FELTED CLAY

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LTH School of Architecture
Spatial Experiments

AAHM10: Degree Project in Architecture, LTH

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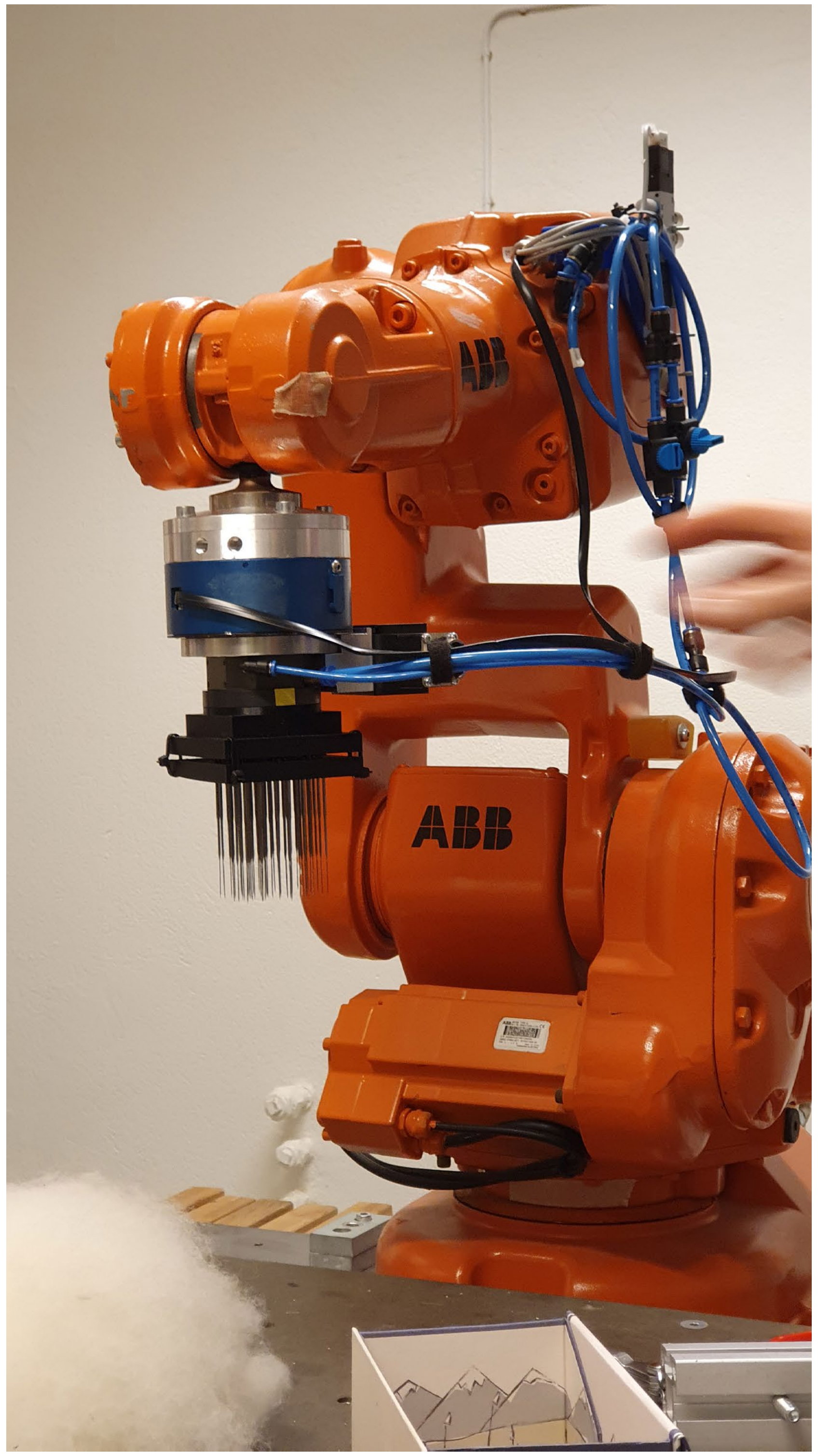


As we are discovering more and more how much the built environment, especially during construction and dis-assembly , has on our planet, We as architects need to constantly re-assess our approach to our designs. From the materials we use, and the construction techniques.

Throughout studying this masters programme, I have been fascinated by how we can change this through a combination of material choice, design techniques and new fabrication methods.

Felted Clay is a culmination of these interests and investigations. It is an exploration of the relationships between materials, fabrication, and form. Discovering the possibilities and limitations which robotic felting brings, how it combines with clay, and finally what architectural features and considerations this could bring.

With these relationships, I sought to design a shelter.
As the wool is protecting the clay from the external elements, so the structure should protect the occupants.

It is a shelter, constructed of only two materials: adobe clay, and felted wool.

Its form is based on data-driven design decisions, and is constructed using addative manufacturing methods combined with large-scale robotics.

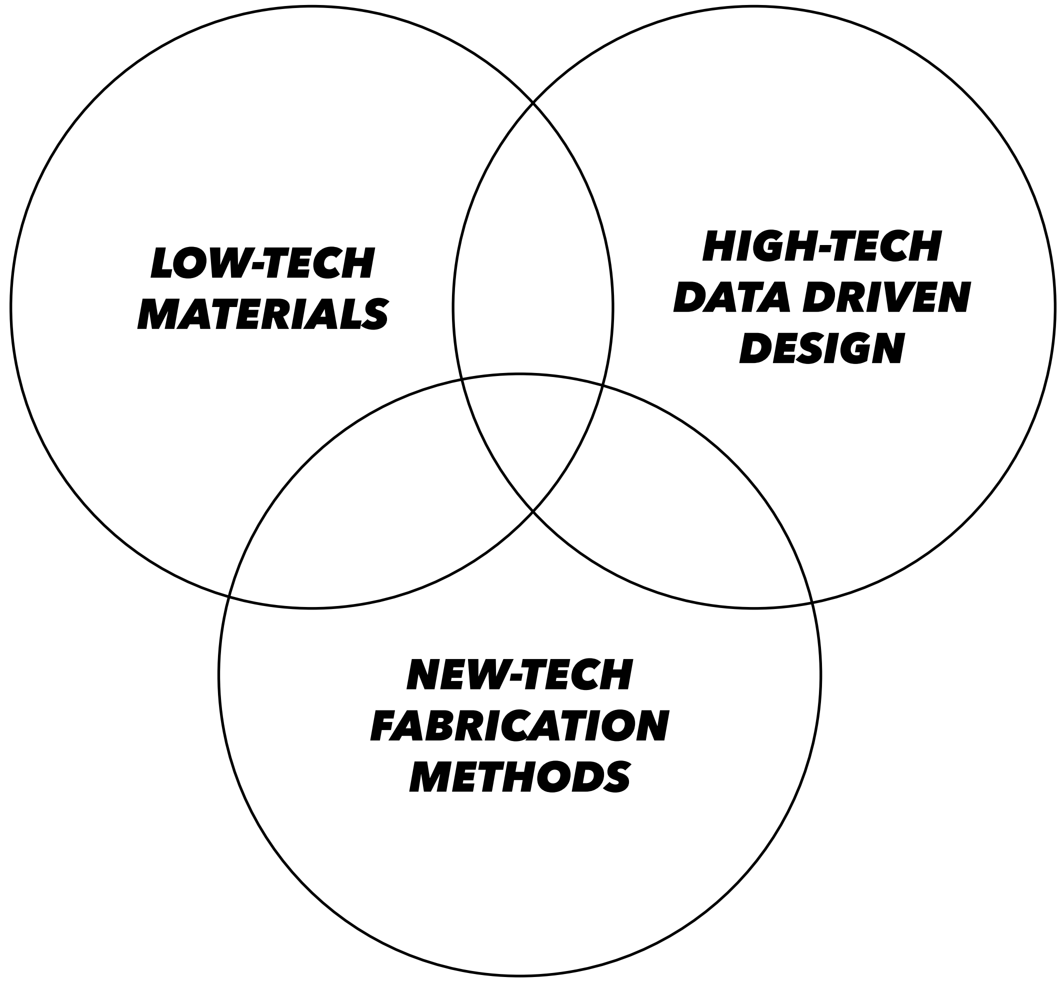
It is a shelter. However beyond protecting its users from the external elements, it also provides space for people to interact, classes to learn, and to bring this niche corner of the architectural world to attention as a possible future architecture.

CONTENTS

APPROACH

The final proposal was developed through experiments and investigations in each topic, with the findings from each influencing the other.

The following pages describe the different aspects of the project, which together led to the final design.



THE SHELTER

A shelter is a dwelling in its most fundamental form.

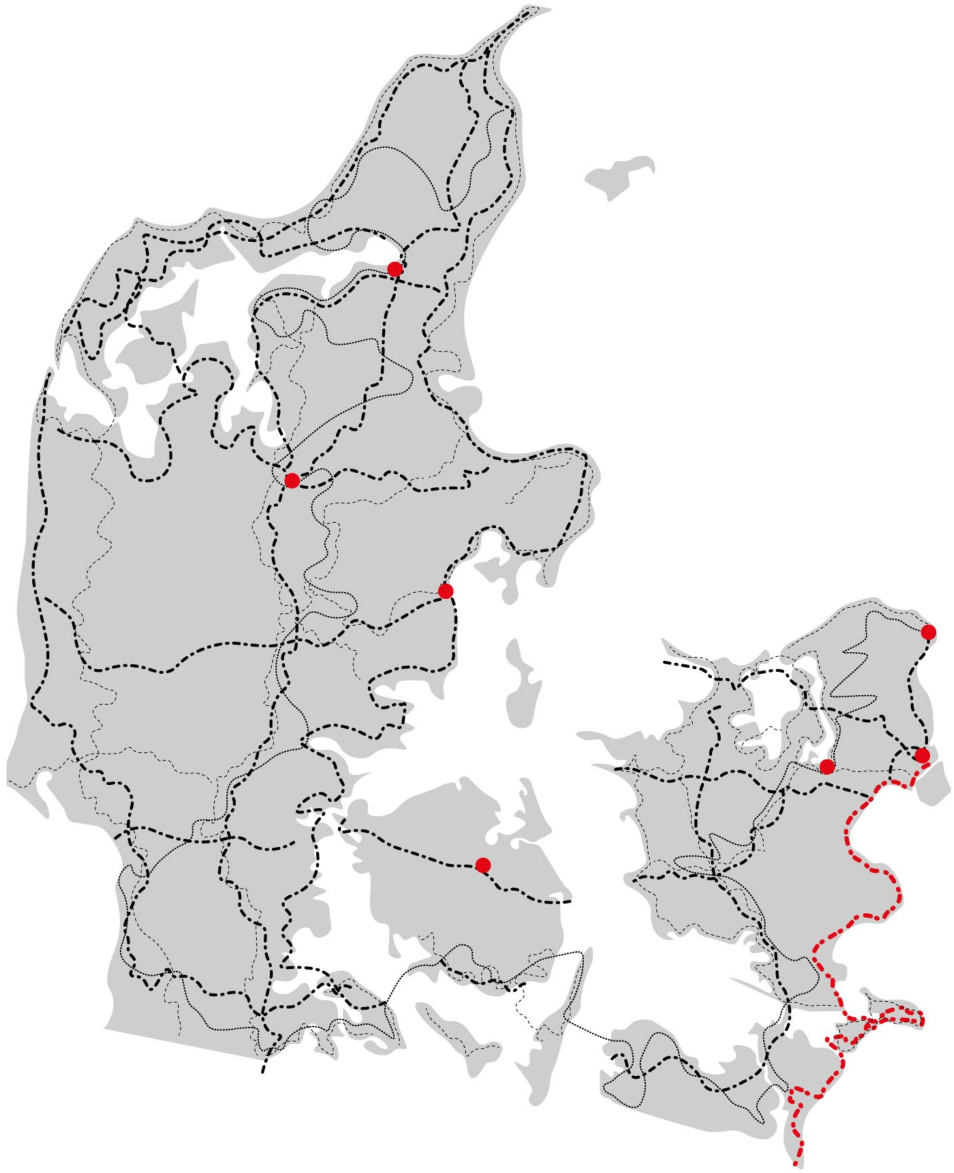
It provides protection to its users from the harshest of the elements, allowing them to rest, for an hour, a day or more.

Shelters can be found throughout Scandinavia. These are free to use, and open to the public all year around, allowing a vast range of users: Hikers, cyclists, touring groups, schools and those seeking rest and protection. They are primitive in their design, they offer little in comfort,

However, 3D printing a shelter introduces the possibility of increase the functionality and complexity of the shelter, allowing a more diverse and interactive connection between the user and the shelters.

The fundamental requirement of providing shelter allows the development of the form to be pushed both by materials and manufacturing processes, but also user engagement, and direct connections with the location. Re-imagining what a shelter can provide.

LOCATION



Major Cities
National cycle tour routes
Hiking Trails
Eurovela Cycle route (from Hamburg)

LOW HIGH
Clay substrate

CITY FOREST
Green Areas
● 'Flagship' free to use shelters
• Free to use shelters

MAP 1
Main cycle and hiking paths around Denmark

MAP 2
Clay levels in soil are highest on the island of Zealand, in particular the east coast south of København.

MAP 3
Current 'Designer' shelters and the Eurovela cycling route

LOCATION

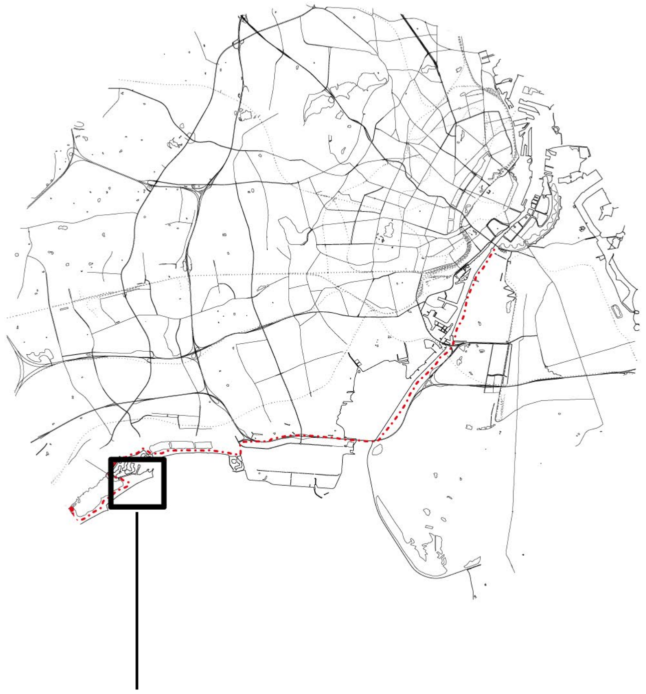
Overlapped analysis of Denmark shows high levels of clay and a relative lack of shelters in the area south of København, and is also situated along the site of one of the most popular European cycling routes,

This location also opens up the possibilities for connections with other user groups in the greater København region.

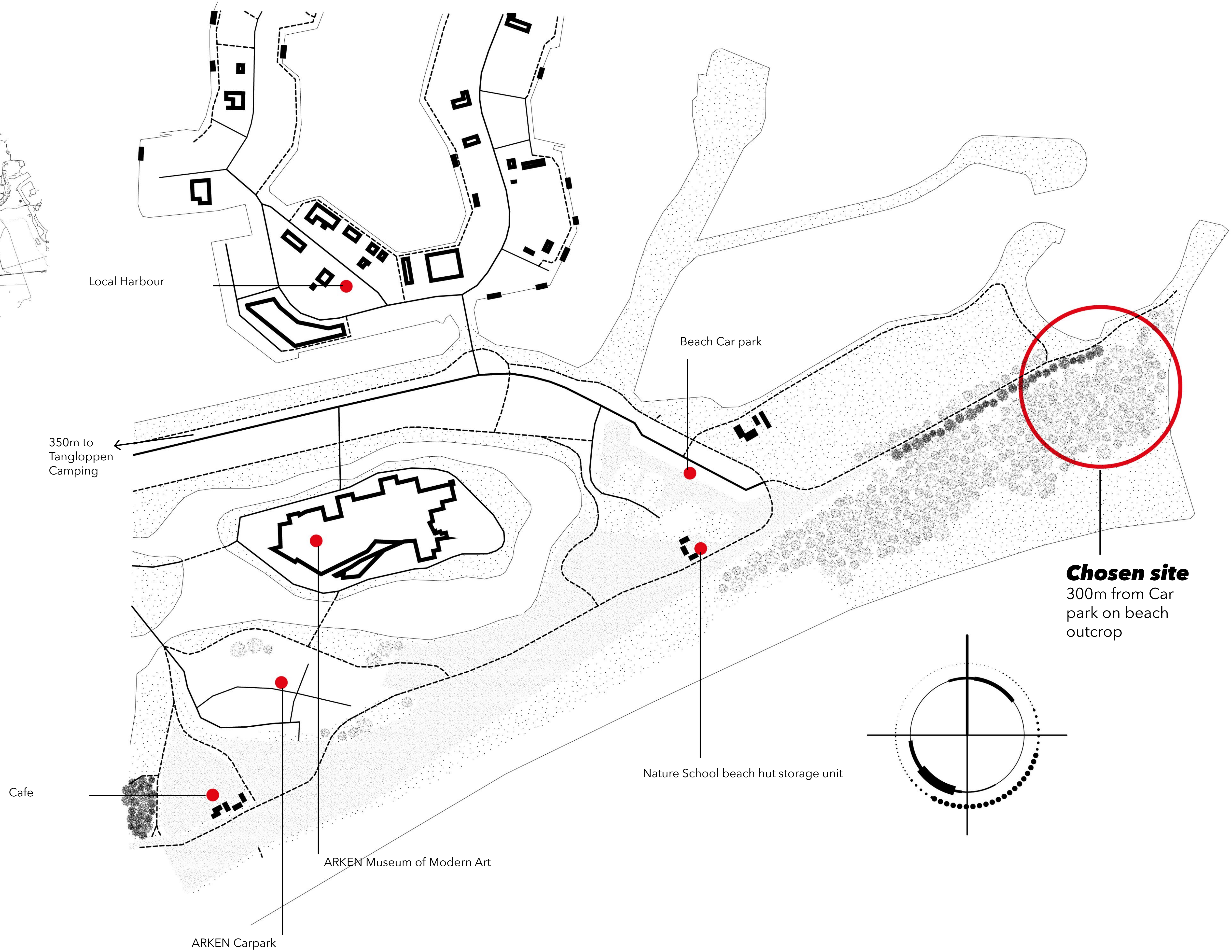
Red dots locate possible users of the shelter: Nature schools, architectural research groups, as well as identifying existing camping grounds, and nature areas and places of interest which draw visitors.

The cycle path follows the coast, and along its way it passes by ARKEN museum of Modern Art. At the same location there is also a camp site with basic facilities, a popular beauty spot on the beach, and two nature schools near-by.

