was taken from three different sources: literature, nature and foam structures. The result of this project is a 3D-printed structure represented mainly in a cubic model, but it also includes how the structure could be implemented in a product.

This master thesis does not present a finished concept ready for manufacturing, but rather a framework for further research into this topic.

Keywords: CAD, Design, Product Development, Foam, Additive Manufacturing, Structure

Sammanfattning

Plast används i ett enormt antal produkter över hela världen, varav en är vanligt skum. Detta skum finns i allt från en kontorsstol till en tvättsvamp. För att kunna röra sig bort från icke förnybara källor i hopp om att skydda vår planet måste vi hitta alternativa material och tillverkningsmetoder för dessa produkter. Denna masteruppsats kommer att fokusera på att försöka ersätta konventionellt skum med hjälp av additiv tillverkning tillsammans med en biobaserad plast.

Inspiration för detta examensarbete hämtades från tre olika källor: litteratur, natur och skumstrukturer. Resultatet av detta projekt är en 3D-tryckt struktur som huvudsakligen representeras i en kubisk form, men det inkluderar också hur strukturen kan implementeras i en produkt.

Detta examensarbete presenterar inte ett koncept färdigt för tillverkning, utan snarare en ram för vidare forskning om detta ämne.

Nyckelord: CAD, Design, Produktutveckling, Skum, tillsatsmetoder, strukturer

Acknowledgments

There were many aspects of this project that were new to me, and it would not be possible to have reached these results without the people around me. Most master thesis projects are completed in pairs, and this one was not, so I would like to specially thank my supervisor Axel Nordin in guiding me through this project, acting as my partner in discussions and thoughts that I had.

Lund, January 2021

Fredrik Sinclair

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1 Introduction

This part of the project contains the introduction to the master thesis where the purpose, goals and limitations are presented.

1.1 Purpose

Polyurethane (PU) is a polymer that is used in many applications, for example the upholstery industry in objects such as an office chair, or in everyday items such as a foam sponge. In other words, it is hard to avoid since there are few, if any, alternatives. However, there are two major issues with PU, firstly, its fossil based, and secondly, isocyanates that are used in the process of manufacturing PU are toxic. There are ongoing efforts to get rid of the fossil-based components and isocyanates by replacing them with more sustainable alternatives, but it is still unclear how this change would affect the performance and properties of the foam (Anon., 2021).

This master thesis will be done within the context of a mission in the STEPS2 research project, which aims to replace polyurethane foam with 3D printed foam-like structures in upholstery applications, mimicking the function of PU but using bio-based plastics without toxic isocyanate chemistry. As the foam-like structures are high in complexity, 3D printing is ideally suited as a production method.

1.2 Project goals

1.2.1 **Overall goals of STEPS2**

STEPS stands form Sustainable Plastics and Transition Pathways and is a research program focusing on making plastics that are sustainable produced in a sustainable way. STEPS was started in 2016 and has a vision of a future with plastics that are sustainable all through the lifecycle. The projects main focus is polyesters which is a group of polymers with a varying range of material properties, making it possible to target a wide range of applications (Anon., 2021).

1.2.2 **Specific goals for master thesis**

Specific goals of this master thesis include the following:

- Evaluate if it is possible to replace conventional foam with a 3D-printed biobased plastic structure
- Evaluate different possible variations of different structures which has similar properties to foam when it comes to flexibility
- Print a sample of the final concept structure that can be applied in an upholstery product or similar

1.3 Delimitations

The goal of the STEPS2 project is to find a structure that as close as possible mimics the flexibility of foam. More specifically this master thesis aims to find a flexible structure in PA11 used in SLS printing. The material used for testing in this project will be PA11 and the printing process will be selective laser sintering (SLS), which is provided by the faculty of LTH. The project will also be restricted and limited to only looking at various variations of cellular structures and patterns. The final prototype will be in the vicinity of 10 x 10 x 10 cm in size. Test pieces will be made in a smaller scale, mostly 2.5 x 2.5 x 2.5 cm. In this project, cyclical material fatigue will not be examined. Optimising via simulations to automatically reach specific structural properties has not been applied in this project.

1.4 Structure of this thesis

In chapter 2 the design and research method used is presented and explained.

In chapter 3 background is presented. This includes a presentation of the software, the additive manufacturing method, materials and the explored structures.

In chapter 4 the process of generating concepts is explained as well as where inspiration was taken from. Thereafter, a detailed explanation of the process of creating the concepts s presented and lastly, the concept evaluation process is described in detail.

In chapter 5 the conclusion is presented which includes an explanation and images of the final concept, where this concept could be implemented and the feasibility of the final concept.

In chapter 6 In this part of the project, a discussion is held, mainly focusing on the method and results and what has been learned throughout the entire master thesis.

2 Methodology

In this part of the project, the design and research method used is presented and explained.

2.1 Double Diamond

This project aims to follow the Double Diamond design process. This process aims to explore a problem extensively and then acting on the problem. Double Diamond was launched in 2004 and is a widely used tool in product design and development (Design Council, 2021). A visual representation of Double Diamond can be seen in Figure 1. The steps of Double Diamond are listed below.

1. *Discover*. The main goal of the first part is for the designer to understand and discover the problem. This may include research or speaking to people about the problem.
2. *Define.* In this step the designer needs to filter through the data collected and taking the time to reflect on what might be the main goals of the end product and looking over the possibilities in relation to limitations.
3. *Develop.* In the development phase the designer aims to come up with different concepts to clear and defined problem. It is encouraged to seek inspiration from different sources to develop different possible variations of the problem.
4. *Deliver*. In the last phase the concepts are tested in a small scale to eliminate any concepts that might not work and to focus more on concepts that have potential. (Design Council, 2021)

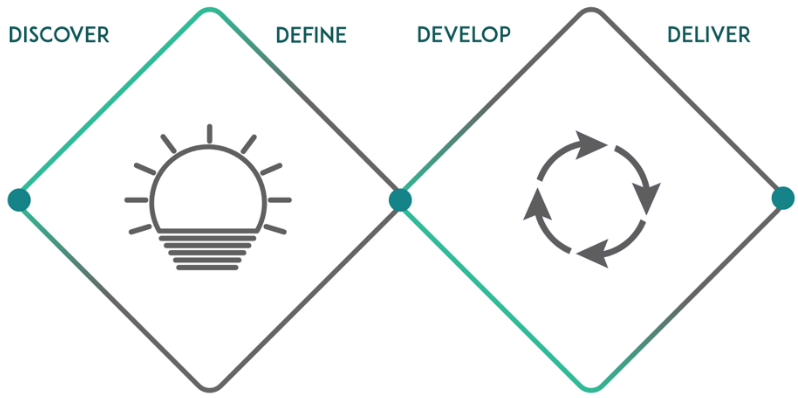

Figure 1: Double Diamond approach displayed visually

2.2 Research

Research about the topic in question was done through the use of LUBsearch, general google web searches and additional sources provided by project supervisor to research and find useful information to complete the project. There was also contact with Jonas Ihreborn AB, a furniture manufacturer in Sweden.

2.3 Planning method

To complete a project successfully, planning and coordination is important. In this project, a Gantt chart is used which consists of horizontally drawing out all the different phases of the project over time (APM, 2021). A Gantt chart is useful to:

- Visualize the whole project
- Address timelines and deadlines in the project
- Address different phases in the project
- Show relationships between different phases of the project

In this project, a preliminary Gantt chart was made for an overview of the project. A second Gantt chart was also made at the end of the project to show how project deadlines changed over time. The charts can be seen in Appendix A. (APM, 2021)

2.4 Concept generation

Concept generation is preformed to find new and/or enhanced solutions to an existing problem. Ulrich and Eppinger (Eppinger & Ulrich, 2012) provide a five-step method to break a problem into different parts.

1. Clarify the problem
2. Search externally
3. Search internally
4. Explore systematically
5. Reflect on solutions and the process

Below these 5 steps are explained further.

2.4.1 **Clarify the problem**

This step involves clarifying and understanding the problem and breaking it down into subproblems

2.4.2 **Search externally**

This step involves searching for information from external sources. In this case this was done by speaking to experts on the subject, researching online and researching published literature.

2.4.3 **Search internally**

This step involves internal search from team or individual knowledge. This is possibly the most creative and open-ended step and in this case brainstorming and quick sketching were some of the methods used.

2.4.4 **Explore systematically**

This step involves organizing all of the concepts to be able to possibly combine them and to put more focus into promising concepts.

2.4.5 **Reflect on solutions and the process**

Throughout the entire concept generation phase the team or individual should take reasonable time to reflect on whether there might be alternative solutions.

2.5 Prototyping

Prototyping was an essential step in this process since the structures needed to be tested. Prototyping was done by 3D-printing the structures at LTH.

2.6 Concept evaluations

The evaluation is done aiming to mimic the properties of foam. The first evaluation, however, is done more to get a general understanding of the material and structural properties of the material. The second evaluations focus on flexibility and deformation and a high force is put on the test pieces. The third evaluation focus on finding the optimal flexibility for a constant force.

3 Background

In this part of the master thesis the background is presented. This includes a presentation of the software, the additive manufacturing method, materials and structures explored.

3.1 Rhinoceros 3D and Grasshopper

Rhinoceros 3D is a computer aided design (CAD) application used in 3D-modelling. Compared to other CAD applications and programs, Rhinoceros can be particularly useful when 3D-modelling for additive manufacturing (Sculpteo, 2020). This project also greatly benefited from the integrated visual programming language called Grasshopper 3D. This visual language is constructed by linking different components together to create a 3D model. Additional plugins can also easily be downloaded which allows for different modelling benefits such as volumetric modelling and structural lattice modelling.

