PAPER DOMUS

the architectural potential of pulp

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Chalmers School of Architecture
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ABSTRACT

Cardboard and paper is a cheap and easily accessible material with a wide variety of uses ranging from packaging of products to furniture design and even structural building elements. Besides being versatile in its area of use the it also has a low environmental impact since it is mainly constructed from renewable sources containing cellulose. On top of that the material itself can be recycled, picked apart and reused for the production of more paper when it has reached its expected lifespan. Still only about half of the around 400 million tons of cardboard and paper being produced each year is recycled. This means that approximately 200 million tons of cardboard leaves the recycle chain and ends up in landfills or is being incinerated which releases the stored carbon dioxide within the material.

This thesis is aiming to make use of the cardboard and paper that is being wasted every year to be upcycled into architectural building elements. There are already projects that utilize cardboard as a building material. From using recycled paper tubes as pillars, to layering sheets of cardboard into building elements. The disadvantage of these methods is that they rely on intact or newly produced cardboard instead of recycled. This paper however is exploring the method of molding with paper pulp in an architectural context. By combining shredded cardboard or paper, water and an adhesive agent the pulp can be compressed or molded into solid elements that can be used to design building elements.

Three different methods of working with the pulp is further investigated in this paper: compressive molds, rammed pulp, manually applied, and printing with pulp. In addition to these production methods a variety of additives will be used in the pulp to alter its material properties. These two variables is then combined to create discrete building elements made from paper pulp. Finally, these elements are put into context through a building proposal in Gothenburg entirely made with waste cardboard and paper.

Keywords

cardboard, paper pulp, upcycling, waste material

STUDENT BACKGROUND

2016-2019	*Bachelor Degree in Architecture & Engineering, Chalmers Tekniska Högskola*
2019-2020	*Internship at Liljewall in Gothenburg, industry and office studio*
2020-2022	*MPARC - Architecture and Urban Design, Chalmers Tekniska Högskola*
Studios	*Architecture and urban space design* *Public buildings* *Material and detail*
Courses	*Sustainable development and the design profession* *Nordic architecture* *History, theory and method 2* *Master thesis prep course 1* *Master thesis prep course 2*

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BACKGROUND

PURPOSE

In Sweden we only met the recycling goals for glas, metal and plastic in 2020 with 94%, 87% and 86% recycled respectively but fell short on the remaining six goals, including paper and cardboard (*SCB, 2021*). Only 78% of the paper products produced was recycled while the remaining 22% ends up in landfills and gets incinerated, thus leaving the recycling chain. Considering that paper and cardboard can be recycled up to 7 times (*Earth911, 2021*) before the fibers get broken down and are too short to reuse in packaging, this is a great loss of recycling potential. However Sweden performs well compared to China which is the largest consumer of paper products world wide (*Statista, 2022*). With about 110 million tonnes produced in 2018 only 47,6% was recycled (*Statista, 2022*), leaving 52,4% of all paper products being incinerated or piled up at landfills.

The technical summary of the climate report from IPCC released in 2022 shows that we risk exceeding the 1,5 degrees target by 2035 (*IPCC, 2022*). The predictions are based on observations of actual development in carbon dioxide emitting industries and show a strong connection between our emission of greenhouse gasses and the global average temperature. The construction industry accounts for almost 40% of global carbon dioxide emissions annually, of which building materials make up about a quarter of those 40% (*Architecture 2030, 2018*). Needless to say the world is in need of a shift from CO_2 producing materials to a more sustainable option.

One way to tackle this problem is to use renewable materials and recycle building materials to the greatest possible extent. As mentioned above paper and cardboard products are partially being recycled but a great part ends up for incineration which releases embodied CO_2 within the material. Since building materials alone stands for about 10% of the global emissions of greenhouse gasses, the need for alternative building materials is of significant importance.

There are already architects, like Shigeru Ban, who are exploring the possibility of using cardboard in architecture. Projects like the cardboard cathedral and The CARTA Collection are great examples of how he works with cardboard in building design. The problems with these projects is that they mainly build on tubes made from cardboard as structural elements which only is a small fraction of the cardboard and paper produced annually. In this thesis however I want to explore the possibilities of using paper products of any condition, not only refined parts. Specifically I want to look into the potential of making building elements from paper pulp which would be a way to upcycle any sort of waste paper into architecture.

THESIS QUESTIONS

What are the structural properties of paper pulp?

How can paper pulp be molded into building elements?

How would a building made from these elements be designed?

THE PULPING PROCESS

Before the invention of paper humans used to paint on cave walls, carve into stone or scribble on clay tablets as a means of communication. Books and documents were being made from bamboo or silk. Neither of them were able to be used conventionally due to either being too heavy and clumsy or too expensive to be mass produced. It was not until about 100 A.D. in Lei-Yang, China, that the first sheet of paper as we know it today was made by Ts'ai Lun (*American Forest and Paper Association, 2021*). It is believed that he mixed bark and hemp together with cloth rags that he made into a pulp which could then be pressed out into thin sheets.

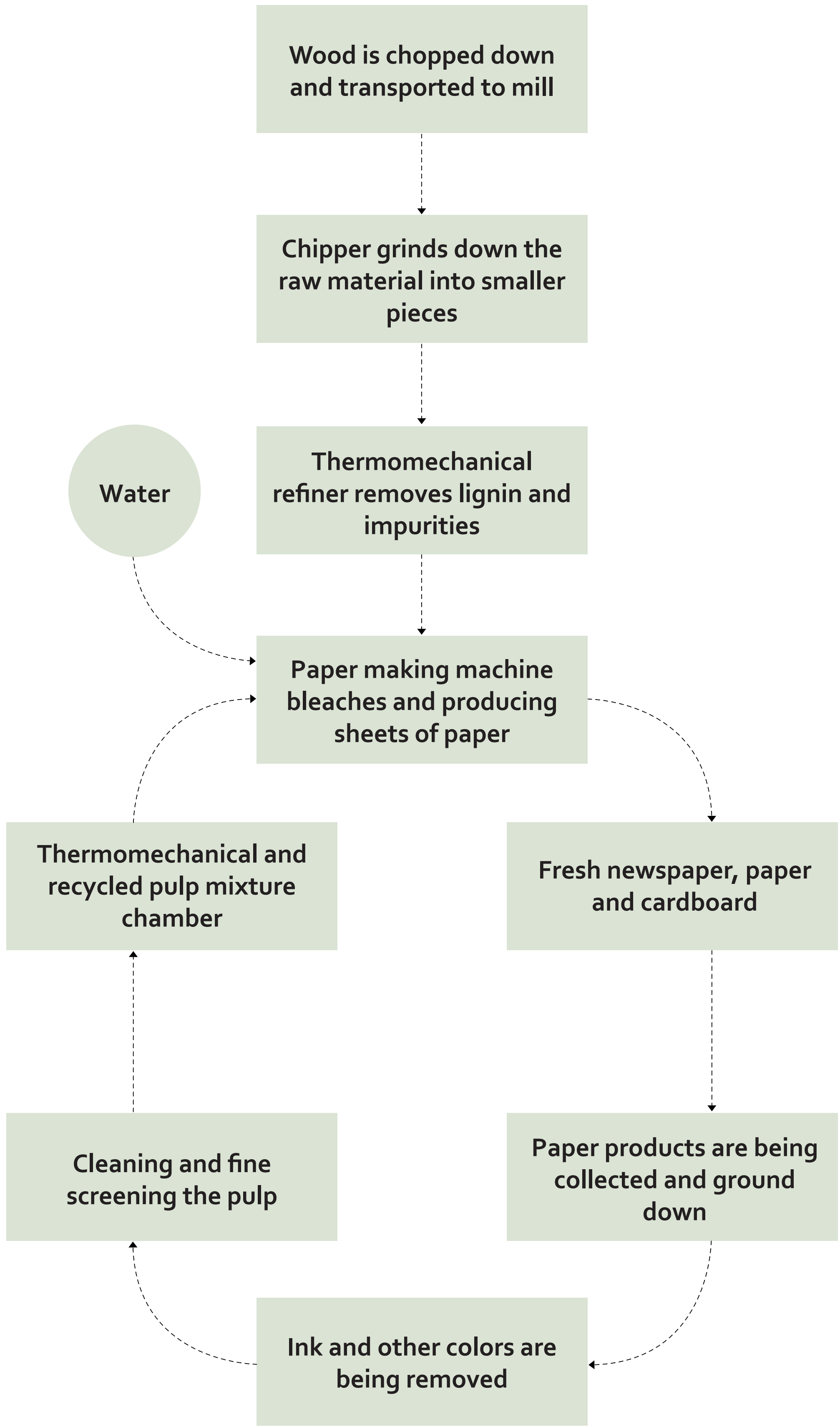
About 800 years after Ts'ai Luns discovery the invention had spread both to the middle east and Europe, where one of the first paper mills was built. The invention of paper as we know it today has since then had a significant role in human civilization and the way we document information.

Since then the production of paper has come a long way. Today it is possible to create paper products from almost any organic material containing cellulose fibers such as hemp, cotton and bamboo. However the far most popular fiber source is coniferous trees which have longer fibers, thus creating stronger paper (*Diarte & Shaffer 2021*). Even recycled paper and cardboard can be used in the production of new paper as long as the fibers are relatively intact. In most cases paper can be recycled between five to seven times before the fibers become too short to be reused.

The first step of the production process is to prepare the pulp to remove any contamination and the lignin found in cellulose structures to isolate the fibers. This is done by cooking the raw material chips in a steamer with the presence of an acid solution to aid the removal of lignin and other impurities. The pulp is then put into a vacuum chamber where the excess steam and other unwanted materials are drawn out.

After this step the pulp is put through a bleaching process to remove any residual discolorations and lignin that can cause the paper to yellow with age. To remove the lignin that is attached to the surface of the fibers, sodium hydroxide is used in addition to other bleaching chemicals, like hydrogen peroxide, to create a white pulp.

The bleached pulp is then refined by mixing it with water and running it through a machine with rotating blades to cut the fibers into a suitable length. This process also roughens the surface of the fibers making them more likely to attach to each other, thus creating stronger bonds in the paper. In this step different additives are mixed in to give the paper a controlled density, making it more opaque and giving it different colors.



Paper production flow diagram

REFERENCE PROJECTS

Cardboard castle by Shigeru Ban, Christchurch, New Zealand

Paper bricks by WooJai Lee, Eindhoven, Netherlands

Pulp Pavilion by Ball-Nogues Studio, Indio, United states

CARDBOARD CATHEDRAL

Project name
Transitional Cathedral / Cardboard Cathedral

Architect
Shigeru Ban

Location
Christchurch, New Zealand

Built
2012-2013

Concept
The old cathedral in Christchurch, New Zealand, was destroyed in an earthquake that struck the region in 2011. While waiting for the new cathedral to be built Shigeru Ban was asked to design a temporary building that could quickly replace the demolished church, hence the name. The design quickly landed in using cardboard tubes as the main structural element since it would both be uncomplicated to transport and construct on site. The walls of the cathedral mainly consist of shipping containers on which the roof rests upon. The roof is constructed as a simple A-frame and is made out of 96 cardboard tubes with a diameter of 60 cm. The roof is then covered with sheets of polycarbon to protect the tubes from direct contact with water. However the local manufacturer could not produce thick enough tubes to work as structural elements on their own. Each tube then had to be reinforced with laminated wood beams.

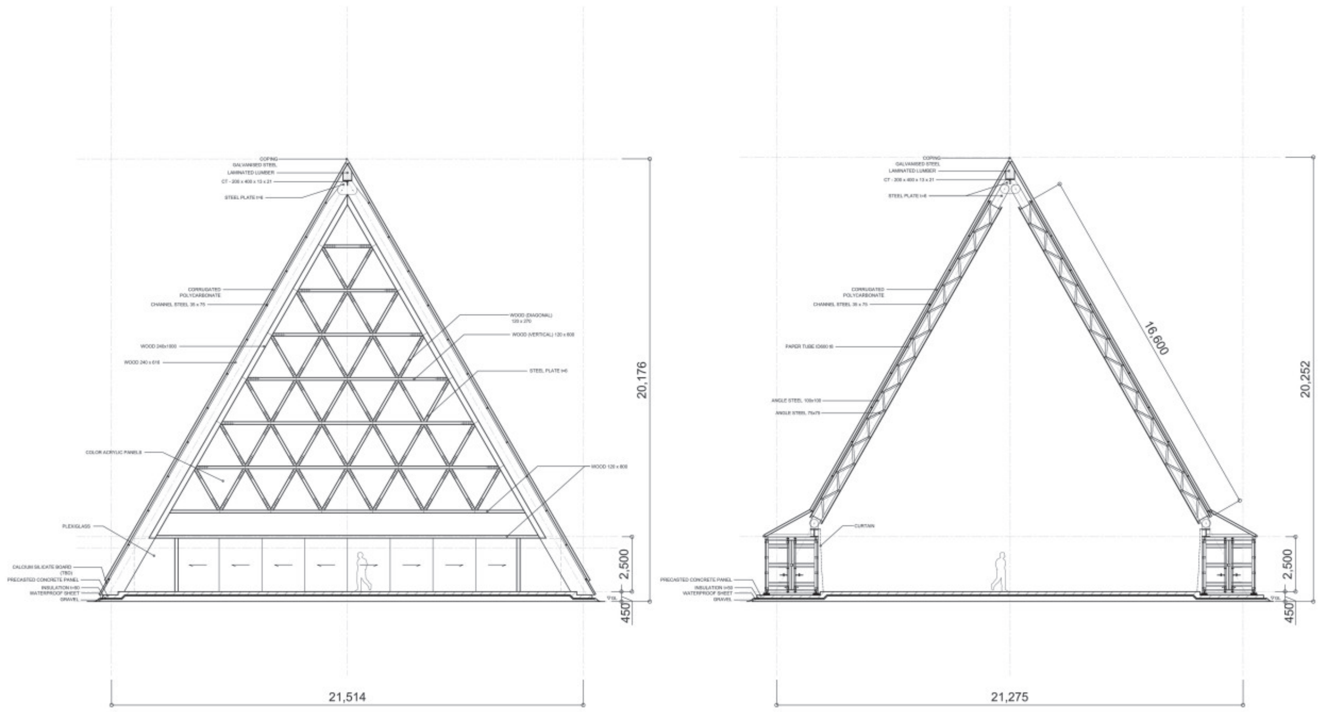


Photo credit: BBC

PAPER BRICKS

Project name
Paper Bricks

Designer
WooJai Lee

Location
Eindhoven, The netherlands

Designed
2016

Concept
WooJai Lee is a dutch-based designer and creator who graduated from Design Academy Eindhoven in 2016 with the paper bricks as his exam project. He got the idea for his project after observing how much newspaper and magazines that are being thrown out each day and pondering about the short lifespan of most paper products.Usually paper downgrades and loses strength every time it is recycled but he wanted to find a method that made the recycled paper solid and stronger. The way he goes about doing this is to collect old newspaper, shredding it down and mixing it with water to create a paper pulp. The pulp slurry is then mixed with glue and dye to give some color to the material and eventually put in a brick-shaped mold to dry. The bricks are then assembled together or combined with a wooden frame to make benches, coffee tables or nightstands. The furniture is safe to use indoors as long as they dont come in direct contact with water.

Photo credit: WooJai Lee

PULP PAVILION

Project name
Pulp pavilion

Architects
Ball-Nogues Studio

Location
Indio, California, USA

Built
2015

Concept
The Ball-Nogues studio started experimenting with applying paper pulp slurry onto different objects and allowing it to dry. Everything from tensioned fabrics to cars got covered in pulp through a pressure sprayer before they came up with the idea to use a system of lattices as a framework. By suspending a matrix of rope inside a fixed frame, spraying it with pulp and allowing it to dry they could create a self supporting structure. At the Coachella music festival in California they decided to put their idea into a full scale architectural context. The proposed design was a pavilion consisting of seven pulp towers, each measuring over six meters in height. Each tower was constructed upside down so that the lattice of ropes would naturally take the form of a catenary. A wooden pentagonal frame at the bottom of the formwork would eventually connect the towers at the top and a metal plate at the bottom would then act as a connector to the ground. The pulp is then mixed with different colours, sprayed on and allowed to harden in the desert climate. When the structure has dried it is flipped upside down and assembled. The hardened pulp is then able to handle the compressive forces while the matrix of rope can withstand some tension in the structure.

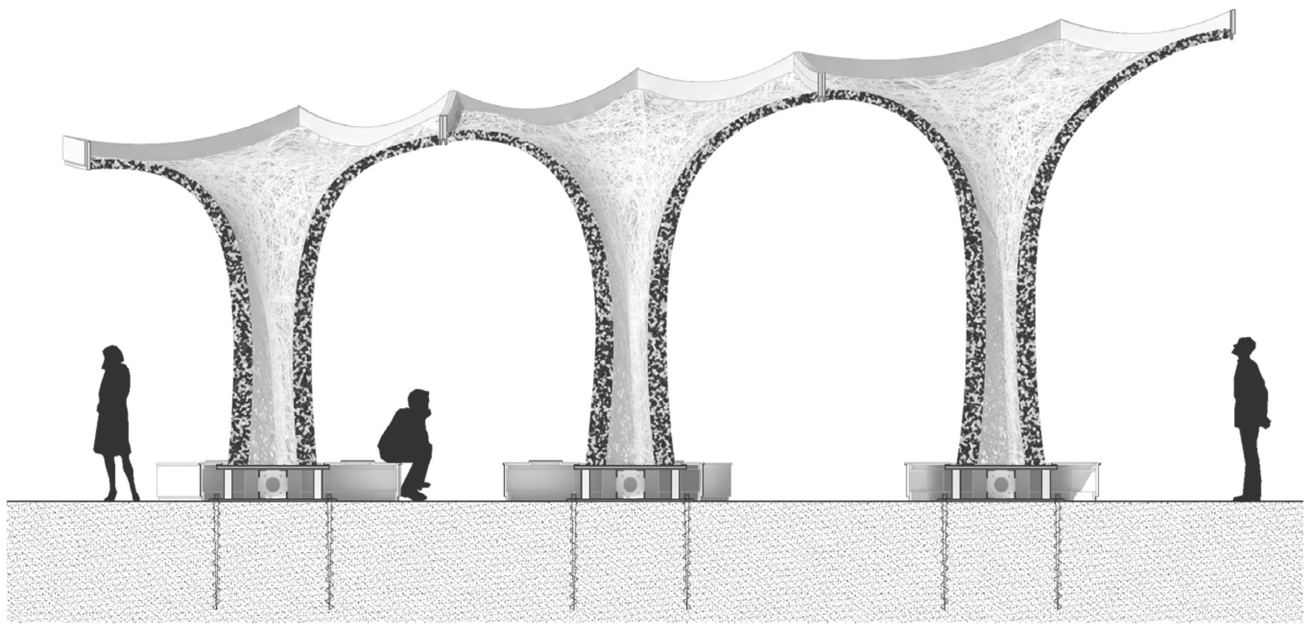
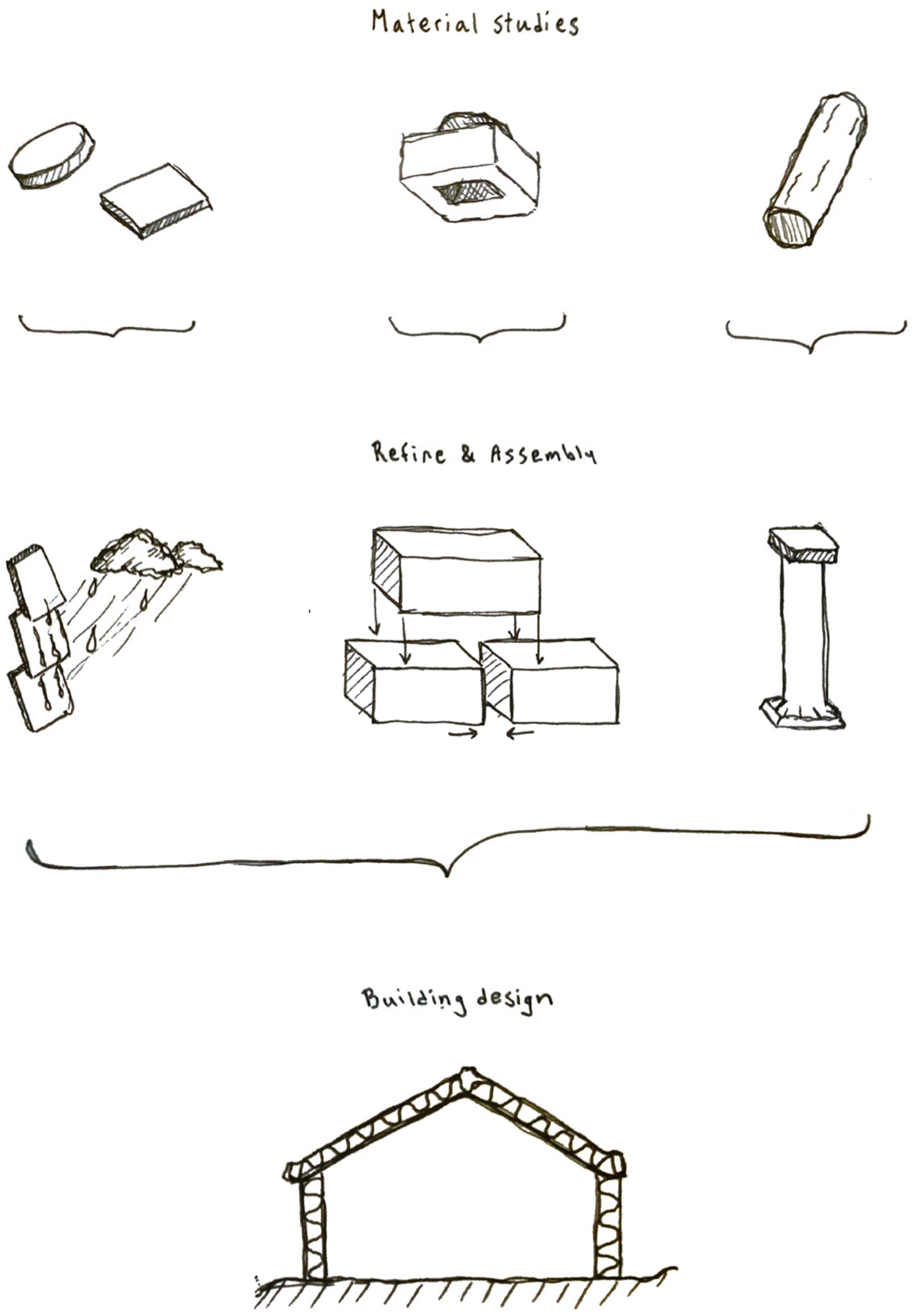


Photo credit: Joshua White



Thesis concept structure

METHOD

This thesis is structured into three coherent phases that together builds on the base of using paper pulp as an alternative construction material.

The first phase is mainly focused on exploring the material itself through material studies where different additives and production methods are investigated.The base of the paper pulp consists of a source of paper fibers (cardboard, newspaper, paper bags or white paper), water and additives to alter the final materials properties.