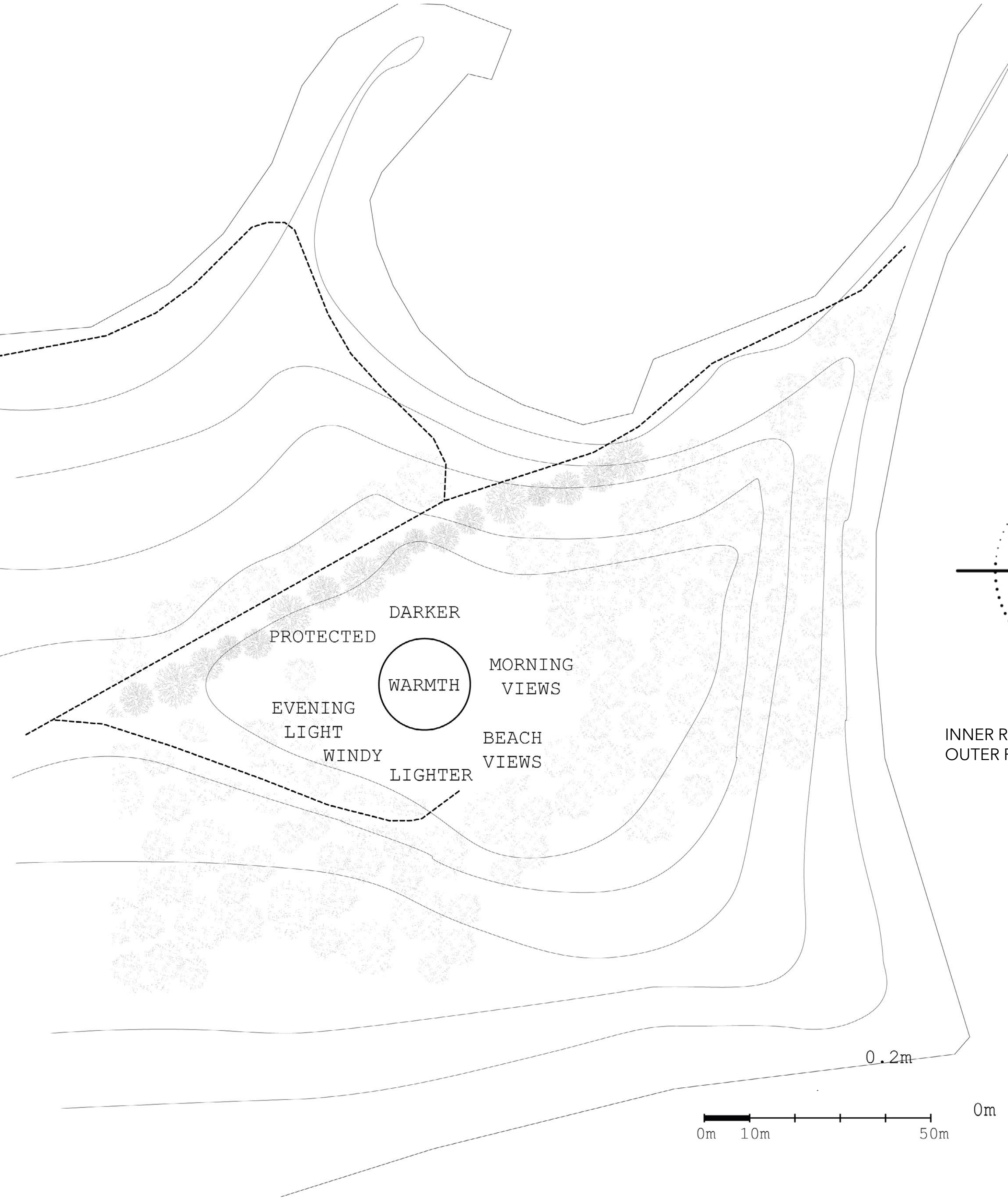
SITE ANALYSIS

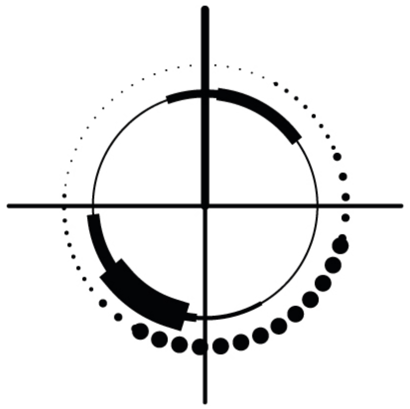


Selected site based
on analysis of greater
København region

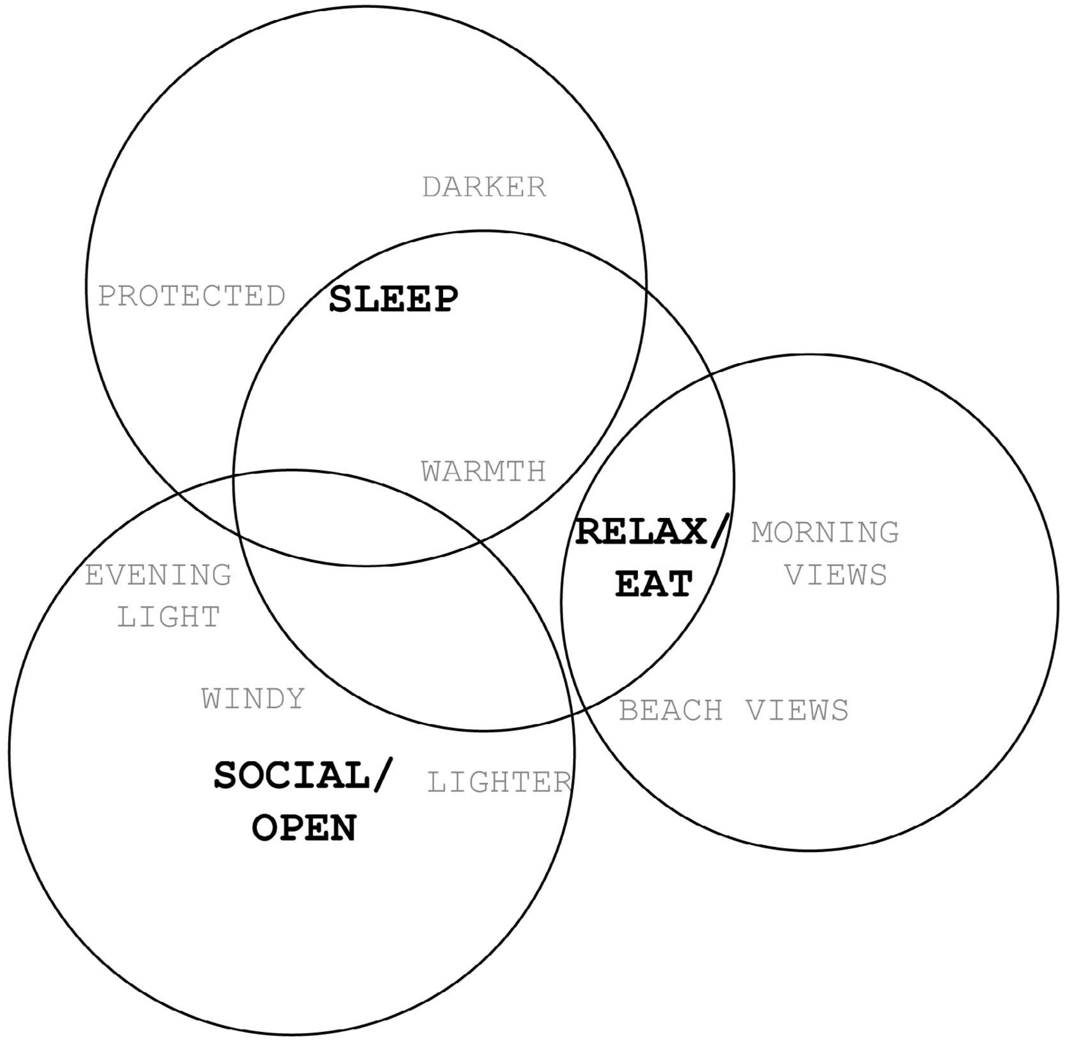


TOPOGRAPHICAL ANALYSIS



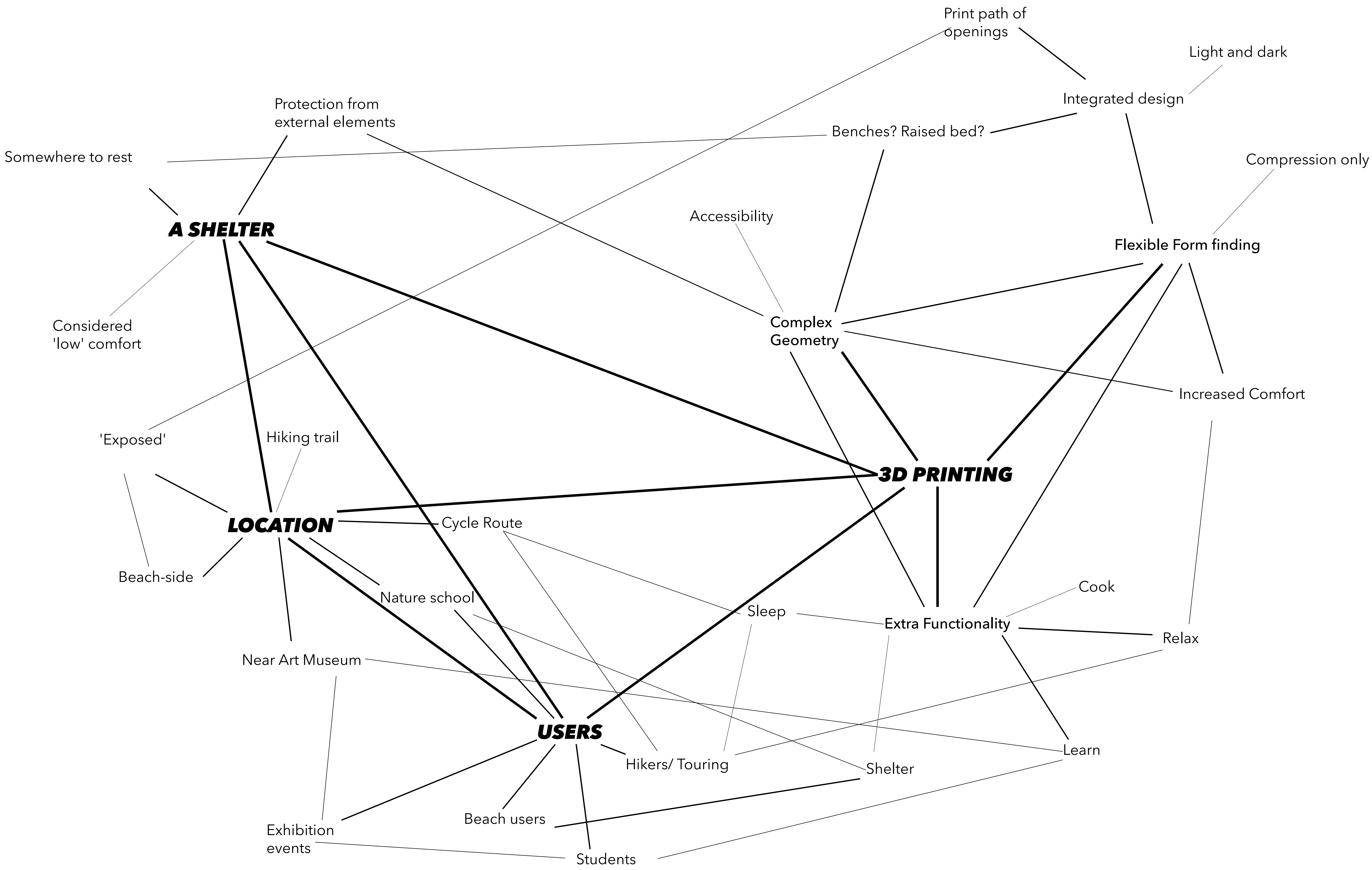


INNER RING: PREVAILING WIND
OUTER RING: VIEWPOINTS



Drafting a layout of what a shelter should have based on the site conditions

CONSIDERATIONS IN DESIGN



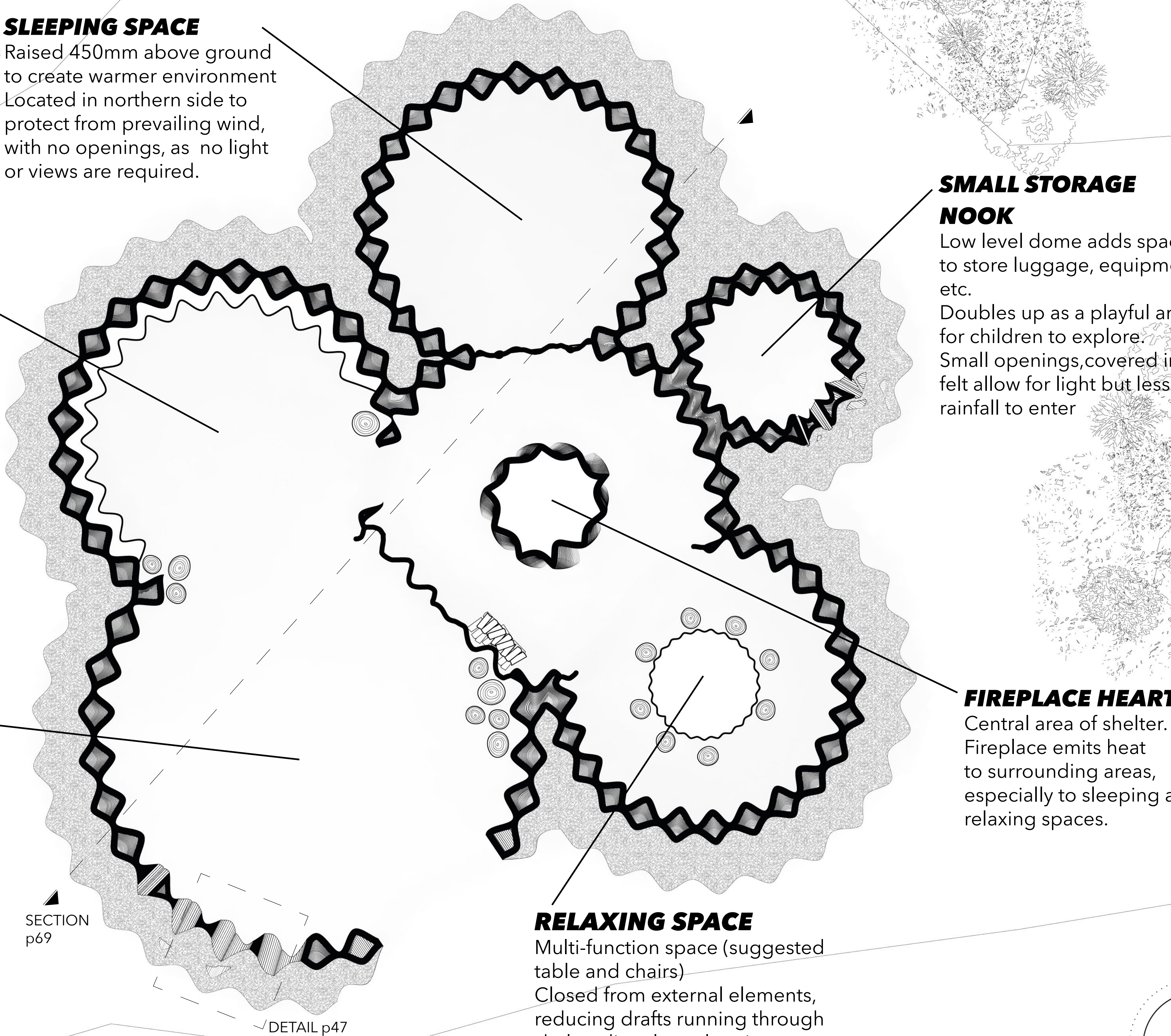
ILLUSTRATIVE PLAN

TO PUBLIC FOOTPATH (25M)
600M TO NATURSKOLEN
1500M TO ARKEN

SLEEPING SPACE
Raised 450mm above ground to create warmer environment Located in northern side to protect from prevailing wind, with no openings, as no light or views are required.

SHARED LEARNING SPACE
Second space connected with entrance. Has built-in bench for classes, as well as access to fireplace.

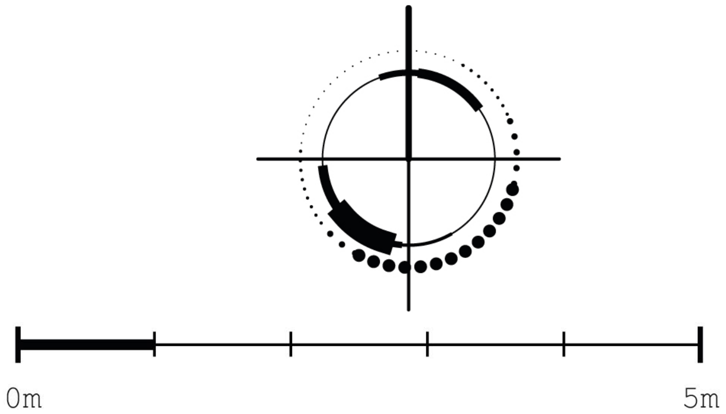
SMALL STORAGE NOOK
Low level dome adds space to store luggage, equipment etc.
Doubles up as a playful area for children to explore.
Small openings,covered in felt allow for light but less rainfall to enter



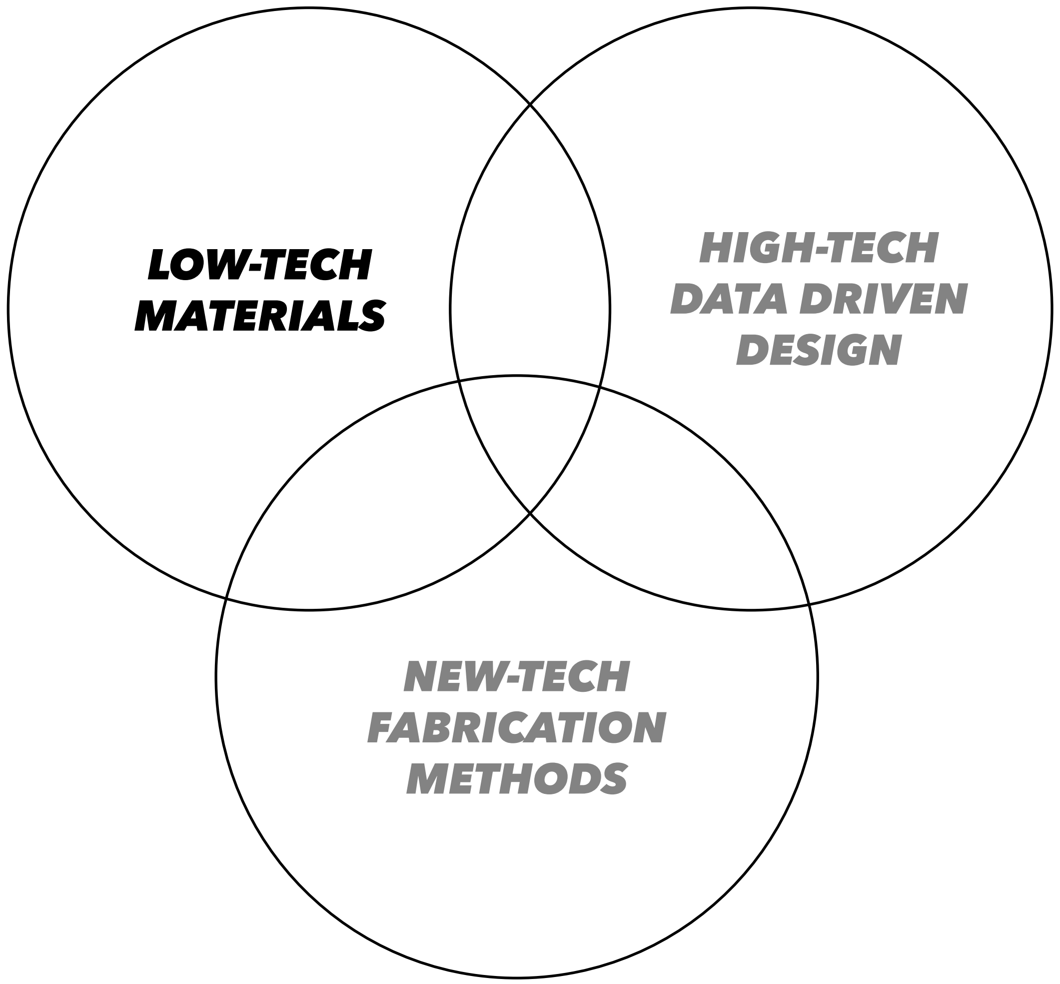
FIREPLACE HEARTH
Central area of shelter. Fireplace emits heat to surrounding areas, especially to sleeping and relaxing spaces.