3.1.1 **Volumetric modelling**

There are different ways to create a geometry in software for 3D-modelling. The most common is called boundary representation, or in short “BREP”. Points called vertices are places in a two- or three-dimensional space and are thereafter connected with two-dimensional curves or three-dimensional surfaces which then form shapes and volumes. Using this type of modelling can lead to very slow Boolean operation speeds and it can also cause issues while modelling, for example waterproofing issues. Instead, volumetric modelling was used. In this case the space in question is not empty to begin with, but instead has a function f(x, y, z) which returns a specific value for every point in the given space. A negative value is inside the shape, a positive value is outside the shape and a 0 represents the surface of the shape or volume (Digital Building Technologies, 2021).

3.1.2 **Plugins**

To aid in the creation of a desired model in Rhinoceros and Grasshopper, different open-source plugins can be downloaded easily from the web. In this case, all plugins used are downloaded from a website called food4Rhino (McNeel Europe, 2020). Many different plugins were used, mainly the plugins that already exist in Grasshopper, however there were a few open-source plugins that particularly aided in the creation of lattice structures.

3.1.2.1 IntraLattice

IntraLattice is an open-source plugin for Grasshopper. This plugin focuses on generating volumetric lattice structures. Its main purpose was to create the different lattice structures. The interface of IntraLattice can be seen in Figure 2.

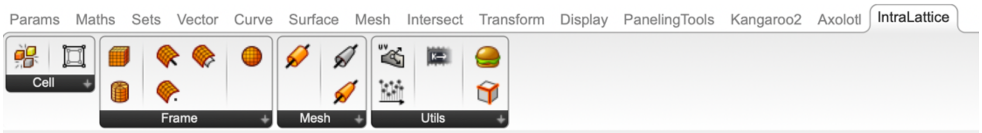

Figure 2: Interface of IntraLattice

3.1.2.2 Axolotl

Axolotl is also an open source-plugin for Grasshopper which focuses on much of the same features as IntraLattice, aiming to create volumetric models. The interface of Axolotl can be seen in Figure 3.

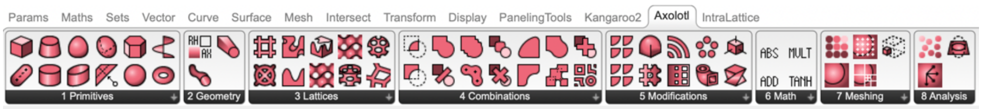

Figure 3: Interface of Axolotl

3.1.2.3 Other tools and pre-existing plugins

Rhinoceros 3D comes with a set of pre-existing tools and plugins and these are also used to an extent in this project.

3.2 Selective Laser Sintering (SLS)

Additive manufacturing (AM), also known as 3D-printing, is a manufacturing method which describes the technology of building three-dimensional models by adding layer-upon-layer of a material, most commonly with different types of plastics. This type of manufacturing method allows for very complex, lighter and stronger parts (TWI, 2020). Selective laser sintering (SLS) is a technique used in AM and uses a laser to sinter a powdered material, often nylon or other polymers, to print a 3D-model. This technique is relatively new and is mostly used in small scale production and rapid prototyping for complex parts. The technique uses the energy from a laser to sinter the powder layer by layer to create a 3D-model. The quality of the powder can greatly affect the performance of the model (Gan, et al., 2020).

Figure 4: Selective laser sintering process (Materialgeeza, 2008)

In Figure 4 the SLS process is illustrated. A powder delivery piston is raised, and a recoater pushes the material over to the fabrication powder bed. The laser then sinters the material, and the fabrication piston is lowered to allow a new layer of material, the cycle then repeats. After printing, there is a cool down time in the enclosure before the print can be removed. This may sometimes be up to half of the print time. The last step is to clean off the excess powder by hand and with compressed air.

3.3 Materials

3.3.1 **Bio-based materials**

Biobased materials are materials that mainly involve substances that are derived from living matter, also known as biomass. These types of materials can either occur naturally or refer to products made from processes that use biomass, which means they are derived from renewable organic sources. By definition, materials such as wood, leather, paper, etc. are therefore all biobased materials, however this definition more commonly refers to newer and more modern materials such biopolymers, bio-composites and other chemical mixtures derived from biomass. Often, these types of materials are seen as greener alternatives because their counterpart materials are derived from non-renewable sources (Curran, 2011).

3.3.2 **PA11 and PA12**

Nylon 11, also called PA11, is one of the less common bio-based materials. It is mostly made out of renewable raw materials derived from vegetable oil, which for PA11 is castor oil. There are different variations and constellations of nylon and in this project the materials used are provided by EOS, a global provider of 3D printing technology. PA11 is ideally suited for components that require high material strength and impact resistance, has a high temperature resistance and constant mechanical properties (EOS, 2020).

The main point of this project was exploring flexible structures in bio-based materials, however, the 3D-printer available was not yet equipped with PA11, but instead with PA12. The printer used was equipped with PA11 in the end of the project so only the last two prints were printed with PA11. PA12 is not bio-based but has similar material properties to PA11 (Arkema, 2020). This meant that the first two prints done in the project were made with PA12, meaning these could not be compared to later results, only to the structures in the same PA12 prints.

3.4 Explored structures

The two major types of structures explored were lattice structure and Voronoi structures. In addition to these, 2D-extruded hexagonal structures were briefly studied, but discarded early in the process due to reasons explained in the chapter Concept Generation.

3.4.1 **Lattice structures**

A lattice structure can be defined as a cell or unit that is continuously repeating in three dimensions. These types of structures are often created from truss structures. As lattice structures are repeating shapes and forms in three dimensions, they are often relatively difficult to manufacture, and have only in recent years have become more prominent due to additive manufacturing. The main purposes of these structures are to reduce material, reduce production time, reduce manufacturing energy and to optimize strength (Helou & Kara, 2017). A lattice structure is therefore a reasonable approach for modelling flexible structures. An example of a lattice structure can be seen in Figure 5.

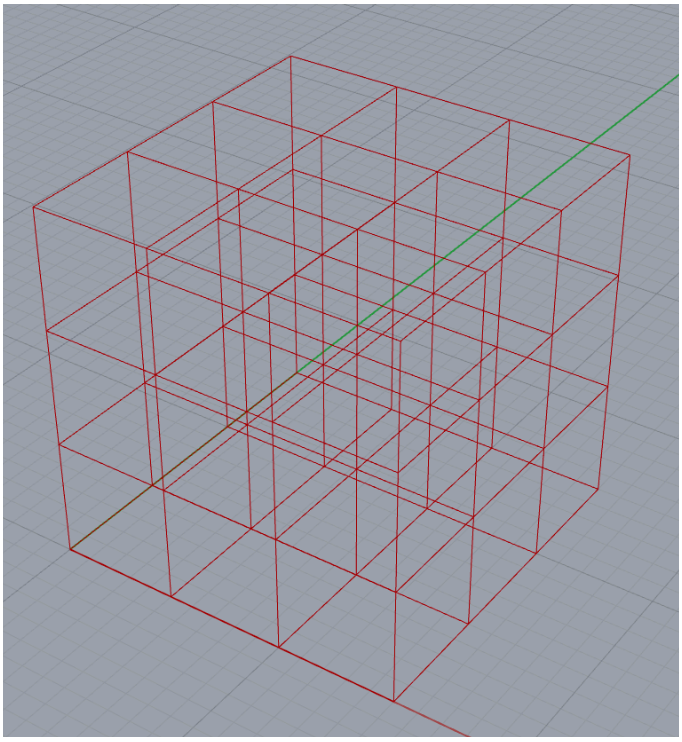

Figure 5: Example of lattice structure

3.4.2 **Voronoi structures**

A Voronoi pattern, also known as a Voronoi diagram, is a division of a plane into areas by a set of points, also called seeds. The areas are called cells and consist of the region of the given plane nearer to that seed than any other seed on the plane. In a 3D-version of a Voronoi diagram, the same method applies, only this time in three dimensions instead of two. Simply adding a thickness to the areas in a 3D-Voronoi pattern is not possible with SLS since there would be no place for the excess powder to go. However, by segregating the lines from a 3D-voronoi and giving each line a radius, an interesting structure closely imitating foam structure can be modelled. An example of a 3D Voronoi structure can be seen in Figure 6.

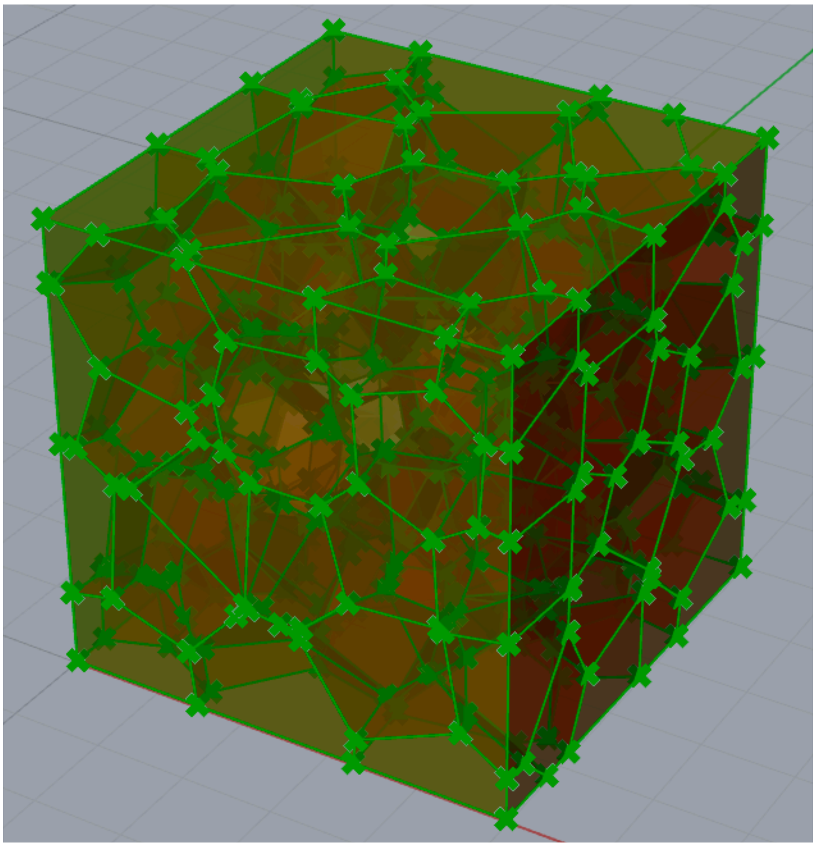

Figure 6: Example of 3D Voronoi structure

4 Concept Generation

In this chapter, the process of generating concepts is explained as well as where inspiration was taken from. Thereafter, a detailed explanation of the process of creating the concepts s presented and lastly, the concept evaluation process is described in detail.