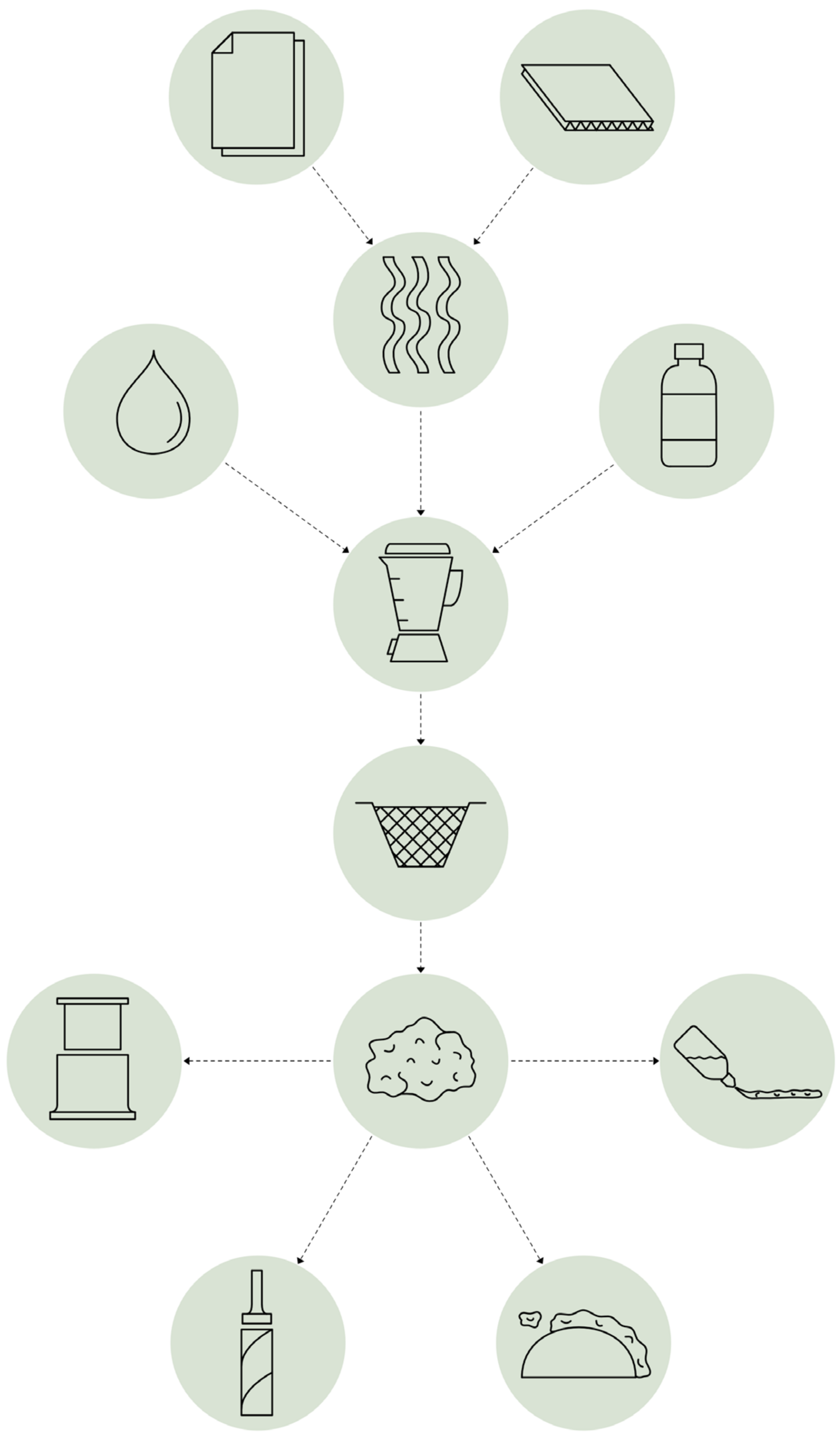
The chosen paper source is manually shredded into pieces which is then mixed in a kitchen blender together with water. This allows the fibers to separate from each other and create the base of the pulp. Next, one or more additives are added to the pulp and thoroughly mixed together to ensure a homogeneous pulp. When everything is mixed together the pulp is run through a filter cloth to manually drain most of the excess water. How much water that needs to be extracted depends on the chosen production method.

The second phase is all about refining and putting the sample pieces into the context of building design. This is achieved by evaluating the tests of the first phase based on material properties and visual aspects. By doing so it is possible to sift out samples that potentially could be used to design building elements and further elaborate these. The experiments are put into one or more categories: wall system, pillars, roofing structure and furniture/decoration.

In each category a scale model is done of the given element with the pulp mixture and production method assigned to it. The result is a collection of building elements made out of waste paper and cardboard that, in the final phase, is implemented in an architectural building proposal.

The building design will consist of derivatives of the paper elements where each concept is adapted to the building proposal. Instead of introducing new materials or reinforcement structure, the material properties of the paper pulp will be the framework for the building design. Since the material is strong in compression but weak in tension and bending, the structural system would have to be designed so that all components work mainly in compression. The approach to this challenge is to design a shell structure that spans over the building site and act as a roof. In order to make the shell work only in compression form-finding through both digital and physical models is used as a design tool.

The digital model is designed with a plug-in to Rhino called Kangaroo 2. The plug-in uses dynamic relaxation to calculate the shape of the shell based on an initial mesh, anchor points and a load distribution over the mesh vertices. Similar but more analog methods will be used to design the physical model. The base mesh is replaced with an elastic fabric that is anchored to a base plate and the load that deforms the shell comes from the weight of the applied pulp.



Process flow diagram

DELIMITATIONS

There is much to be explored in terms of working with paper pulp in architecture but since this thesis is conducted in just one semester some delimitations have to be done. Due to the limited time the aspect of how the material age over a longer time period is neglected. The effects of long term load on the elements and creep is neglected as well as exposure to UV light.

Since this is an architectural thesis the main focus lies on the architectural qualities of the material and less on structural engineering. More in depth analysis on shear forces and optimization will have to be ruled out. Since the shell encapsules a rather large volume, sound will most likely resonate for a long time before diminishing, depending on how well the material reflects sound. The acoustic properties however is disregarded in the design of the building since tools and knowledge in this area lies too far away from my personal knowledge. This thesis is aiming to produce a material made from waste paper with a focus on using only sustainable materials. Papercrete is considered to be a sustainable option to regular concrete where paper pulp is used as a filler together with cement. However, producing cement is extremely energy-intensive which explains the materials high carbon footprint. Therefore cement is ruled out as an alternative to be used in this project. A big challenge will be to waterproof the material as paper is subject to easily swell and lose material strength in contact with water. The way the packaging industry deals with this problem is to line the containers with layers of a plastic called polyethylene (*Plastic Ingenuity, 2021*). For the same reason as mentioned above, coating the paper elements with plastics is not considered an option.

PHASE I

MATERIAL STUDIES

As to be seen from the mentioned reference projects there are many different ways to implement cardboard as a design tool in architecture. However one method that is not very commonly used in architecture is to produce elements made from paper pulp. This way of working with cardboard is widely used within the packaging industry to make moulded pulp containers like egg cartons. It usually serves as a replacement for plastic mold containers as these can often be more expensive to produce. These products are usually very thin but materially strong enough to endure impacts during transportation and considered as a sustainable packaging material (Sustainable Packaging Coalition, 2005).

The first step of this thesis is to further explore the opportunities of working with cardboard and paper pulp as a potential design element. This is done through a range of experiments with paper pulp as the main ingredient. In addition to the cardboard and paper, different additives will be added to the mixture in order to control the outcome of the experiments in terms of texture, color, strength and stiffness.

Traditionally molded pulp containers are made from vacuuming the pulp onto a shape with a filter that removes the water and leaves a layer of moist pulp on the mold. The vacuum generates a pressure that allows the fibers to be packed densely during the hardening process. How tight the fibers are packed has a direct relationship with the strength of the finished product. In these studies four different ways of molding with paper pulp is explored. Two of them are methods that rely on compacting the fibers, one that relies on strength through geometry and one method that can produce more complex shapes.

+ **FULLY COMPRESSED**
  The mold is made in two pieces - one with the desired shape where the pulp is placed and one pressing piece that goes on top. The mold is then held together with the help of a screw clamp. After allowing it to dry for 24 hours the pressing piece is removed and the sample is set aside to thoroughly dry out at room temperature for another two to three days.

+ **PARTIALLY COMPRESSED**
  The mold used for this production method is a simple cardboard tube wrapped in plastic to protect it from sticking to the pulp. The material is gradually added in layers which is then rammed in order to compact the fibers. When the mold is completely packed it is set aside to dry out the remaining water that was not extracted during the process. Once it is dry the paper tube is carefully dismantled.

+ **PRINTED**
  This production method is meant to simulate what 3d-printing with the material would look like. Instead of a 3d-printer a plastic container with a small nozzle is used to additively apply the material layer by layer. The pulp mixture is prepared as usual and then put in the container until it is filled to about 75 %. By squeezing the container the material can be applied additively layer by layer, creating geometries that would not be possible with the previous mentioned methods.

+ **MANUALLY APPLIED**
  In this production method the pulp is applied manually to objects and then allowed to dry, creating a cast of the object. In these studies a convex cupola or bowl is being used as the mold to generate some sort of shell structure. The shell can then be made relatively thin but still possess structural strength when loaded in compression.

LIST OF ADDITIVES

+ **PAPER AND CARDBOARD**
The main ingredient of the paper pulp is either cardboard or paper. In order to change the color of the finished product different colored paper sources will be used.

+ **PVA-GLUE**
Polyvinyl acetate (PVA) glue is a water soluble thermoplastic adhesive that is commonly used for porous materials like wood and is expected to act as a binding agent to hold the paper fibers together.

+ **CORN STARCH**
Starch is commonly used in the paper industry as a flocculant to clump the paper fibers together and increase tensile strength.

+ **CLAY**
In these experiments a water based and air drying white clay is used to hopefully give a smooth and more ceramic end result.

+ **SAND**
In concrete sand is mainly used to make cement (with addition of water) more binding but also to decrease porosity. By reducing the porosity of the paper pulp the material is less deformed during compressive stress.

+ **LIQUID LATEX**
Latex is a natural rubber that comes from the sap of the Hevea brasiliensis tree and is used to make elastic, durable and waterproof products, like rubber gloves. Liquid latex is usually made up of 1/3 latex and 2/3 water and a small amount of ammonia. It is used in these experiments to increase the water resistance of the finished products.


Cellulose fiber source

PVA-glue


Corn starch


Clay


Sand

Liquid latex

3D PRINTED MOLDS

The first step in making the fully compressed cardboard piece was to design a mold for the paper pulp. For the prototype a three part press was made through additive manufacturing. The purpose of the three part mold is to facilitate the process of removing the cardboard piece from the press after the drying is done. Since 3d-printed structures usually are weak in sharp corners the molds were designed with beveled or rounded edges.

The bottom is designed with four pins and a raised middle part in order to fixate the walls. Drainage holes with a diameter of 1,5 mm were put in the middle part in order to let water escape from the bottom without letting out any of the pulp.

In order to ensure the fitting of the walls onto the bottom part the holes for the pins were designed with a 0,2 mm gap. For the same reason the inner measure of the walls was made 0,2 mm larger than the measurement of the pressing part. The walls were also made 5 mm thick in order to withstand the great horizontal force that the press exerts.

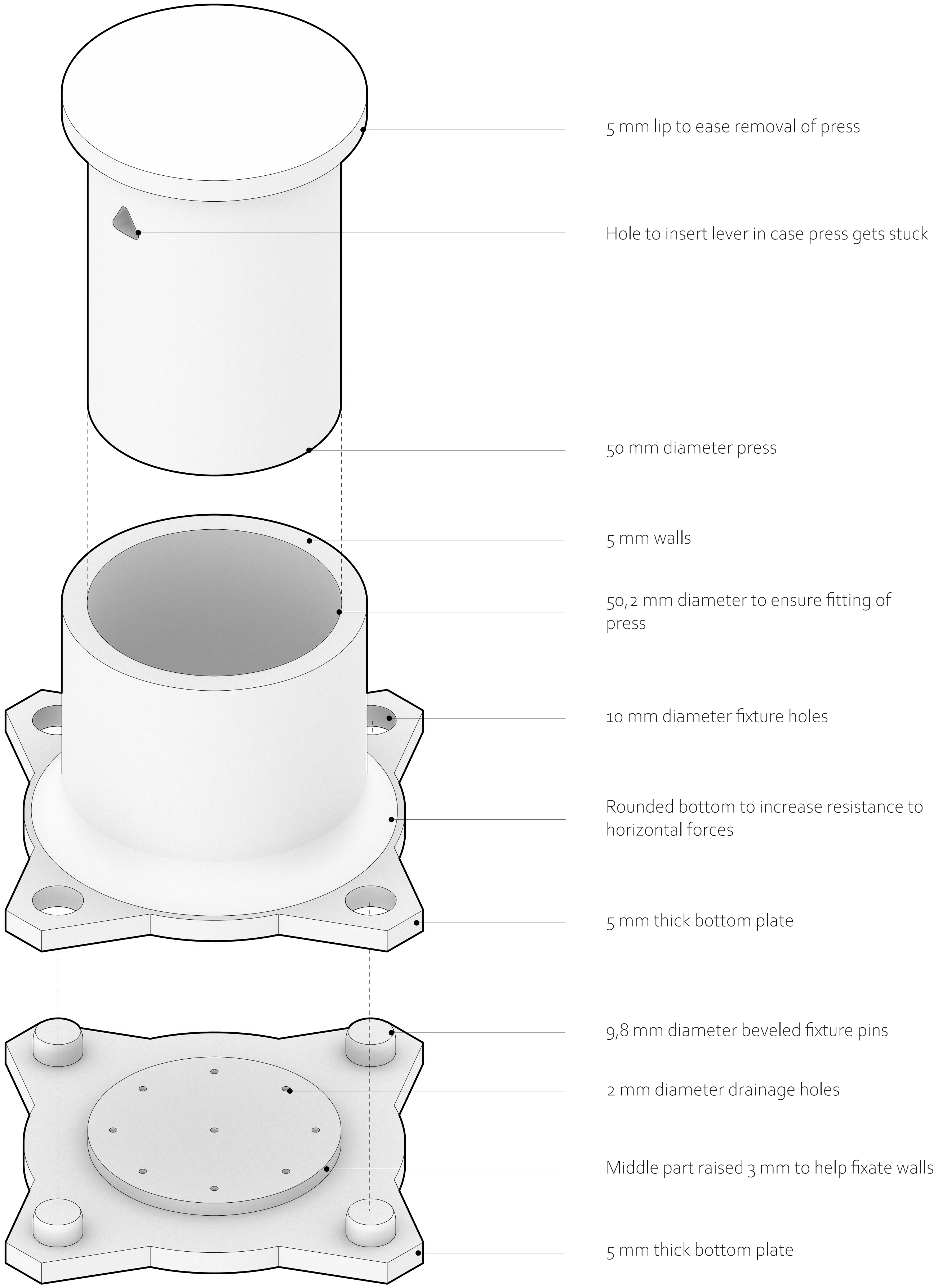
The pressing part is designed with a lip to ease the removal of the part after pressing is done. In case the press should get stuck a hole is made through the part where a lever could be inserted and aid the removal process.

The overall quality of the 3d-printed molds turned out well without any failures. However some miscalculations were done regarding the tolerance of pieces that were supposed to fit together. Since the size of the nozzle head printing the filament is 0,8 mm there should be at least a 0,4 mm tolerance for the pieces to fit together (assuming ideal printer conditions). This slight miscalculation led to the walls not fitting on the base and the press not fitting inside the walls. This drawback was remedied by reprinting the walls with a tolerance of 0,8 mm to ensure proper fitting of the pressing part and the fixture pins.

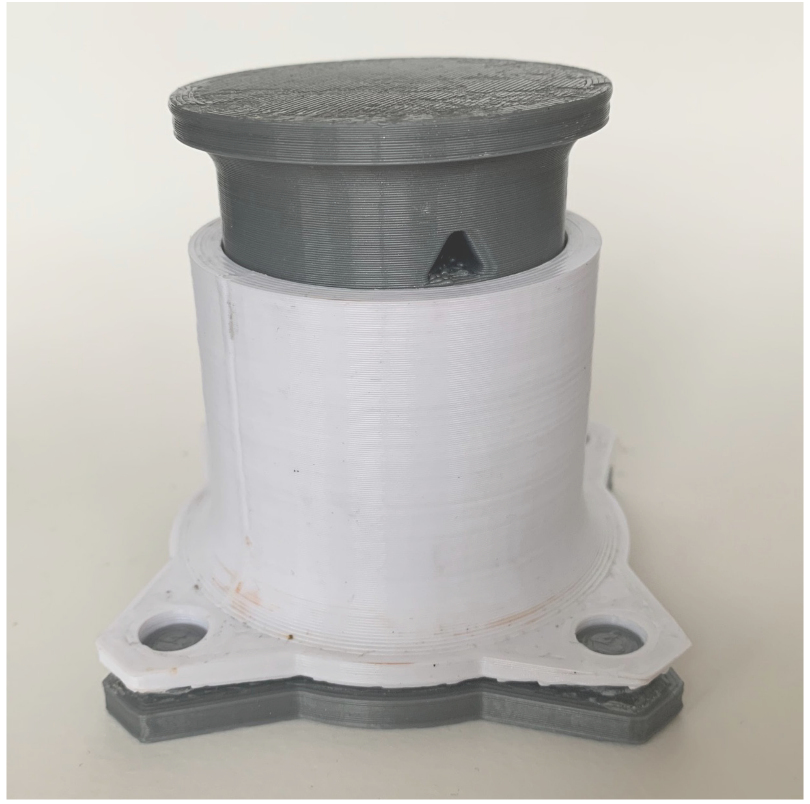
Another flaw in the printing process can be seen in the bottom plate where the drainage holes were supposed to be. The first layer height is set to 0,1 mm to flatten out the first layer of filament and ensure that it sticks to the printing bed. Because of this the drainage holes at the bottom layer got filled up entirely with filament. The bottom part was instead reprinted with increased diameter of the drainage holes from 1,5 mm to 2 mm in diameter which resulted in success.

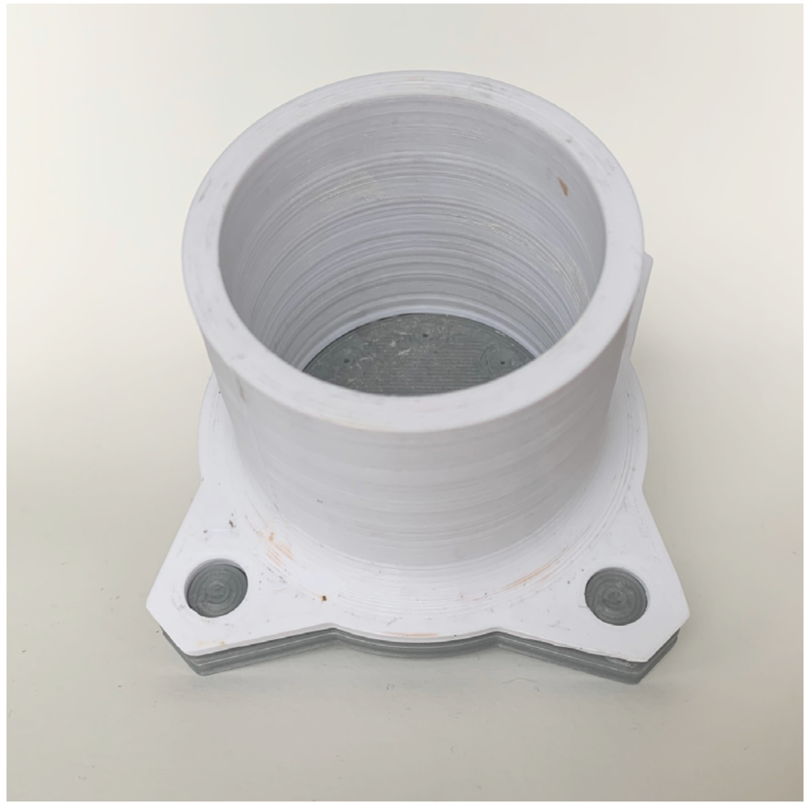
PRINT SETTINGS

Filament	*PLA*
Nozzle size	*0,8 mm*
Layer height	*0,3 mm*
First layer height	*0,1 mm*
Infill	*25%*
Wall count	*3*
Top layers	*3*
Bottom layers	*3*

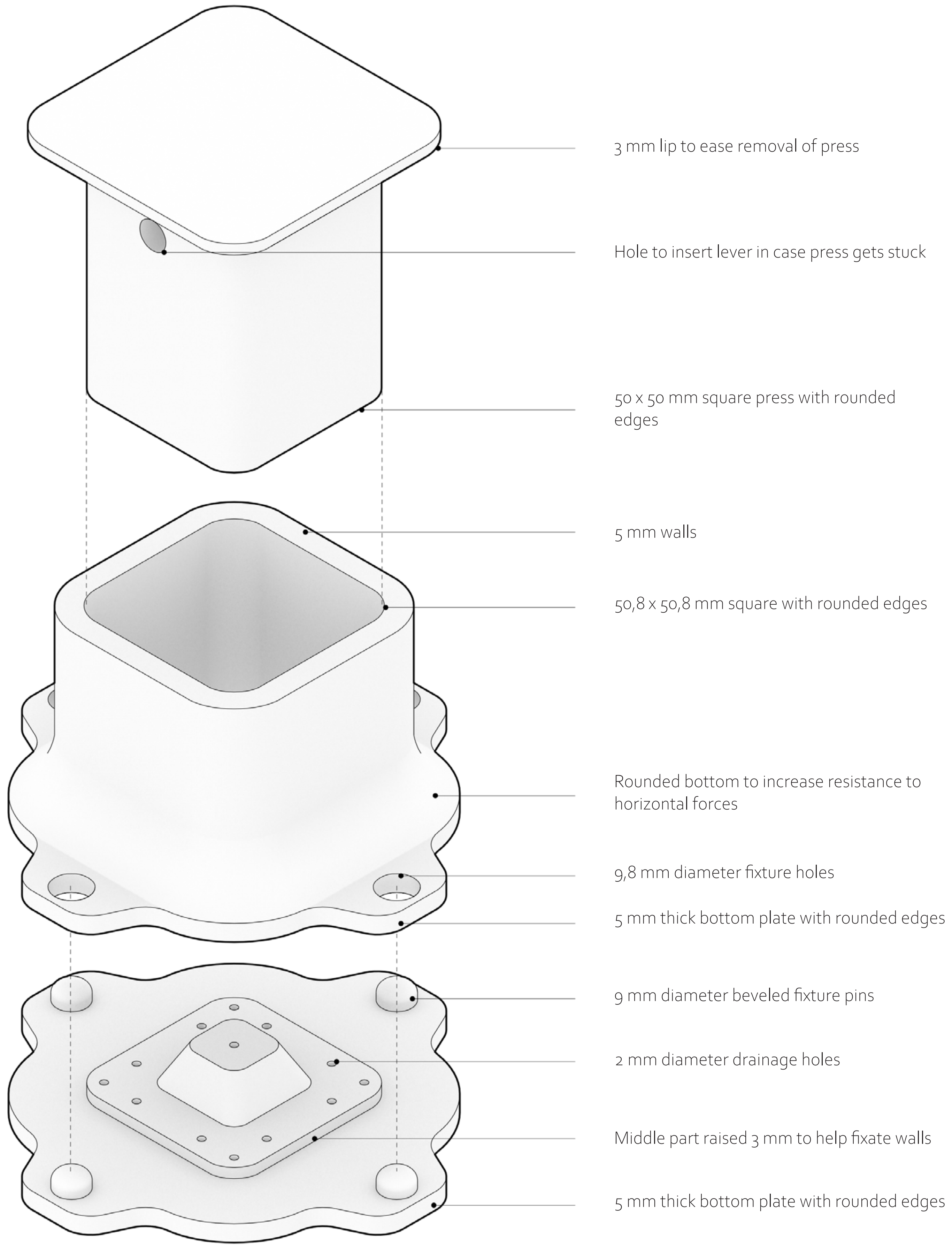


Digital model





3d printed model



Digital model

3d printed model

SELECTED EXPERIMENTS

Batch F
Ingredients:
+ *25 grams of grey cardboard*
+ *25 grams of PVA-glue*
+ *50 grams of sand (fine)*

Production method:
+ *Fully compressed*

Batch G
Ingredients:
+ *25 grams of grey cardboard*
+ *100 grams of clay*
+ *50 grams of sand (fine)*

Production method:
+ *Manually applied*

Batch H
Ingredients:
+ *20 grams of white paper*
+ *10 grams of green paper*
+ *50 grams of clay*
+ *150 grams of sand (fine)*

Production method:
+ *Printed*

Batch I
Ingredients:
+ *20 grams of white paper*
+ *15 grams of red paper*
+ *35 grams of PVA- glue*
+ *100 grams of sand (coarse)*

Production method:
+ *Partially compressed*

A full list of conducted experiments can be found the *Material Studies* appendix

EXPERIMENT H1

Tactility	Rough	**Fire resistance**	Good
Texture	Scattered	**Water resistance**	Poor
Density	Semi heavy	**Compression**	Semi robust

Ingredients

+ *20 grams of white paper*
+ *10 grams of green paper*
+ *50 grams of clay*
+ *150 grams of sand (fine)*

Production method

Printed

Motive

This experiment aimed to find a suitable material composition for the printing method. From previous experiments it is found that both clay and sand has a positive impact on the consistency of the material.