SHARED ENTRANCE SPACE
Entrance area, high ceilinged with large openings showing off views to beach, as well as the possibilities in print paths. Space for exhibitions, and also allowing users to rest and shelter from extreme weather whilst also keeping a connection to the outside.

RELAXING SPACE
Multi-function space (suggested table and chairs)
Closed from external elements, reducing drafts running through shelter directly to sleeping area.



TO ISHØJ STRAND


LOW-TECH
MATERIALS
HIGH-TECH
DATA DRIVEN
DESIGN
NEW-TECH
FABRICATION
METHODS

FELT

Felt is one of our most natural water resistant fabrics. For centuries it has been used as protection for clothing, and has often been used within the interior of architecture for its thermal and visual qualities.

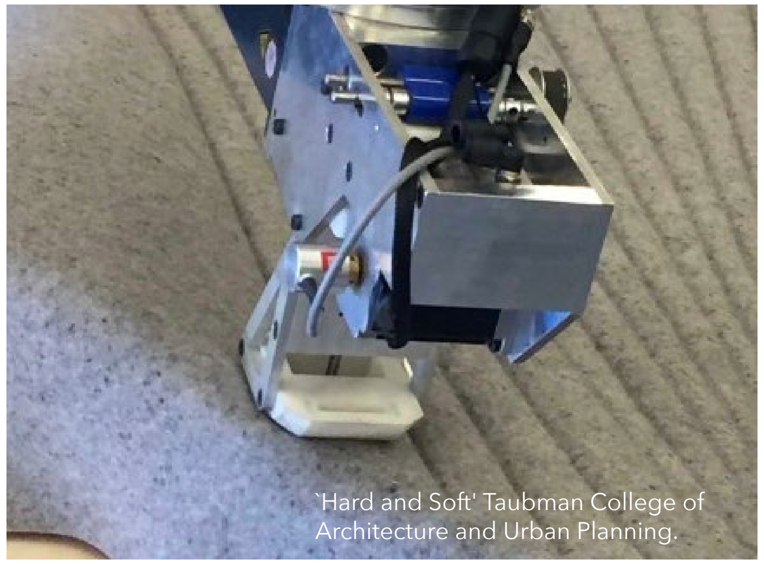
However it has never used as an exterior membrane on a building. Mainly, because it is not 100% waterproof (something considered a requirement in most new-builds) but also it would just take way too long to felt an area big enough to cover a building, meaning it has never been a practical, viable option.

But now, with the development of large scale robotic arms and real-time photogrammetry and positioning, it is possible to programme a robot to move within space, and reposition itself according to world co-ordinates.

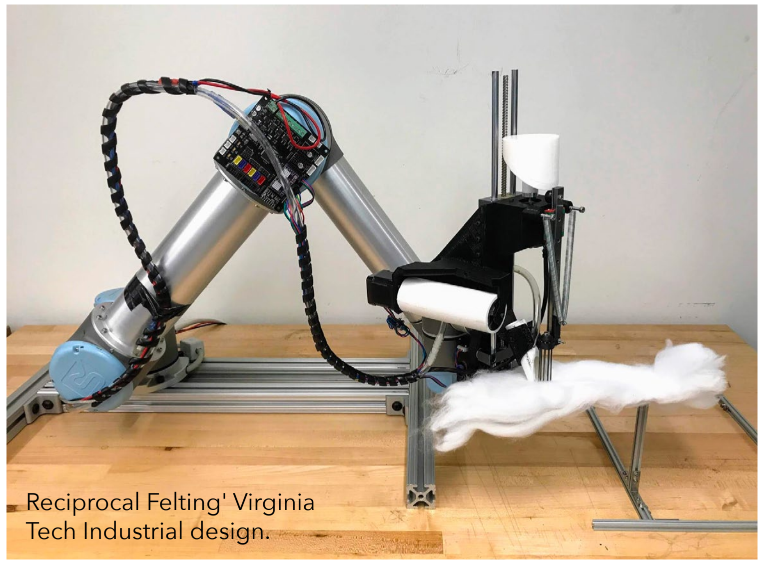
This opens up the possibility of using a robotic arm to perform the felting at large scale, introducing the potential of felt as an outer membrane to an architectural structure.

Hydrophobic water droplet on felt

A roll of carded wool



'Hard and Soft' Taubman College of Architecture and Urban Planning.



Reciprocal Felting' Virginia Tech Industrial design.

CLAY

The same can be said for Clay. One of the oldest building materials in the world, it has long been used as the main structural element in construction methods. In dry climates it is still used to construct buildings and structures.

The properties of clay make it extremely strong when used in compression. This can be seen in the ancient buildings constructed in unfired clay, their catenary domes reaching over large spaces. It is also environmentally friendly, and readily available around the world.

3d printing now allows us to explore and push the forms that can be created with unfired clay. Projects by the 3D print manufacturers WASP are already showing the potential to create large scale structures from extruded clay. However, these structures are still openly exposed to elements, and in time will disappear.

This provides the reasoning behind this thesis. Is it not possible to combine these two materials, creating a protective coating to a 3D printed structure, allowing it to better survive in wet climates found in northern Europe?

WASP 3D printer house

WASP 3D printer house

MUD frontiers

PROPERTIES OF 3D PRINTED CLAY.

- Compression only
- Fast
- Cheap
- No kiln required- just air-dried
- Low thermal conductivity and high heat capacity
- Brittle once dry- unless reinforcements are added
- Varies enormously in different locations
- Until recently used as the main building material for structures around the world, especially in dry climates
- Lasts as a building material only in dry arid climates

PROPERTIES OF FELTED WOOL

- Centuries old material
- In past-times used for insulation against cold, in the form of clothing and building insulation
- Renewable and easy to source- natural material
- Natural wool has 'lanolin' oil, which is antibacterial, and also hydrophobic
- The fibres are agitated together, to produce a dense 'layer' making it much harder for water to penetrate
- Flame and heat resistant

TYPES OF WOOL AND FELTING

The next step was deciding what natural fibres to use.

There are multiple natural fibres which are suitable for felting. All have different properties, However I came to the conclusion that it was more efficient and logical to use a naturally produced fibre where there is as little 'processing' of the material as needed.

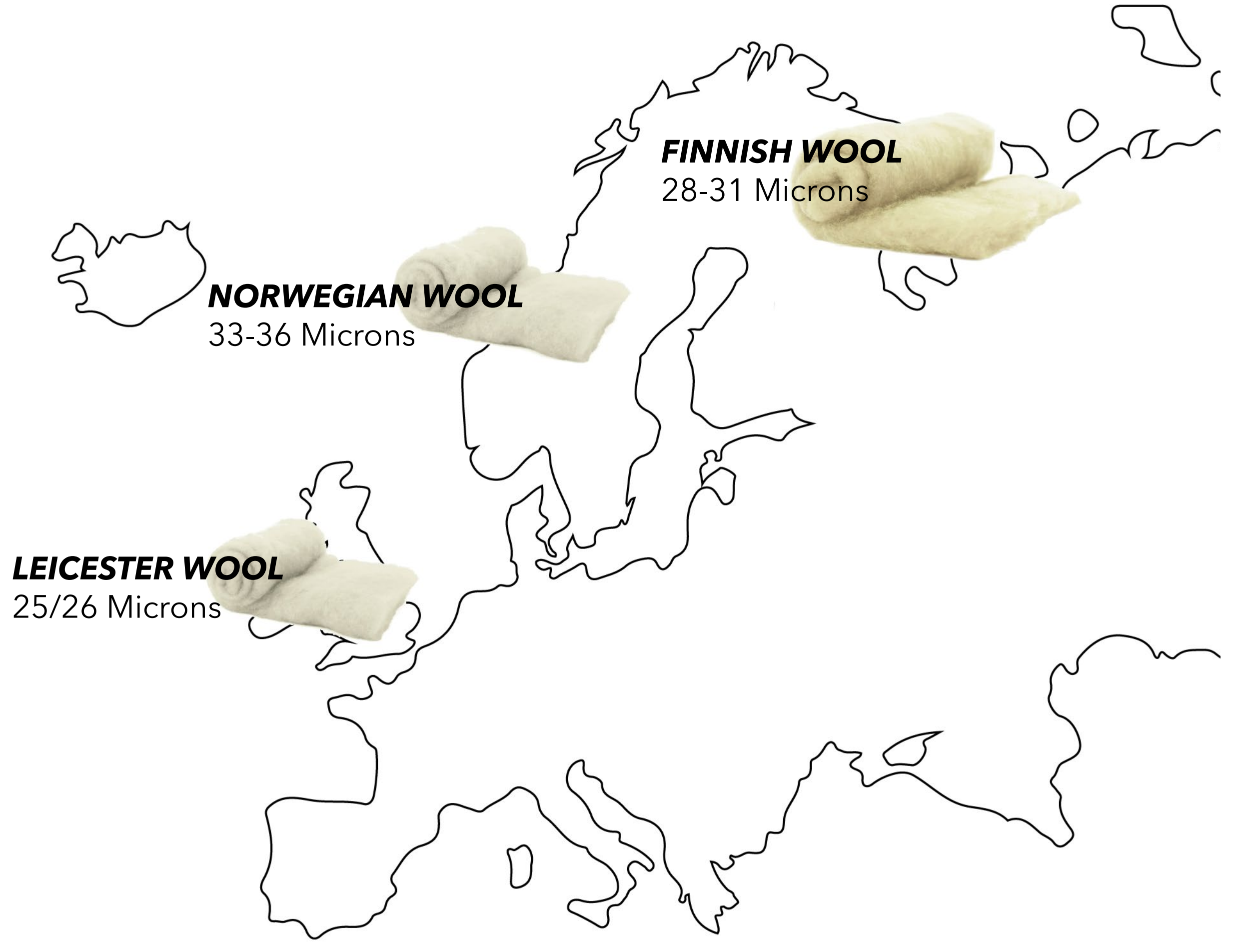
This led to wool, and immediately focussed on sheeps wool in particular.

Other wools, such as alpaca, llama, or even angora rabbit could also theoretically be used for the process, however these are animals which are not native to northern Europe. If the project were to be based in South America, then of course I would focus on using a wool or fibre local to the area.

Sheep though, are native to this area, and there is already a long and strong history of using local sheeps wool to produce the clothing and products mentioned earlier.

This also was a clear advantage, as the knowledge of the properties of sheeps wool has been explored and documented far more.

PROCESSING WOOL

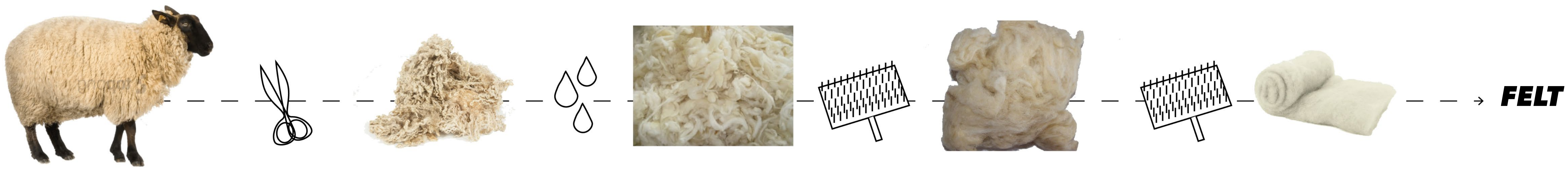


There are many different 'types' of sheeps wool. Just like humans hair is varied across our species, do does sheeps. To narrow down the selection, I looked into what properties I was looking for in the wool:

- DENSITY. A thicker wool would allow me to create a denser felt, which therefore is more water resistant.

-LOCATION. As I want the materials to be as local, I am looking for sheeps wool from this area, rather than New Zealand or Patagonian Wool.

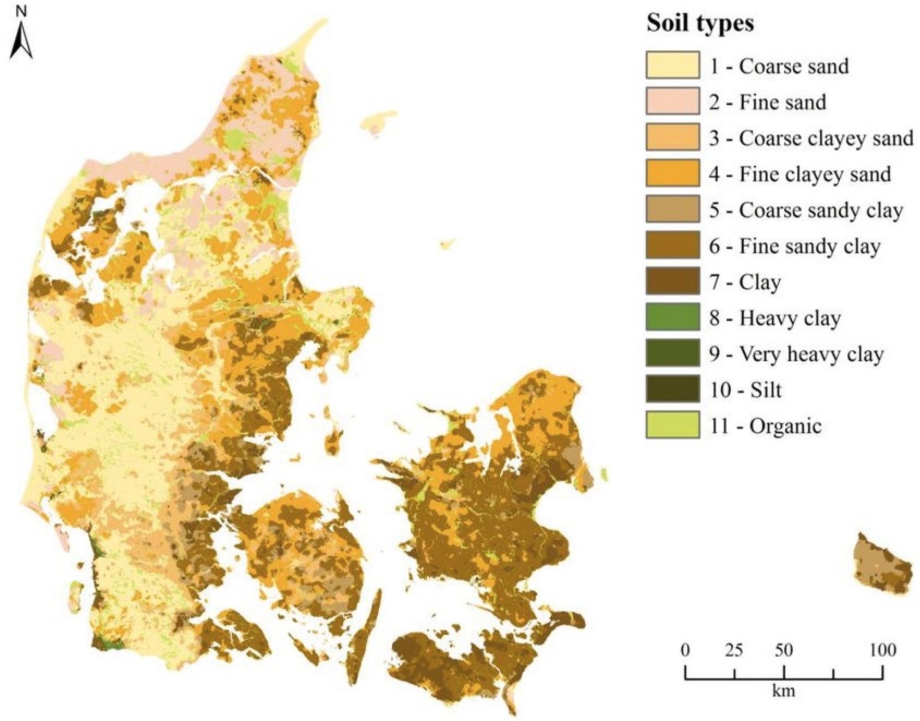
- AVAILABILITY. This project is not aiming to be exclusive. It is looking into a new fabrication and construction method within architecture, which could viably be developed and used in 'real-life'. This means the materials I use shouldn't be hard to source, overly expensive or finite.



DANISH CLAY

As the project will be based within rural Scandinavia, I explored what the local soil types of different regions were.

Denmark, and in particular Zealand, has a high level of clay-based soil, which is ideal for additive manufacturing processes.



Soil types of Denmark according to the Danish Soil Classification (Madsen and Jensen, 1992).

BLÅLER

A low quality clay, cheap clay which has been processed for personal and commercial use. It has had living matter, and large lumps and stones removed, but is still a 'rough' clay.

Suitable to use on most 3D printing machines.

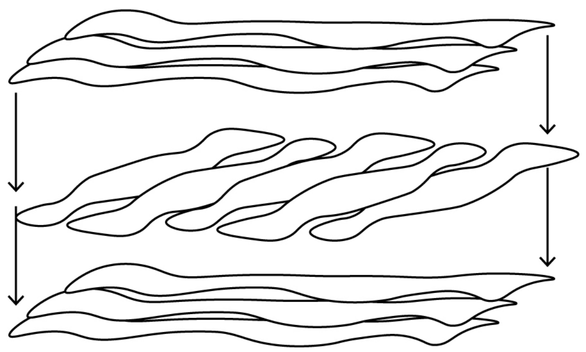
(Ideally would use raw natural mud, however for consistency in production and testing,
It was decided that it would be best to use a processed clay, to avoid variables in texture and strength,and to also allow for ease of use when using in additive manufacturing processes.

Basic clay available for commercial/ private use

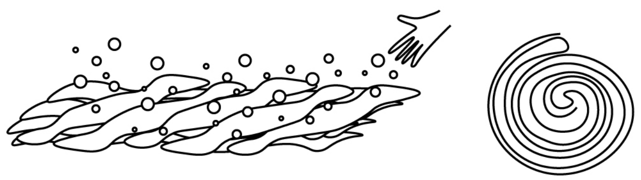
EXPERIMENTS

HOW TO FELT

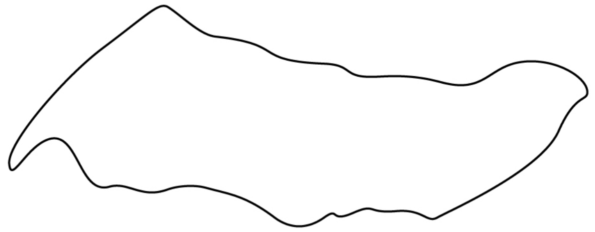
WET FELTING



1- layer thin carded felt batts on-top of each other,
Each layer perpendicular to the one below



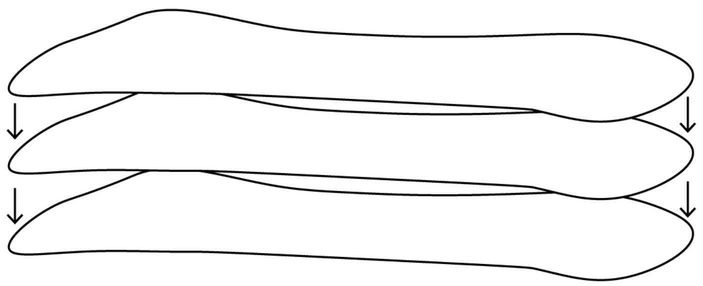
2- using water and soap, agitate the fibres by
Rubbing them together, rolling and 'scrubbing'



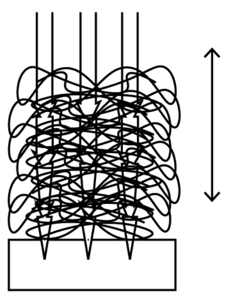
3- allow layers to air-dry. Shrinkage will occur as the
fibres mesh together and tighten

- Faster to felt
- Hard to predict shrinkage
- Messy
- Large amounts of waste water

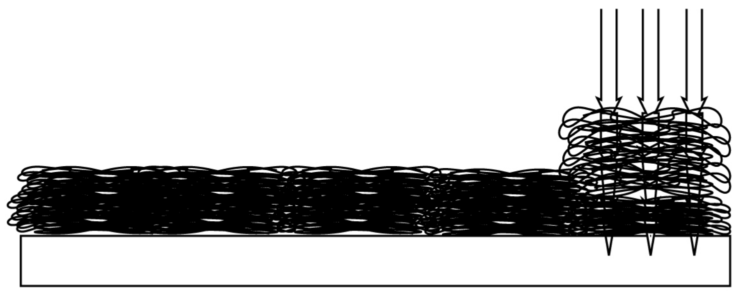
NEEDLE FELTING



1- lay the carded batts of wool on-top of each other
(direction doesn't matter) over a soft surface. The
more layers, the longer the process but the thicker
the final felt



2- Push the razored needles (felting needles)
through the rough wool material to tangle the fibres
together



3- Repeat the process, adding more layers to the
felted wool to create a thicker denser layer until
desired outcome is reached.