4.1 Concept requirement specifications

During the research, requirements for the ideal material properties of foam needed to be established. The discussion with Jonas Ihreborn AB resulted in the following criteria were listed as necessary properties to be able to mimic foam:

- Flexibility
- Heat resistance
- Softness
- No plastic deformation

The two main criteria that were possible to test in this project was flexibility and minimizing plastic deformation. Softness is also slightly taken into account as the feel and touch does make a difference. However, testing for heat resistance while only focusing on one material was considered unnecessary so this criterion was ignored.

4.2 Concept generation process

In order to be able to generate concepts, a reasoning behind the different types of concepts and from where these concepts came from needed to be established. These inspirational sources are merely a foundation to what shapes and structures that are explored in this project and the purpose of this was not in any way to exactly mimic or copy exact structures.

4.3 Concept inspiration

To get inspiration for different concepts, three different approaches toward forming a concept were explored.

4.3.1 **Nature-inspired structures**

The first type of structure was inspired by nature. There are structures in nature that have developed over a long period of time to have certain properties. In many cases, these structures are made for strength, but in some cases, it can be seen how nature has adapted to allow structures to have flexibility. This mainly inspired to making the X-structure later on in the project.

Figure 7: Snaky vine (Struwe, 2008)

4.3.2 **Foam-inspired structures**

The second structure was inspired by the structure that can be found in foam. This is an obvious type of structure to examine and explore since the properties in foam is what this project aims to mimic. This inspired the creation of the Vintiles-structures and the Voronoi-structures.

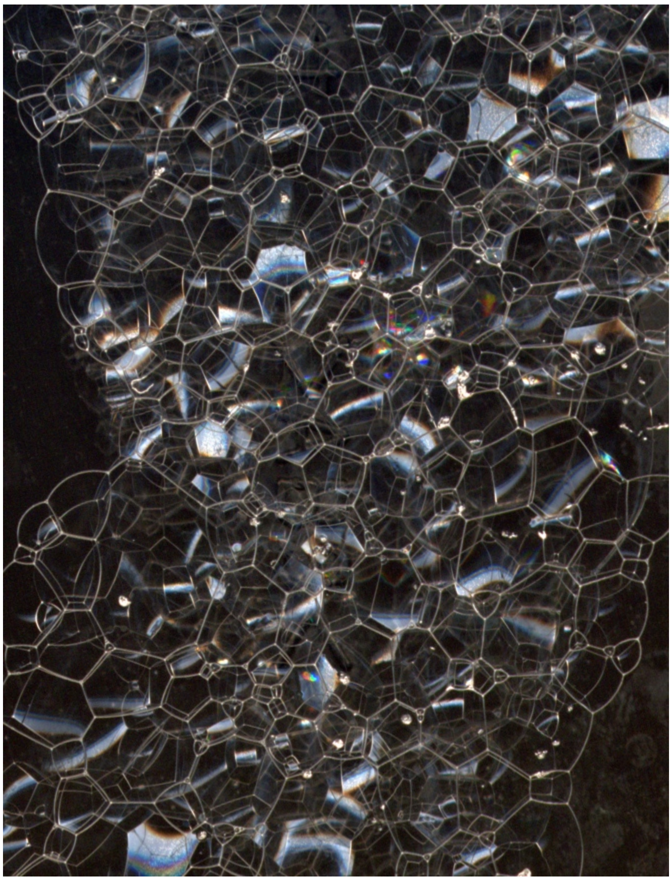

Figure 8: Soap foam bubbles (Karwath, 2004)

4.3.3 **Literature study**

During the course of initializing this project, several interesting articles and reports were read. One of these articles was "Flexible Patterns for Soft 3D Printed Fabrications" by Kanygul Chynybekova and Soo-Mi Choi. This article explores homogenous honeycomb structures and non-homogenous honeycomb structures (Chynybekova & Choi, 2019). Honeycomb patterns are usually known to be quite strong structures but can be designed to be more flexible. (Chynybekova & Choi, 2019)

4.4 Idea generation

To start of the idea generation, a couple of different concepts were drawn up with pen and paper. The only restriction to this process was that concepts had to be represented in a cubic form since the test-pieces were to be 25x25x25mm. The drawings done were 2D-representations and further 3D concepts were all done in CAD. Some of the initial sketches can be seen in Figure 9.

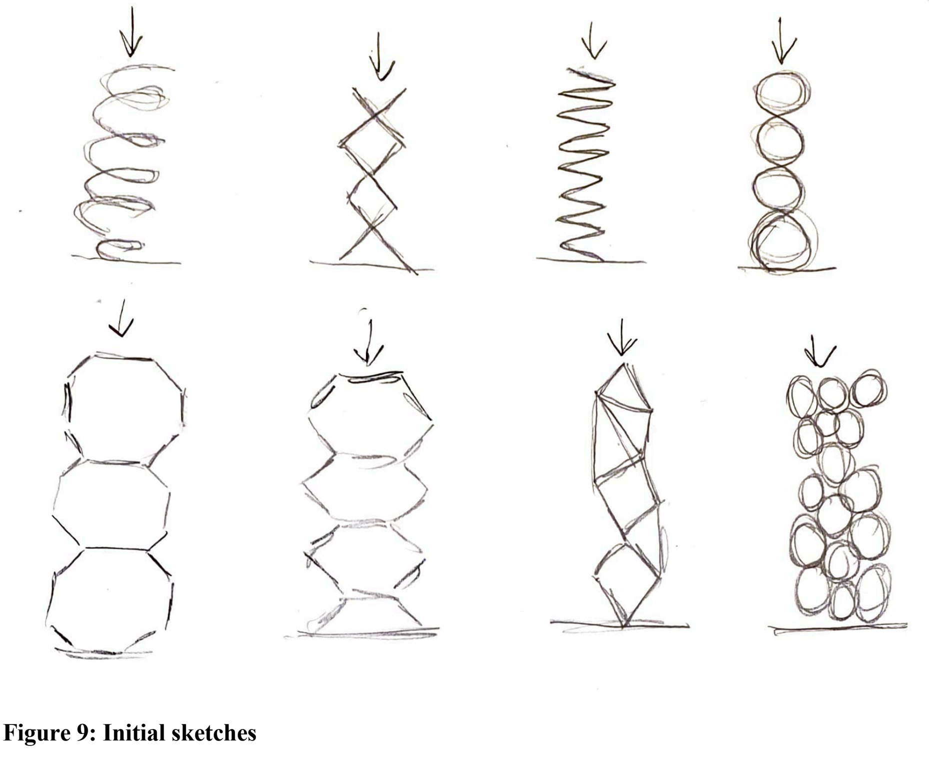

Figure 9: Initial sketches

Thereafter, the concepts were transferred into Rhinoceros and Grasshopper and the idea generation continued by mostly exploring different plugins and settings in grasshopper to find interesting and promising structures. In the following figures, concepts have been generated and printed. The process of how the concepts were made can be seen in following phase Concept development.

4.5 Concept development

To create the different concepts and ideas from the previous phase, the visual programming language Grasshopper inside Rhinoceros 3D was used. The X-structure is demonstrated n Figure 10.

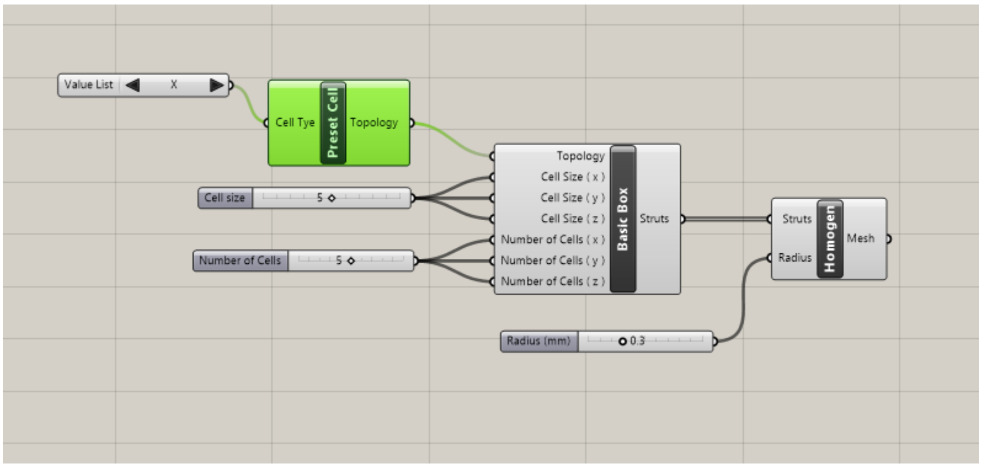

Figure 10: Creating X-structure in Grasshopper

In this case IntraLattice was used to create the model. First a cell needs to be defined, in this case a preset "X"-structure was used. Thereafter, the cell is linked to a "basic box" which creates a box array where the size and number of cells can be decided. Lastly, the "basic box" is linked to a "homogen" which is a homogenous solidification into a completed volumetric model. This method was also applied to the Diamond-structure, Vintiles-structure and Honeycomb-structures. The X-structure can be seen in Figure 11.