Expectations

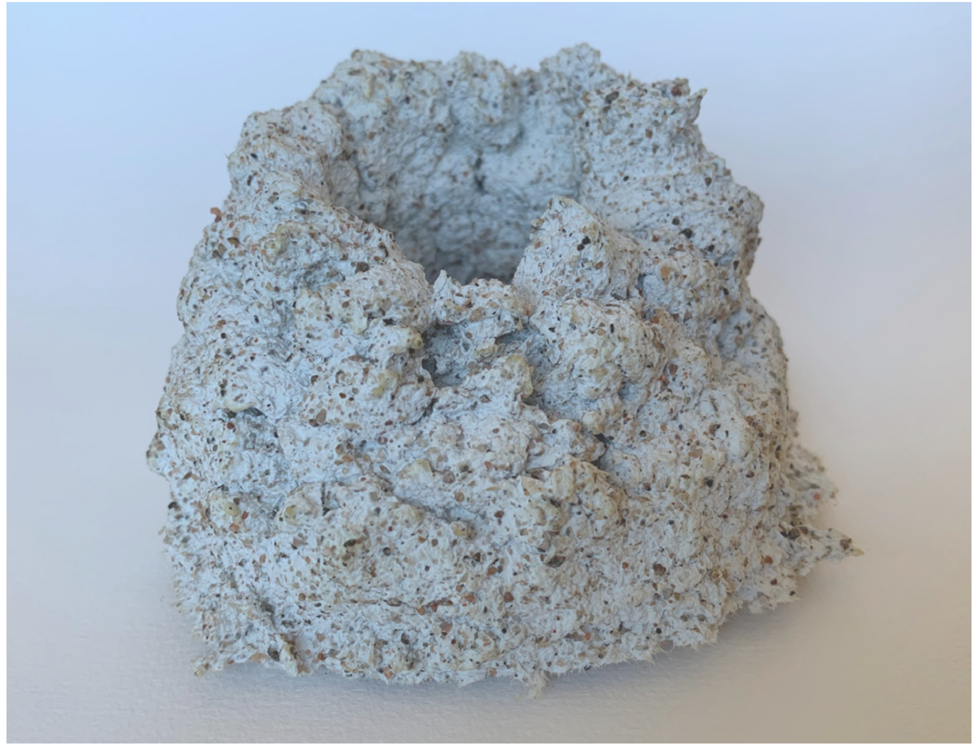
Since clay has shown to work in previous printing tests and sand has helped to reduce porosity, the combination of clay+sand should be an ideal composition for the printing method.

Result

At first it was challenging to find the right amount of water to give the pulp the desired consistency. With too much water the material would not stack in layers and too much water made it hard to extrude the pulp. When the right amount of water was found the printing could be carried out as desired. The end result was the best printed sample so far even though it was hard to apply the layers evenly on top of each other by hand.

Possible uses

+ Since the material is not compacted it will not be able to serve as a structural element but instead work as a decorative piece or furniture.
+ The material could work as a rendering element to create interesting textures or surfaces.



EXPERIMENT G3

Tactility	Smoothm paper-like	**Fire resistance**	Semi good
Texture	Rough	**Water resistance**	Poor
Density	Semi light	**Compression**	Semi-robust

Ingredients
+ *25 grams of grey cardboard*
+ *100 grams of clay*
+ *50 grams of sand (fine)*

Production method
Manually applied

Motive
This experiment aimed to find a composition of additives that gives a rigid and sturdy shell once the pulp has hardened. A small bowl was chosen as the mold.

Expectations
When the clay hardens it becomes somewhat ceramic and more resistant to cracking during compression compared to hardened paper pulp. In addition to the sand that also contributes to compressive strength the finished shell should be more robust than the sample with only 50 grams of clay.

Result
The hardened shell turned out with a smooth surface on the side facing the mold and somewhat inconsistent on the outside with a papery feel to it. Even though the pulp contained both sand and clay that usually result in a heavier material, the finished product was rather light due to the fibers being loosely packed. The shell was able to support about 80 kg of weight stacked ontop of it before cracks began to form.

Possible uses
+ Due to the materials ability to withstand compressive forces the sample could be used in a upscaled version of a form-found shell.

EXPERIMENT F1

Tactility	Smooth, sand like	**Fire resistance**	Good
Texture	Uniform	**Water resistance**	Poor
Density	Semi heavy	**Compression**	Robust

Ingredients
+ *25 grams of grey cardboard*
+ *25 grams of PVA-glue*
+ *50 grams of sand (fine)*

Production method

Fully compressed (stackable mold)

Motive

This experiment aimed to examine the presence of fine sand in the fully compressed block in terms of post drying shrinkage and robustness.

Expectations

Shrinkage in the material happens mainly for two reasons. The first one is that the cellulose fibers swell up in contact with water and contract again when the water evaporates. The second reason is that the water expands the pores of the material. When the water then evaporates the pores shrink thus causing the whole sample to shrink in size. Since sand is convenient at filling out pores some of the shrinkage in the material could be eliminated. Another benefit to replacing the air in the pores with sand is that the sample should become more robust and less likely to deform in compression.

Result

The sample was easy to remove from the mold without damaging the piece. After allowing it to acclimatize to the surrounding humidity it was found that it had shrunk about 1,3 %, whereas the blocks with only cardboard and glue shrunk about 2,4 %. The sand seems to have made the block a bit more robust to compressive forces with the biggest difference being that the sample cracks during compressive deformation. Additionally the sample turned out smooth with a nice sandy-beige color to it and an interesting texture due to the sand grains.

Possible uses
+ The block could be used for a wall system due to its robustness and nice finish.

EXPERIMENT I1

Tactility	Rough, concrete like	**Fire resistance**	Very good
Texture	Uniform	**Water resistance**	Semi poor
Density	Semi heavy	**Compression**	Robust

Ingredients
- + *20 grams of white paper*
- + *15 grams of red paper*
- + *35 grams of PVA- glue*
- + *100 grams of sand (coarse)*

Production method

Partially compressed

Motive

This experiment tested the presence of coarse sand in the partially compressed "pillar". In addition to this one sample is made with a thin strip of fabric that is continuously placed in a spiral as material is added and packed.

Expectations

Since sand helps reduce porosity in the material the sample will most likely be more compact and thus have less tendency to compress while loaded. The thin strip of fabric reinforcement will most likely help the sample from cracking during axial load.

Result

The samples came out with a smooth surface compared to previous samples with the same production method. The small pebbles add some weight and robustness to the sample and, in addition to the red paper, gives the overall appearance a nice texture. During compressive stress both the samples were able to withstand more pressure than I could exert using the screw clamps which is a great improvement from previous samples. However the sample without fabric did deform slightly more than the one with fabric reinforcement.

Possible uses
- + Since the material seems less likely to deform during compression it could be used as a pillar element or foundation

PHASE I, REFLECTIONS

What are the structural properties of paper pulp?

A considerable amount of time was set aside for the material experiments in order to get as much knowledge as possible about the material and how to work with it. For each experiment conducted another two ideas emerged on how the experiments could be elaborated which led to the allotted time for this phase being exceeded. In hindsight it might have been better to close this chapter earlier and put more time into the assembly and contextualization phase since it is closer connected to the building proposal. However, this phase has been exceptionally rewarding to work with in terms of learning and enjoyment from a personal perspective.

Since the goal of this thesis is to propose a building design made from paper elements the biggest challenge in these studies have been to find a way to waterproof the material. A great example of how to do this can be found in the material papercrete - a combination of concrete with paper pulp as filler material. But as stated in the delimitations this thesis aims to find a sustainable material thus it would not make sense to use cement as an additive. Another idea considered was to infuse the material with epoxy resin, a technique commonly used together with carbon fiber to create extremely durable and lightweight components. For the same reasons as above this alternative was also ruled out. The goal instead became to find a material composition that would make the paper pulp more resistant to water, or in best case, waterproof. It was found to be harder than expected. The result that came the closest to being water resistant was when liquid latex was added to the paper pulp. Due to the fact that the latex did not mix quite well with the rest of the pulp slurry the result only became partially waterproof. The parts of the sample where hardened latex had accumulated were as good as waterproof while the other parts swelled up and dissolved in contact with water. Ultimately the method for waterproofing landed in coating the given piece with a layer of wax or latex on the side that would be exposed to water.

Since paper is made up of cellulose fibers it is vulnerable to catching fire which is why the samples were tested for fire resistance. This problem however turned out to be less of a challenge to solve. One of the main components needed for combustion is oxygen, heat and fuel. Hence the hypothesis became that the less air and combustible material the samples contained the harder they would have to catch fire. One way to reduce air in the material was to pack the fibers more tightly thus reducing pores with air. The way this was done was to use the production method *fully compressed* or *partially compressed*. To reduce the amount of combustible material, paper, filler additives like sand and clay were added. It turned out that sand had the biggest impact on fire resistance as the samples with higher amounts of coarse or fine sand were less subject to catching fire. Even the samples with loosely packed fibers were left with only a small patch of soot after being exposed to an open flame.

From the experiments it became clear that when the pores in the material were mostly filled out with coarse sand the compressive strength of the material increased. The experiments without sand would deform quite a bit on the load axis whereas the ones with coarse sand were more likely to crack instead of deforming. Similar properties could be seen in experiments where clay was used. The samples would deform more than the ones with coarse sand but the cracking was not as severe. Another impact of both coarse and fine sand could be seen in the drying process. Normally samples with only paper shrunk in average with about 2,5 % where the samples with sand shrunk about 1,4 % depending on the amount used. However the shrinkage is not a critical factor as the blocks are easy to trim and sand down in post production. This means that each element could be made larger by some tolerance and then refined once it is dry to enhance precision.

CONCLUSIONS

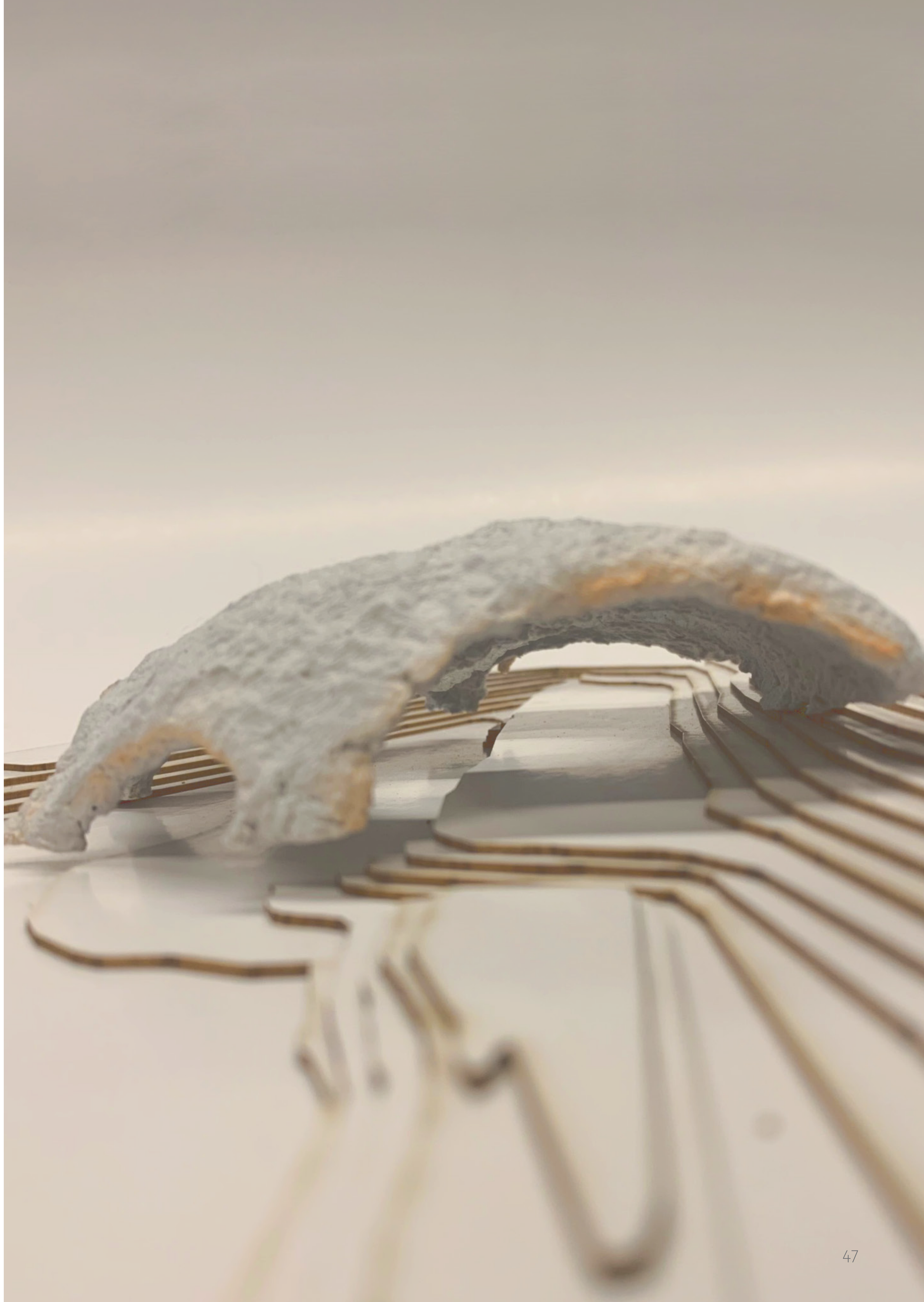
+ *Versatile material when in terms of molding, shaping and creating.*
+ *Generally a light-weight material.*
+ *Works well in compression but weak in bending and tension.*
+ *Shrinkage occurs during drying in different degrees depending on material composition.*
+ *Hard to get water resistant unless covered in wax, latex or water repellant spray.*
+ *Is able to be made fire resistant if composed in the right way.*

PHASE II

CONTEXTUALIZATION AND ASSEMBLY

This chapter will present concepts of how the different building elements can be constructed through digital and physical models based on the findings from the material studies. From phase I it is found that paper pulp as a material can be very adaptable depending on the additives used and the production method chosen. Even though the material properties can vary depending on these factors it still resembles the ones of unreinforced concrete or stone - strong in compression but weak in bending and tension. Since the aim is to design with only recycled paper the choice was made not to introduce reinforcement elements such as steel to make the material more durable. Instead these material limitations work as a framework or boundary conditions for the design of building elements. In other words the design choices is a direct consequence of both the strength and weakness of the material.

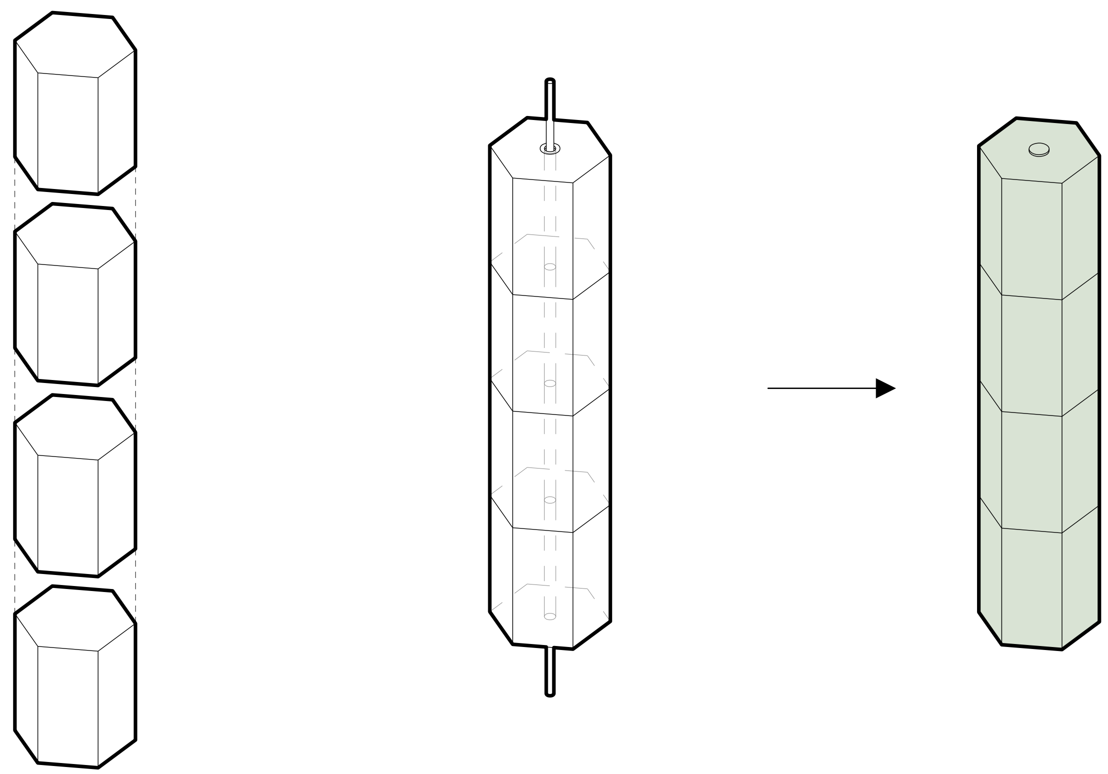
One of the strongest boundary conditions is the materials inability to withstand tension. This means that load bearing beams or trusses can not be constructed to roof an area. Instead the roof is designed in such a way that it is only in compression. A great example of how to span large areas with elements in compression can be seen in the works of Felix Candela or Philippe Block. By the use of geometrical equilibrium and form found design these architects are able to create large spanning shells with unreinforced concrete or pre cut stone. Hence to satisfy this condition a form found shell structure is chosen as the “roof” element. In order to increase the stability of the shell weight needs to be added. This is done through adding clay to the paper pulp and by doing so the structure will be less affected by wind or point loads.



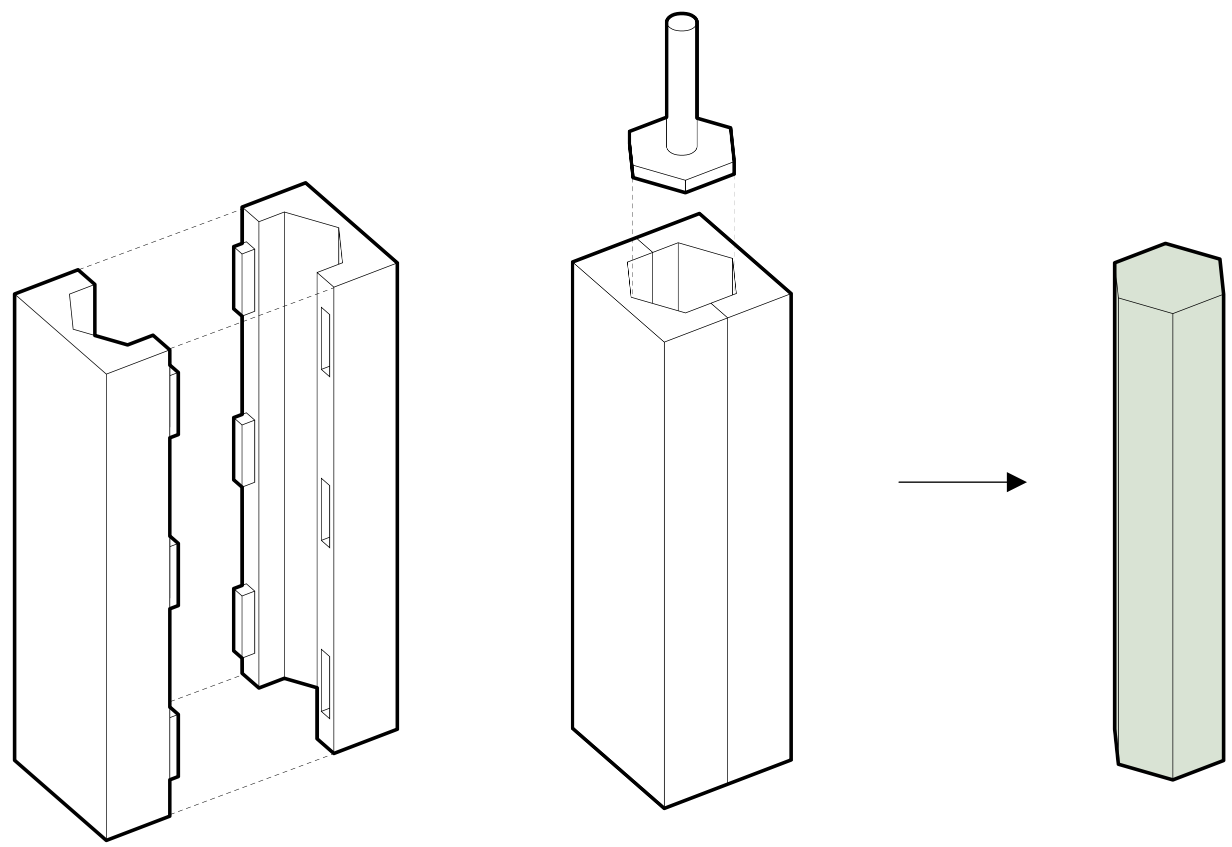
PILLAR CONCEPT

Based on the learnings drawn from phase I, there is two production methods suitable to construct a pillar from paper pulp. The first one resembles the way ancient Roman columns were constructed. When the columns were too big to be carved as a single element they instead carved out separate pieces. These pieces were then fitted together with a connector in the middle and stacked on top of each other which made it easier to erect taller structures. The same principle could be utilized with the paper block where each piece is compressed in individual molds and then connected with a tension wire. This production method would result in the most compact and thus strongest pillar element. The drawback however is that this method would require either a lot of individual molds or a long production time.

The second method is to make a partially compressed pillar in the same fashion as in the material experiments. Constructed from two symmetrical pieces in the shape of the pillar that easily can be assembled and disassembled, the material is then rammed into the mold layer by layer. This method allows for each pillar to be cast in place or prefabricated and only requires one mold per element, as opposed to the previous mentioned method where several molds for each pillar would be needed. Even though the method will not get the fibers packed as densely, the material strength would still be sufficient for the amount of load exerted by other paper elements. A way to increase strength in the element is to use the same additives in the pulp as in experiment I1, namely coarse sand and PVA-glue. The coarse sand particles generate a denser and stiffer material as well as some interesting color variation to the pillar, while the glue acts as a binder.