- No waste products
- Consistent density
- Process binds wool to surface below
- Flexibility in density over different areas

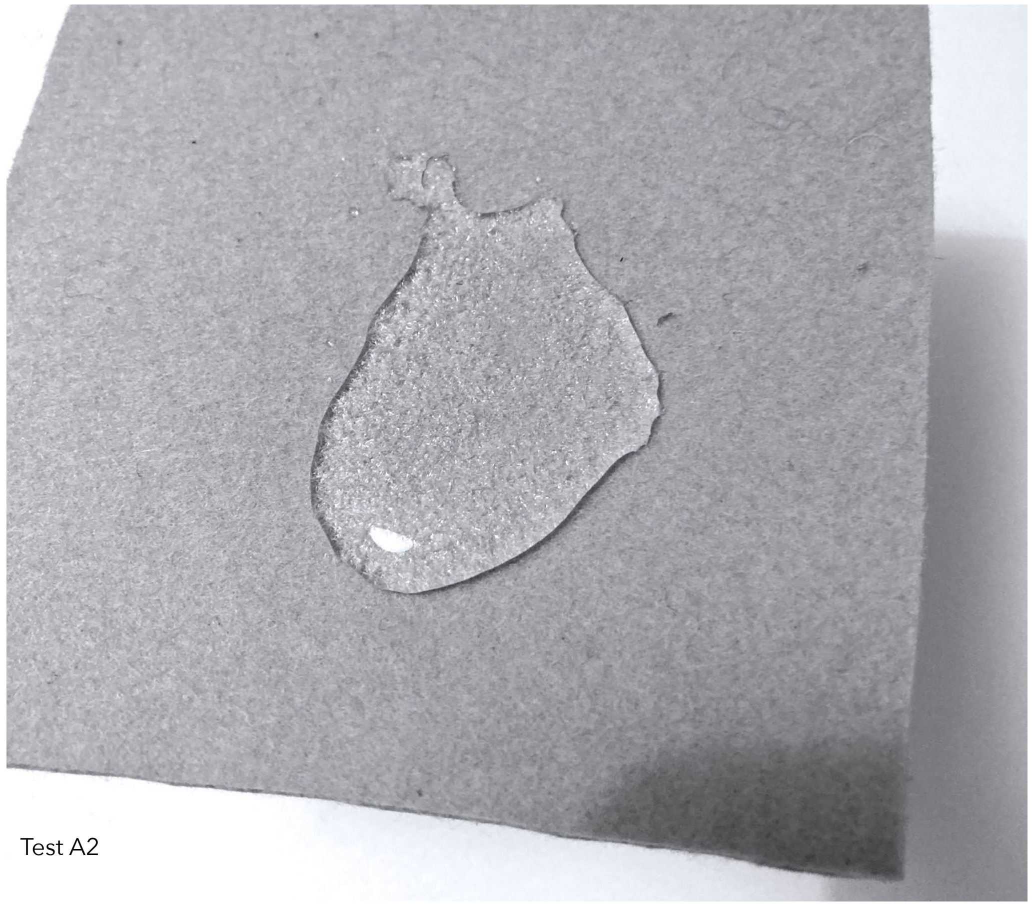
INDUSTRIAL FELTING

This process is used to produce the 'felt' as we are used to in craft and industrial products.

Often the felt is made from synthetic fibres which are heat compressed to form a 'felt'.

This produces a thick, dense felt which is less flexible and harder to mould to a non-flat surface.

Test A1

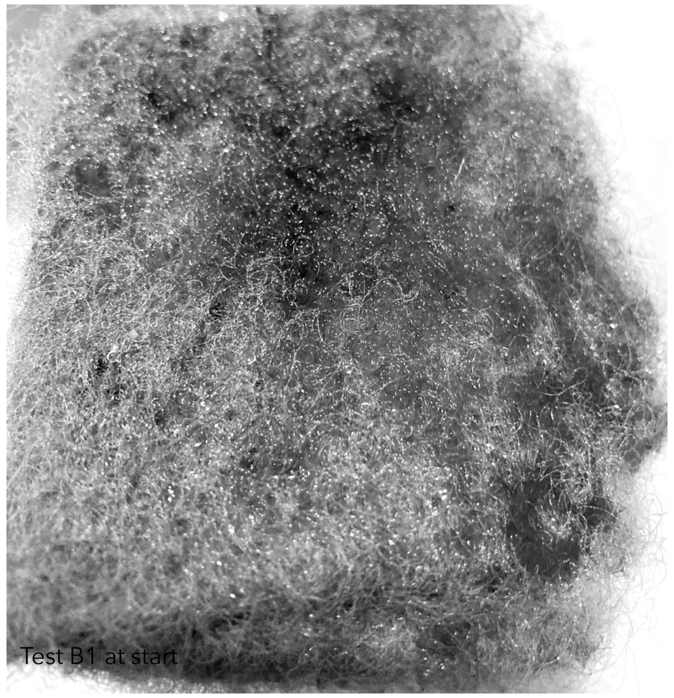


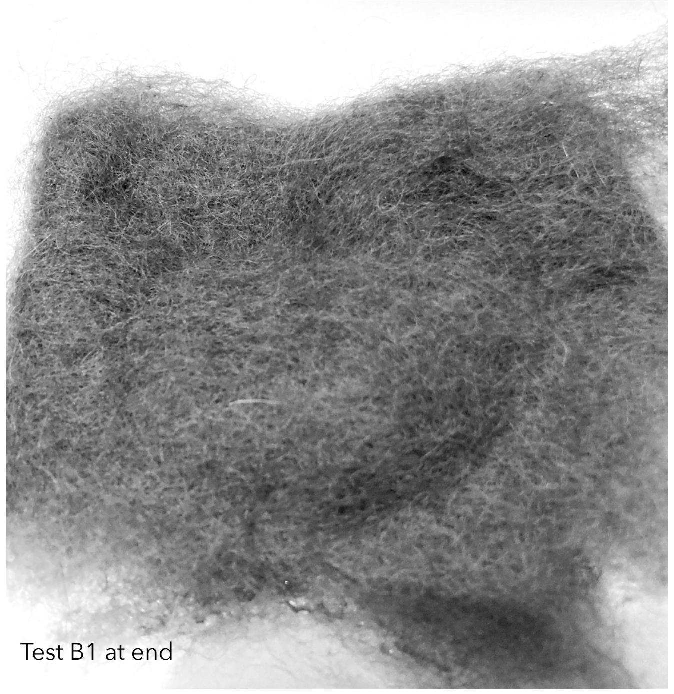
Test A2

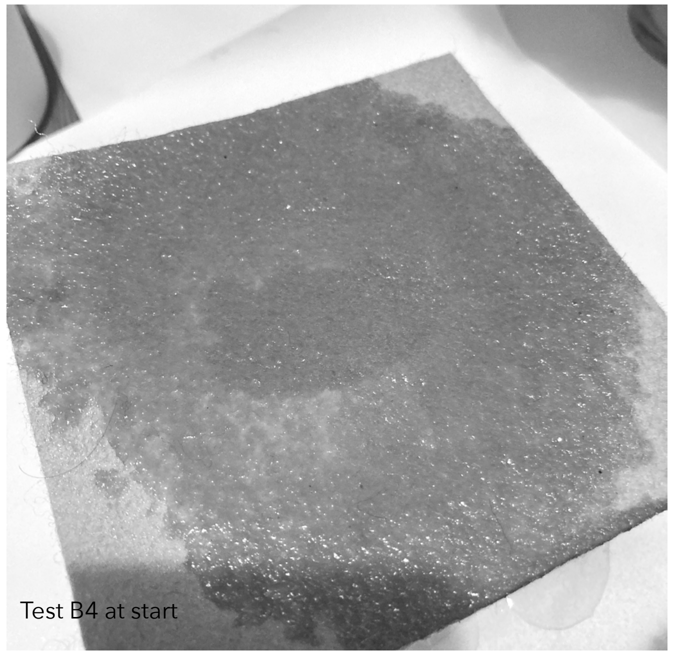
INITIAL TESTS: WATER PERMEABILITY

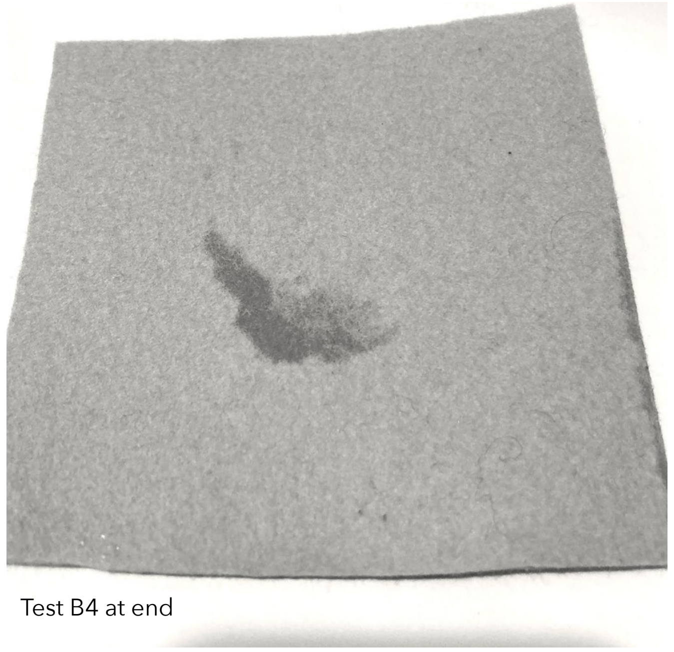
The first step was determining whether pre-felted wool, or loose carded wool batts (wool fibres) were better, both at repelling water, and attaching to clay.

TEST NUMBER	***A1***	***A2***	***A3***	***A4***	***A5***	***A6***
MATERIAL	Needle-felted Sheeps wool	Industrial Pressed wool felt	Needle-felted Sheeps wool	Industrial Pressed wool felt	Needle-felted Sheeps wool	Industrial Pressed wool felt
THICKNESS	10mm	4mm	4mm	4mm	15mm	4mm
TEXTURE	Some loose fibres on surface. Sponge-like	Dense and smooth	Some loose fibres. Thin and delicate	Dense and smooth	Thick but light, still sponge like and less dense.	Dense and smooth
APPLICATION	5ml rested on surface	5ml rested on surface	5ml rested on surface	5ml rested on surface	5ml rested on surface	5ml rested on surface
TIME UNTIL WATER PENETRATION	NA Water never fully penetrated	4 hours	35 minutes	3 hours	NA Water never penetrated	5.5 hours
OBSERVATIONS	Water spread along fibres laterally, moving through layers but never all the way before evaporation (10hrs)	Did not spread across surface. Soaked slowly through submerged area, then started dripping from underside at 4hrs	Water spread along fibres laterally as A1, but moved down through thin density quickly before dripping out the underside	Same as test A2: no lateral spread of water. Penetrated through area covered by original water drop.	Water spread across surface but appeared to hold at top surface more. After 24hrs observation no water was visible on either side	Same as A2 and A4: appears that water can pass through compressed fibres in one location creating channel once through.


Test B1 at start


Test B1 at end


Test B4 at start


Test B4 at end

INITIAL TESTS:
WATER PERMEABILITY

TEST NUMBER	B1	B2	B3	B4
MATERIAL	Needle-felted Sheeps wool	Industrial Pressed wool felt	Needle-felted Sheeps wool	Industrial Pressed wool felt
THICKNESS	10mm	4mm	15mm	4mm
TEXTURE	Some loose fibres on surface. Sponge-like	Dense and smooth	Thick but light and sponge-like	Dense and smooth
APPLICATION	Lightly sprayed water every 5mins for 2hrs	Lightly sprayed water every 5mins for 2hrs	Heavily sprayed water every 5mins for 2hrs	Heavily sprayed water every 5mins for 2hrs
TIME UNTIL WATER PENETRATION	NA Water never penetrated	2 hours	NA Water never penetrated	1.5
OBSERVATIONS	Water particles sat as small bubbles across 'hairy' top surface. Water seemed to be dripping off ends rather than pooling in centre.	Water particles quickly joined together to create thin film on top. Repeated spraying made the water soak through fibres.	Same as B1: underside never felt damp and water appeared to stay on upper most layers of felt	Same as B2: water seemed to be absorbed through fibres faster, and ends up passing through full depth of felt, less dripping.

CONCLUSIONS

Industrial felted wool, though denser, seems like the make-up of fibres is such that the water actually can pass through with relative ease.
Needle felted wool, as it is more tangled, acts more like a sponge, absorbing and dissipating the water across the fibres, as long as it is thick enough.

Test C1 (left) and C2 (right)

INITIAL TESTS: ATTACHING TO CLAY

TEST NUMBER	***C1***	***C2***	***C3***
MATERIAL	Needle-felted Sheeps wool	Industrial Pressed wool felt	Industrial Pressed wool felt
THICKNESS	3 layers	1mm	4mm
TEXTURE	Loose wool fibres in carded batt	Smooth and flexible,	Dense and smooth
APPLICATION	Laying fibres onto surface, then felting together on-top of clay	Laying felt material onto surface, sing needle felter to bind to clay	Laying felt material onto surface, sing needle felter to bind to clay
OBSERVATIONS	Wool felted together faster on clay than regularly. Was easy to shape to non-flat surface.	Took a long time to attach. Appears loose and can be pulled off easily.	Did not bind onto clay: felt too dense for needles to pass through.

CONCLUSIONS

Carded wool being needle felted onto clay seemed to be the more versatile material, producing more interesting results in the binding to the clay.

It bound much faster to the surface of the clay, and the tangle between the clay and wool fibres sped up the felting process considerably.


Wet (plastic) clay


semi-dry (leather)


dry clay

INITIAL TESTS: WETNESS OF CLAY

TEST NUMBER	D1	D2	D3
CLAY TYPE	Blårens Wet (Plastic)	Blårens semi-dry (Leather)	Blårens dry
MATERIAL	Needle-felted Sheeps wool	Needle-felted Sheeps wool	Needle-felted Sheeps wool
THICKNESS	3 layers	1 layer	1 layer
TEXTURE	Clay: wet and mould-able. Not sticking to fingers	Clay: cold to touch and can be shaped but takes force.	Clay: cold to touch but solid: cannot be moulded. Brittle.
APPLICATION	Laying fibres onto surface, then felting together on-top of clay	Laying fibres onto surface, then felting together on-top of clay	Laying fibres onto surface, then felting together on-top of clay
OBSERVATIONS	Fibres bound well with clay, speeding up felting process and attaching at the same time. Needles penetrated clay easily.	Although felting needles entered the clay surface, the fibres did not bind with clay well, and could be pulled out. Felting was minimal.	Did not bind. Needles could not enter clay, meaning wool could not be felted at all.

CONCLUSIONS

By far the best state for the clay to be in was when it was still considered wet (or plastic) clay. This describes clay that is taken straight from the bag: mould-able and soft, but not sticking to hands.

This was the only time the clay helped the felting process, and allowed the two materials to be bound together well, and even once dried the felt was joined to the clay.

OBSERVATIONS

Warping from pressure: form must be stable when being felted.

Needles poking through: must have a minimum depth

DENSITIES OF NEEDLE FELT

INITIAL TESTS: LIGHTLY FELTED

TEST NUMBER	E1	E2	E3	E4
MATERIAL	Grey carded wool	Grey carded wool	Norwegian wool	Norwegian wool
NUMBER OF LAYERS	4	2	3	2
PASSES	10	5	8	3
FINAL THICKNESS	~25mm	~15mm	~25mm	~18mm
FINAL TEXTURE	Sponge like. Some loose fibres	Lightweight and fluffy	Very sponge-like. Compresses when pressed.	Loose and fibrous
OBSERVATIONS	Layers are bound together, but feels loose when moving about. Feels like it could be pulled apart, and is not very strong.	Feels like some felting has occurred, but can still be teased apart. Felt is transparent in places.	Top side much more felted than underside. Density appears to reduce through layers as not much time given to tangle them together, however still feels like one.	Feels very similar to carded wool batt. Only difference is the two layers stay together when picked up.

*Felted area is approximately 140x140mm

Test E3

Test E1

INITIAL TESTS: HEAVILY FELTED

TEST NUMBER	F1	F2	F3	F4	F5	F6
MATERIAL	Grey carded wool	Norwegian wool	Norwegian wool	Norwegian wool	Norwegian wool	Norwegian wool
NUMBER OF LAYERS	4	2	3	4	5	5
PASSES	40	20	20	30	25	35
FINAL THICKNESS	~10mm	~8mm	~16mm	~18mm	~30mm	~20mm
FINAL TEXTURE	Dense but flexible.	Flexible, smooth (ish) surface, with some density	Same as F3, slightly more spongey			
OBSERVATIONS	Took a long time, but density compared to other tests is definitely noticeable.	Easy to bend and feels felted, but still is quite thin: light easily passes through.	Similar in appearance to F2, layers easily felted together, but still feels like it is too thin.	Second most dense after F1. Noticeably starts to felt faster in last 15 minutes.	Top layers feel well felted but lower layers are still loose.	Noticeable difference to F5: thinner and feels more robust. Felted through.

*Felted area is approximately 140x140mm

CONCLUSIONS

Heavier felts feel much more robust, and like they will protect clay best.

They take much longer to felt though, and will need to consider parameters carefully when converting to robotic felting technique.

Test F2

Test F5

TEST EXPERIMENTS: leaving out in rain

To test whether the theory of having a woollen felt 'coat' on the exterior of the wool would actually protect the surface of the clay, I produced a series of test tiles covered with different layers and densities of felt, with one tile fully exposed.

These were then placed outside on raised plinths, and exposed for 14 days to the autumnal wind and rains of Copenhagen.

THE TILES

CONTROL: T0

layers of wool: 0

start weight: 597g

start dimensions: 128x130

application: none

observations: thicker than other tiles, weighs most.

T1

layers of wool: 2

start weight: 440g

start dimensions: 126x129

application: felted all at once

observations: quick to bind felt, doesn't feel thick though.

T2

layers of wool: 1

start weight: 244g

start dimensions: 99x100

application: all at once

observations: felting holes visible and clay can be seen through felt

T3

layers of wool: 5

start weight: 303g

start dimensions: 134x96

application: all at once

observations: takes a long time to bind to surface. Feels spongy.