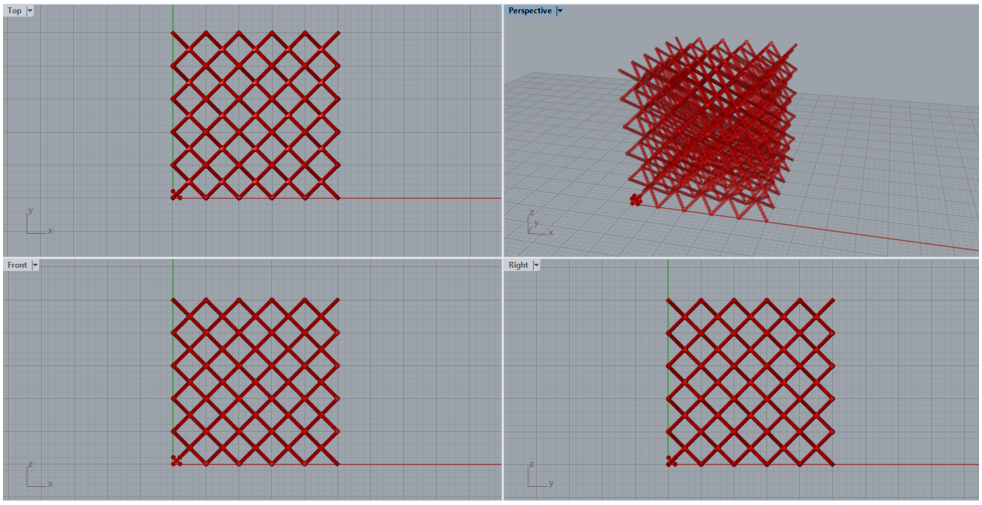

Figure 11: Volumetric model for X-structure in Rhinoceros 3D created in Grasshopper

These structures were also slightly modified with a plug-in called “Weaverbird” which is demonstrated in Figure 12.

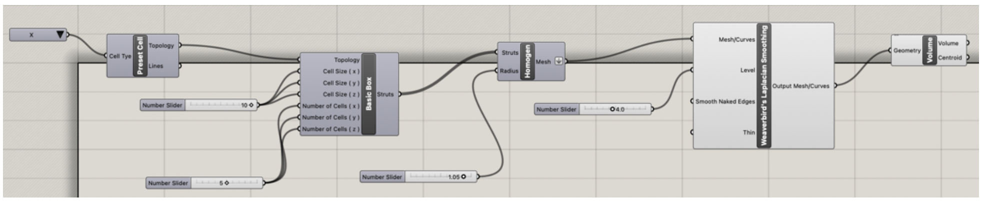

Figure 12: Modified X-structure with Weaverbird

Here a “smoothing”-tool is used to create a structure with more material around the joints. This can be seen in Figure 13.

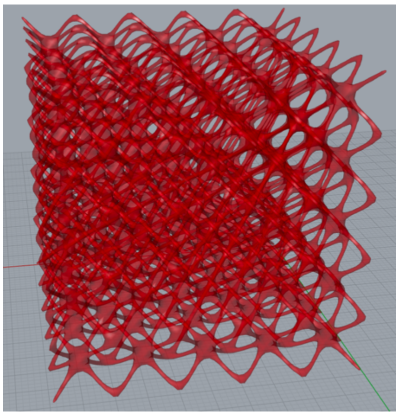

Figure 13: Modified X-structure demonstrated in Rhinoceros

Another concept was the Voronoi-structure. This was made in a slightly different and more complex way from previous structures. The approach is demonstrated in Figure 14 and Figure 15.

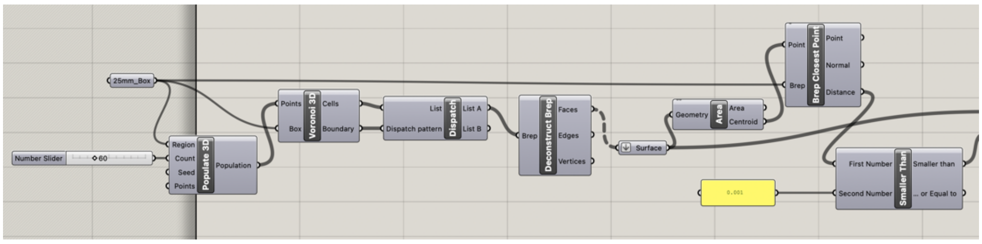

Figure 14: Part 1 of Voronoi-structure in Grasshopper

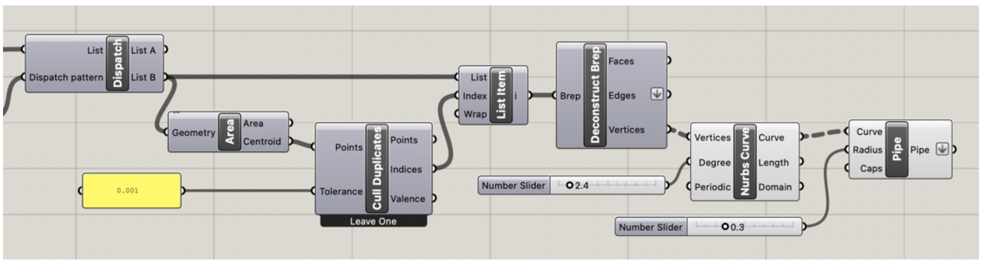

Figure 15: Part 2 of Voronoi-structure in Grasshopper

This method uses the pre-existing functions in Grasshopper and the result of this can be seen in Figure 16.

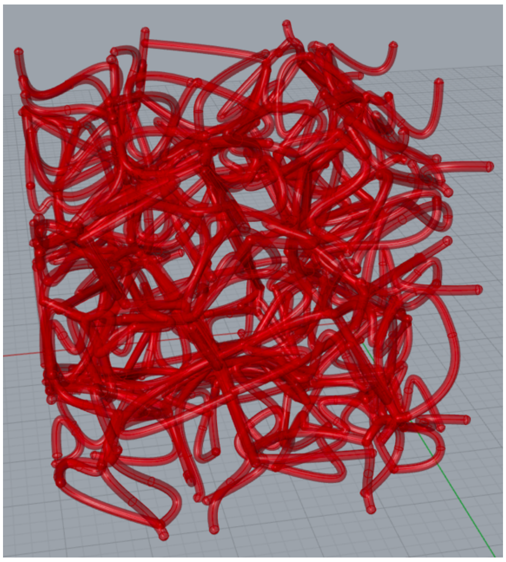

Figure 16: Voronoi-structure represented in Rhinoceros

The concept development was a big part of this project and there were about seven or eight different concepts that were printed and tested which equaled around 40 individual test structures developed in Grasshopper. Some examples of these can be seen in Figure 17. The columns from left to right include: Voronoi-structure, X-structure, Diamond-structure, Vintiles-structure and modified X-structure. Each of these types can also be seen in Figure 18 to Figure 22. There were also a few additional larger prints which can be seen in Figure 23.