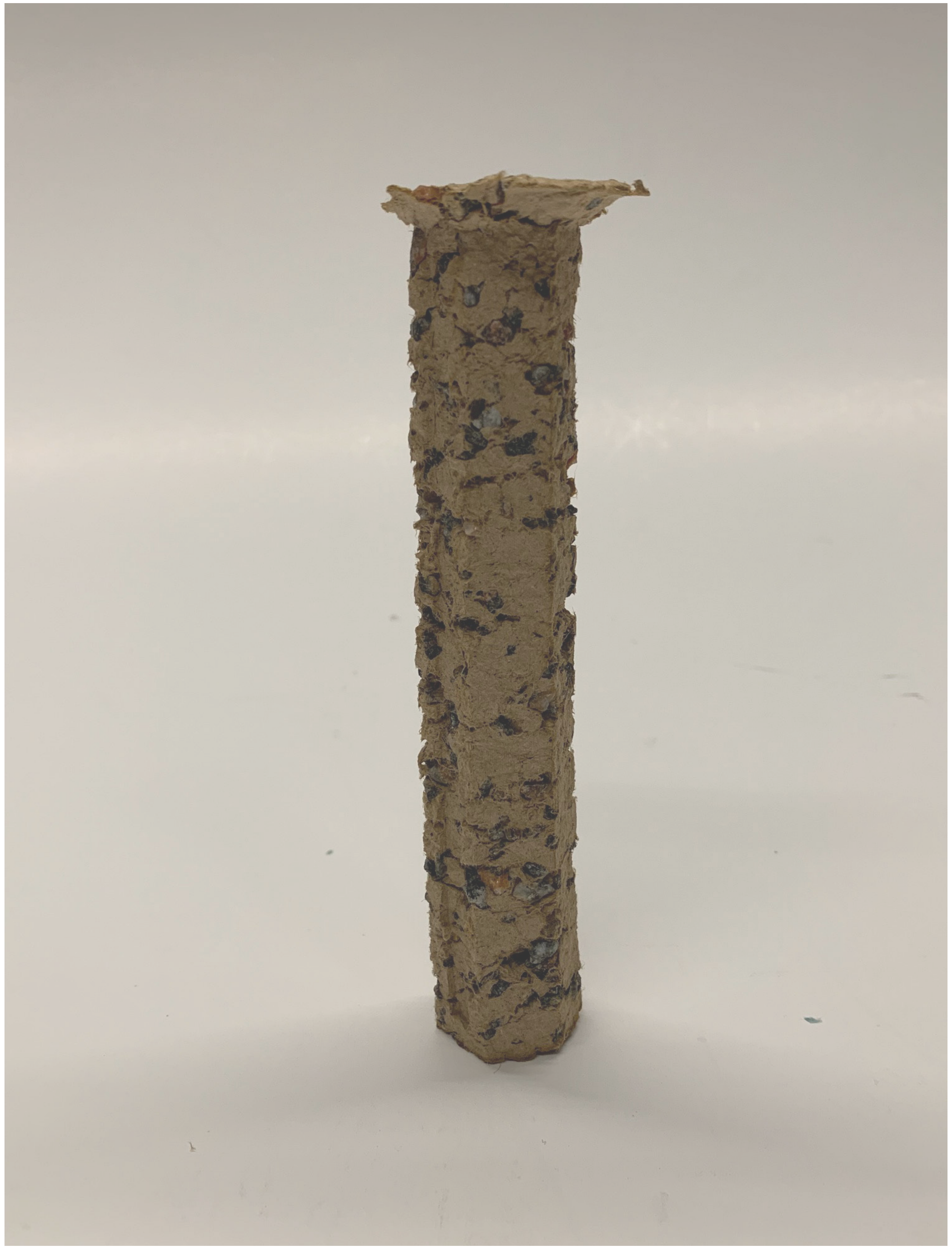


Fully compressed pillar



Partially compressed pillar

Pillar 3d printed mold

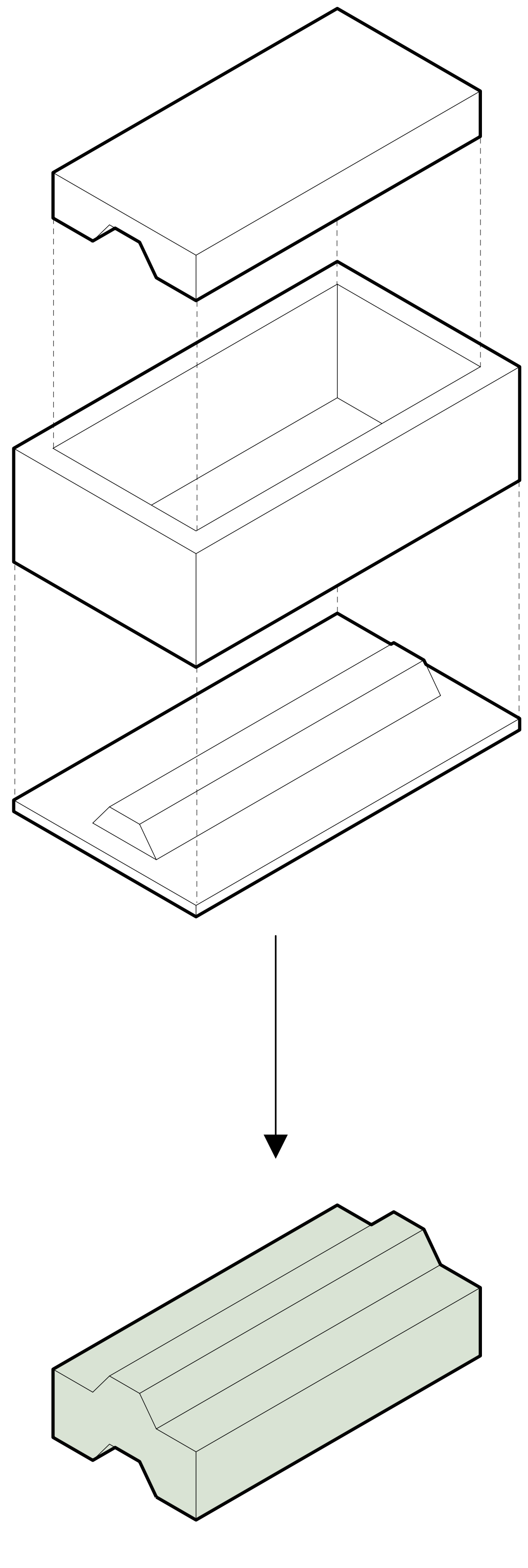


Hardened pillar
Batch I with cardboard

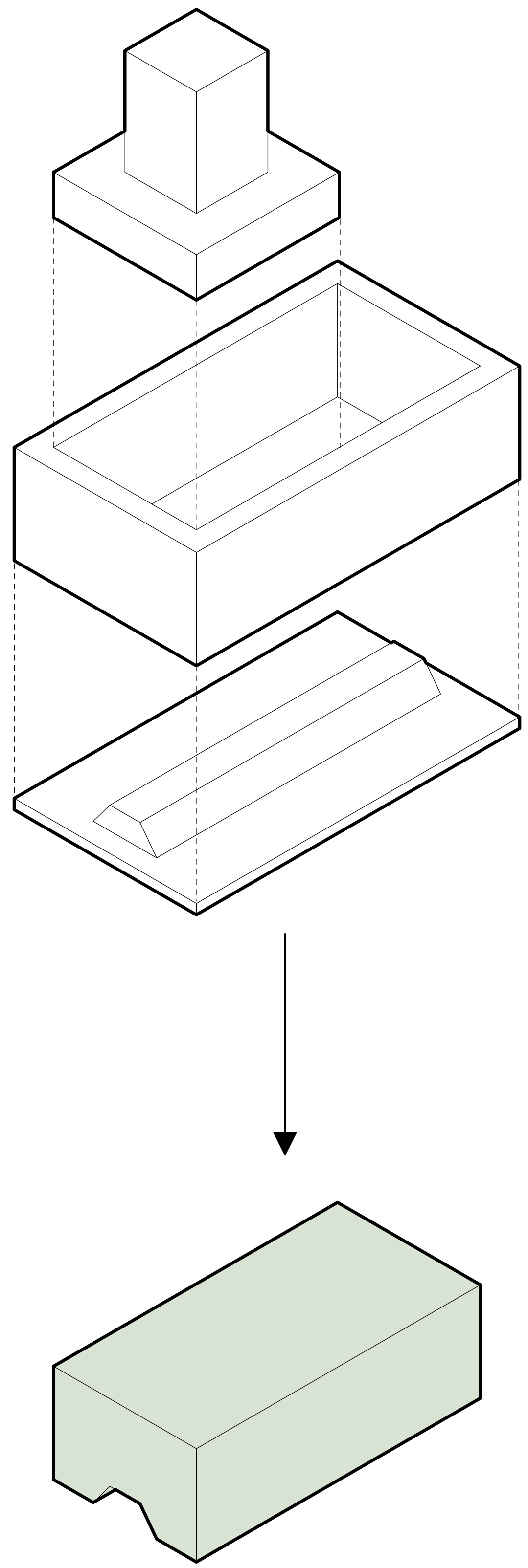
WALL CONCEPT

From the material studies it is found that the pulp becomes more resistant to compressive force when the fibers are more compact. Both the methods "partially compressed" and "fully compressed" allow the fibers to be packed more densely. The latter method that lets the element dry under compression grants a higher degree of freedom when it comes to shaping. Both the top and the bottom of the element can have customized geometries where in the partially compressed method one side will always be flat. Another way to get the material more compact is to use sand in the pulp. Not only does the sand help to fill out pores in the material but it also contributes to heightened fire resistance and reduces some of the shrinkage during the drying process.

For the reasons mentioned above the wall elements will be produced with the "fully compressed" method and contain coarse sand as its main additive to the pulp. Similar to the 3d printed molds from the material studies the blocks will be produced in the same way but on a larger scale. A wooden plate with the desired shape of the block makes out the base, detachable walls are extruded from the plate. The pressing tool is a separate piece with a geometry that allows the blocks to notch into one another. For the building design two main types of blocks is used - stationary and movable. The stationary blocks is used as permanent walls whereas the movable blocks is used to create flexible spaces that can adapt to temporary needs.
To further increase stability in the stationary blocks a post-tensioned metal wire is run through the vertical direction and keeps the blocks in place.



Fully compressed block



Partially compressed block

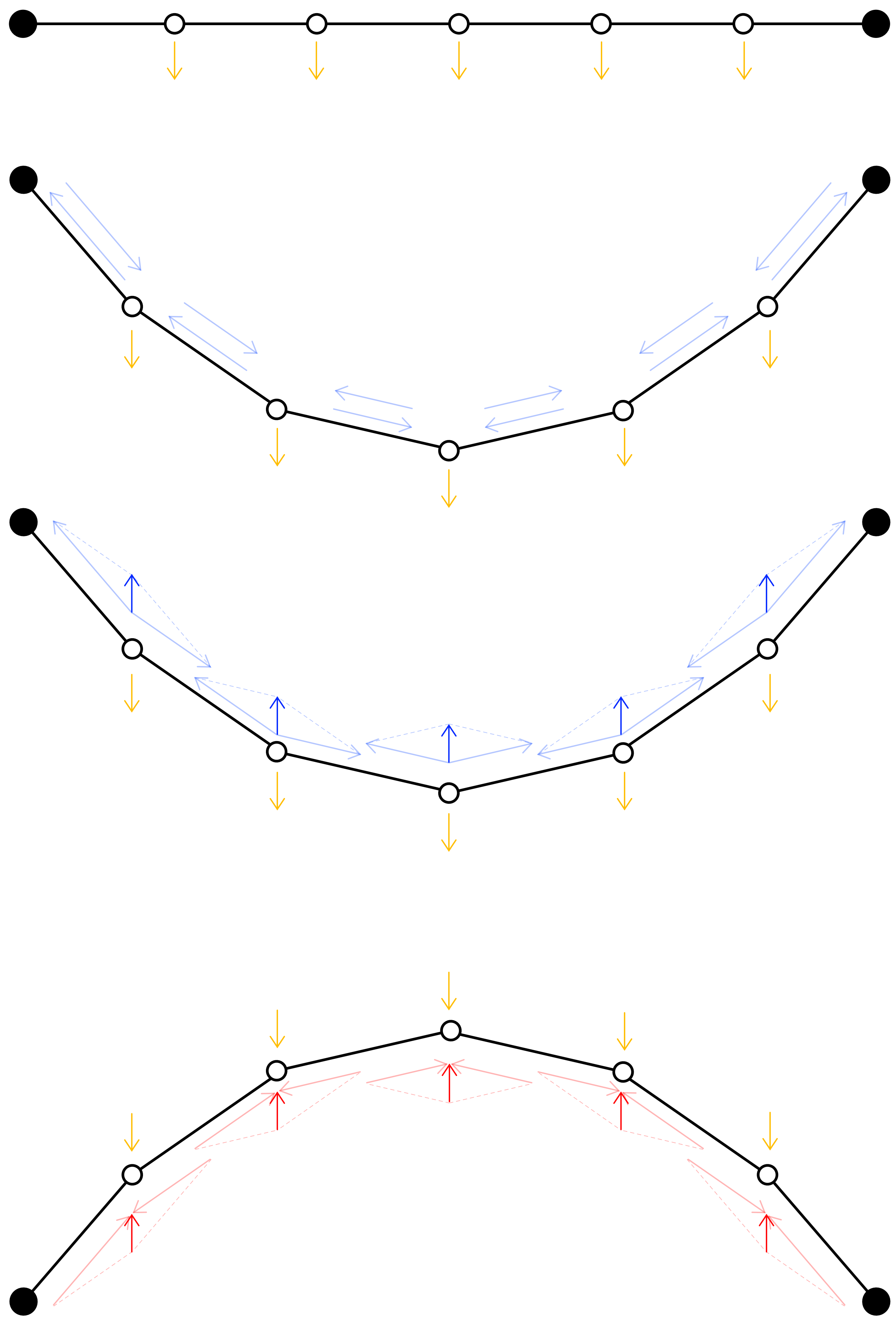
Block wooden mold

Hardened block
Batch F + blue dye

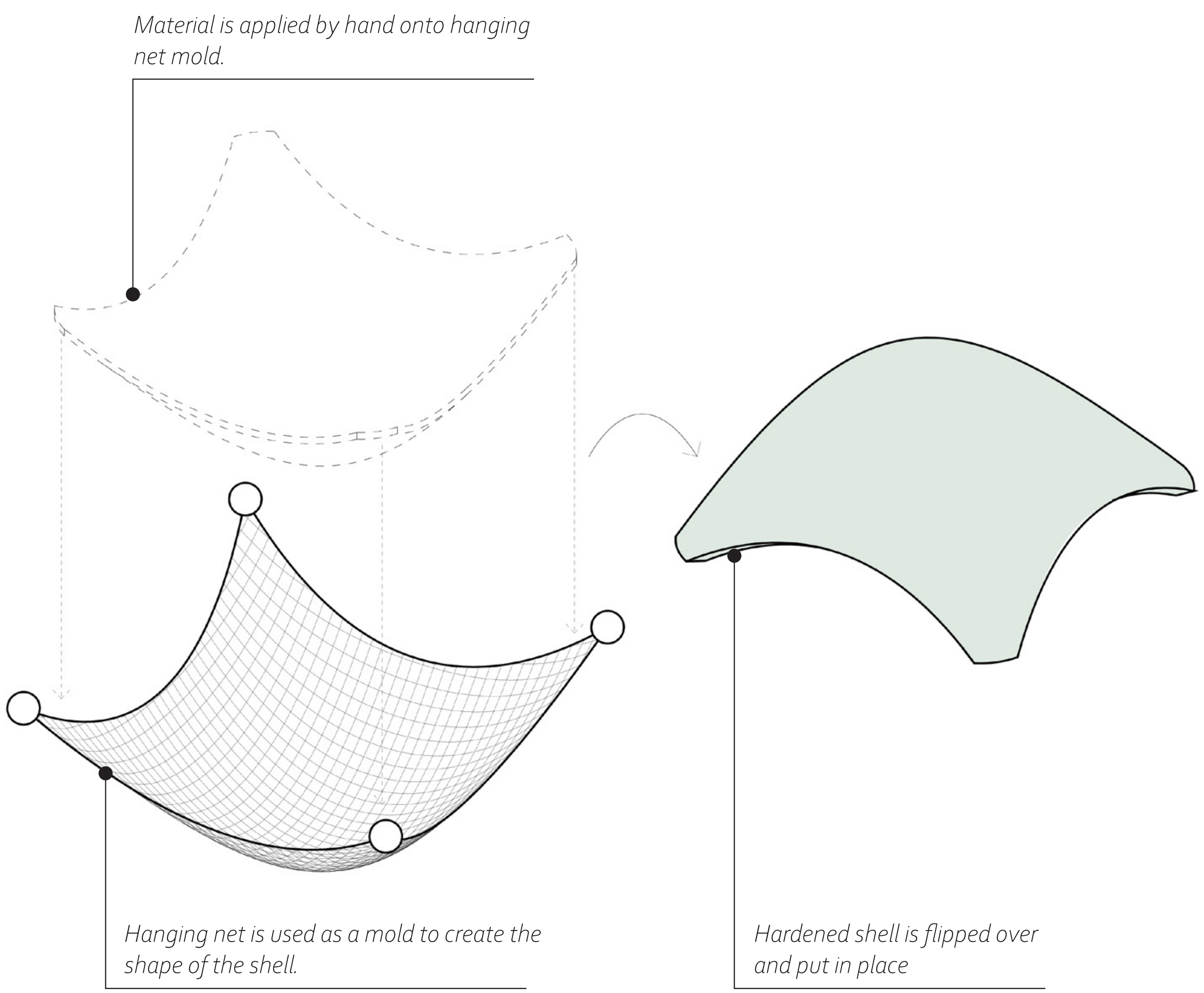
SHELL CONCEPT

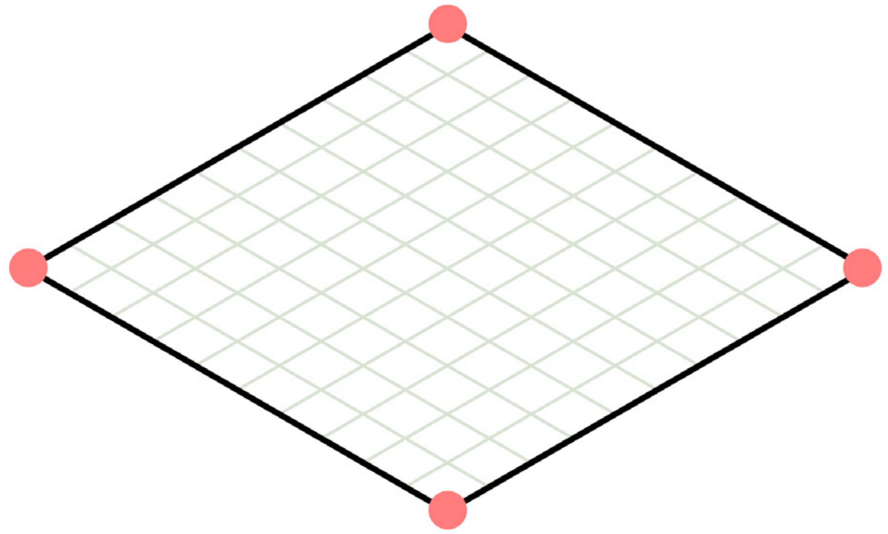
As mentioned above the roofing element will be constructed as a shell in pure compression as the material is weak in tension. The most straight-forward way of constructing a structure like this is to use a three dimensional catenary system. A catenary is a curve that represents the shape of a uniform chain fixed at both ends that is hanging freely under its own weight. Since the chain is unable to withstand any compressive loads the shape at equilibrium under the force of gravity will be purely in tension. If the shape is then mirrored on the axis perpendicular to the gravitational pull the forces will be shifted from tension to compression and the equilibrium state will instead be under pure compression. This is easily visualized through a simplified node diagram. Each node is under the influence of gravity (yellow force vector) and in tension with each adjacent node (blue force vector). The two tension vectors form a resultant with the same magnitude as the gravitational vector but with opposite direction, hence creating a state of equilibrium. When the shape is flipped upside down the nodes are now instead under compression (red force vector). Once again the resulting compression vectors add up to a resultant equal to the gravitational force in its opposite direction and the structure is in equilibrium.

The same principle can be used with catenaries in two directions to create a surface in pure compression. For the physical model however, instead of hanging chains a stretchy fabric will be used and the deformation will come from the weight of the added pulp. The digital model will be developed in Rhino 3D and grasshopper with the add-on Kangaroo 2. The add-on uses dynamic relaxation to calculate the surface based on an initial mesh, anchor points and a load vector on each vertice of the mesh.

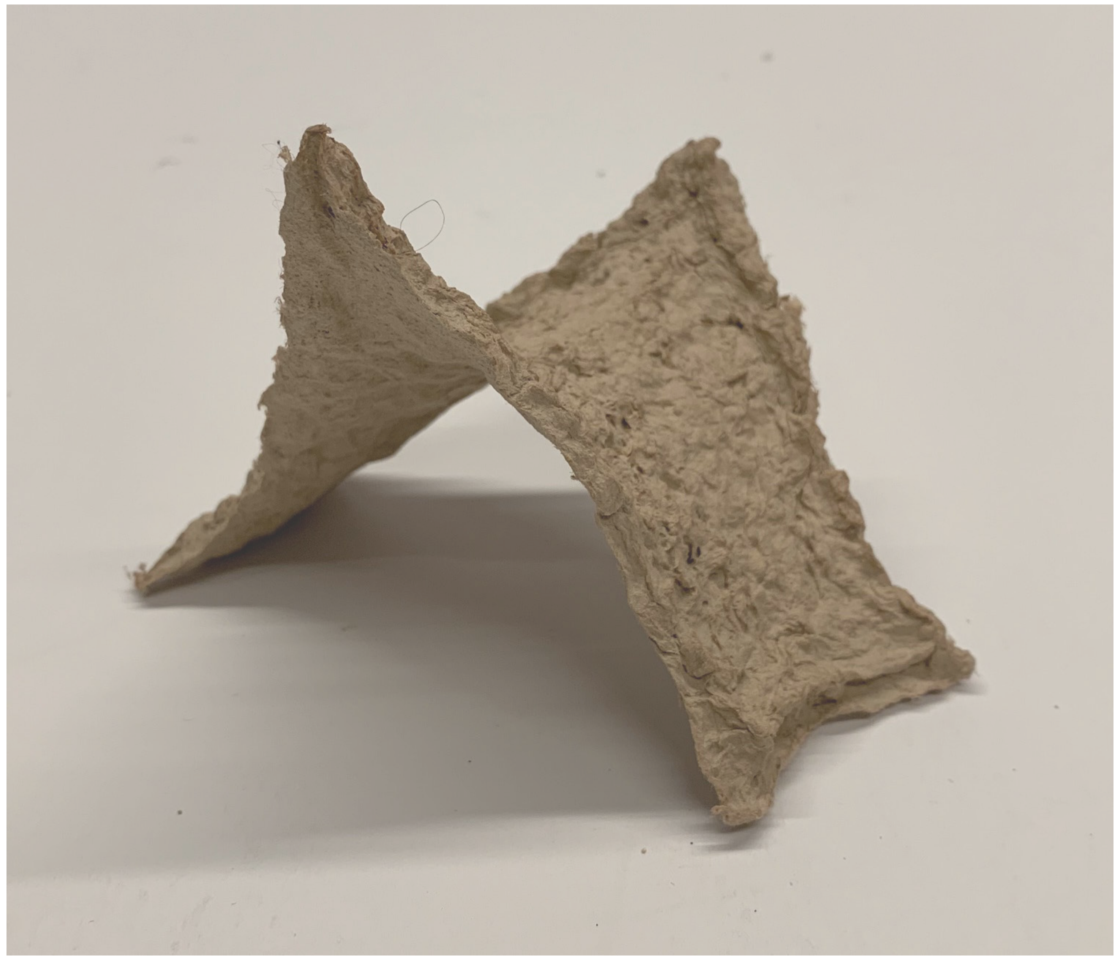


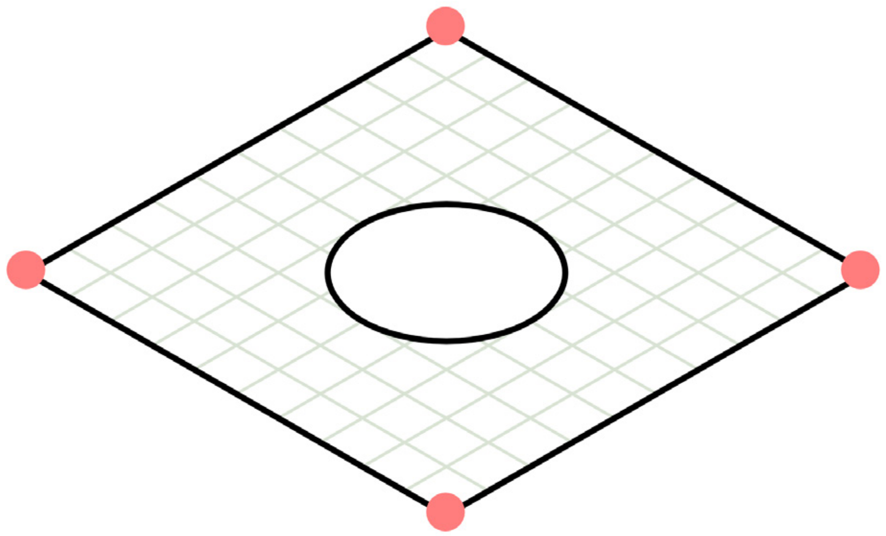
Chain node diagram



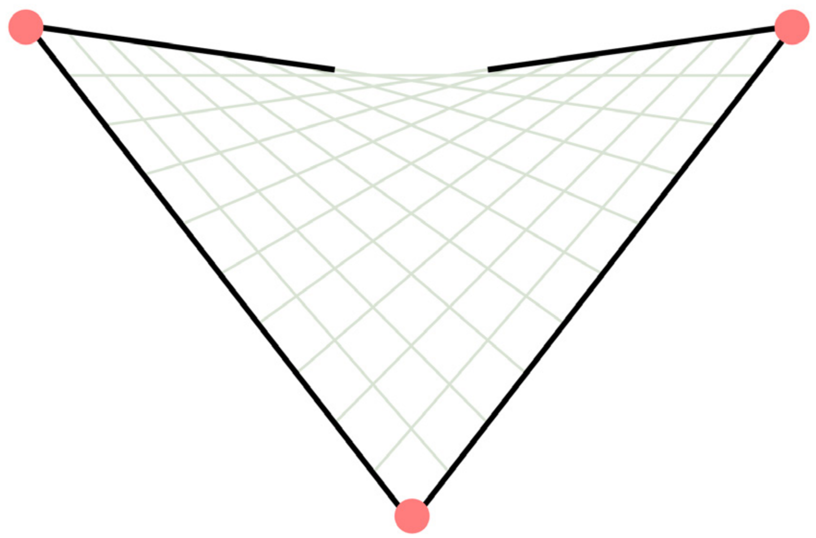


Mesh node diagram
Post tensioned





Mesh node diagram
Post tensioned



Mesh node diagram
Pre tensioned

PHASE II, REFLECTIONS

How can paper pulp be molded into building elements?