T4

layers of wool: 4

start weight: 219g

start dimensions: 107x83

application: two layers at a time

observations: first two layers bind well, second two do not bind well to original layers, making them feel loose and unstable.

T5

layers of wool: 3

start weight: 336g

start dimensions: 112x113

application: two layers together, third on-top.

observations: same as 04: top layer feels unstable. Was very hard to bind.

T0

layers of wool: 0

final weight: ~520g

% difference: -12.9%

final dimensions: NA (crumbled)

observations: tile had fully crumbled. When picked up it dissolved into multiple small pieces

T1

layers of wool: 2

final weight: 430g

% difference: -2.3%

final dimensions: 126x128mm

observations: when it was raining, could see that rain was penetrating the wool

T2

layers of wool: 1

final weight: 255g

% difference: 4.5%

final dimensions: 98x100mm

observations: tile is still wet even after not being exposed to rain for over 24h. Tile has cracked, but wool keeps it in place

T3

layers of wool: 5

final weight: 302g

% difference: -0.3%

final dimensions: 134x96mm

observations: seems most robust of all tests felt seemed to stay in place and tile still appeared solid afterwards

T4

layers of wool: 4

final weight: 218g

% difference: -0.5%

final dimensions: 107x83mm

observations: second most robust tile. Wool stays fixed in place even in high winds, but could still see some water penetration during rain

T5

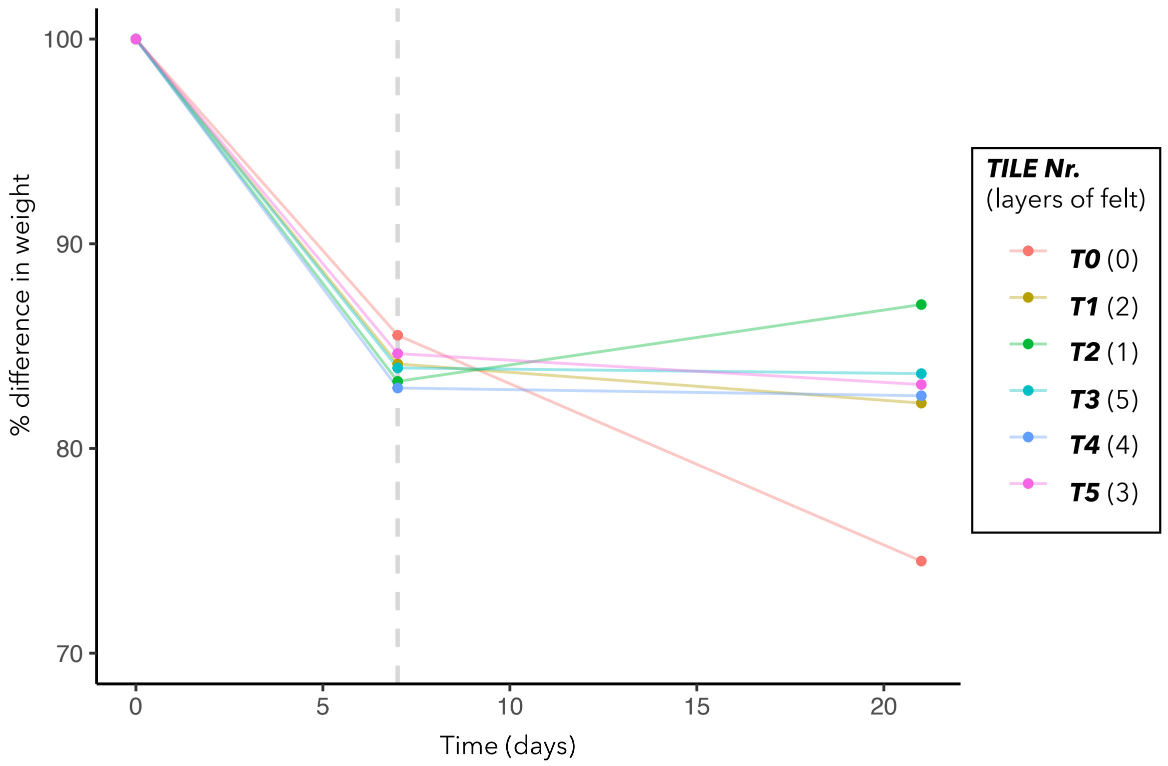
layers of wool: 3

final weight: 330g

% difference: -1.8%

final dimensions: 112x113mm

observations: although protected tile, wool was extremely loose and seemed less protective than other tiles



The graph shows the % weight loss of all the tiles over time.

The control tile had the biggest difference, completely crumbling within the 14 days. However the rest of the tiles stayed intact, with only minimal losses were found.

Its also worth noting that the Green line for Tile 2 had a gain of weight, as even though it was protected and held together thanks to the one layer of felt, it had still absorbed water and was wet even after 24 hours of being inside.

CONCLUSIONS: SET PARAMETERS

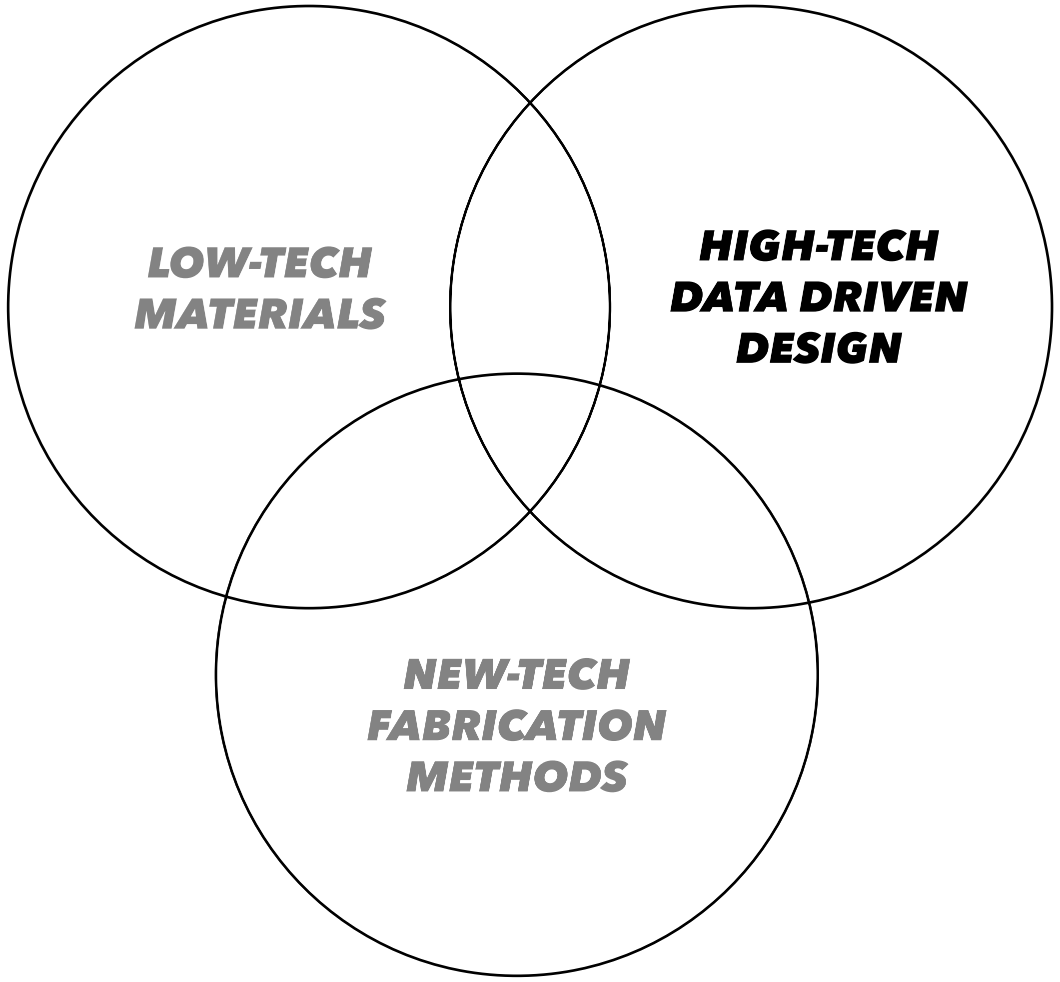
- Clay extrusion must be a minimum thickness to withstand pressures from felting.
- Wall must still be 'wet' for felting
- Needle felting must be 'woodpecker' motion to clay
- Density and number of layers of felt: must be at least 4 layers, and felted together. The denser the better.

DEVELOPMENT: AUTOMATING THE PROCESS

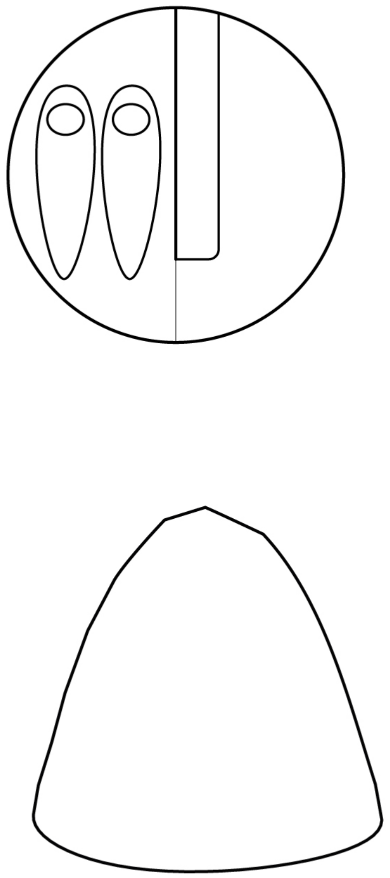
Robotic felting, unlike by hand, cannot see and adjust its pathways or intensity intuitively. It requires set target points and pre-programmed motions based on a precise form. Incidentally, 3D printing produces exactly that. However, the interaction between the two processes must be considered.

The overall form of the structure is also developed with the structural limitations of unfired clay, and whether the form can physically be felted robotically (considering the Euler angles of the arm, and the dimensions and reach of the tool head).

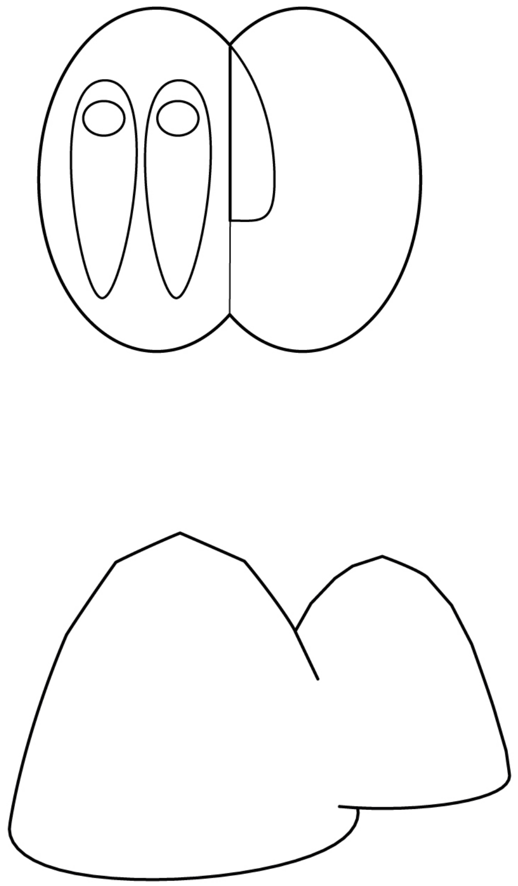
The design of the shelter is informed by all these parameters, using them to drive the form just as much as traditional architectural considerations of location and site analysis do.


LOW-TECH MATERIALS
HIGH-TECH DATA DRIVEN DESIGN
NEW-TECH FABRICATION METHODS

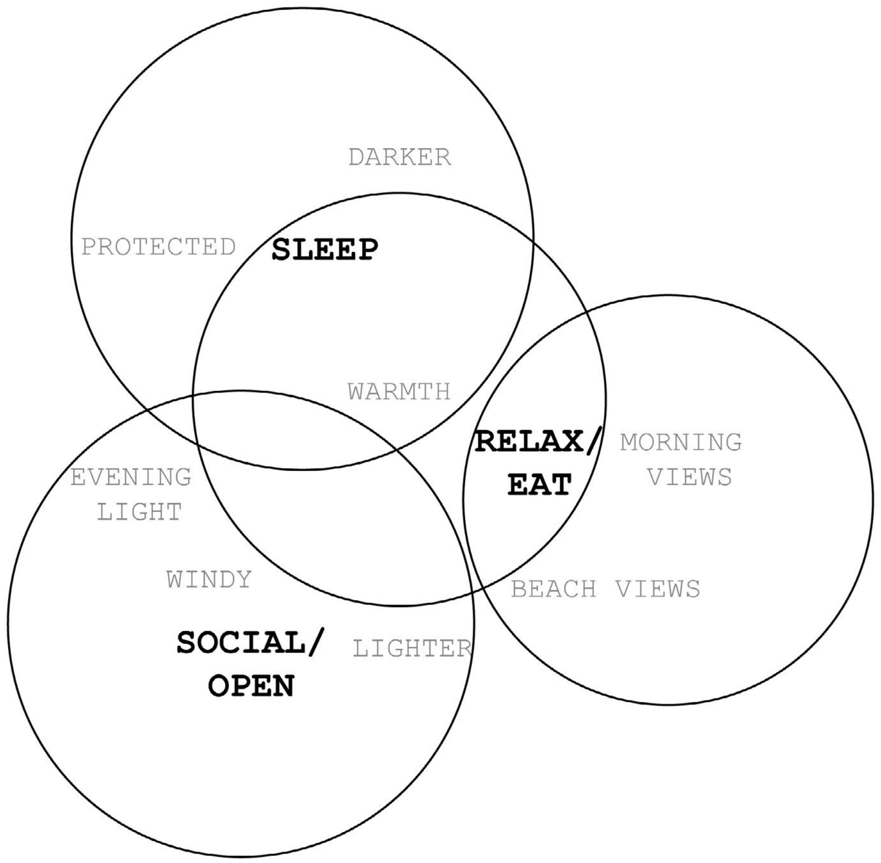
A COMPRESSION ONLY SHELTER



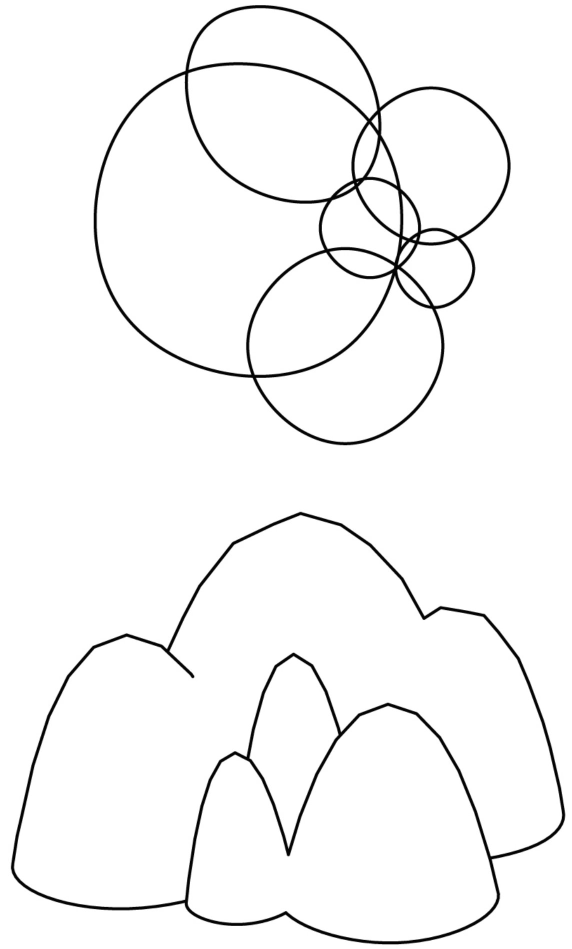
01
Basic compression only dome



02
Doubling up: separating sleeping area

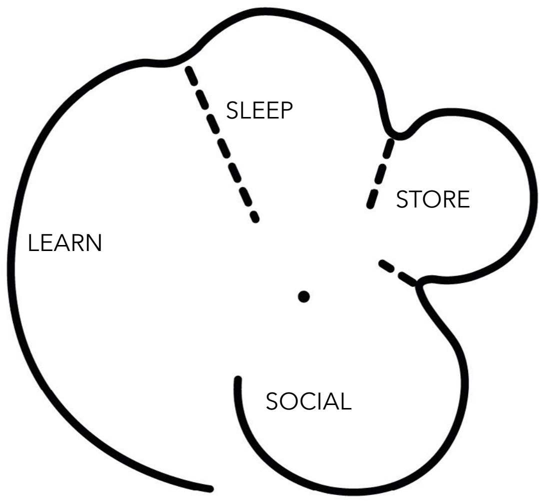


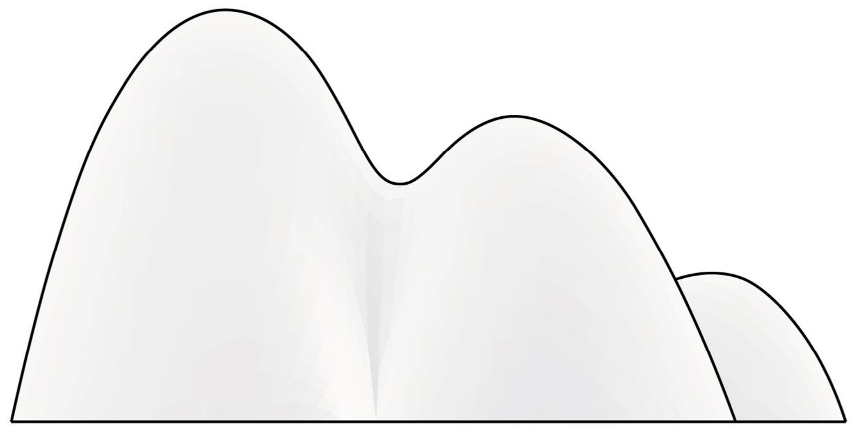
03
Reviewing design aims based on site location