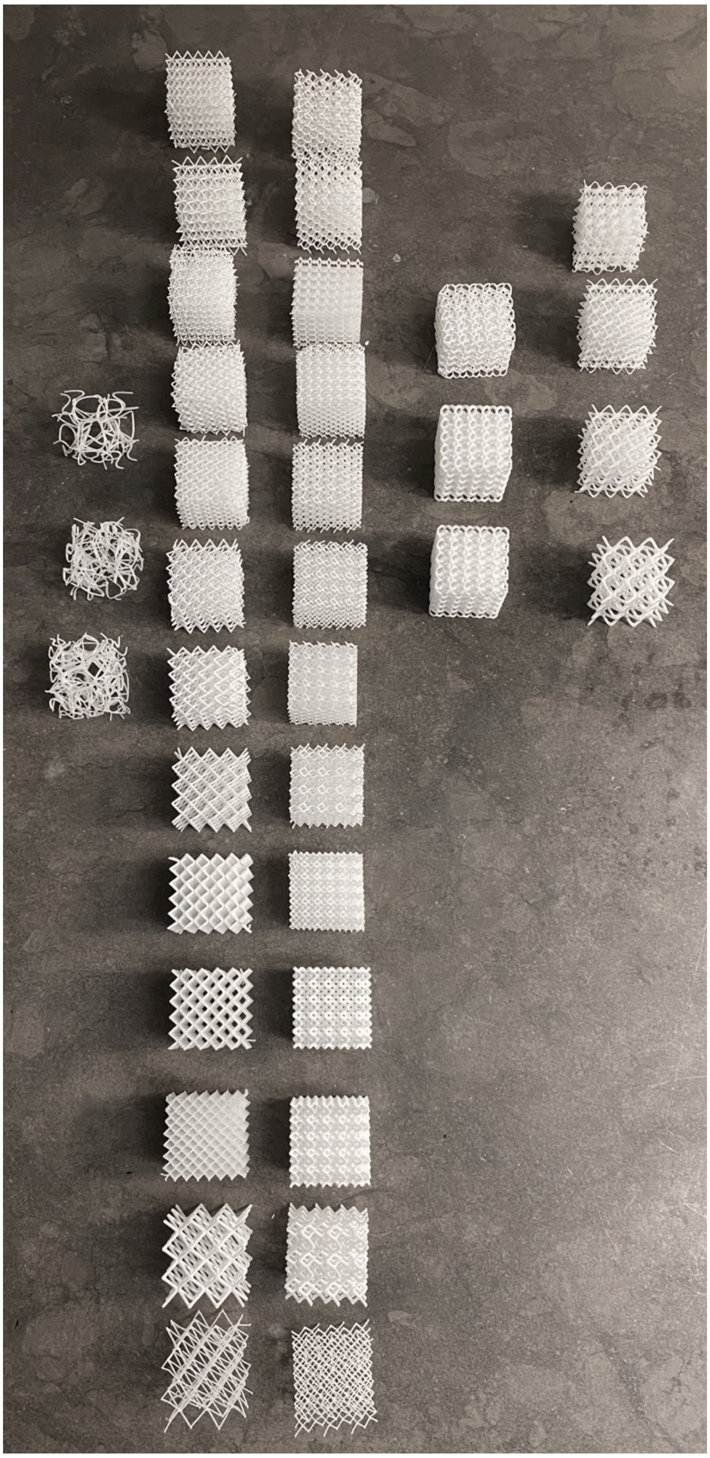

Figure 17: Examples of printed structures

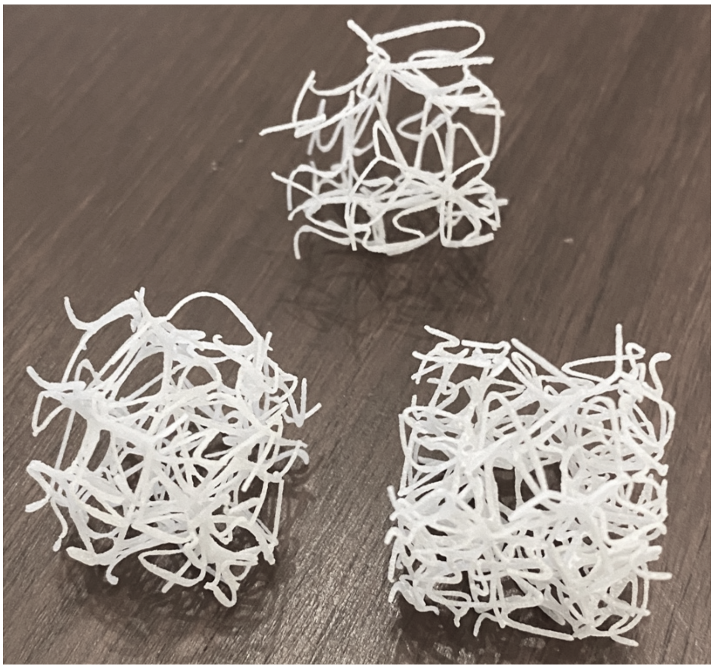

Figure 18: Voronoi structure type

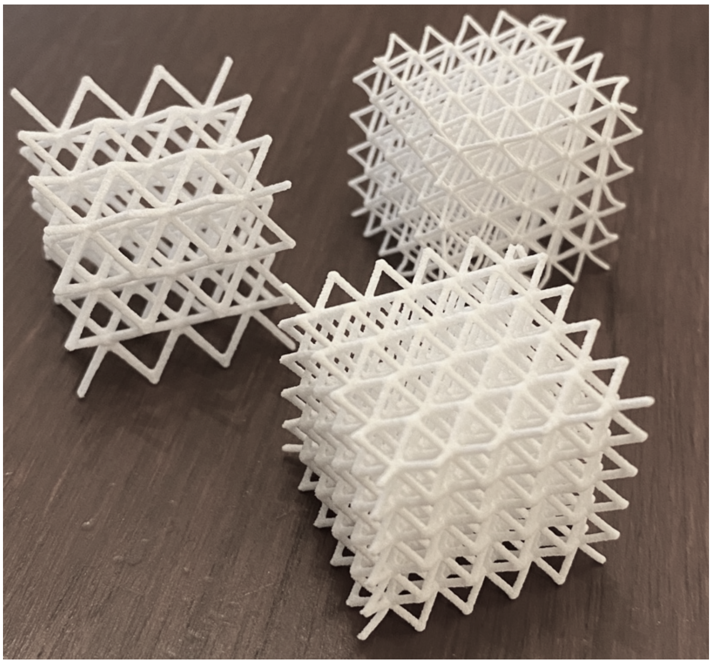

Figure 19: X structure type

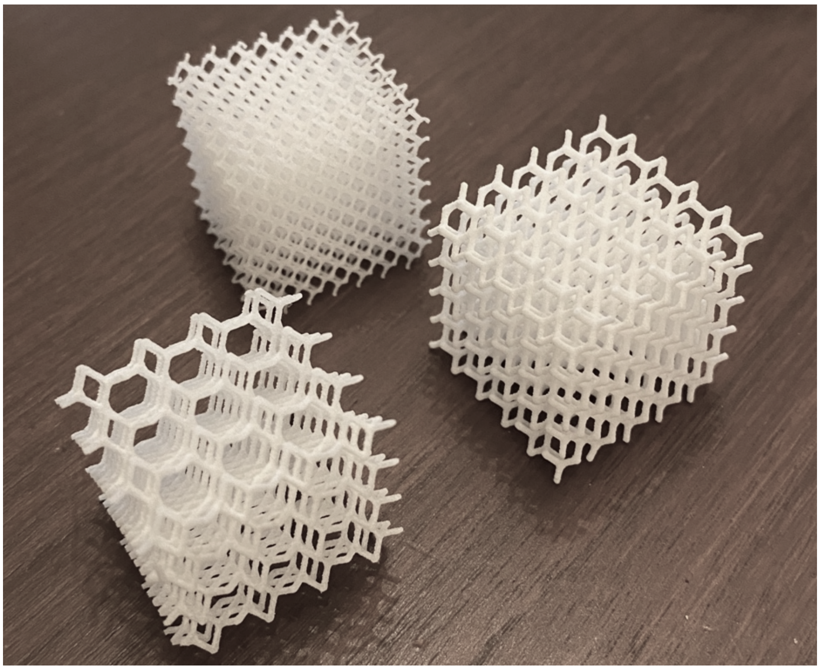

Figure 20: Diamond Structure type

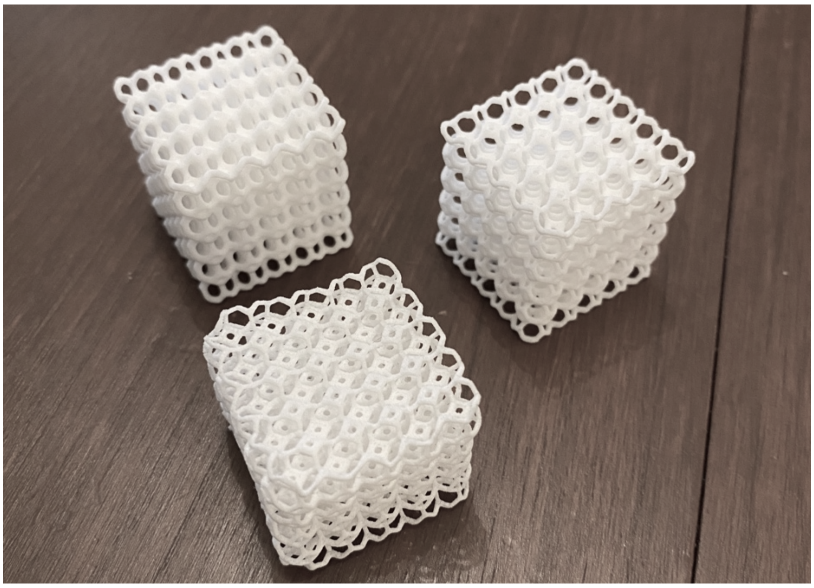

Figure 21: Vintiles Structure type

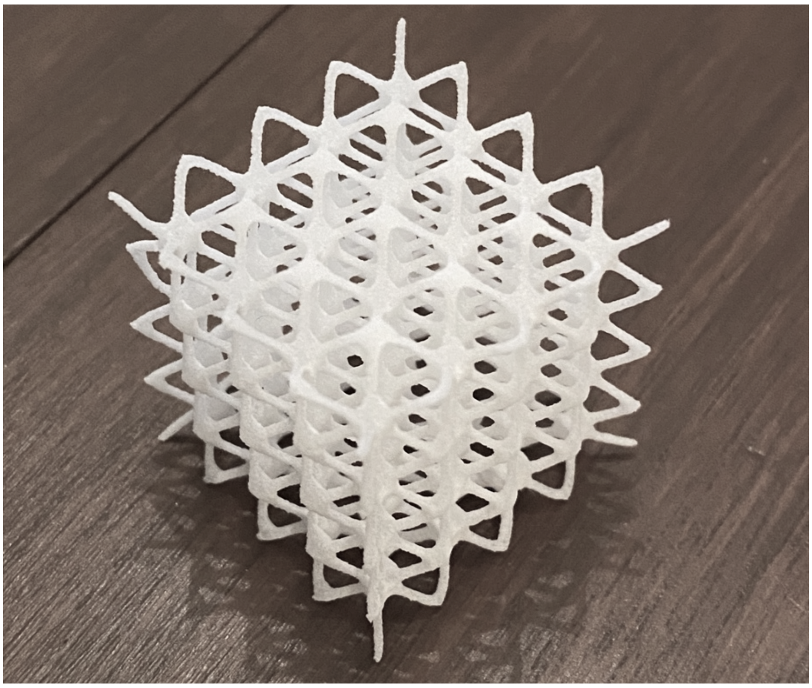

Figure 22: Modified X structure type

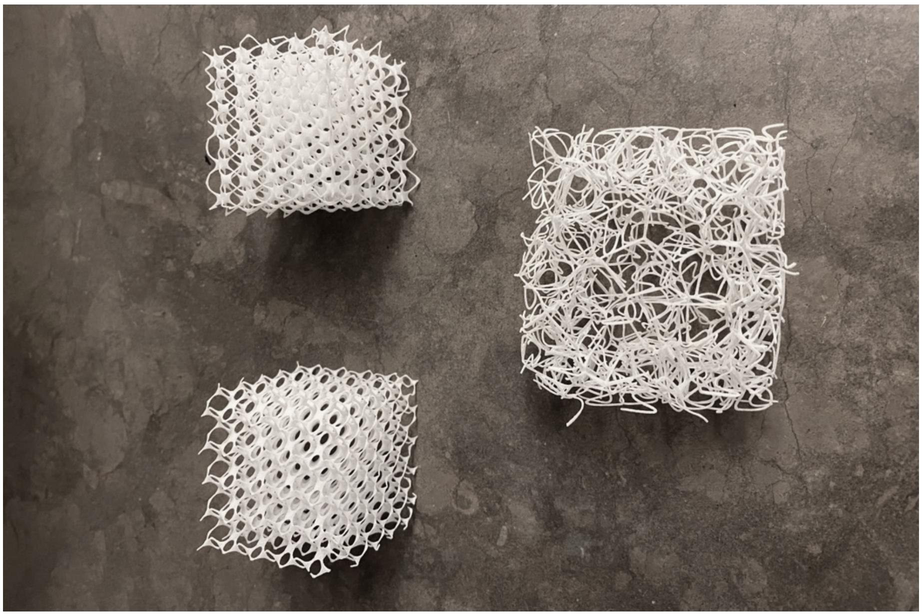

Figure 23: Additional larger structures printed

4.6 Concept evaluation

4.6.1 **Initial testing**

From the Idea Generation section, there were 6 structures that were moved on to the initial testing stage, these can be seen in Figure 24. For these structures, there were several factors that were kept constant, such as the thickness of the structure and the size of the structure. The thickness was set to be 0.6 mm and is at the lower boundary where the print will not risk breaking during its print.