After working with the assembly and contextualization for a while it was obvious that this phase would have needed more time. From the initial time plan it was scheduled that at least 3 concepts of each element should be designed. Since each concept took longer than expected to properly work out, both digitally and physically, the choice was made to instead make one concept for each part of the building. This instead led to a less enriched palette of paper elements but also concepts that could be more thought through in full scale manufacturing. Another unexpected aspect was the representation of each element in the final design. Throughout the material studies most of the focus shifted towards the fully compressed method since this was thought of to be the most viable method of producing paper elements. During phase II it was found that the most adequate way to create some form of roofing over the building a shell had to be used. When this realization was made the focus shifted from working with fully compressed blocks to instead finding ways to properly design a shell with paper pulp. Ultimately the method landed in using a suspended stretchy fabric for the physical models and a plugin to Rhino that uses dynamic relaxation for the digital model.

The type of shell structures that are being investigated builds on an equilibrium of compressive forces in each section of the shell. This means that the greater the compressive forces are in the material, the smaller the impact of external loads will be in comparison. In other words the shell would need to have a great self weight in order to increase stability.

Based on the experiments that were done through manually applying pulp, batch G that consists of both clay and sand was found to generate the most self weight. However, additional filling material will most likely be added homogeneously over the shell to further increase its weight.

In digital space the design for pillars and wall blocks was untroubled since the focus was on architectural aesthetics. The physical models were a bit harder to realize. The wall blocks are meant to be stacked on top of each other which means that all units must be equal in height to ensure proper fitting. Since the mold is held together with hand tightened clamps it was next to impossible to get the same amount of pressure on each mold, which led to each element varying slightly in height. This was however solved by manually sanding away from parts that turned out to be taller in size. The height of the pillars was easier to control since material is added gradually and then rammed until the mold is full. The problem instead lied in the drying time since it was harder to squeeze out the water with this method. The next design iteration of this mold would include more ways for the water to escape during the ramming.

CONCLUSIONS

- *Wall blocks are manufactured with the fully compressed method and consist of the ingredients from batch F. When pressing the wall blocks it is hard to reassure the same height of all blocks. Therefore, manual fine tuning will be done in post production.*
- *Pillar elements are manufactured with the partially compressed method and consist of the ingredients from batch I. The pillars requires more time to fully dry out compared to wall blocks since not as much water is extracted from the material during the ramming process.*
- *The shell structure are manufactured from manually applying pulp to a layer of stretched fabric and will consist of the ingredients from batch G. For the full scale model a falsework would have to be used since the structure would be too big to be manufactured upside down and then flipped over.*

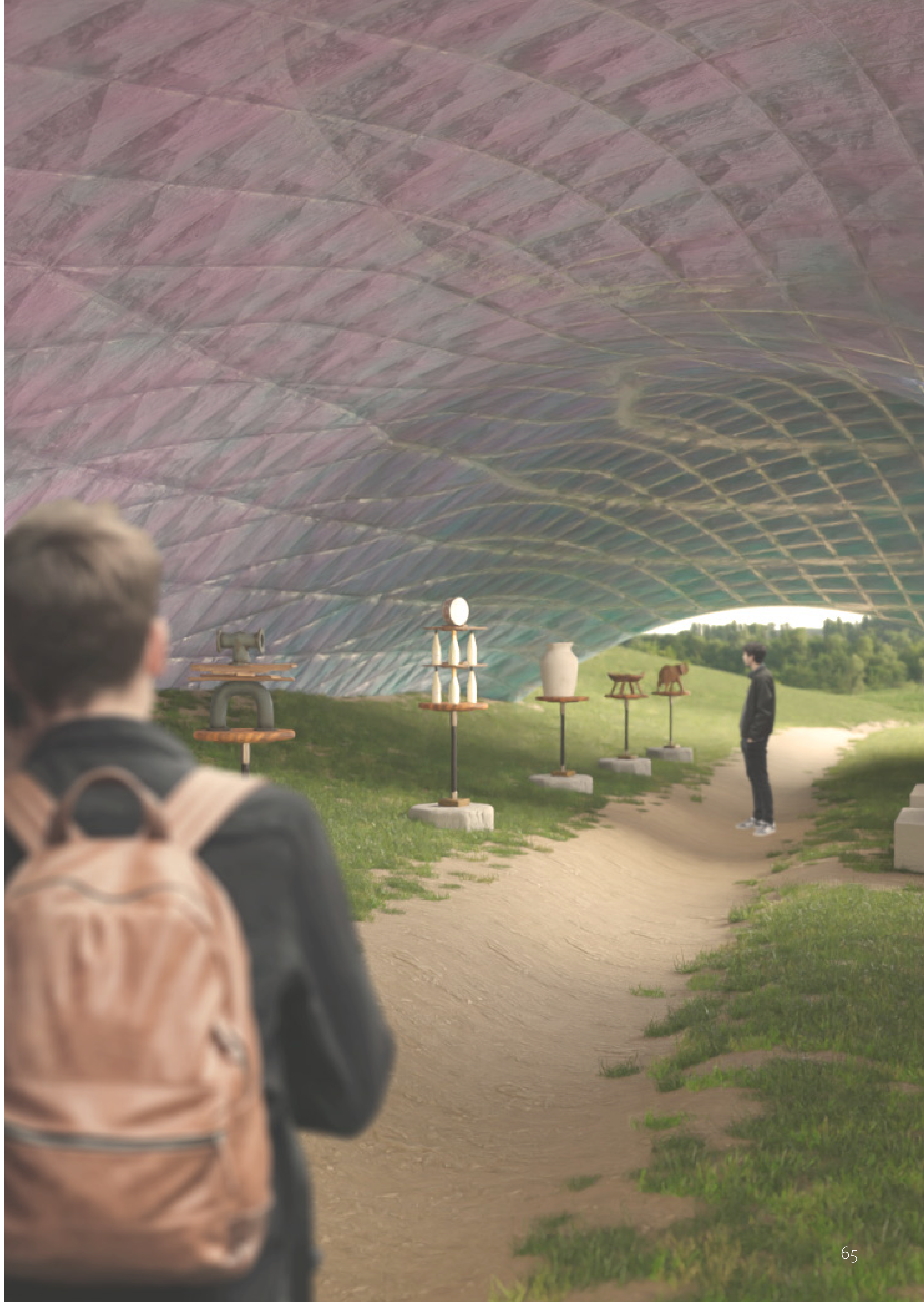
PHASE III

BUILDING DESIGN

The core of this thesis is to investigate how far one could take the concept of upcycling a waste material like paper and turning it into architecture. Since we are already living beyond our limited resources it is of great importance that we can recycle and reuse what we already have to the greatest extent. Thus to further connect this project to the concept of recycling, a plot called Kretsloppsparken in Alelyckan, Gothenburg has been chosen as the proposed building site. In addition to the return stations Kretsloppsparken also has three different second hand stores for building materials, appliances and household items. Here people come to find everything from recovered doors and windows to bathroom tiles and electronics.

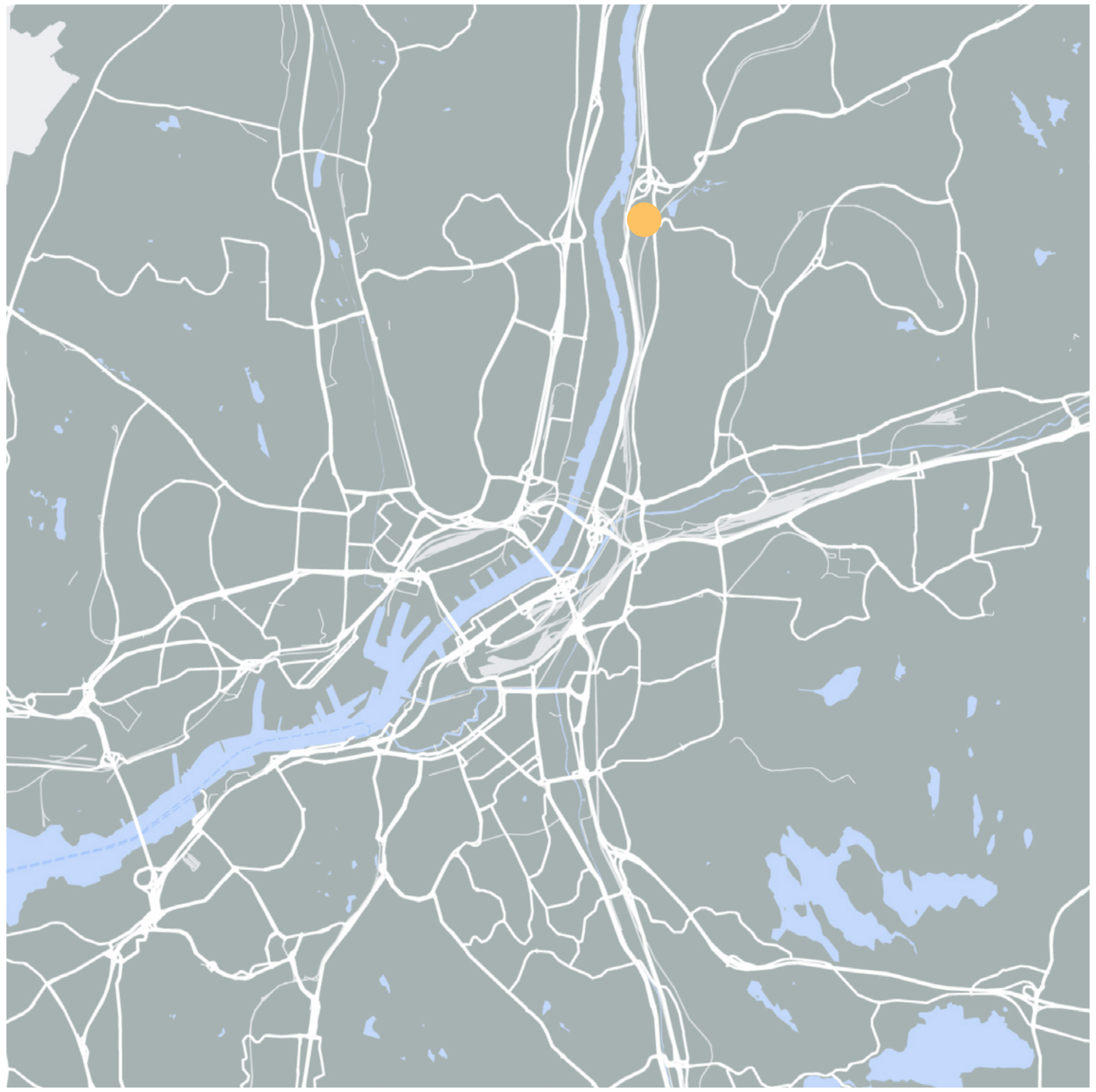
The building will work as an extension to the existing buildings on the plot with a focus on combining recycling and art. The idea is to organize an art workshop on the lower level of the building where people can collect litter in the area and turn it into sculptural pieces. The workshop have workspaces integrated into the walls or working benches made from paper pulp blocks. The area also have a set of light weight pulp blocks that can be used as movable walls to create a desired work space depending on the amount of people in the building. The upper level is the exhibition space for the junk sculptures. Podiums are placed alongside the walk path where bypassers can look at and be inspired by the artworks.

In the smaller models it was fairly easy to flip the hardened shell upside down. In the full scale production however it is not possible to flip the shell upside down without damageing it. Instead a wooden falsework is constructed at the site in the shape of the shell which is then covered with a fabric. When the fabric is fitted onto the falsework, pulp is manually applied or sprayed on in layers. Once the shell has hardened additional pulp is added to further sculpt the shape of the shell and add detail.

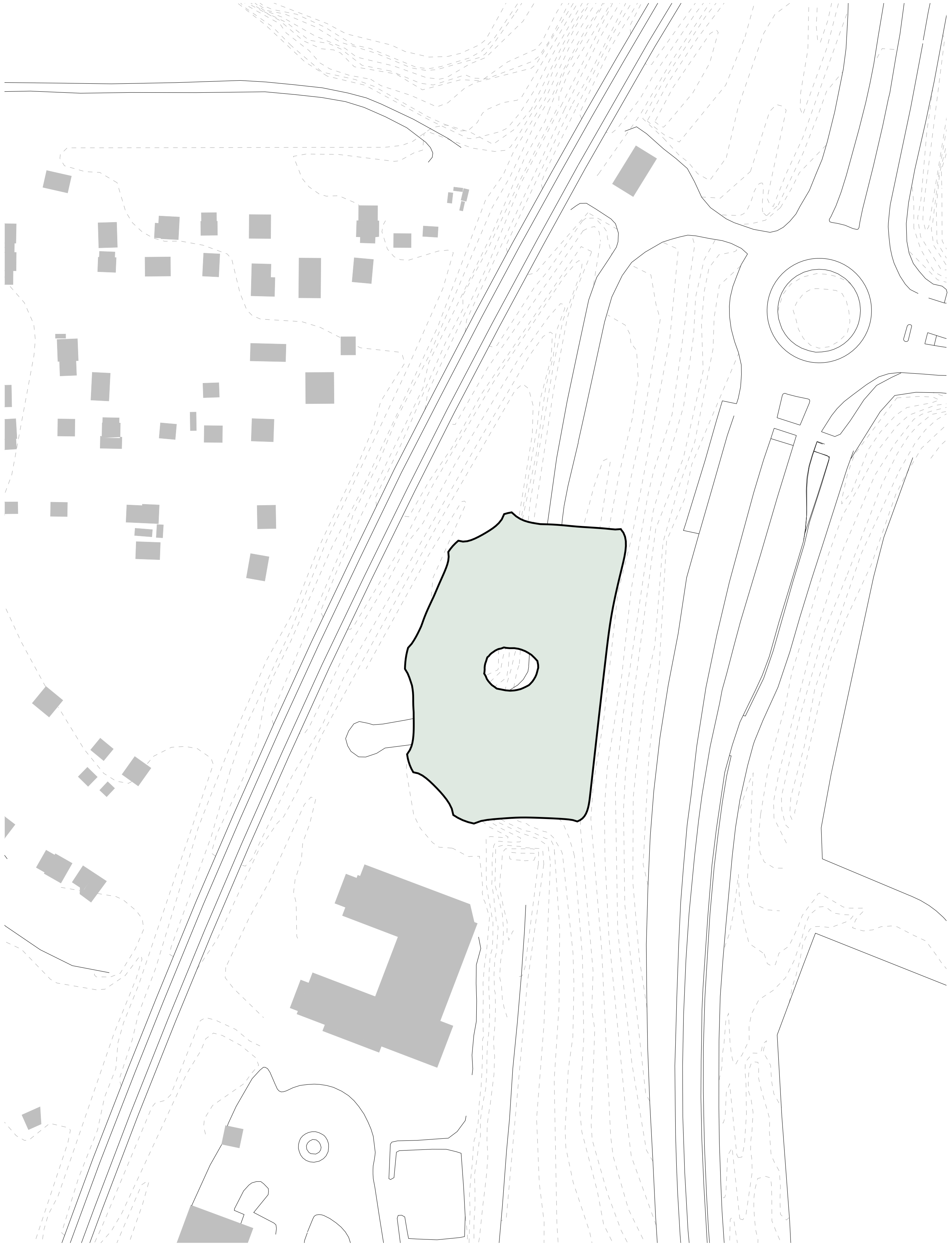


SITE ANALYSIS

The proposed site lies just on the outskirts of the area. A pathway to the nearby train station runs along the site, with a trafficked road to the west and a view over a nearby allotment area to the east. The proposed building will be built over the existing path to enhance the space and make use of the natural flow of people passing by. This is done by sheltering the walkway from noise from the road while at the same time framing the view to the east. Plenty of openings allow for daylight to enter the otherwise large shell. A raised platform is placed in the middle of the site where parts of the shell can anchor onto and create an opening to the east to let plenty of indirect sunlight into the building. The terrain on site has two distinct plateaus that are emphasized by leveling out the ground and placing a retaining wall between them. To connect the two plateaus stairs are placed alongside the platform.