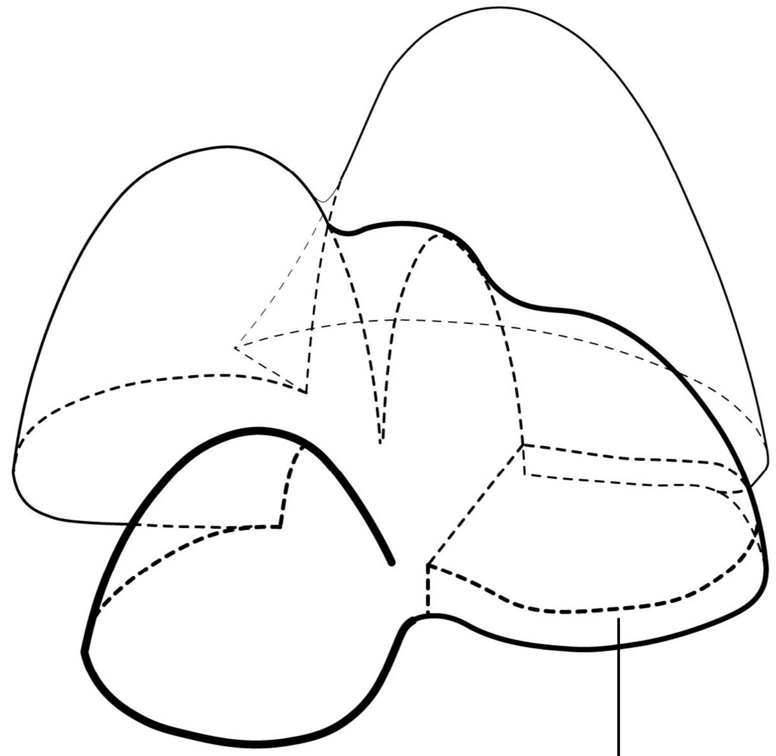


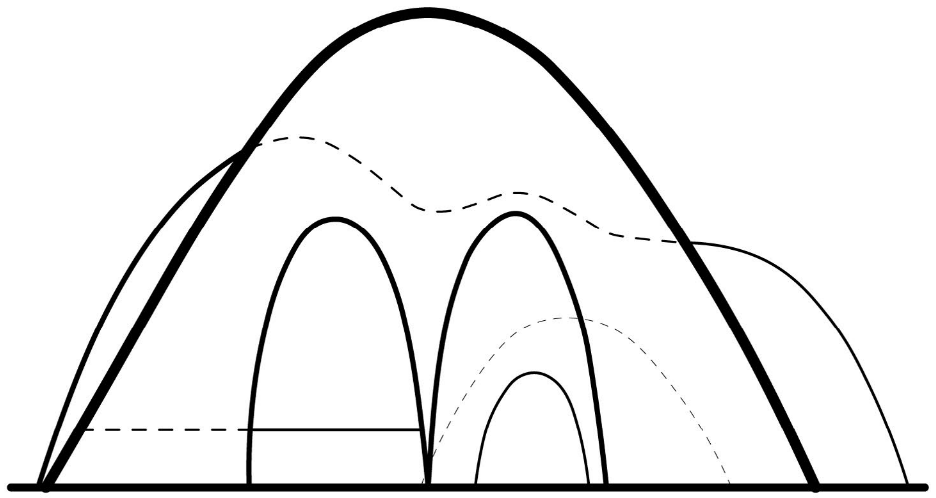
04
Increasing complexity: more spaces and more functions for divers users

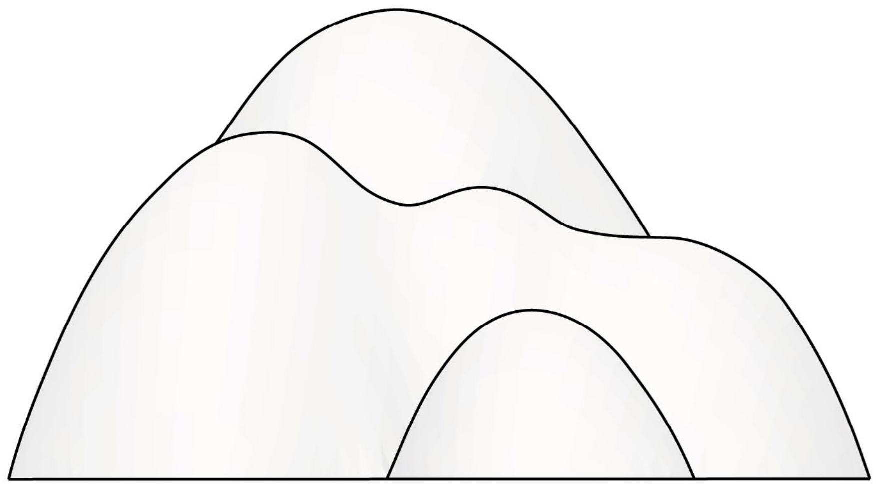
KANGAROO: COMPRESSION ONLY FORM FINDING

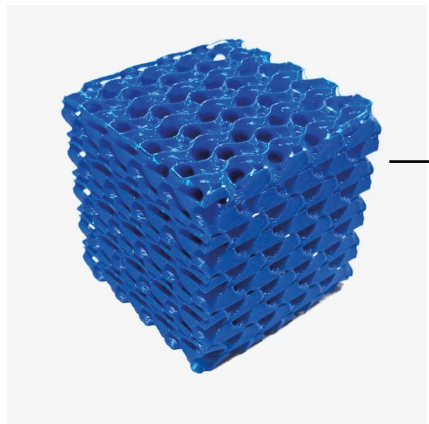








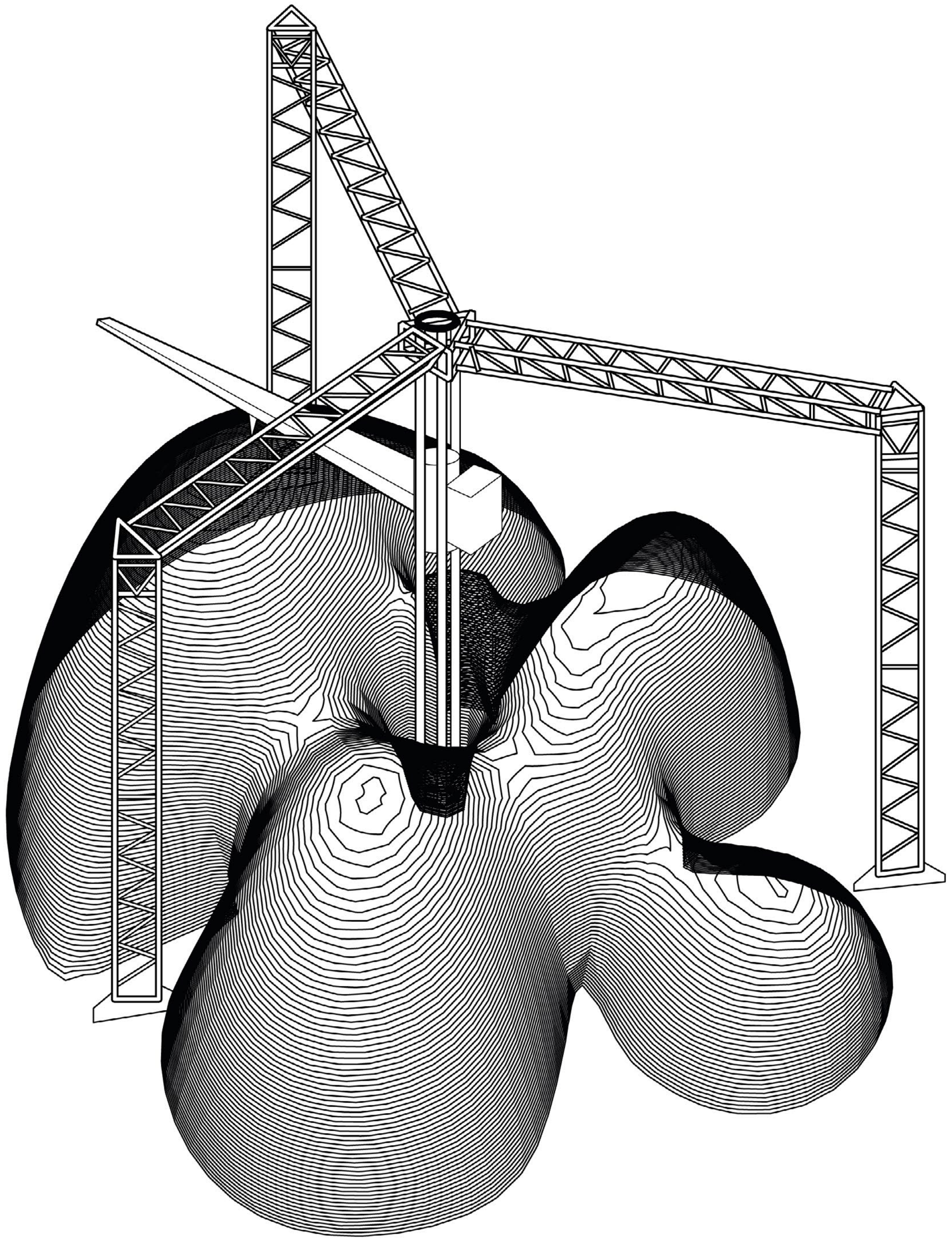




Incorporating a raised sleeping area with honeycomb structure printed below: trapped air and clay making a 'warmer' surface to sleep on

Using Grasshopper Kangaroo form finding:
Creating a flowing compression-only structure from initial anchor points and gravity loads.

FABRICATION TEST

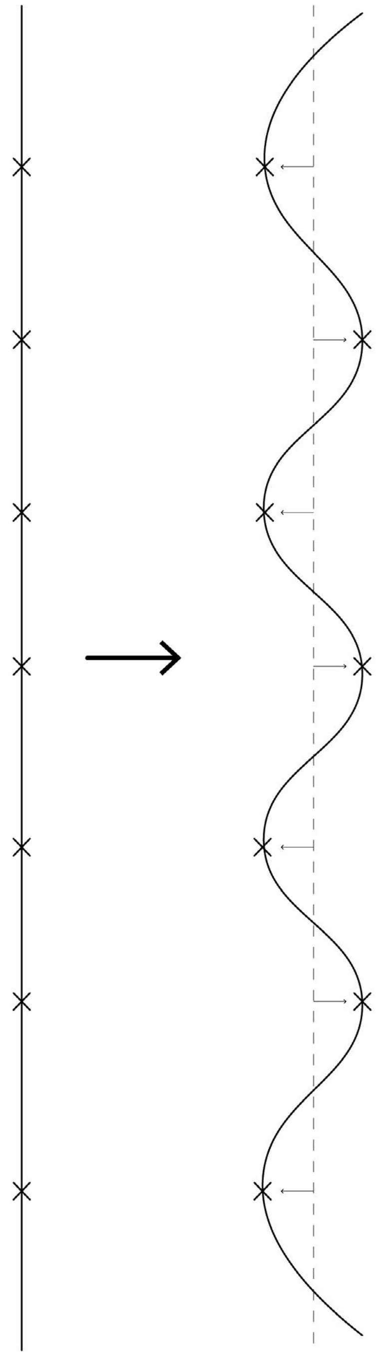


The print was scaled, so the extrusion would be 100mm at full scale, however critical failures at multiple points show structure would need added supports during construction or a changed geometry.

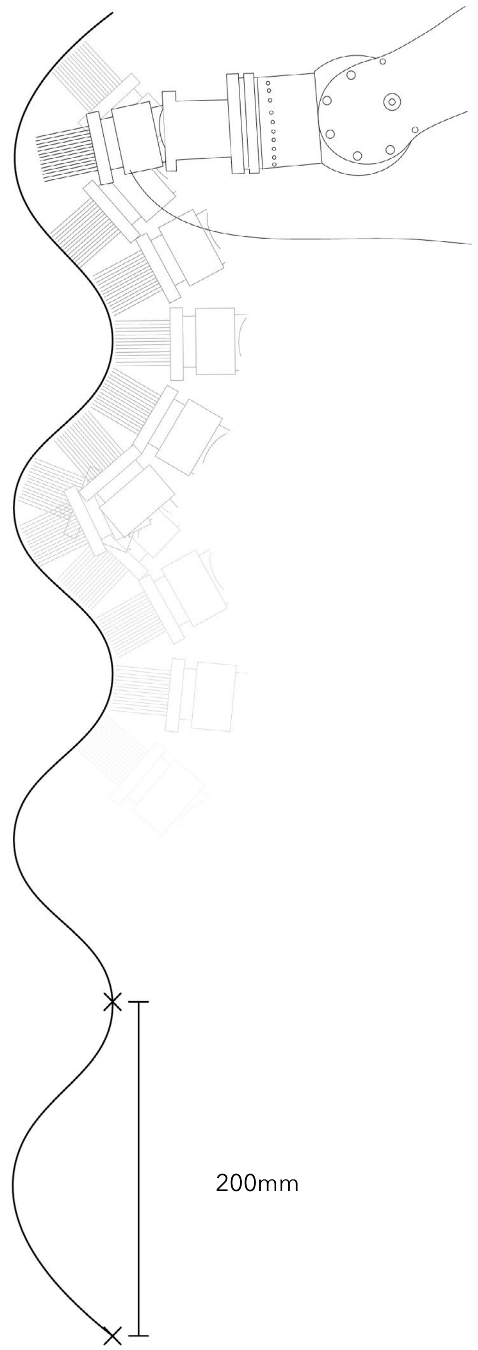
Openings and overhangs of some print paths showed that the overall form was also unstable, and would need:

- A wider print path
- Adjustments to the contouring
- Adjustments to print path to make more stable

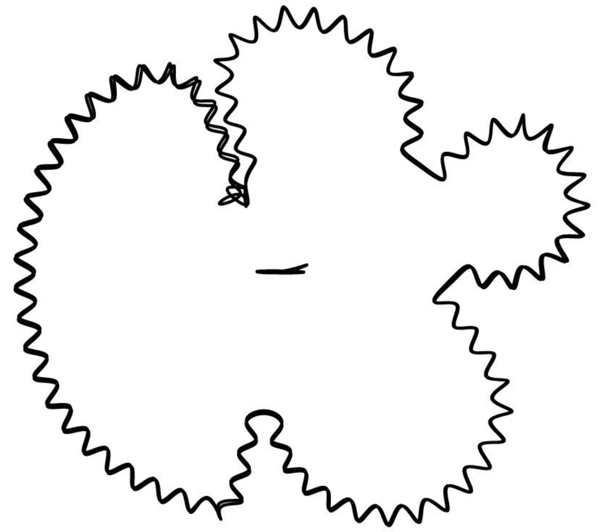
FORM DEVELOPMENT: ADDING STRENGTH

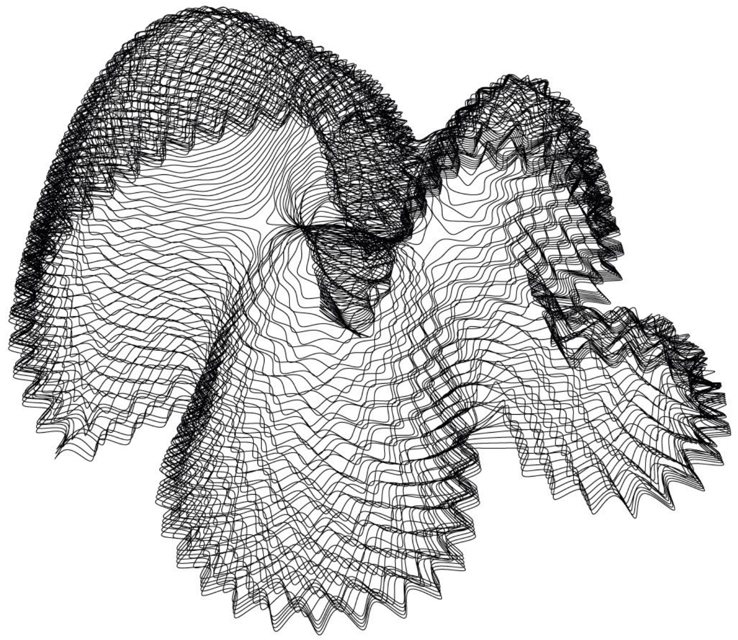


Add a sinus wave pattern to line to add depth to line, increasing stability in print.



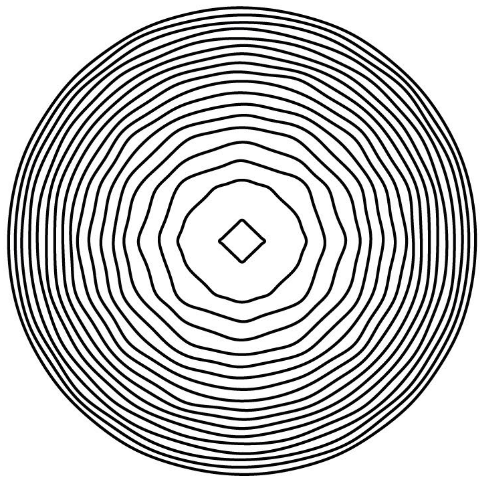
Ensuring rib is wide enough to allow for felting arm to work



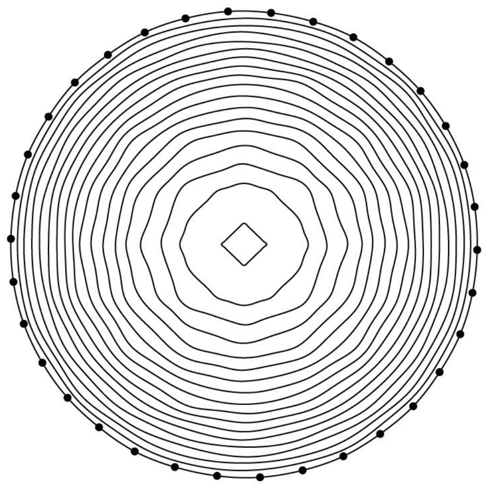


Adding of sinus curve directly to contours
Creates uneven effect which would be extremely hard to felt onto, and also doesn't appear to add any visual quality or structural integrity.