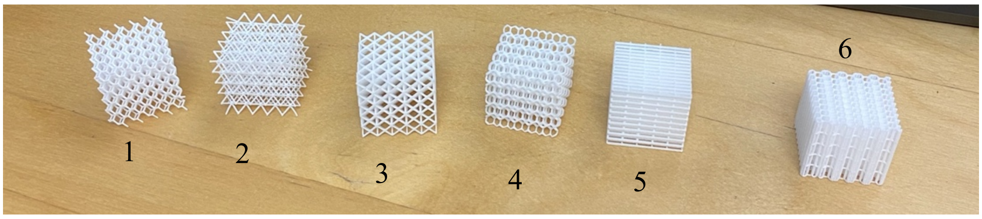

Figure 24: Initial test structures (printed in PA12)

Just by the touch, pressing the model between the index finger and the thumb, structure 5 and 6 could be eliminated due to being much too stiff (no flexibility at all before total structural failure). Structure 3 is also eliminated due to breakage in most of the joints.

4.6.2 **Thickness/diameter testing**

Structures 1, 2 and 4 were all moved on to the second part of the testing which was to optimize for thickness. As stated in the limitations, the minimum thickness has been set to 0.6 mm. This is still a relatively small diameter which could lead to breakage, and therefore only larger diameters than 0.6mm were tested. This test was done with the help of a "pressure tester" that was modelled and 3D-printed with to purpose of quickly being able to pressure test the printed structures. This tester can be seen in Figure 25.

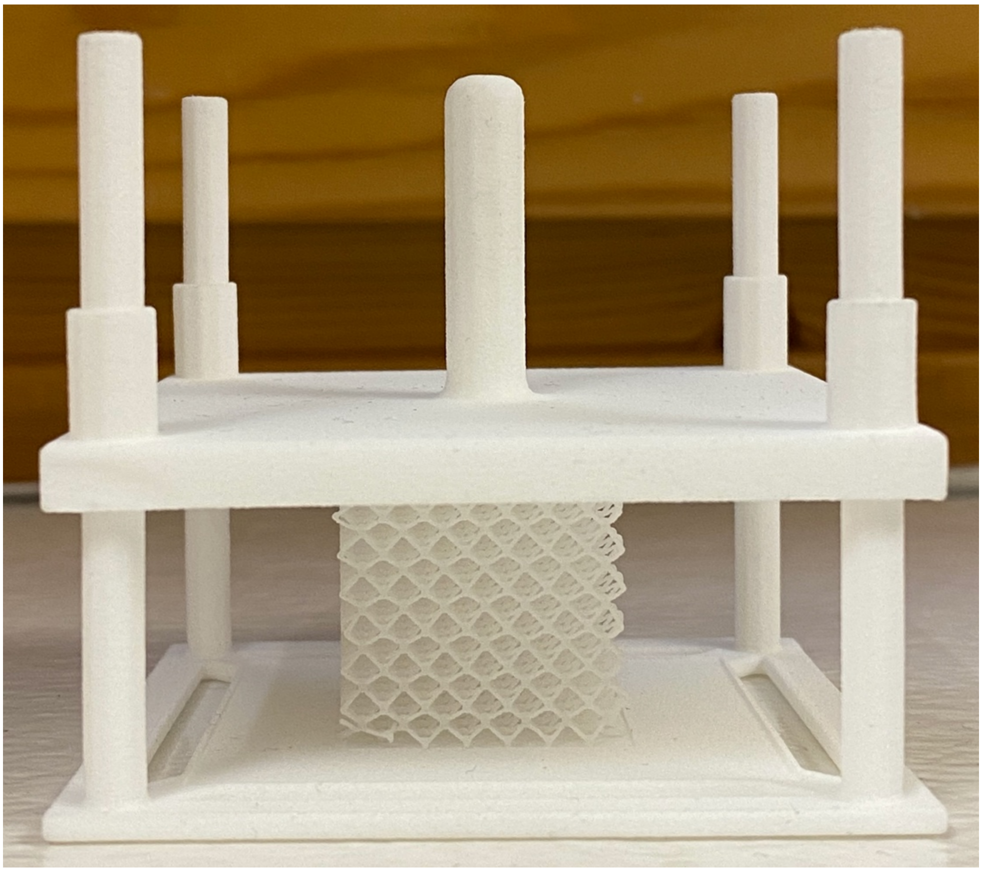

Figure 25: Pressure tester for 25x25x25 mm structures

The test was carried out by putting pressure on the structure, so it deformed to about 5 mm 10 times each and then measuring the height of the structure with pressure applied and after the maximum pressure was applied. The results can be seen in

Table 1.

Table 1: Thickness test

	Structure 1 [Diamond Structure]			Structure 2 [X-structure]			Structure 4 [Vintiles structure]		
Initial height [mm]	25	25	25	25	25	25	25	25	25
Thickness/diameter [mm]	0.6	0.8	1.0	0.6	0.8	1.0	0.6	0.8	1.0
Height with max pressure[mm]	5	5	-	7	7	-	10	-	-
Height after max pressure [mm]	17	16	-	17	18	-	17	-	-
Visible breakage	Low	low	None	Low	Low	None	Medium	None	None
Flexibility index [height with pressure/height]	0.20	0.20	-	0.28	0.28	-	0.40	-	-
Deformation index [Deformation after pressure/height]	0.68	0.64	-	0.68	0.72	-	0.68	-	-

As can be seen in the results, there was a “medium” amount of visible breakage for the Vintiles-structure, which occurred in the joints and could be heard when asserting the pressure on the piece. This eliminated this structure for further analysis. The two remaining structures, the X-structure and the Diamond-structure, were moved onto the next stage in the process.

4.6.3 **Cell variation testing**

Cell variation testing is done by varying the number of cells to see which cell has the least deformation when asserting the pressure described in earlier steps. The size, diameter and type of structure is kept constant to be able to only compare number of cells. In this test only X-structures were tested since the other structures should have a similar response. The test was done by exerting a large on the test piece and measuring both the height with the force applied and after the force had been removed. The results can be seen in

Table 2.

Table 2: Cell variation testing

X-structure			
	3 cells	5 cells	7 cells
Initial height [mm]	25	25	25
Height with max pressure [mm]	4	7	8
Height after max pressure [mm]	19	21	23
Visible breakage	None	None	None

As can be seen in

Table 2, there was a slight decrease in the height after max pressure.

4.6.4 **Flexibility testing**

Flexibility testing is done to evaluate which structure is most similar to foam. The first step of this test is to calculate an assumed pressure that the foam would be exposed to. An example of where these types of foam structures would be present is in an office chair. The calculations assume a body weight of 100 kg, to account an above average pressure, and the area is assumed to be 200x200 mm. As already mentioned, the text pieces are 25x25x25 mm in volume, and the pressure is put on an area of 25x25 mm. The first step is to calculate the pressure one person would put on the given object, which is done by the following calculation:

$$\frac{100}{200 \times 200} = 0.0025\, kg/mm.$$

Thereafter, to calculate the weight that should be put on the test pieces, the pressure is multiplied with the surface that the test piece has as shown by in the calculation below.

$$0.0025 \times 25 \times 25 = 1.56\, kg$$

The test pieces are therefore tested with a weight of approximately 1.6 kg. The results can be seen in Table 3.

Table 3: Final test results

	X-Structure	**Diamond-structure**
Initial height [mm]	25	25
Height with 1.6 kg weight [mm]	19	20
Height after 1.6 kg weight[mm]	24	25
Visible breakage	None	None
Flexibility	24%	20%
Plastic deformation	1 mm	0 mm

The final test shows similar results in flexibility for the two structures; however, the Diamond Structure has 0 mm of plastic deformation which made this the final choice.

5 Conclusion

In this part of the project the conclusion is presented which includes an explanation and images of the final concept, where this concept could be implemented and the feasibility of the final project.

5.1 Final concept

The final concept is a 25x25x25 mm cube that is called earlier in the process as the “Diamond structure”. The structure has a total of 343 cells which equals to 7 cells in each direction (x, y, z direction), and has a radius of 0.6 mm. One cell is demonstrated in Figure 26, and the whole structure can be seen in Figure 27 as a representation in Rhinoceros, in Figure 28 as a render and in Figure 29 as a printed version of the final concept.