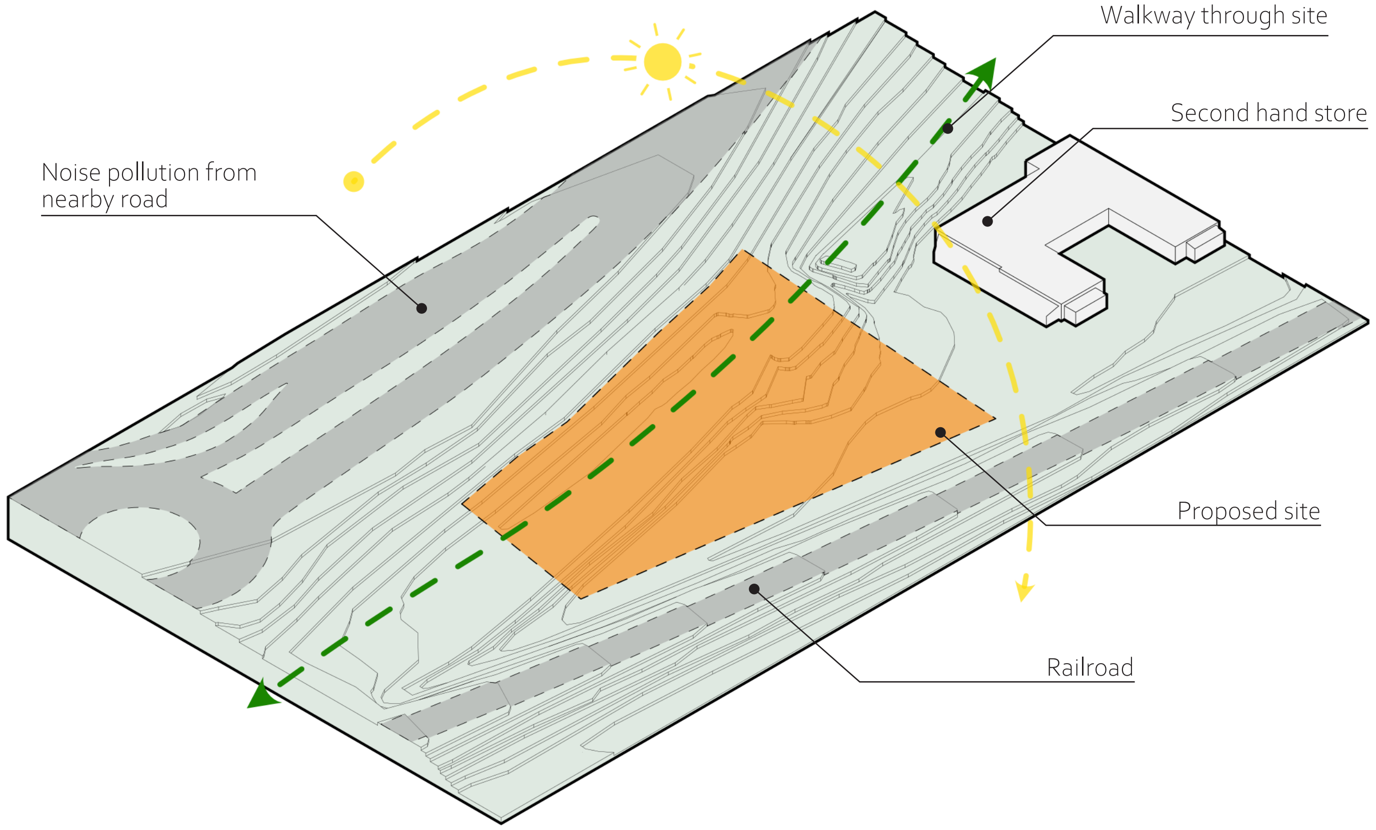


Gothenburg overview

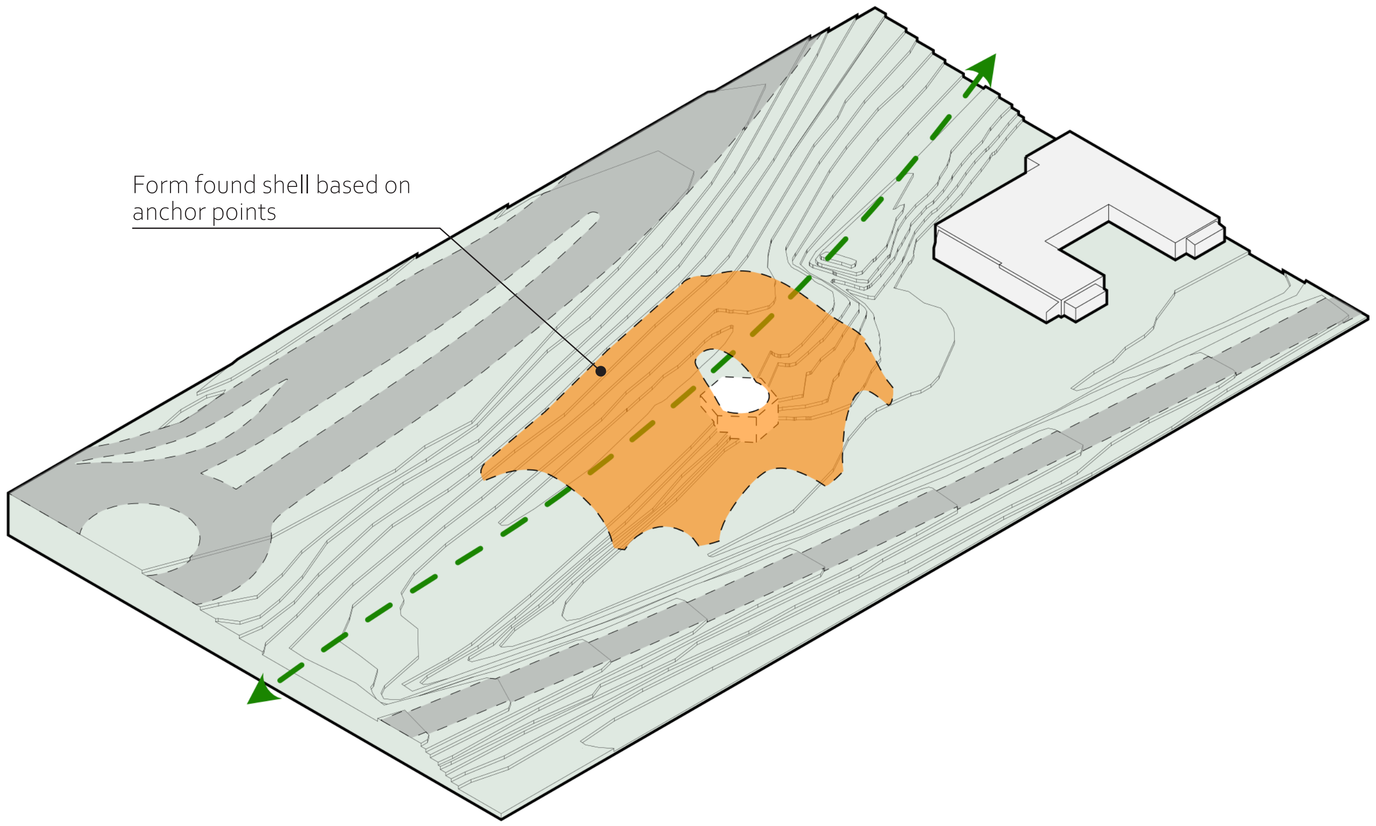


Situation plan

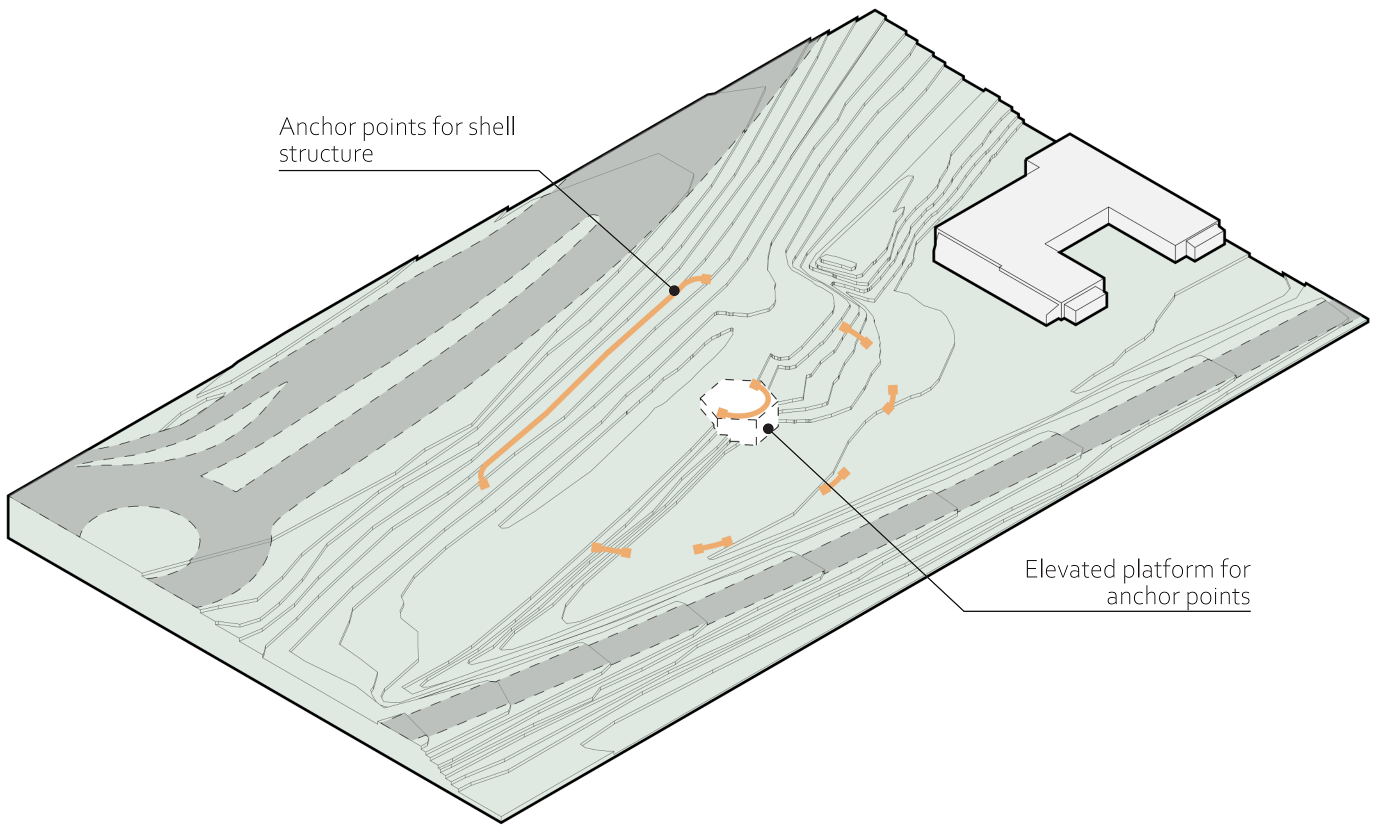
1:1000



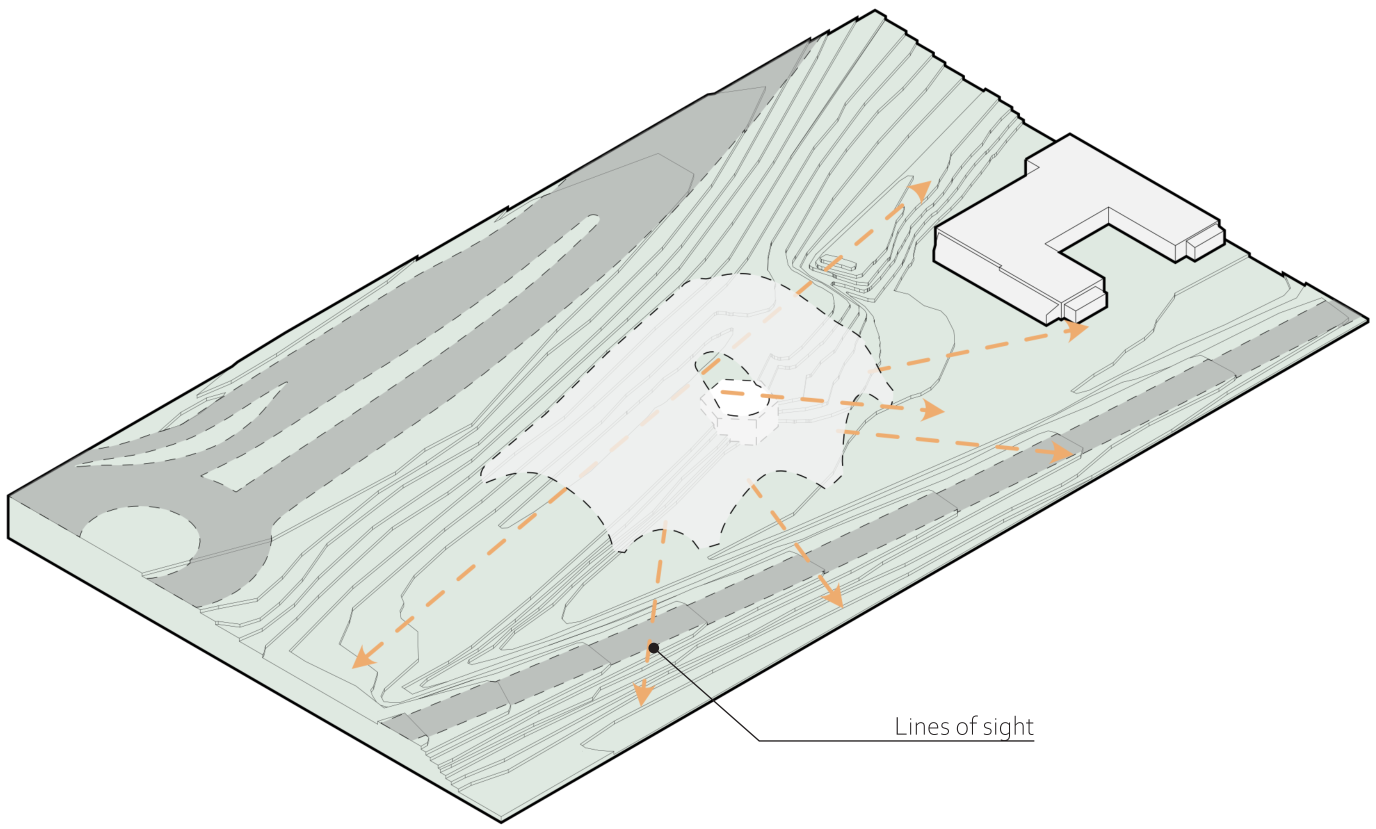
Site diagram
Sun path, infrastructure, proposed site



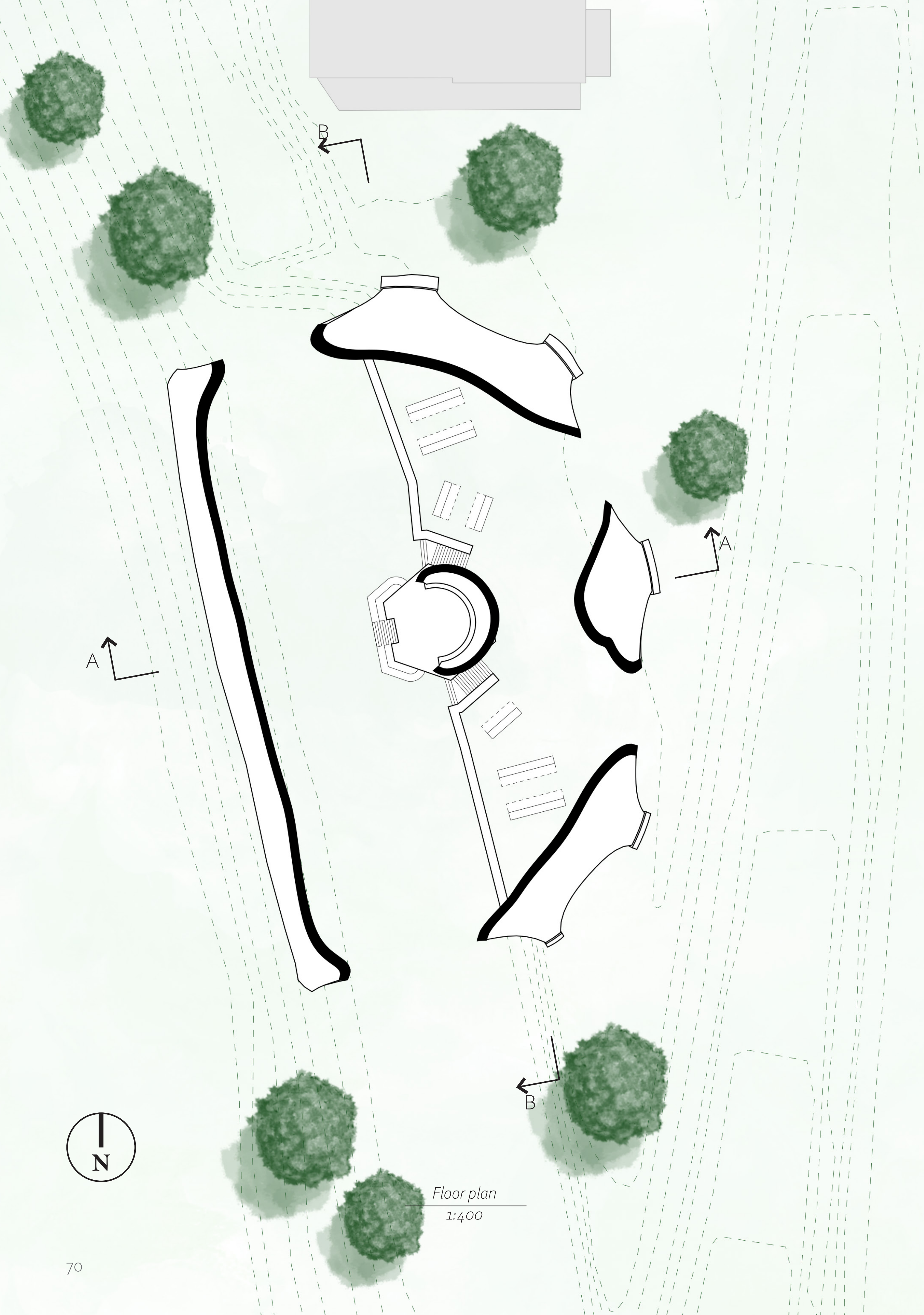
Site diagram
Shape of shell structure



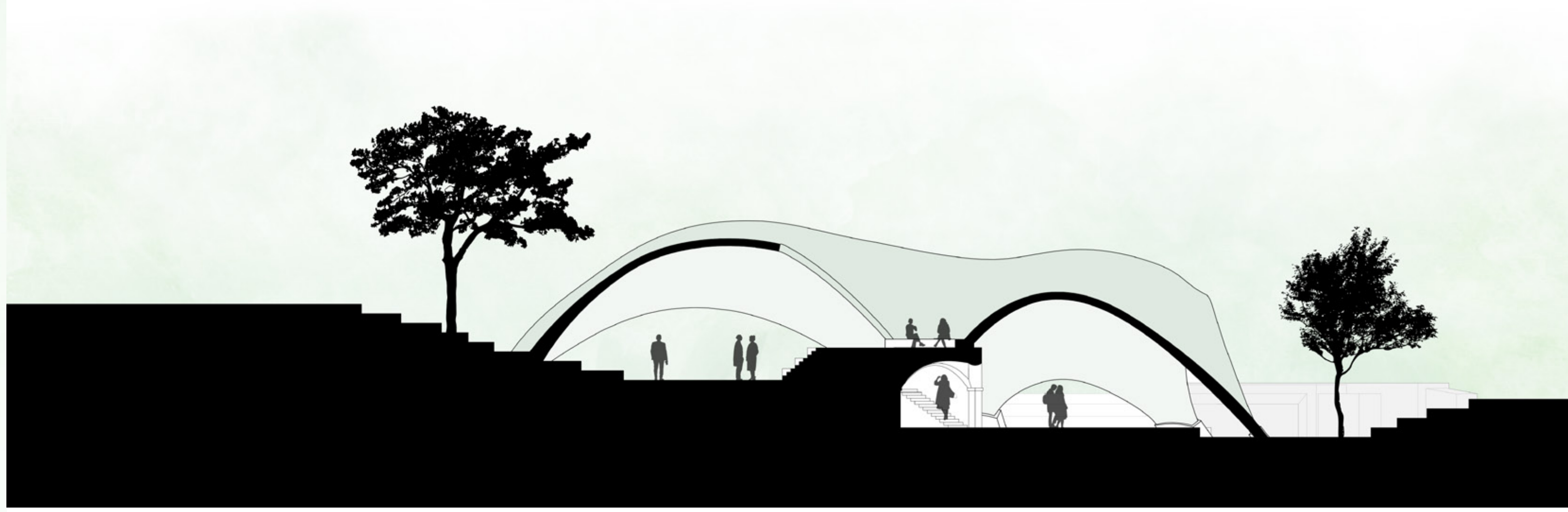
Site diagram
Anchor points



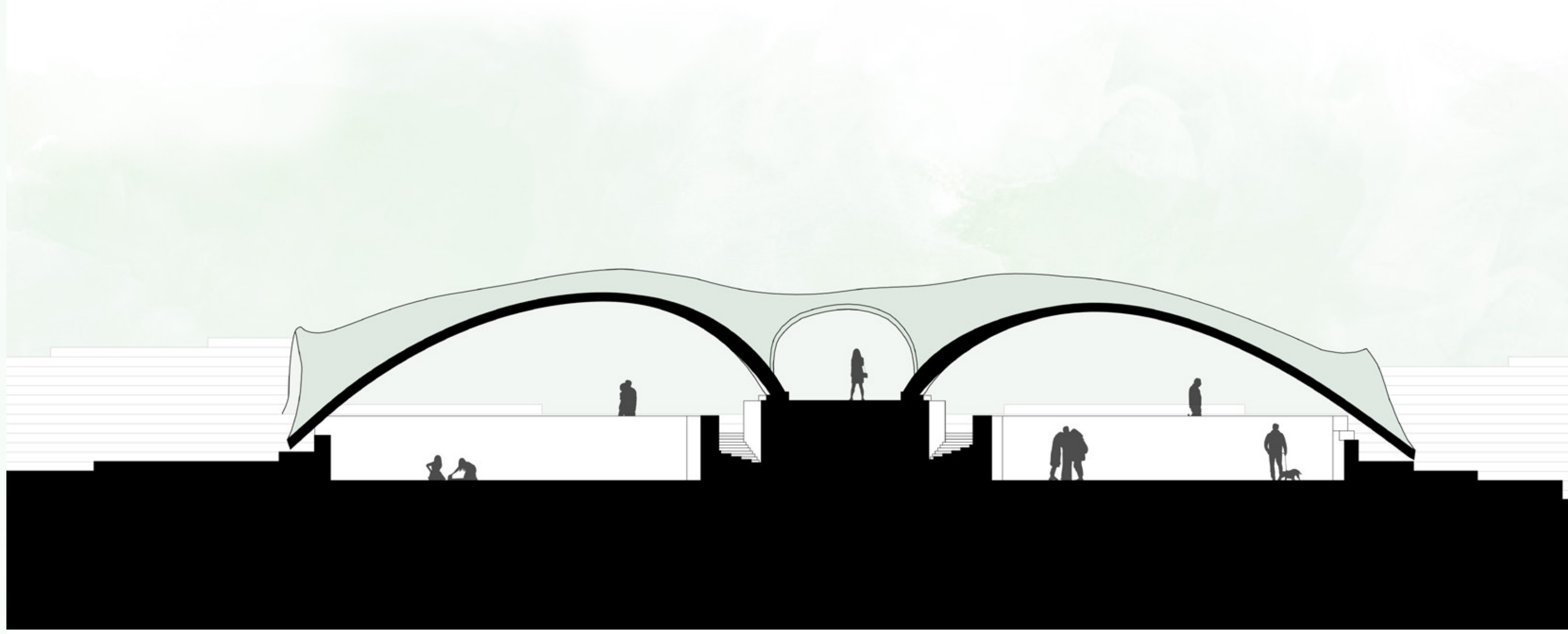
Site diagram
Lines of sight



Floor plan
1:400



Section A-A
1:400



Section B-B
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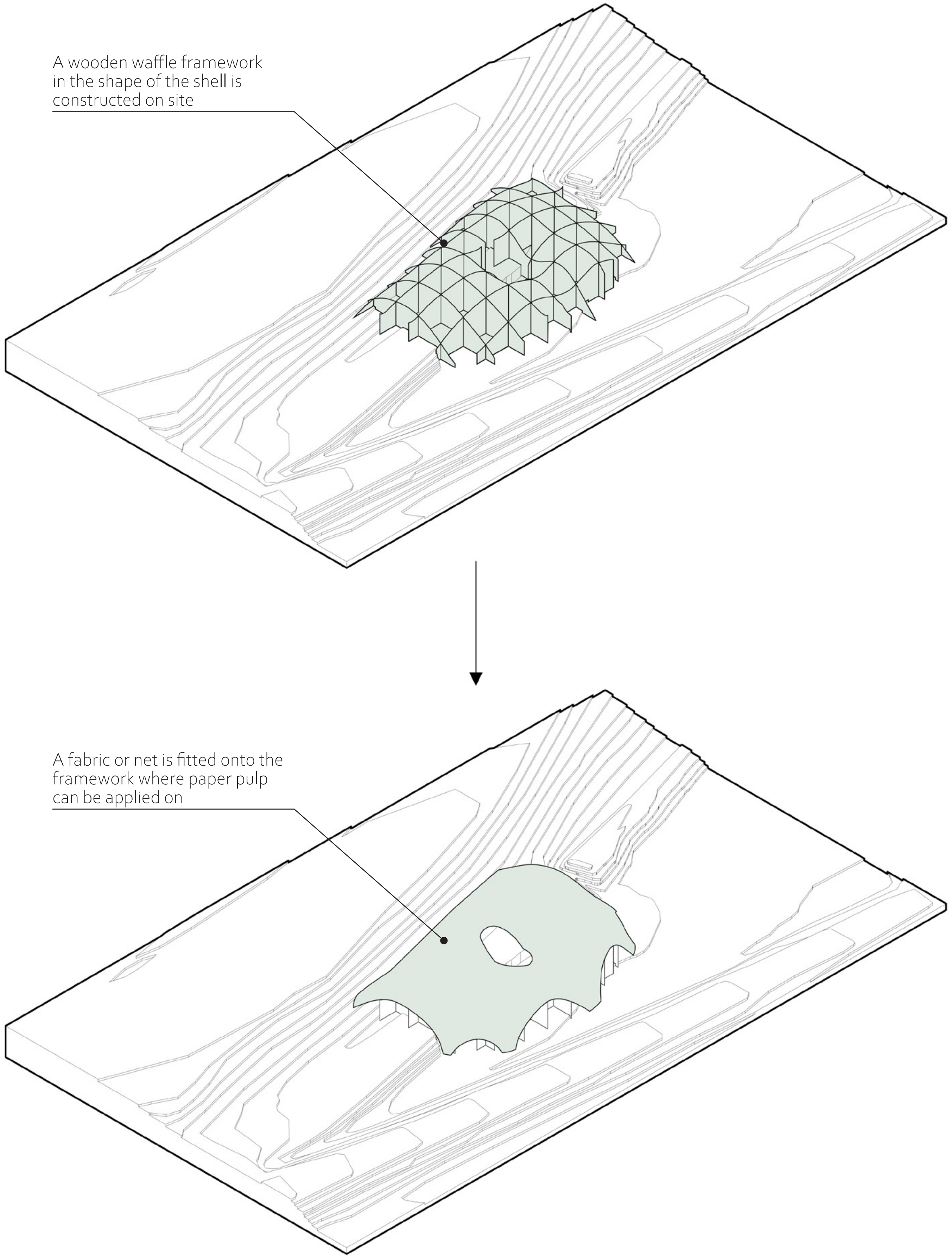
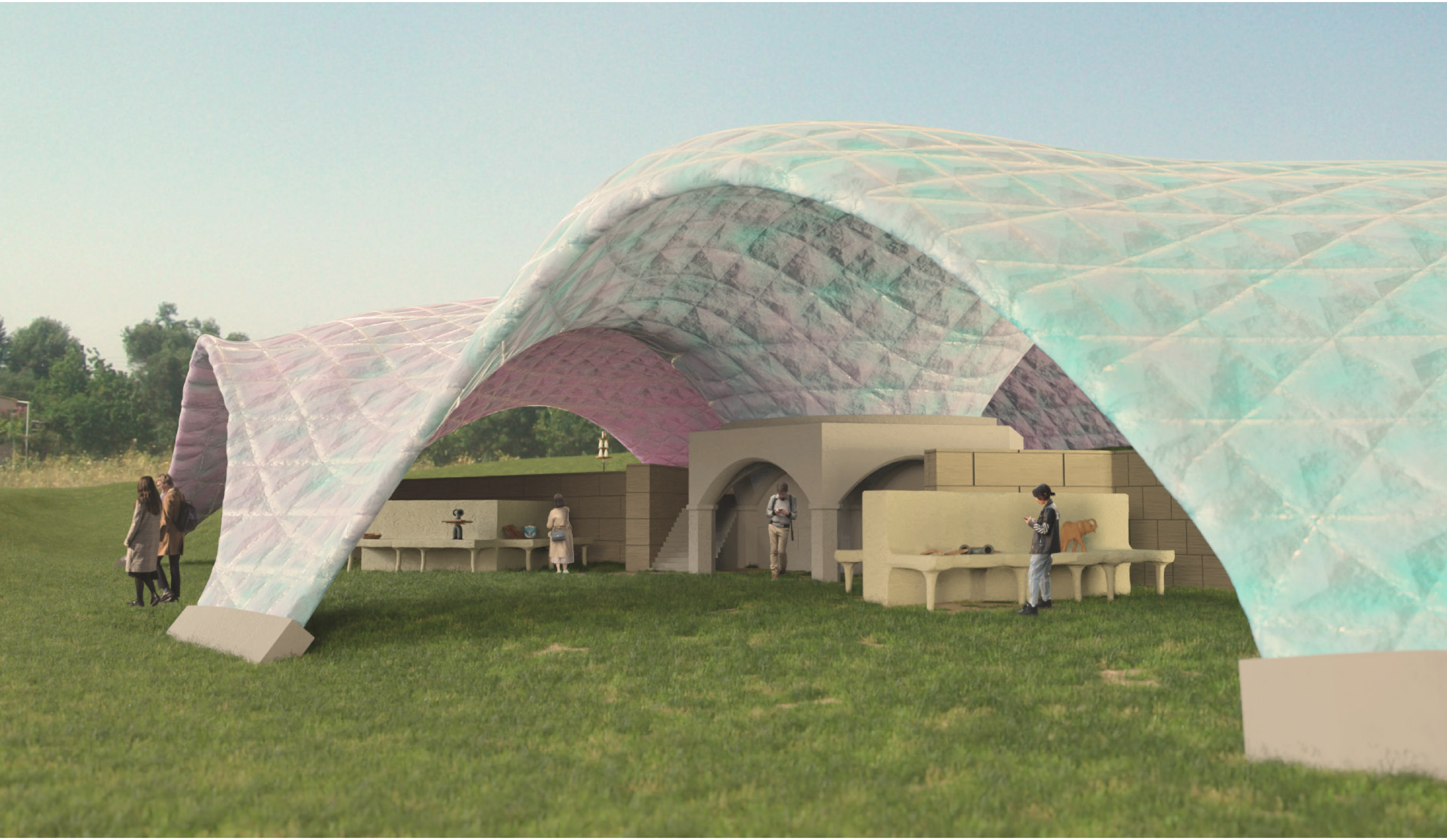
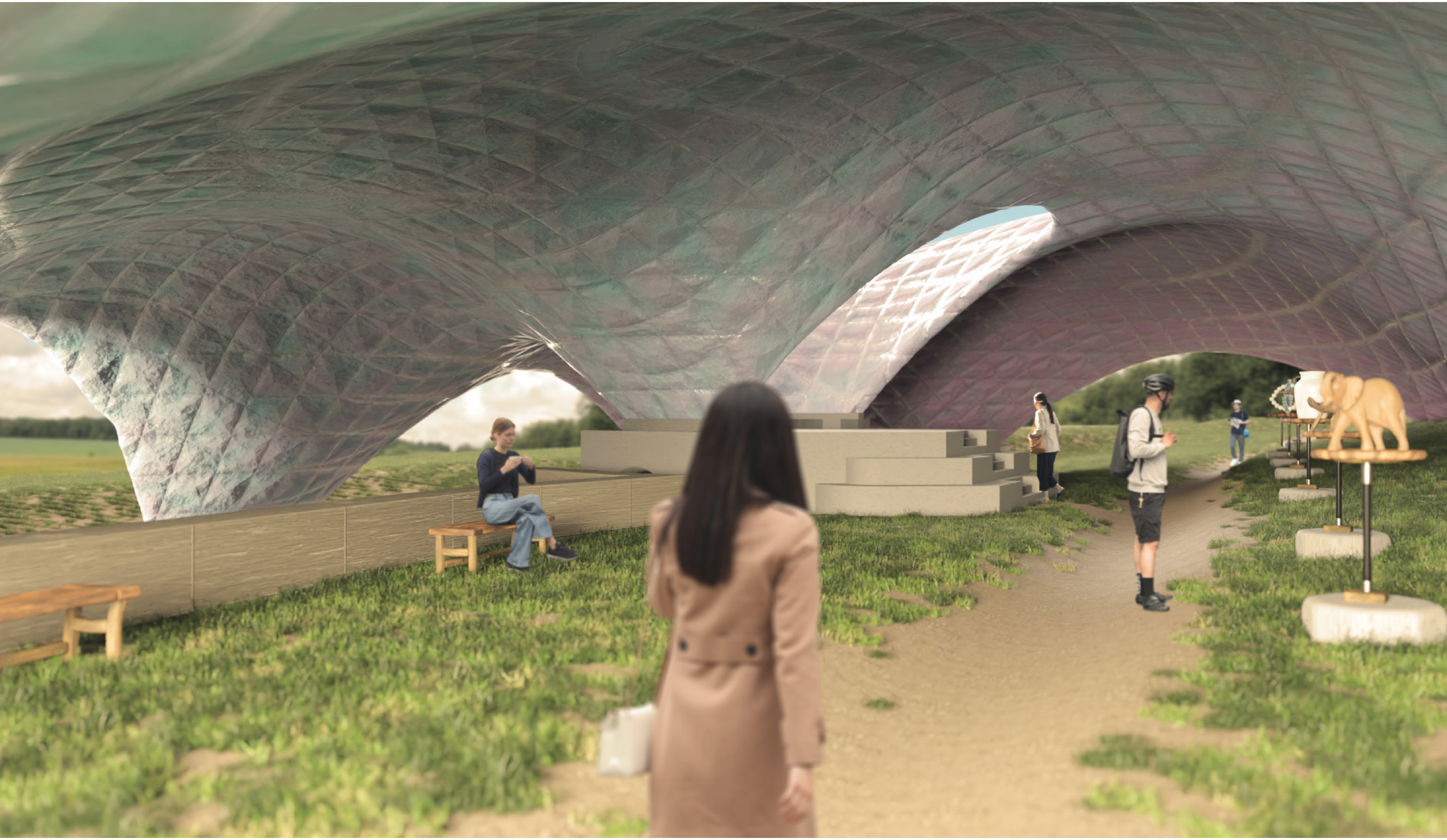