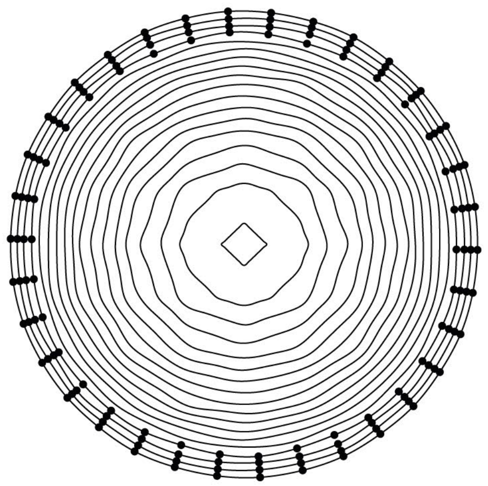
RETHINKING DESIGN FLOW FOR CREATING RIBS



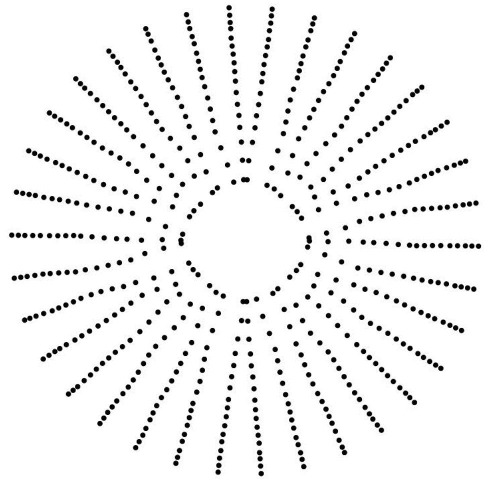
Contour dome(s)



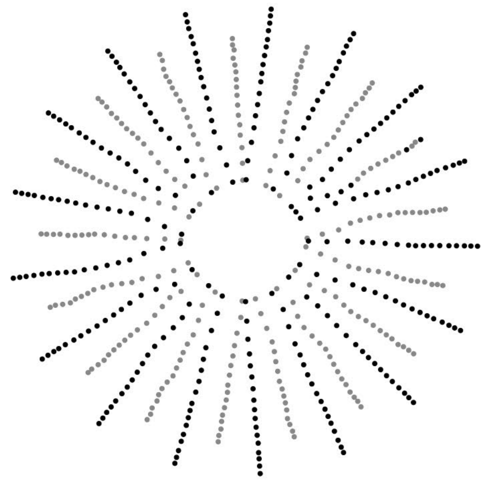
Divide base curve by set amount (close to 200mm to allow felting to work)



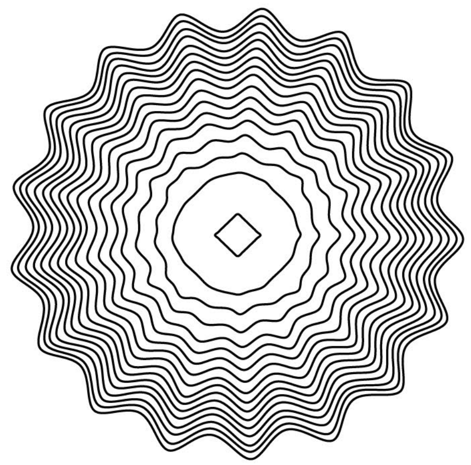
Using an anemone script, find the closest point on the curve above



Run the script to flow up every contour, aligning points on each one

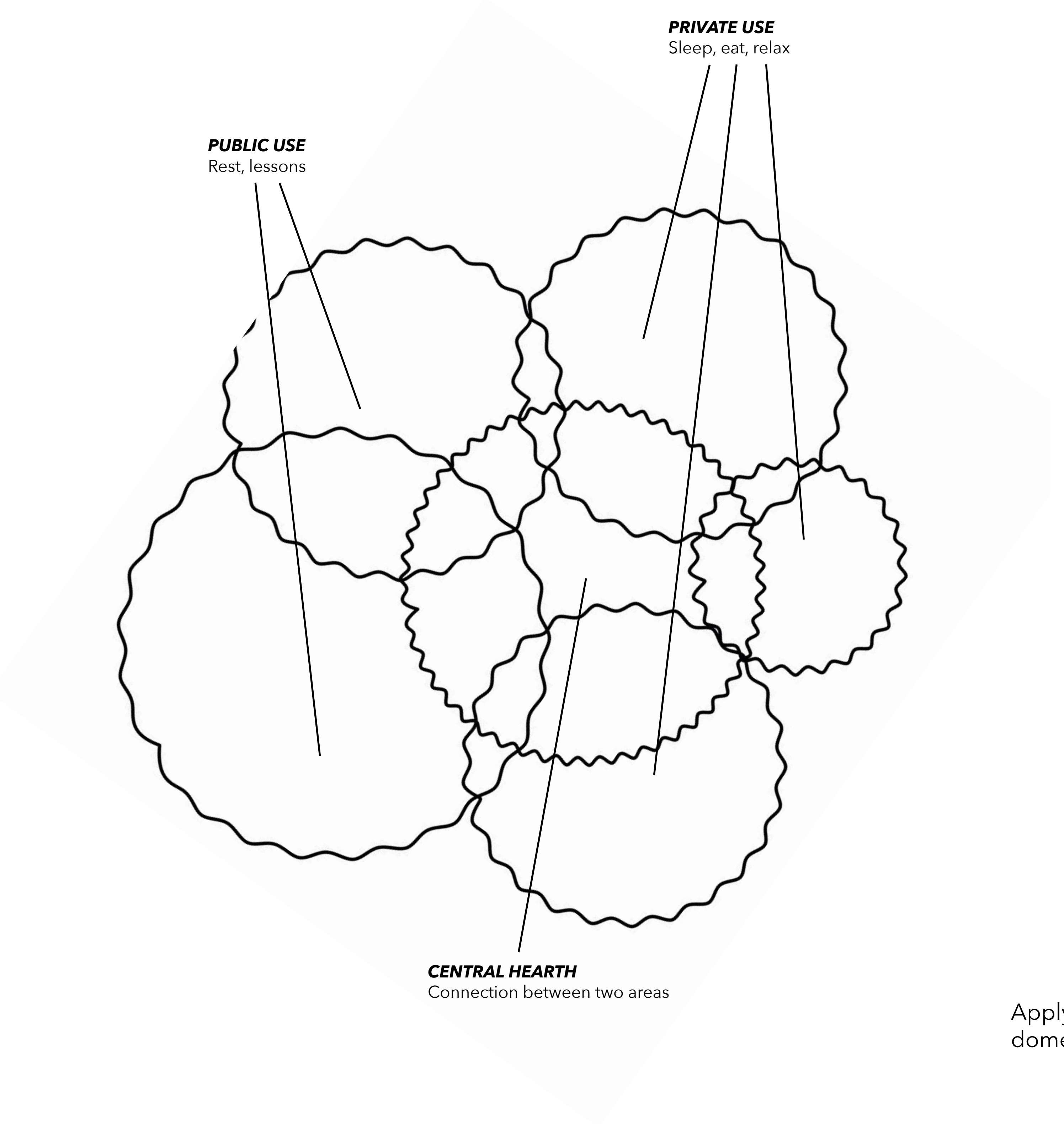


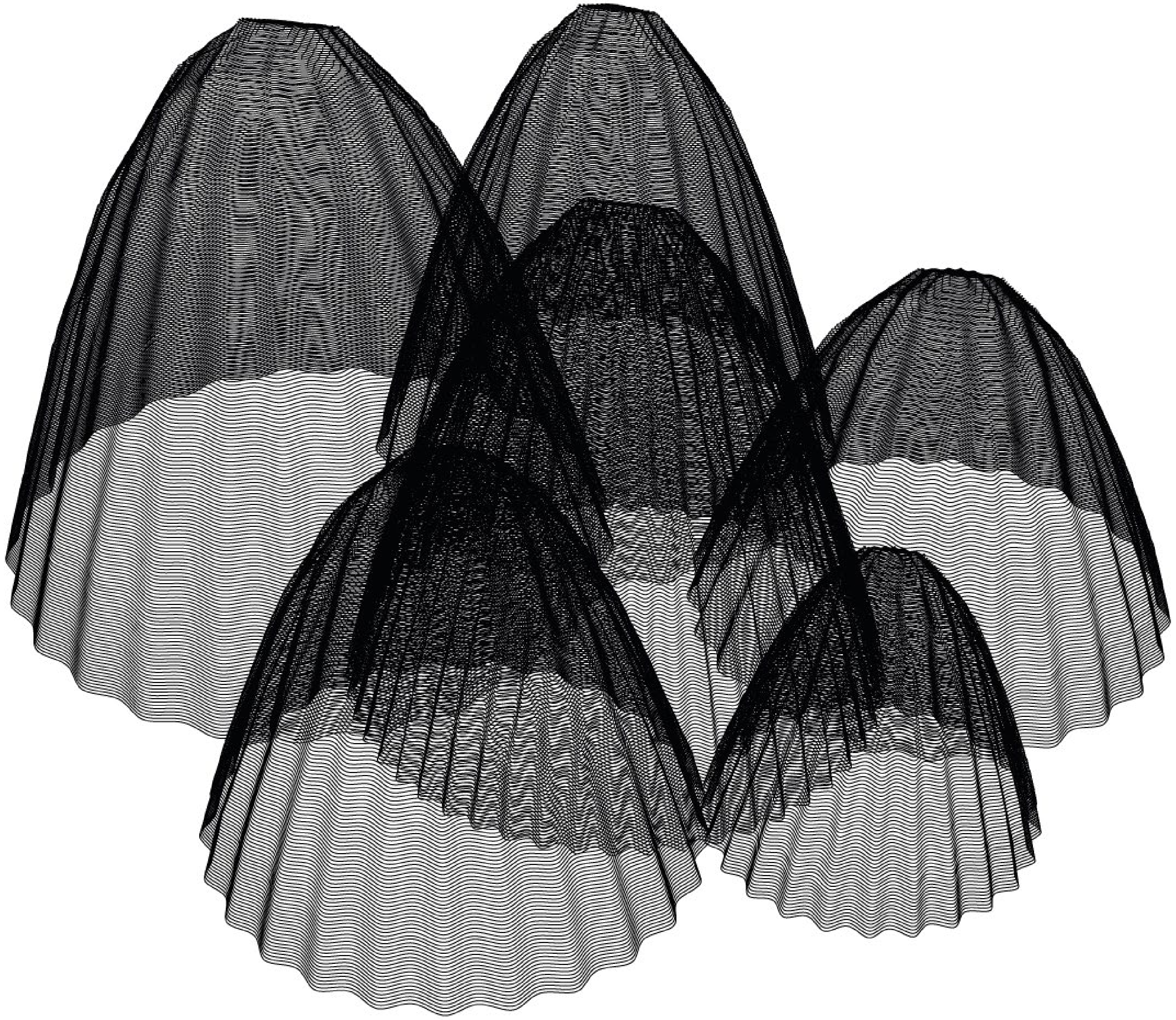
Select every other point and pull inwards by 200mm



Interpolate curve through each point, re-creating contours with even ribs.

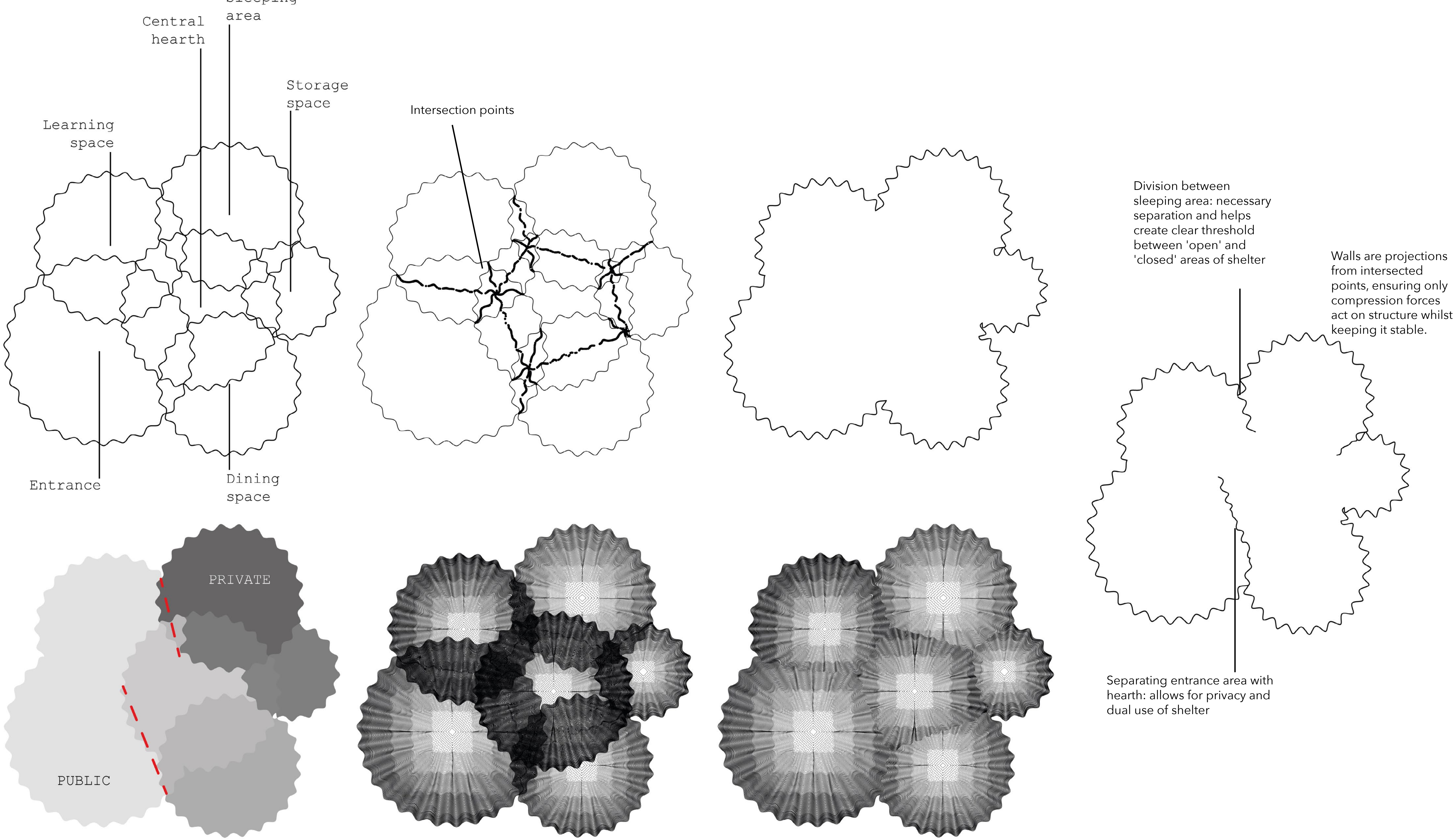
DESIGN DEVELOPMENT





Applying anemone script to individual domes for each zone.

TRIMMING INTERSECTIONS FOR FUNCTIONAL SPACE TRANSITIONS



1
Considering the different functions of the shelter, and what areas are more public and 'open' and what are more private and 'closed'

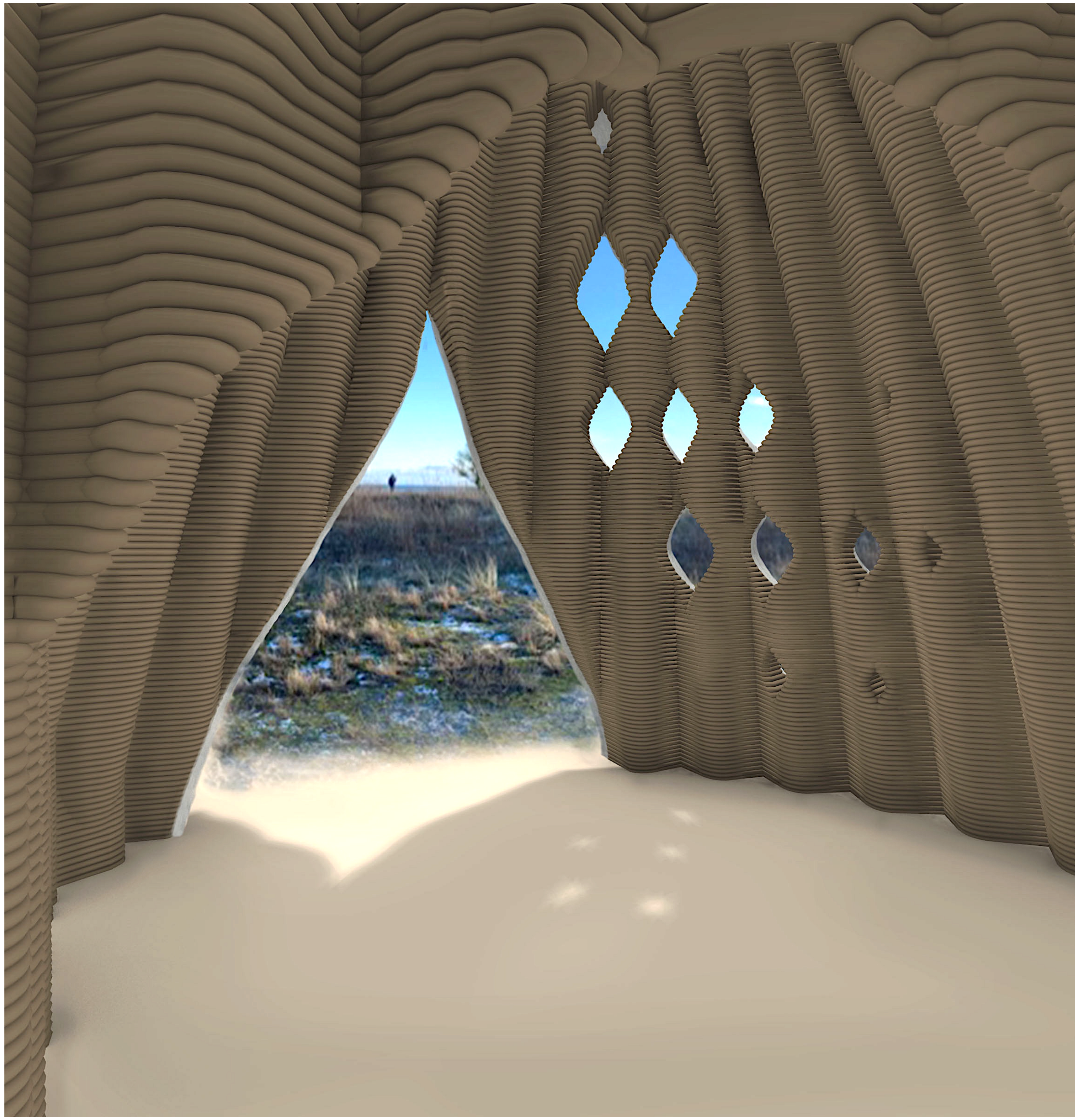
2
Finding all intersecting points between each dome in order to trim and create openings.

3
Trimming all domes at intersections, and joining each contour to create a smooth print path on each layer.

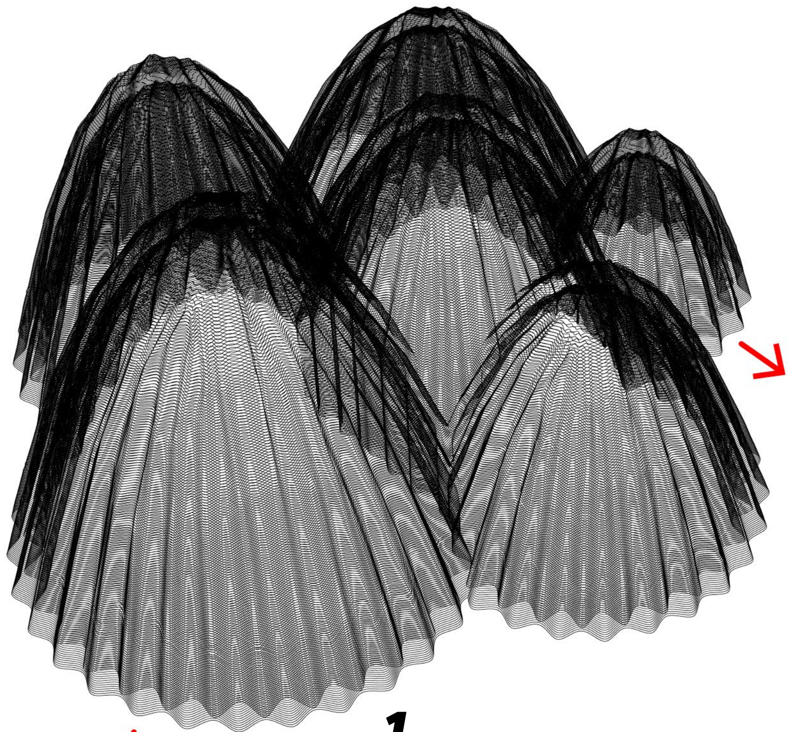
4
Re-inserting separating walls between areas to define space and control movement.