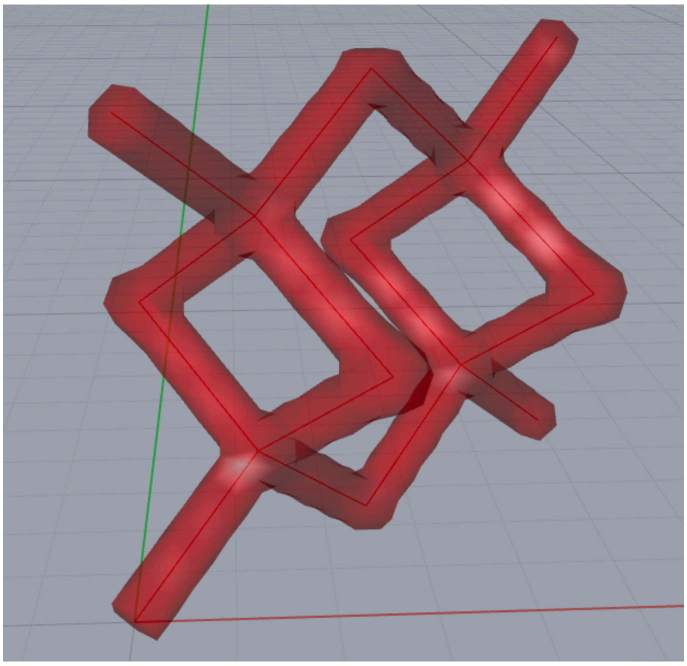

Figure 26: One cell of the final structure

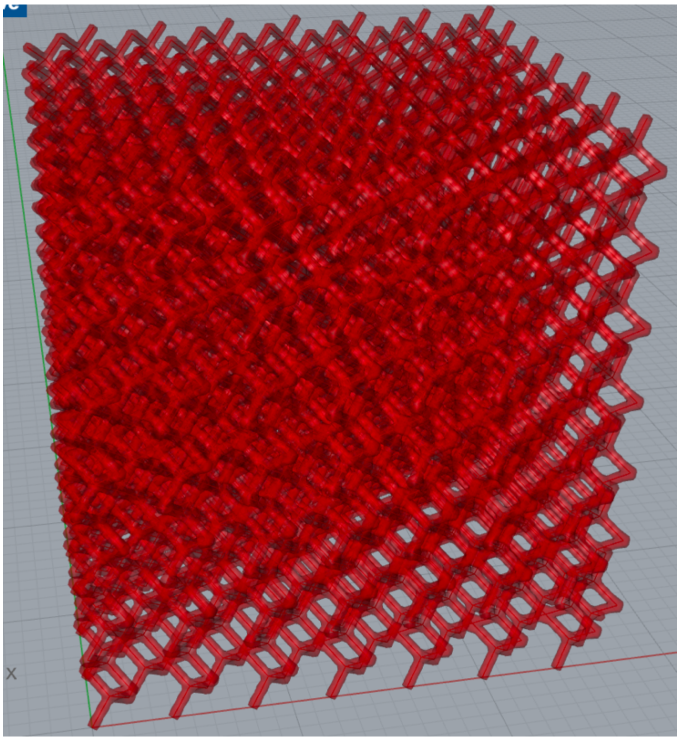

Figure 27: Figure of final concept in Rhinoceros

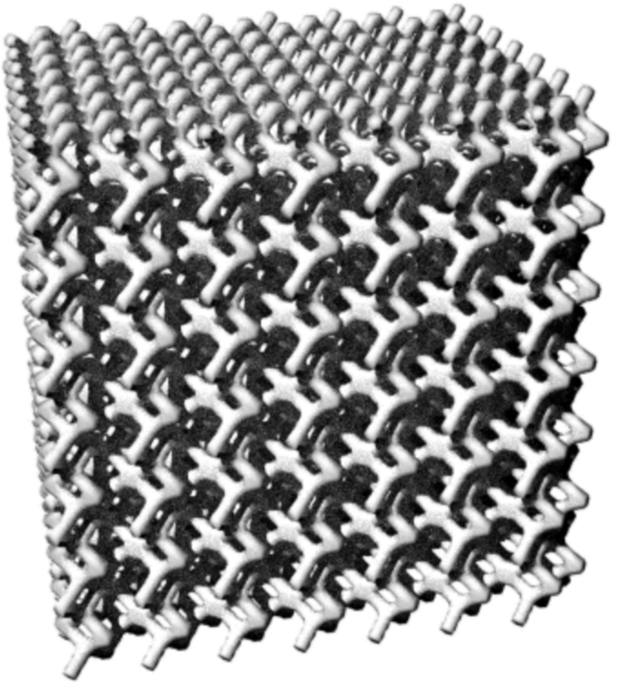

Figure 28: Render of final concept

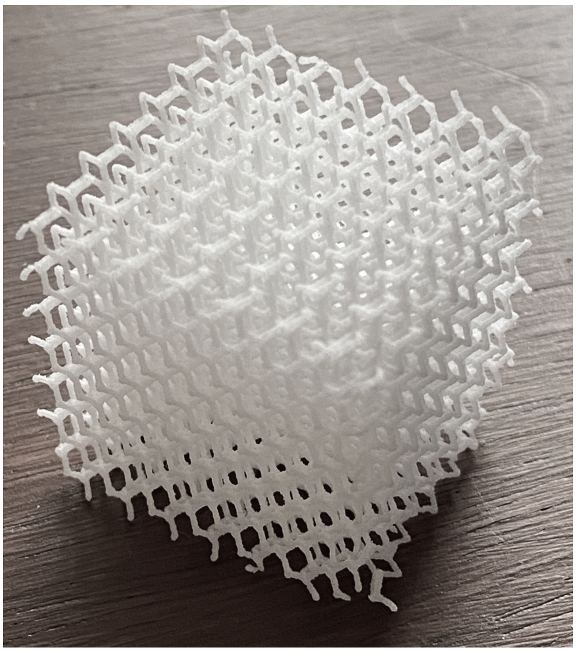

Figure 29: Printed version of final concept

5.2 Implementation

One of the goals of this project was to print the final structure as an application in an upholstery product or similar. Due to the Covid-19 pandemic, this was not possible. Instead, the structure is demonstrated in model in Rhinoceros of how it could be implemented in reality. This can be seen in Figure 30 and Figure 31.

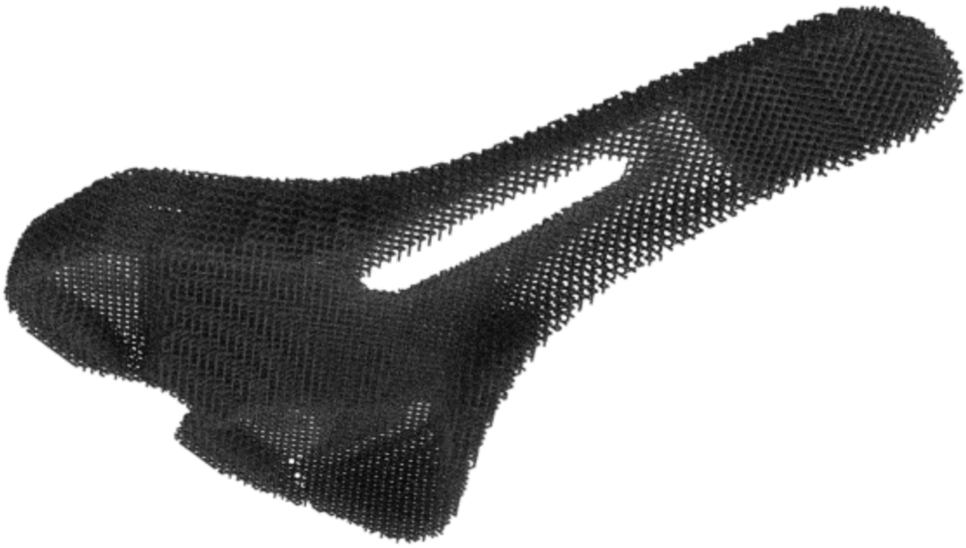

Figure 30: Implementation of final concept in bicycle saddle

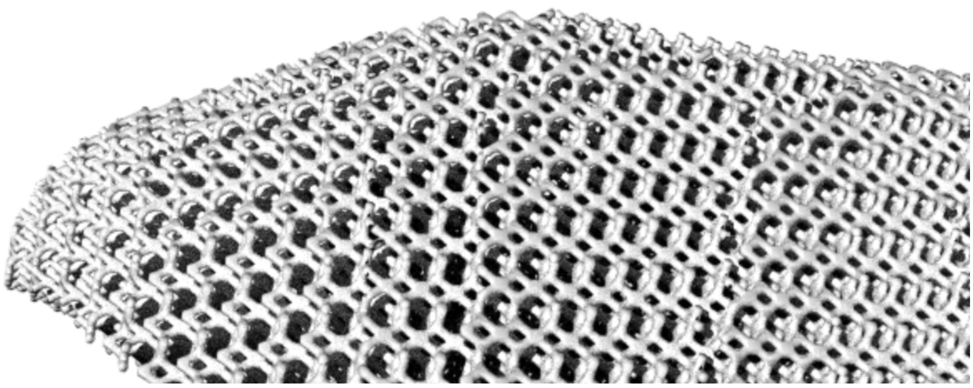

Figure 31: close up of Diamond-structure in implemented bicycle saddle

5.3 Feasibility

Is it feasible to replace conventional foam with a 3D-printed plastic structure? The simple answer is no, since the technology available today doesn't allow cheap and fast enough 3D-printing at the scales that would be acceptable for a manufacturer.

5.3.1 **Price**

Currently, the price of additive manufacturing is significantly higher than other manufacturing methods and is therefore mainly used for concepts and very complex parts. It is therefore possible to draw the conclusion that this concept is not feasible to implement on a large scale in the near future.

5.3.2 **Time**

With a very up to date and modern SLS machine, the printing speed is up to 1.2 l/h, not including the time for part cleaning and cool down time (EOS, 2020). This makes it an unreasonable manufacturing method since the conventional way of making foam is considerably faster.

5.3.3 **Properties**

The testing in this master thesis clearly shows that trying to mimic the properties in conventional foam is possible. There are obvious limitations, such as minimum printing diameters and limited printing space, but with further improvements in additive manufacturing technology, it is not unreasonable to believe that large scale production and manufacturing of very complex parts is possible. Further research into this concept is therefore encouraged.