Shell assembly

Physical model





PHASE III, REFLECTIONS

How would a building made from these elements be designed?

Based on the learning from phase I and phase II it was found that there are many different answers to this question. Even though it would be interesting to explore several alternatives for building designs, the limited timeframe restricts this thesis to only one proposal.

The biggest challenge was to create some sort of roofing while at the same time taking into consideration the structural limitations of the material. That means that no long spanning beams or trusses can be used as these would have to be rather large to withstand bending moment. One solution could have been to work with barrel vaults or cross vaults to generate roofing. These methods would however limit the degree of freedom of the design to one or two directions whereas the shell can bend and curve in almost any direction. One disadvantage of the shell compared to the vaults can be found during the construction phase. A large amount of wooden falsework would have to be produced and assembled on the site which both extends construction time and would most likely be more costly. The vaults on the other hand could be constructed in smaller pieces and be put together by hand like brickwork.

It was found early in the building design process that the shell needed to cover the whole area in order to limit the amount of elements that would be exposed to rain. From that decision most of the design work was put into developing the shell in order to get the desired spatial qualities and architectural expression. This led to a shift in focus towards the shell structure and less on the fully compressed blocks that initially were thought of to have the most potential as building elements. The consequence of this decision was that the main part of the building did not have time to fully develop in terms of details and ornamentation. Instead more time was put into placing openings, framing views and responding to the site and landscape. The fully compressed blocks and pillar became more of a secondary structure in the design. Instead of encapsulating spaces they accentuate what is already there and contribute to the resolution of the building.

Another aspect that needs to be considered when working with paper in architecture is how to waterproof the structure. Even though some progress was made in finding ways to waterproof the building further research needs to be done in this area. The additives used in the material studies did not satisfy the expected level of water resistance which resulted in the use of surface treatment instead.

CONCLUSIONS

+ *There are numerous strategies to design a building with paper elements. The shell was chosen as a way to work with the structural limitations of the material while at the same time maintaining design freedom.*

+ *The fully compressed blocks and pillars are used to define the spaces created by the shell rather than generating spaces on their own.*

+ *In further research it would be worthwhile to find an alternative to surface treatment as a way of waterproofing the paper elements.*

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APPENDIX

MATERIAL STUDIES

EXPERIMENTS OVERVIEW

Batch A
Ingredients:
+ *25 grams of cardboard*
+ *30 grams of PVA-glue*

Production method:
+ *Fully compressed*
+ *Printed*

Batch B
Ingredients:
+ *25 grams of paper bags*
+ *100 grams of clay*

Production method:
+ *Fully compressed*
+ *Partially compressed*

Batch C
Ingredients:
+ *25 grams of paper bags*
+ *25 grams of PVA-glue*
+ *50 grams of clay*

Production method:
+ *Partially compressed*
+ *Manually applied*

Batch D
Ingredients:
+ *25 grams of paper bags*
+ *35 grams of corn starch*
+ *100 grams of clay*

Production method:
+ *Fully compressed*

Batch E
Ingredients:
+ *25 grams of white paper*
+ *35 grams of corn starch*
+ *200 grams of clay*

Production method:
+ *Fully compressed*
+ *Printed*

Batch F
Ingredients:
+ *25 grams of grey cardboard*
+ *25 grams of PVA-glue*
+ *50 grams of sand (fine)*

Production method:
+ *Fully compressed*
+ *Partially compressed*
+ *Manually applied*

Batch G
Ingredients:
+ *25 grams of grey cardboard*
+ *100 grams of clay*
+ *50 grams of sand (fine)*

Production method:
+ *Partially compressed*
+ *Printed*
+ *Manually applied*

Batch H
Ingredients:
+ *20 grams of white paper*
+ *10 grams of green paper*
+ *50 grams of clay*
+ *150 grams of sand (fine)*

Production method:
+ *Printed*

Batch I
Ingredients:
+ *20 grams of white paper*
+ *15 grams of red paper*
+ *35 grams of PVA- glue*
+ *100 grams of sand (coarse)*

Production method:
+ *Fully compressed*
+ *Partially compressed*

Batch J
Ingredients:
+ *30 grams of white paper*
+ *30 grams of PVA- glue*
+ *100 ml of liquid latex*

Production method:
+ *Fully compressed*

EXPERIMENT A1

Tactility	Smooth, paper like	**Fire resistance**	Poor
Texture	Uniform	**Water resistance**	Poor
Density	Semi light	**Compression**	Flexible

Ingredients
- *25 grams of cardboard*
- *30 grams of PVA-glue*

Production method
Fully compressed (cylindrical mold)

Motive
This experiment tested the metod of compressing cardboard by only using the basic ingredients; cardboard and binder. The sample mainly serves as a benchmark for later experiments. A second sample was also made from the same batch but with thin layers of fabric built into it as reinforcement.

Expectations
A solid, dense piece of compressed material with a smooth and wood-like texture. The sample with fabric reinforcement will hopefully be able to withstand a higher load as the fabric creates friction within the material

Result
The finished product had a smooth surface that felt more like paper than wood and rather than being dense the material turned out light and airy. The sample without fabric shrunk about 12% in height and 6% in diameter after 4 days of drying in room temperature while the reinforced sample only shrunk about 10% in height and 2% in diameter. The material was put in the hydraulic press to see how it reacts to a compressive load of around 1200 kg/cm². Instead of breaking or cracking the material demonstrates plastic properties by compacting gradually as the load increases, resulting in a denser material with a glossier surface. The reinforcement did not seem to have any impact on the materials compressive strength.

Possible uses
- The material could work as a building block for moavble walls.
- In addition the material could be used for decoration or furniture.

EXPERIMENT A2

Tactility	Soft	**Fire resistance**	Very poor
Texture	Scattered	**Water resistance**	Poor
Density	Very Light	**Compression**	Semi flexible

Ingredients
+ *25 grams of cardboard*
+ *30 grams of PVA-glue*

Production method

Printed

Motive

This experiment tested the metod of "3d-printing" with cardboard pulp to see if it is a viable way of working with pulp. Additive manufacturing in this sense could be a way to create more complex geometries that can not be achieved with a pressing mold.

Expectations

A free-form geometry generated by layers of pulp. Since this is the first iteration of the printing method a primitive shape like a square will be extruded vertically to create an open cube.

Result

Nothing went as expected. Even though the pulp was mixed thoroughly it still clumped up making it hard to evenly apply in layers. The amount of water it takes to find the right consistency was hard to approximate. Too much water led to the layers falling apart and too little made it hard to extrude anything at all as the material got stuck in the container. Although the result might not be as neat as expected it still has some visual qualities in its seemingly incoherent surface. The rough surface reminds of a cave wall and creates some interesting shadows when lit up in the right position.

Possible uses
+ The material could work as an interior rendering element to create interesting wall surfaces or decorate other pulp elements.

EXPERIMENT B1

Tactility	Smooth, paper like	**Fire resistance**	Semi poor
Texture	Semi scattered	**Water resistance**	Poor
Density	Semi light	**Compression**	Flexible

Ingredients
+ *25 grams of paper bags*
+ *100 grams of clay*

Production method

Fully compressed (stackable mold)

Motive

This experiment tested the presence of clay in the pulp to observe its impact on tactility and fiber bonding.

Expectations

The hypothesis is that the clay will mix with the fibers and bind them together once it has hardened, thus giving the sample a ceramic tactility.

Result

The clay seems to have some binding ability but not as good as the PVA-glue. The surface had a smooth feel to it just like in experiment A1 and felt more like paper than a ceramic piece.

Possible uses
+ Could work as a movable wall because of its light weight.

EXPERIMENT B2

Tactility	Smooth	**Fire resistance**	Poor
Texture	Scattered	**Water resistance**	Poor
Density	Light	**Compression**	Flexible

Ingredients
- *25 grams of paper bags*
- *100 grams of clay*
- *Fabric reinforcement*

Production method

Partially compressed

Motive

This experiment tested out the impact of clay and layered fabric reinforcement in the partially compressed production method.

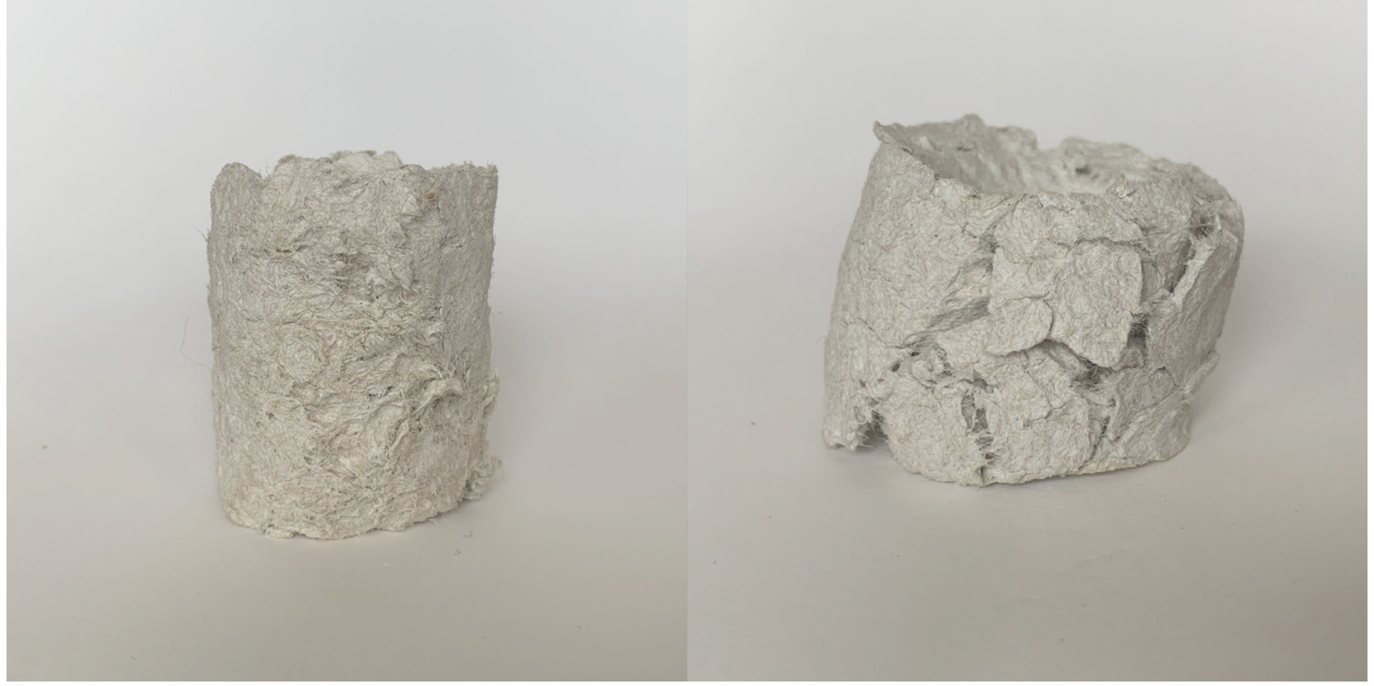
Expectations

The fabric layers will hopefully generate a higher friction between the layers of pulp and reduce cracking in the material during axial load.

Result

The sample without fabric layers turned out smooth and uniform while the reinforced one got separated between the layers. However the fabric did help the sample to not crack during axial load. The unreinforced sample cracked in bigger chunks instead of compacting like the experiment A1.

Possible uses
- Due to not being able to withstand any axial load without big deformation or cracking the sample will not be useful.



EXPERIMENT C1

Tactility	Smooth	**Fire resistance**	Poor
Texture	Uniform	**Water resistance**	Poor
Density	Light	**Compression**	Flexible

Ingredients
+ *25 grams of paper bags*
+ *25 grams of PVA-glue*
+ *50 grams of clay*

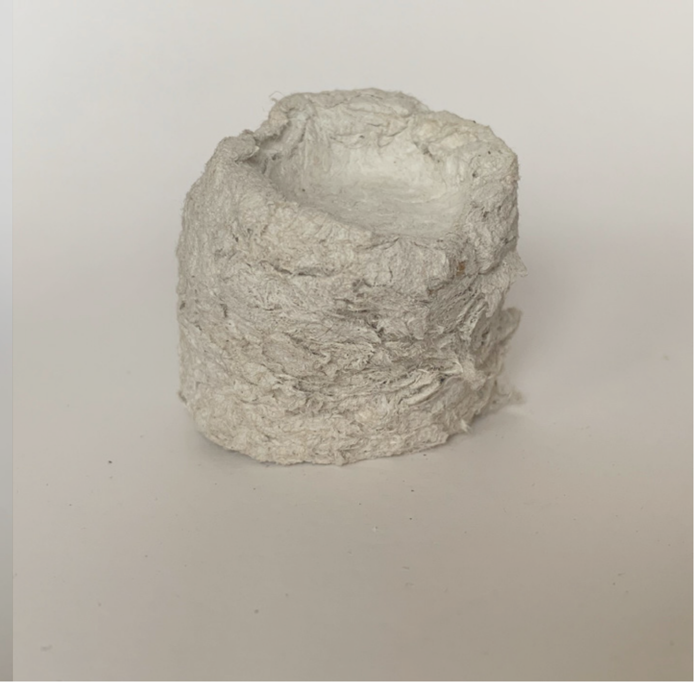
Production method
Partially compressed

Motive
This experiment tested out the presence of clay in combination with PVA-glue as well as a wrapping layer of fabric reinforcement.

Expectations
The glue will most likely help with the binding of fibers and the reduced amount of clay may cause the sample to not crack as much as experiment B2. In addition to this the wrapped fabric might reduce axial deformation as the fabric will hold the piece together.

Result
The glue helped to generate a stronger material and the small cracks resemble the tearing of paper more than the cracking of a ceramic piece. The fabric did have some impact on the samples compressive strength as it did not deform as much. Small cracks can also be seen underneath the fabric that are not as severe as in the unreinforced piece.

Possible uses
+ Due to not being able to withstand any axial load without big deformation or cracking the sample will not be useful.


EXPERIMENT C2

Tactility	Smooth, paper like	**Fire resistance**	Poor
Texture	Semi scattered	**Water resistance**	Poor
Density	Semi light	**Compression**	Brittle

Ingredients
+ *25 grams of paper bags*
+ *25 grams of PVA-glue*
+ *50 grams of clay*

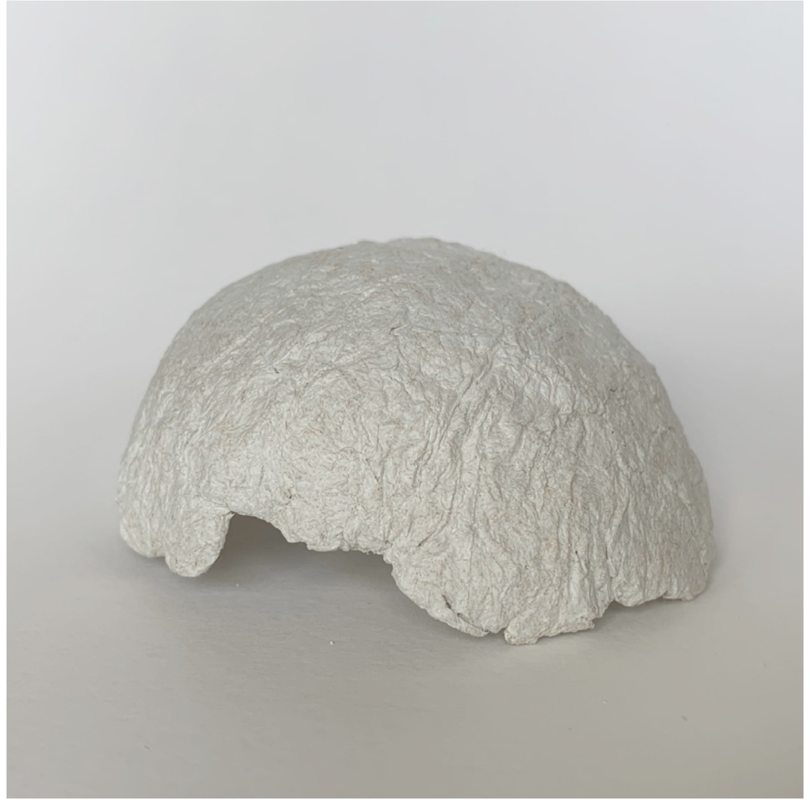
Production method
Manually applied

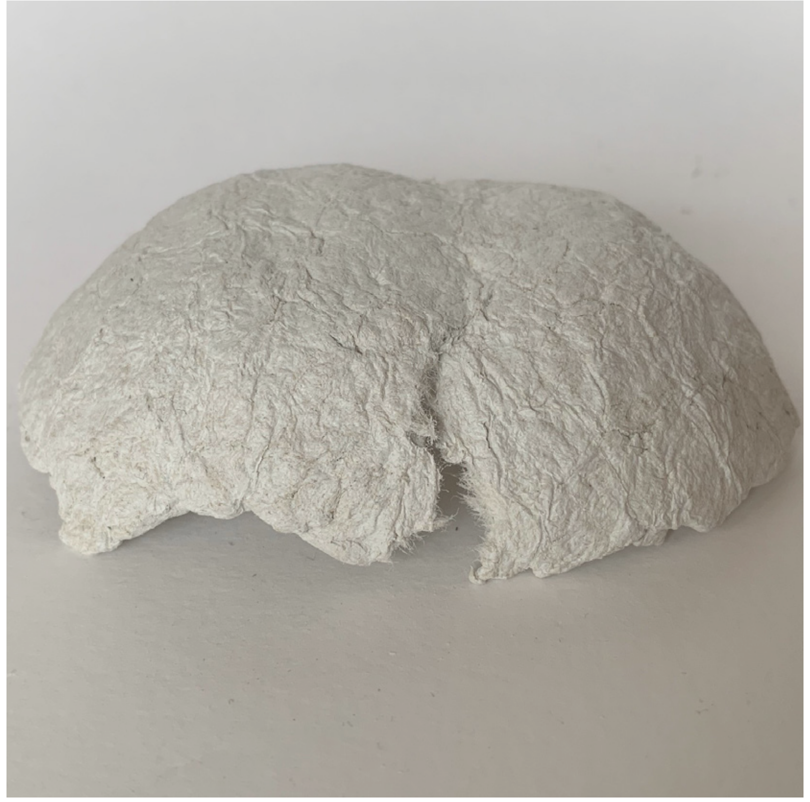
Motive
This experiment tested out the presence of clay in combination with PVA-glue in the manually applied production method.

Expectations
The shell will most likely have a smooth paper like feel to it due to the low amount of clay and will hopefully be relatively strong in relation to its thickness.

Result
The sample took about 4 days to fully dry out which was longer than expected given that the shell is only 4 mm thick. Once it was dry it was able to withstand about 12 kg stacked on top of it before tearing up like paper.

Possible uses
+ The sample could be used as a smaller shell that is fairly protected from external loads.





EXPERIMENT D1

Tactility	Semi rough	**Fire resistance**	Semi good
Texture	Scattered	**Water resistance**	Poor
Density	Light	**Compression**	Flexible

Ingredients
+ *25 grams of paper bags*
+ *35 grams of corn starch*
+ *100 grams of clay*

Production method

Fully compressed (stackable mold)

Motive

This experiment tested the combination of corn starch and clay as an alternative to adhesive in the fully compressed production method.

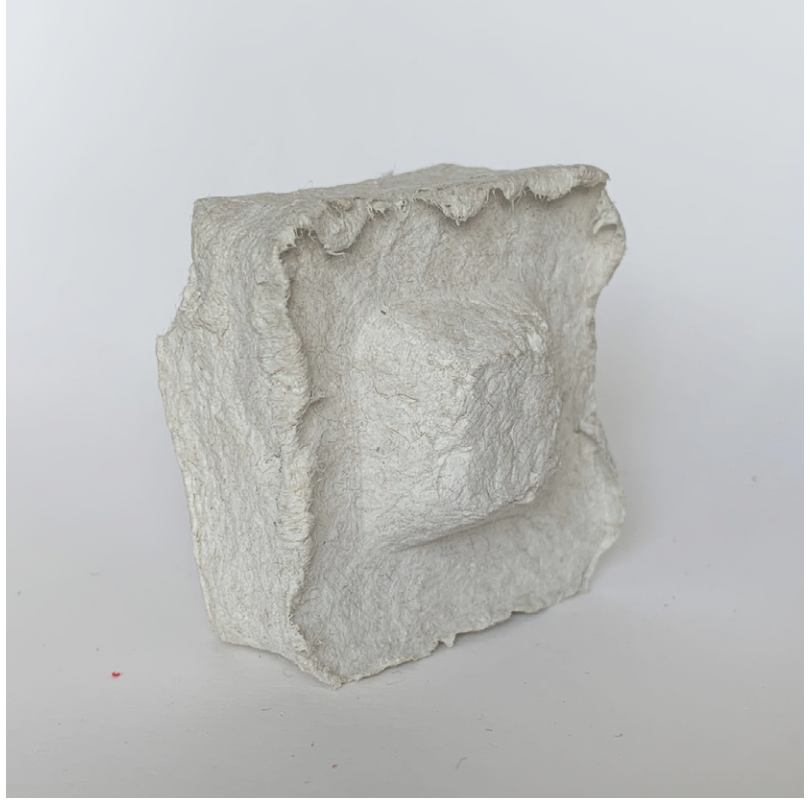
Expectations

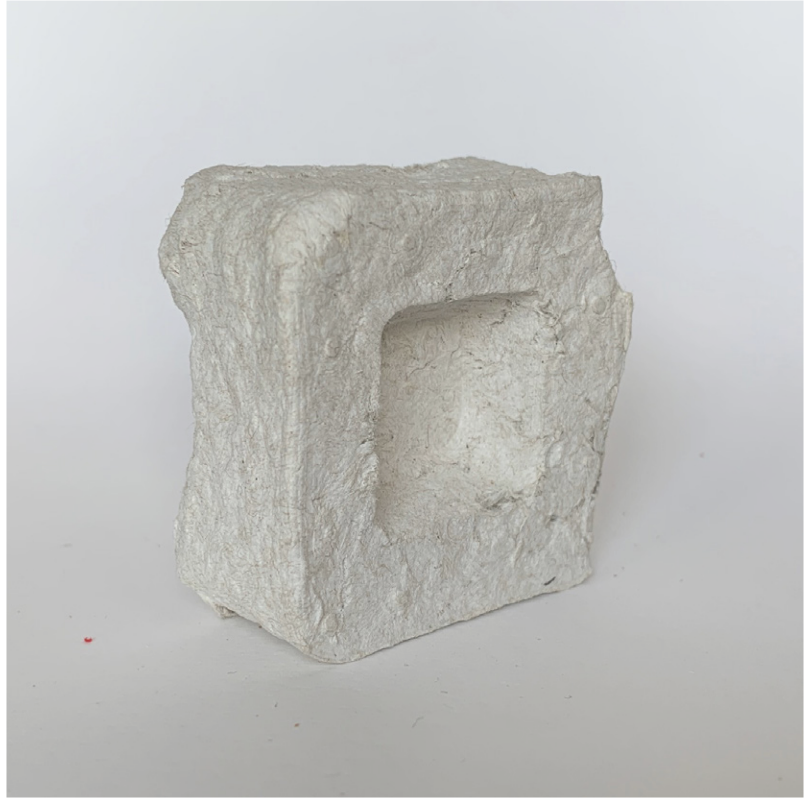
A solid block with a ceramic-like finish due to the presence of clay in the sample. It will most likely be hard and brittle with a smooth surface.

Result

The corn starch in combination with clay did not turn out to be a good substitute for adhesive as the block was hard to extract without damaging it. The surface came out bumpy and incoherent which was probably a consequence of the fibers not being able to bind together properly. The sample did not have much of the anticipated ceramic-like characteristics but felt more like a rough piece of paper. The overall result however made for an interesting surface with tactile qualities.

Possible uses
+ Due to the tactile qualities of the sample it could be used as interior wall coverings.
+ Even though the adhesive effect of starch and clay was a failure the sample was still rather sturdy and could be used for furniture design.





EXPERIMENT E1

Tactility	Smooth, ceramic like	**Fire resistance**	Good
Texture	Uniform	**Water resistance**	Poor
Density	Semi heavy	**Compression**	Semi robust

Ingredients
+ *25 grams of white paper*
+ *35 grams of corn starch*
+ *200 grams of clay*

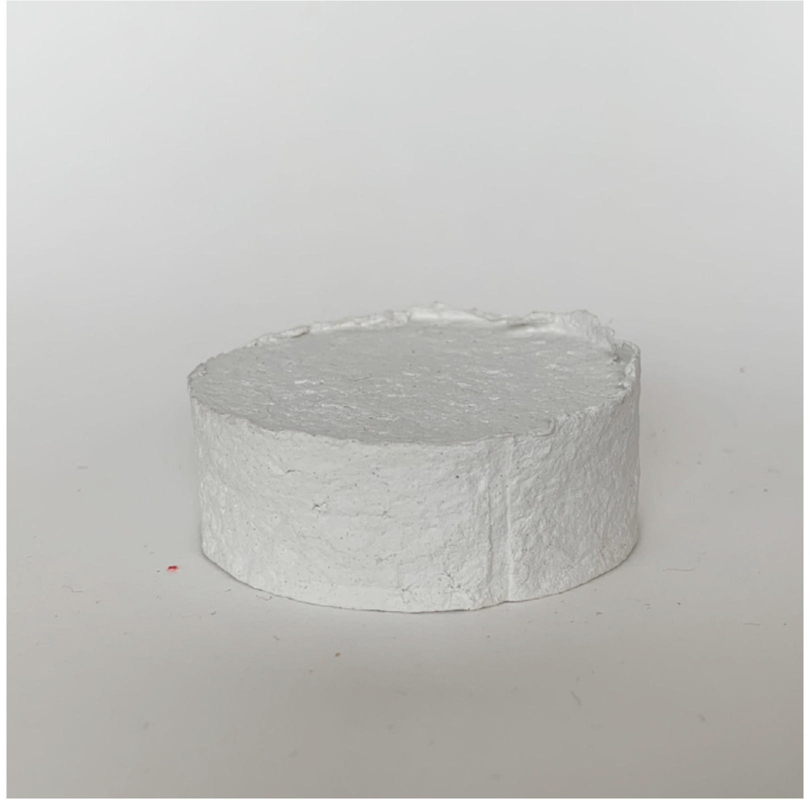
Production method
Fully compressed (cylindrical mold)

Motive
This experiment was the next iteration of batch D where the amount of clay was increased to improve the bonding strength.

Expectations
Since the amount of clay is doubled the sample will most likely have more ceramic than paper like characteristics.

Result
This experiment was more of a success than experiment D1 as the piece seemed to be more uniform and easier to extract from the mold. During compressive load the piece did deform quite a bit but the rim cracked up like ceramic pieces.

Possible uses
+ The material could work as a building block for stationary and movable walls.
+ In addition the material could be used for decoration or furniture.



EXPERIMENT E2

Tactility	Semi rough	**Fire resistance**	Poor
Texture	Scattered	**Water resistance**	Poor
Density	Light	**Compression**	Brittle

Ingredients
+ *25 grams of white paper*
+ *35 grams of corn starch*
+ *200 grams of clay*

Production method

Printed

Motive

This experiment aimed to find a more suitable pulp for the printing production method.

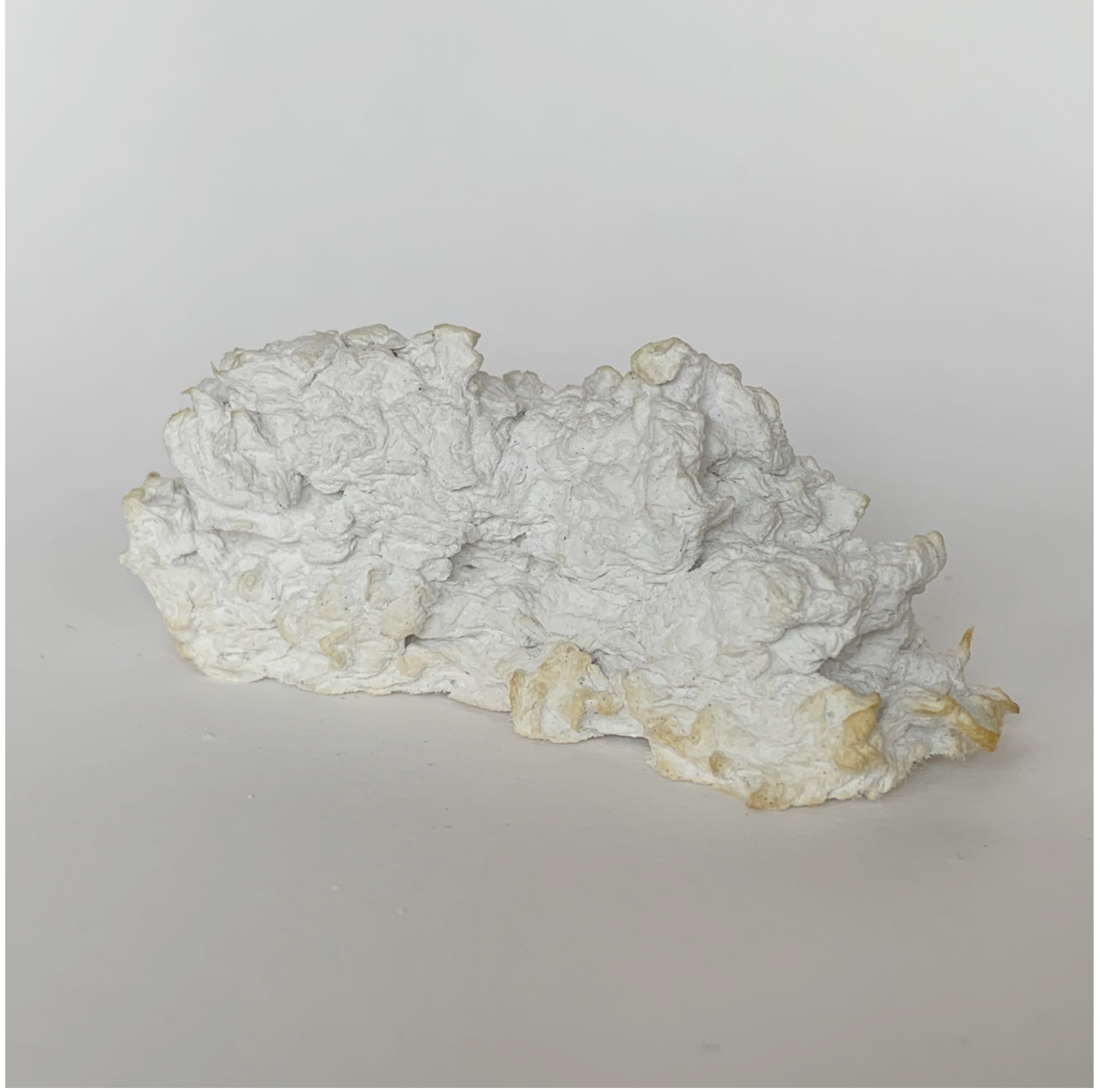
Expectations

The clay makes the pulp more smooth and uniform as pulp made from only cardboard can be rather lumpy. The increased smoothness will most likely allow for a finer printing result.

Result

Even if the clay did make the pulp run much smoother through the container it was still hard to get even layers without lumps in the finished result. The lumps were however smaller than in experiment A2 and the tactility was more ceramic like than paper like.

Possible uses
+ The material could work as an interior rendering element to create interesting wall surfaces or decorate other pulp elements.



EXPERIMENT F1

Tactility	Smooth, sand like	**Fire resistance**	Good
Texture	Uniform	**Water resistance**	Poor
Density	Semi heavy	**Compression**	Robust

Ingredients
+ *25 grams of grey cardboard*
+ *25 grams of PVA-glue*
+ *50 grams of sand (fine)*

Production method

Fully compressed (stackable mold)

Motive

The experiment aimed to examine the presence of fine sand in the fully compressed block in terms of post drying shrinkage and robustness.

Expectations

Shrinkage in the material happens mainly for two reasons. The first one is that the cellulose fibers swell up in contact with water and contract again when the water evaporates. The second reason is that the water expands the pores of the material. When the water then evaporates the pores shrink thus causing the whole sample to shrink in size. Since sand is convenient at filling out pores some of the shrinkage in the material could be eliminated. Another benefit to replacing the air in the pores with sand is that the sample should become more robust and less likely to deform in compression.

Result

The sample was easy to remove from the mold without damaging the piece. After allowing it to acclimatize to the surrounding humidity it was found that it had shrunk about 1,3 %, whereas the blocks with only cardboard and glue shrunk about 2,4 %. The sand seems to have made the block a bit more robust to compressive forces with the biggest difference being that the sample cracks during compressive deformation. Additionally the sample turned out smooth with a nice sandy-beige color to it and an interesting texture due to the sand grains.

Possible uses
+ The block could be used for a wall system due to its robustness and nice finish.

EXPERIMENT F2

Tactility	Semi rough	**Fire resistance**	Poor
Texture	Semi scattered	**Water resistance**	Poor
Density	Semi light	**Compression**	Flexible

Ingredients
+ *25 grams of grey cardboard*
+ *25 grams of PVA-glue*
+ *50 grams of sand (fine)*

Production method
Partially compressed

Motive
This experiment tested out the presence of sand in the partially compressed production method.

Expectations
The hypothesis is that the sand will fill out the pores in the material thus creating a denser and stronger sample.

Result
The result was similar to the one in experiment C1 but a bit heavier and a more rough tactility. The piece disconnected in the middle during the drying process which might be a consequence of the sand not being evenly spread.

Possible uses
+ Due to the failure of this experiment the sample will not be useful.

EXPERIMENT F3

Tactility	Soft, sand like	**Fire resistance**	Semi good
Texture	Scattered	**Water resistance**	Poor
Density	Semi light	**Compression**	Brittle

Ingredients
+ *25 grams of grey cardboard*
+ *25 grams of PVA-glue*
+ *50 grams of sand (fine)*

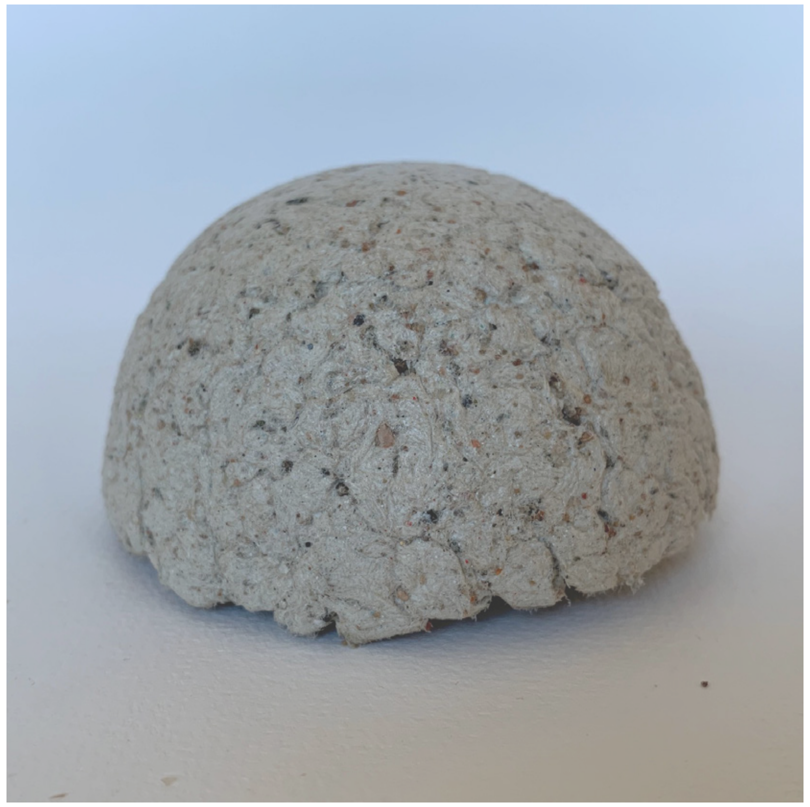
Production method
Manually applied

Motive
This experiment tested the presence of sand in the manually applied production method to find out if the shell would remain intact after hardening or if it would break like sample F2.

Expectations
If the sand gets mixed around properly and areas where sand accumulates can be avoided, the shell should be even stronger than sample C2 due to the reduced porosity.

Result
The sand seems to have been evenly distributed in the pulp as the hardened shell remained intact during the drying process. The structure was able to withstand around 25 kg before cracking which is an improvement since previous experiments. In addition the sand gives the sample some variation in colour and a grain like finish.

Possible uses
+ The element could be used as a larger shell structure as it is rather robust and more dense than previous shell experiments.



EXPERIMENT G1

Tactility	Soft	**Fire resistance**	Semi good
Texture	Scattered	**Water resistance**	Poor
Density	Semi light	**Compression**	Flexible

Ingredients
+ *25 grams of grey cardboard*
+ *100 grams of clay*
+ *50 grams of sand (fine)*

Production method

Partially compressed

Motive

This experiment tested the combination of clay and sand in the partially compressed production method.

Expectations

The sample will hopefully be more robust than experiment F2 as the clay might bind better together with the sand than what the PVA-glue did.

Result

The resulting piece did not break during the drying process but still some larger creases can be seen between the layers of pulp. When it comes to compressive strength this experiment shows a slight improvement.

Possible uses
+ The sample could be used as a pillar element for lighter weights.
+ Additionally it could be used for decorative purposes.

EXPERIMENT G2

Tactility	Rough	**Fire resistance**	Semi poor
Texture	Scattered	**Water resistance**	Poor
Density	Light	**Compression**	Brittle

Ingredients
+ *25 grams of grey cardboard*
+ *100 grams of clay*
+ *50 grams of sand (fine)*

Production method

Printed

Motive

This experiment tested if sand could have a positive effect on the smoothness of the pulp which would make printing easier to control.

Expectations

Hopefully the fine sand would help to reduce lumps in the pulp which would make it easier to print fine layers.

Result

It was found that the fine grains of sand did reduce the lumps in the pulp to some degree. Even though it was hard to apply the pulp evenly by hand, the layers are more defined which is an improvement from previous experiments.

Possible uses
+ The material could work as an interior rendering element to create interesting wall surfaces or decorate other pulp elements.

EXPERIMENT G3

Tactility	Smoothm paper-like	**Fire resistance**	Semi good
Texture	Rough	**Water resistance**	Poor
Density	Semi light	**Compression**	Semi-robust

Ingredients
+ *25 grams of grey cardboard*
+ *100 grams of clay*
+ *50 grams of sand (fine)*

Production method

Manually applied

Motive

This experiment aimed to find a composition of additives that gives a rigid and sturdy shell once the pulp has hardened. A small bowl was chosen as the mold.

Expectations

When the clay hardens it becomes somewhat ceramic and more resistant to cracking during compression compared to hardened paper pulp. In addition to the sand that also contributes to compressive strength the finished shell should be more robust than the sample with only 50 grams of clay.

Result

The hardened shell turned out with a smooth surface on the side facing the mold and somewhat inconsistent on the outside with a papery feel to it. Even though the pulp contained both sand and clay that usually result in a heavier material, the finished product was rather light due to the fibers being loosely packed. The shell was able to support about 80 kg of weight stacked ontop of it before cracks began to form.

Possible uses
+ Due to the materials ability to withstand compressive forces the sample could be used in a upscaled version of a form-found shell.

EXPERIMENT H1

Tactility	Rough	**Fire resistance**	Good
Texture	Scattered	**Water resistance**	Poor
Density	Semi heavy	**Compression**	Semi robust

Ingredients
+ *20 grams of white paper*
+ *10 grams of green paper*
+ *50 grams of clay*
+ *150 grams of sand (fine)*

Production method
Printed

Motive
This experiment aimed to find a suitable material composition for the printing method. From previous experiments it is found that both clay and sand has a positive impact on the consistency of the material.

Expectations
Since clay has shown to work in previous printing tests and sand has helped to reduce porosity, the combination of clay+sand should be an ideal composition for the printing method.

Result
At first it was challenging to find the right amount of water to give the pulp the desired consistency. With too much water the material would not stack in layers and too much water made it hard to extrude the pulp. When the right amount of water was found the printing could be carried out as desired. The end result was the best printed sample so far even though it was hard to apply the layers evenly on top of each other by hand.

Possible uses
+ Since the material is not compacted it will not be able to serve as a structural element but instead work as a decorative piece or furniture.
+ The material could work as a rendering element to create interesting textures or surfaces.

EXPERIMENT I1

Tactility	Rough, concrete like	**Fire resistance**	Very good
Texture	Uniform	**Water resistance**	Semi poor
Density	Semi heavy	**Compression**	Robust

Ingredients
+ *20 grams of white paper*
+ *15 grams of red paper*
+ *35 grams of PVA- glue*
+ *100 grams of sand (coarse)*

Production method
Partially compressed

Motive
This experiment tested the presence of coarse sand in the partially compressed "pillar". In addition to this one sample is made with a thin strip of fabric that is continuously placed in a spiral as material is added and packed.

Expectations
Since sand helps reduce porosity in the material the sample will most likely be more compact and thus have less tendency to compress while loaded. The thin strip of fabric reinforcement will most likely help the sample from cracking during axial load.

Result
The samples came out with a smooth surface compared to previous samples with the same production method. The small pebbles add some weight and robustness to the sample and, in addition to the red paper, gives the overall appearance a nice texture. During compressive stress both the samples were able to withstand more pressure than I could exert using the screw clamps which is a great improvement from previous samples. However the sample without fabric did deform slightly more than the one with fabric reinforcement.

Possible uses
+ Since the material seems less likely to deform during compression it could be used as a pillar element or foundation

EXPERIMENT I2

Tactility	Rough, concrete like	**Fire resistance**	Very good
Texture	Uniform	**Water resistance**	Semi poor
Density	Heavy	**Compression**	Robust

Ingredients
- *20 grams of white paper*
- *15 grams of red paper*
- *35 grams of PVA- glue*
- *100 grams of sand (coarse)*

Production method
Fully compressed (cylindrical mold)

Motive
This experiment tested the presence of coarse sand in the fully compressed mold. The aim is to explore the impact of coarse sand in regards to water and fire resistance.

Expectations
Since sand helps to reduce porosity in the material the sample will most likely have fewer air pockets which would make it more resilient to fire. A less porous material would also be more resistant to moisture since water has a harder time to penetrate the material.

Result
The samples came out with a smooth surface compared to previous samples with the same production method. The small pebbles add some weight and robustness to the sample and, in addition to the red paper, gives the overall appearance a nice texture. As expected the material turned out to have great fire resistant properties. After being exposed to an open flame for 30 seconds the material was left with only a small patch of soot. However it did not perform much better than any of the previous samples when it comes to water resistance.

Possible uses
- Since the material seems less likely to deform during compression and has a great fire resistance it could be used as a wall element or foundation.

EXPERIMENT J1

Tactility	Semi smooth, rubber like	**Fire resistance**	Poor
Texture	Uniform	**Water resistance**	Semi poor
Density	Semi light	**Compression**	Semi flexible

Ingredients
+ *30 grams of white paper*
+ *30 grams of PVA- glue*
+ *100 ml of liquid latex*

Production method

Fully compressed (stackable mold)

Motive

This experiment tested the impact of liquid latex in regards to water resistance. Liquid latex is a natural rubber that hardens in contact with air.

Expectations

Since latex in its hardened state becomes extremely water repellent the sample piece should show similar properties once it dries out.

Result

The liquid latex was hard to mix properly with the rest of the pulp which led to the ingredient not being distributed evenly in the sample. This can be seen in the darker areas where latex have clumped together. These areas had a rubbery feel to them compared to the rest of the piece which felt more like compact paper. The additive did bind well together with the pulp and the piece came out with a smooth surface. The latex did seem to have a small impact on the water resistance of the material. When sprayed with water it took longer than previous samples before the block started to dissolve. The areas with a high amount of latex lasted longer before they dissolved.

Possible uses
+ Because of the variation in color caused by the latex the piece could be used as a decorative wall element.

"We're all gonna make it"