6 Discussion

In this part of the project, a discussion is held, mainly focusing on the method and results and what has been learned throughout the entire master thesis.

6.1 Concept selection

In this project, the main purpose was to find a structure that was as similar to foam as possible. Concepts therefore had to be evaluated mostly by how flexible they were, but also by touch and feel. The tests were done with a manual pressure testing designed by the user, which could possibly lead to some errors. Also, having only one person (the designer) test the feel of the structures also leads to possible bias and preferential treatment of some concepts, even though the designer tried to be as objective as possible. Having more people play around and test the printed concepts would have been preferred, but due to the current pandemic this was not included in this project.

6.2 Modelling

A big challenge in this project was modelling the concepts. I had no prior experience using Rhinoceros and Grasshopper and therefore had to learn to use it from scratch. In the time span that was available, there was not room to become an expert with this software, and the modelling of the parts was slightly limited. The modelling also took a lot of the project time and less time was left for the actual testing of the concepts.

6.3 Sources of error

6.3.1 **Local deformation**

Since the test pieces were quite small, there is a possibility of the structures having local deformation causing large variations in the results when testing.

6.3.2 **Print quality**

As mentioned earlier, there was a switch from PA12 to PA11 in the SLS-printer during the course of this project. The switch is not instant and with a new material comes new difficulties with settings in the 3D-printer, which made each print differ from the other. Any conclusions drawn would therefore possibly need to be verified with the current and more tested printer settings.

6.3.3 **Breakage**

Breakage in the structures could only be evaluated by looking at the structure and determining if there were any visible breaks in the joints. This made it hard to determine if there was any internal breakage in the structures that was not visible with the human eye. Another possibility was breakage that occurred during the prints or damage during removing of excess powder, which would also be difficult to see while testing.

6.3.4 **Lack of different samples**

Due to the many delays in this project, the early evaluations were based on one sample and the later samples were only done on 1-3 samples. This gives room for differentiating results and should for further research be tested in larger samples.

6.3.5 **Creep deformation**

6.4 Evaluation

The evaluation of the concepts was firstly done by putting a large pressure on the structures, and thereafter changed to putting a smaller constant pressure on the structure. The first method was done to see how well the structures would resist plastic deformation but turned out to not show very differencing results. It was therefore changed for the last test and seemed to be a better way of testing. The earlier test should have been redone but there was no time to do so.

6.5 Time plan

The final time plan differed quite a bit from the original time plan. There were a couple of main factors that contributed to this. It was mainly the Covid-19 pandemic that made planning difficult since public restrictions changed throughout the whole process. For example, there was limited access to prints due to several shutdowns of the lab where the concepts were printed, and these delays hurt the process of this project. Another factor that had an impact on this project was the time it took to get one batch printed. The expected print time after sending the batch for printing was 2-3 days, however it took between 1-4 weeks for each print which made it difficult to keep testing structures.

6.6 Structures

At the beginning of the project, the size of the structure was set to be quite small to be able to print a large number of different structures for testing. This might however have had an impact on how accurate the tests were. A possibility for further research would be to scale up the test pieces and test the structures in an actual environment.

6.7 Material

The material used to in this project were set before the project start. This makes it possible to reflect on whether there are other possible plastics that could be used. However, since the material was a delimitation, no other materials have been considered or researched.

6.8 Future improvements

There are many possible further improvements that can be done to this project since the final concept of this project only has been tested in small numbers and sizes. Scaling up both the testing and the sizes of the samples would be a great start to continuing this project. Iterating though and re-evaluating discarded concepts or adding new concepts to find improved solutions would also be a necessary step to continue this project. Another possible improvement would be to test other bio-based materials to compare it to PA11 and to find the best possible environmentally friendly material for this application. A delimitation in this project was to not focus on cyclical material fatigue, adding this into further research would be important to see how the structures would resist pressure with normal use.

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A. Appendix A

A.1 Time plan

To present the time plan a Gantt chart was made at the beginning of the project and then a corrected Gantt chart was made with the actual time plan. These two charts can be seen in the figures below. The project was set to 20 weeks with a starting point at the beginning of September. The goal was to finish and present by 15^{th} of January, but this was delayed to the 12^{th} of February. The delay is visible in the second Gantt chart which has a delay of 4 weeks.

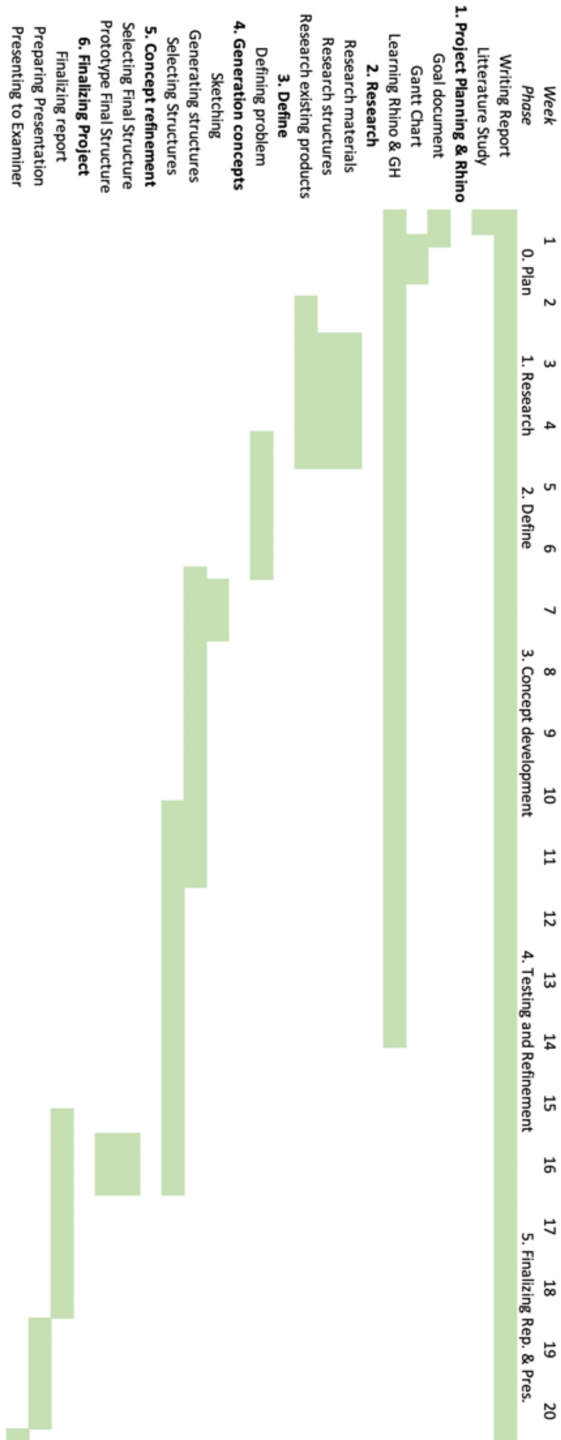

Figure 32: Gantt Chart created at the beginning of the master thesis

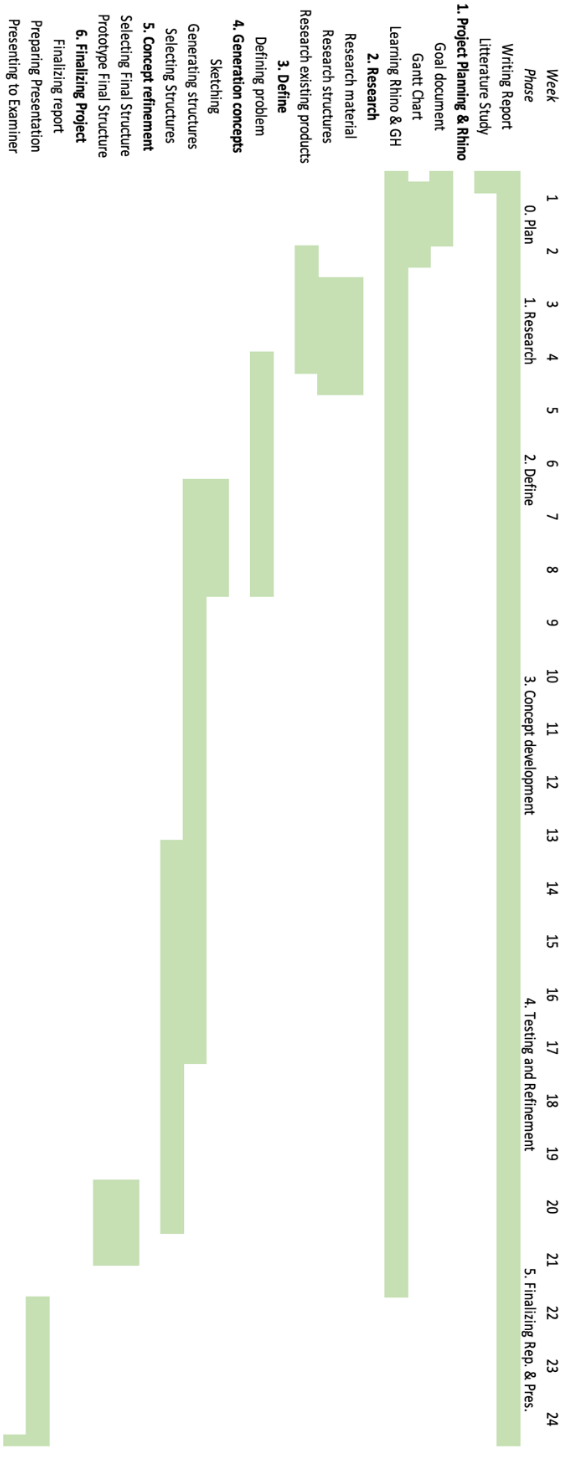

Figure 33: Gantt Chart created at the end, showing how the project outcome