TEST PRINT 02

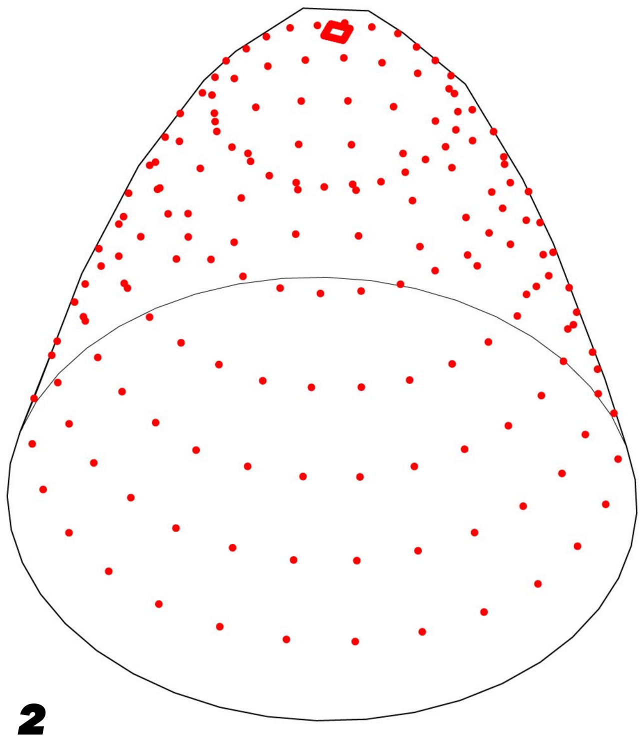
OPENINGS



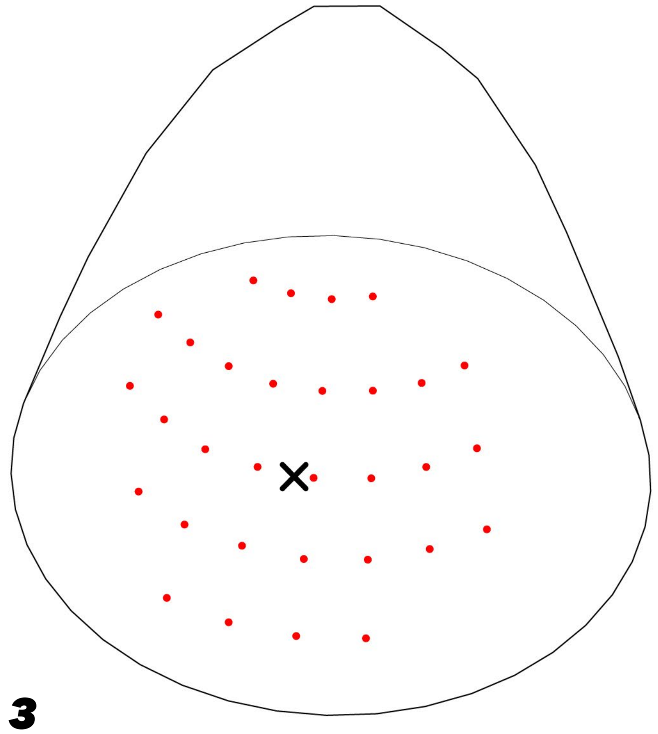
CREATING OPENINGS: ATTRACTOR POINTS



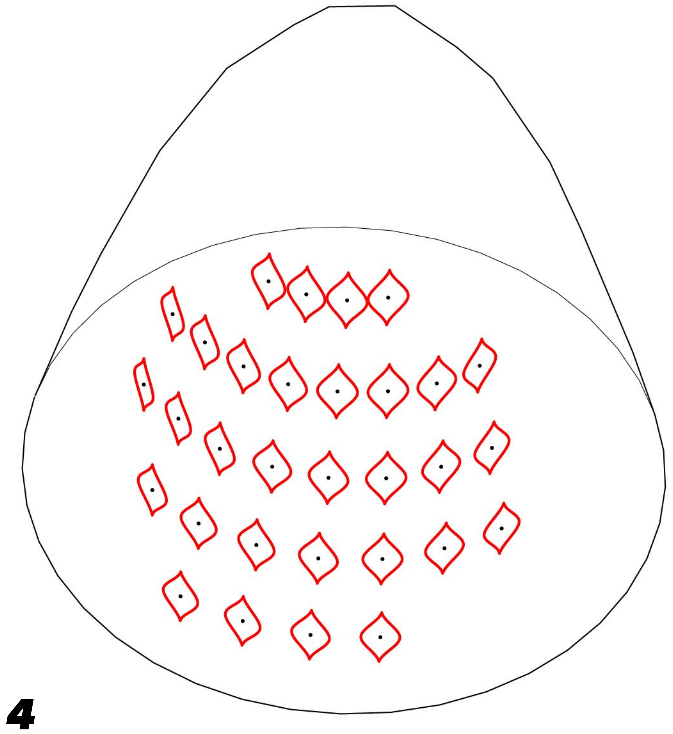
1
Determining where openings should be based on the site



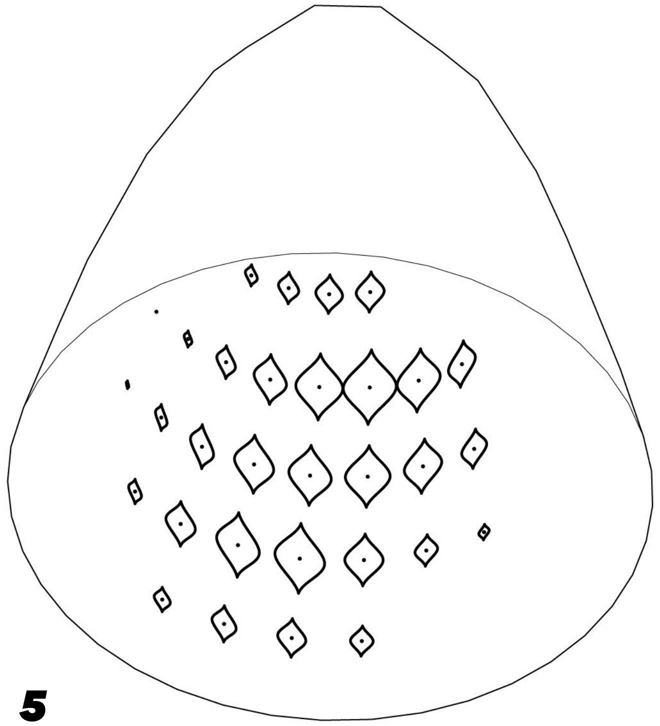
2
On selected dome, filling area with points to act as centre points of openings



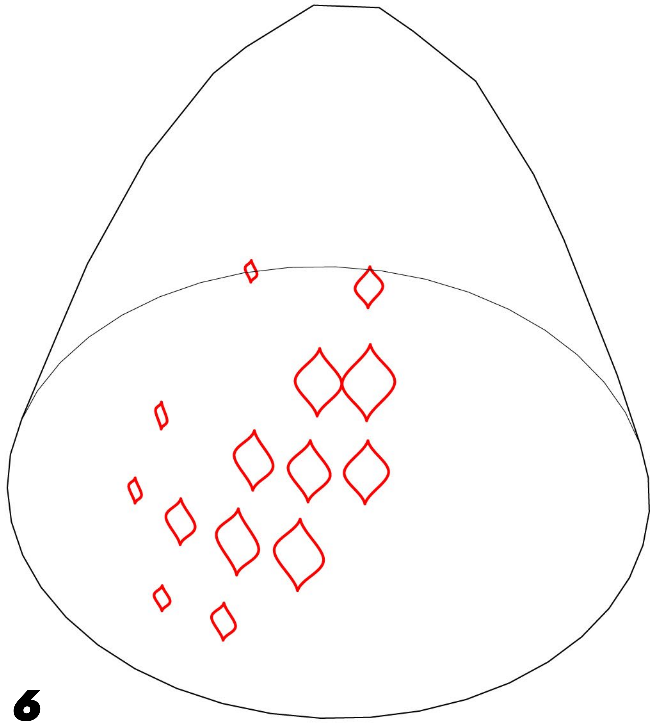
3
Reducing points based on distance, to only cover a certain area (based on site conditions)



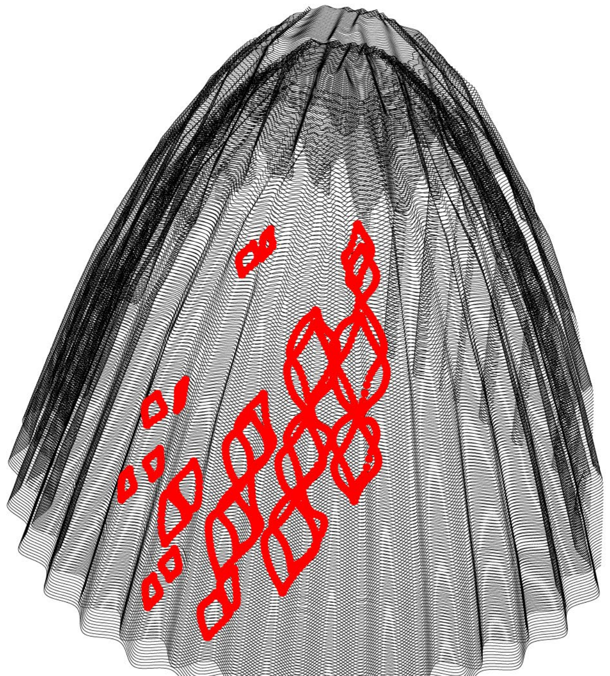
4
Mapping a sinus based curve onto the selected points



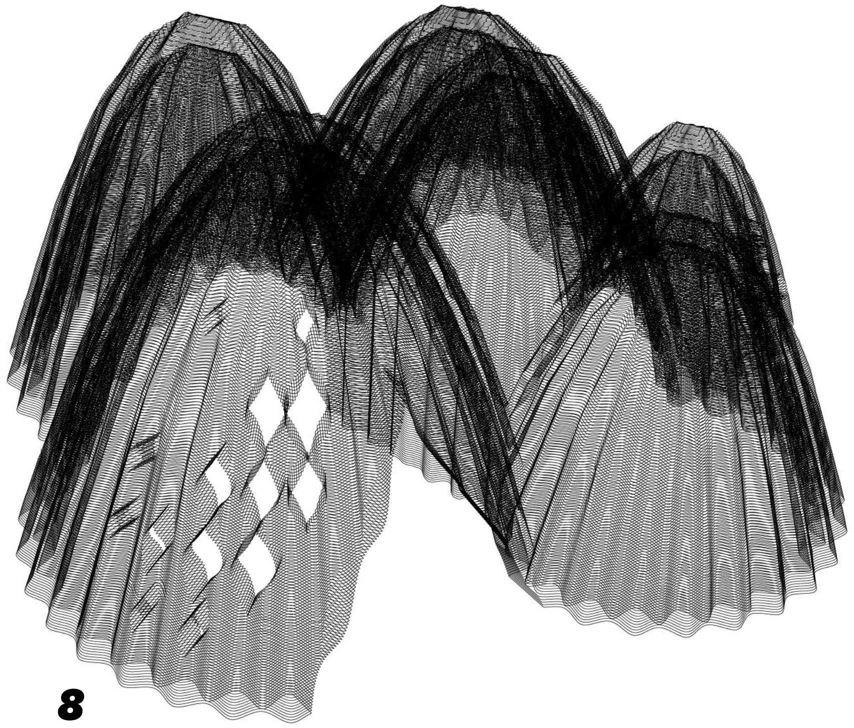
5
Scaling the openings based on attractor point proximity



6
Further reducing the amount of openings with a random reduce algorithm

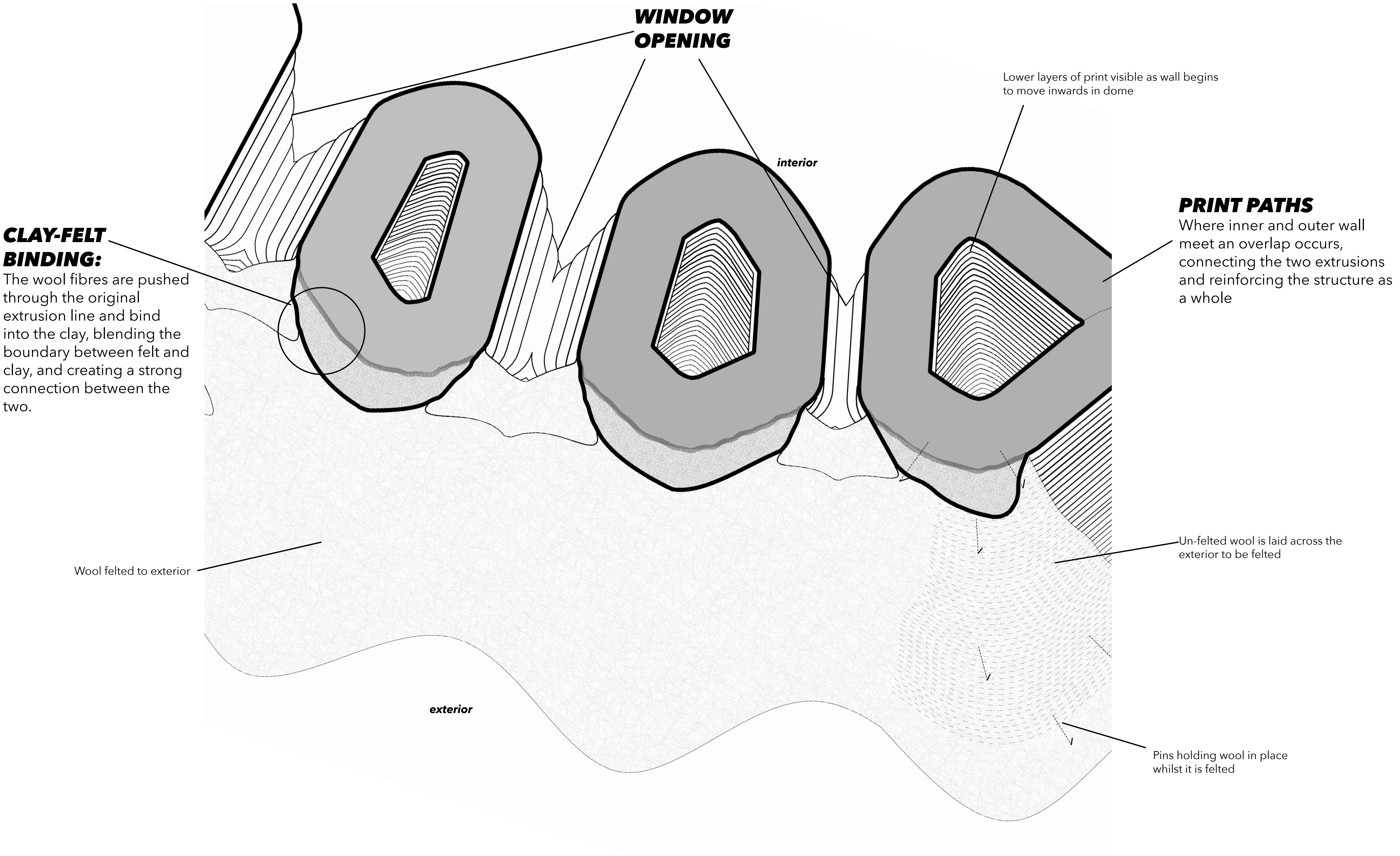


7
Projecting curve points onto the inner and outer contours of the shelter, finding intersection points

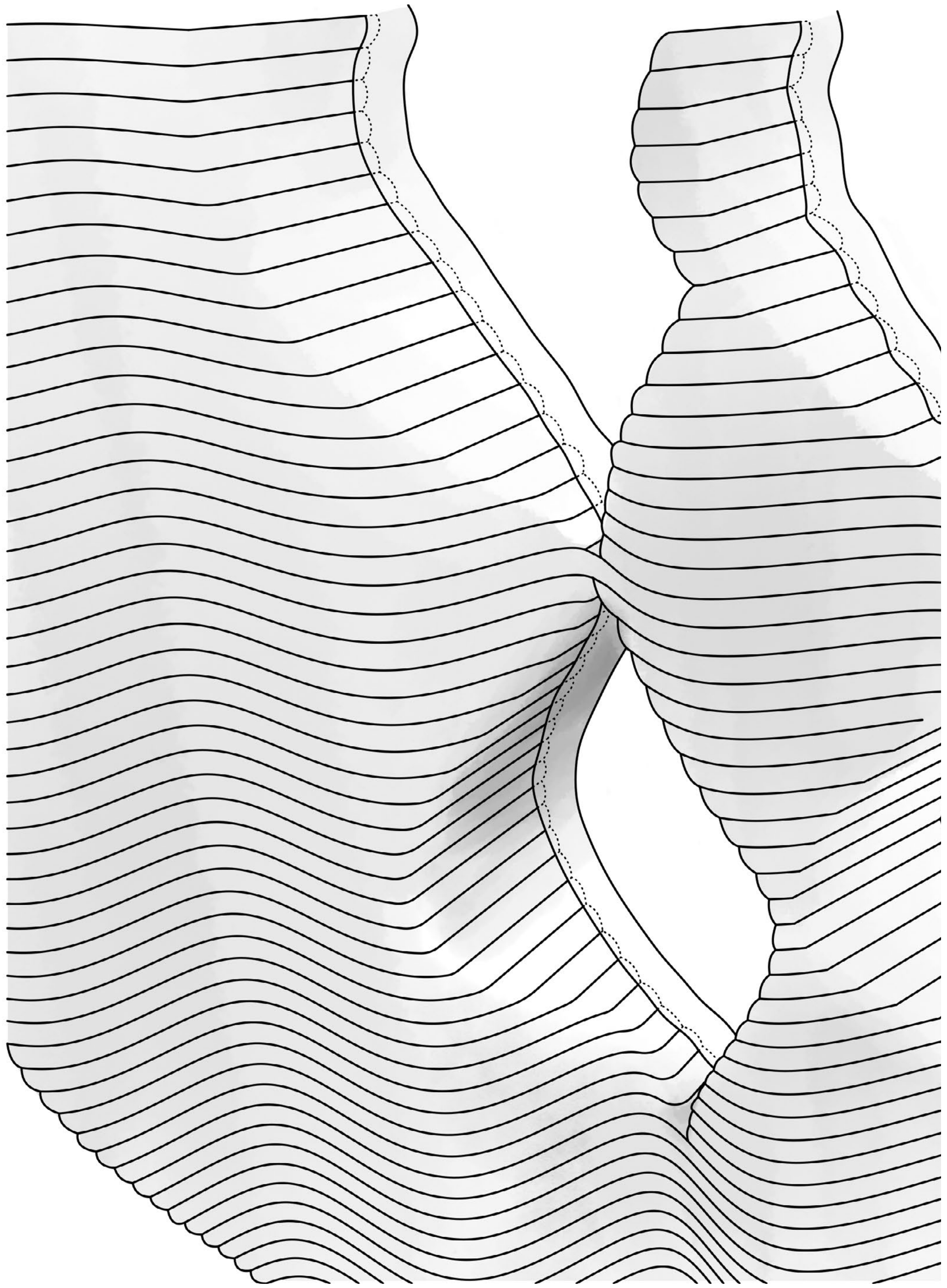


8
Trimming contour curves and connecting inner and outer contours to create smooth paths

DETAIL OF OPENING



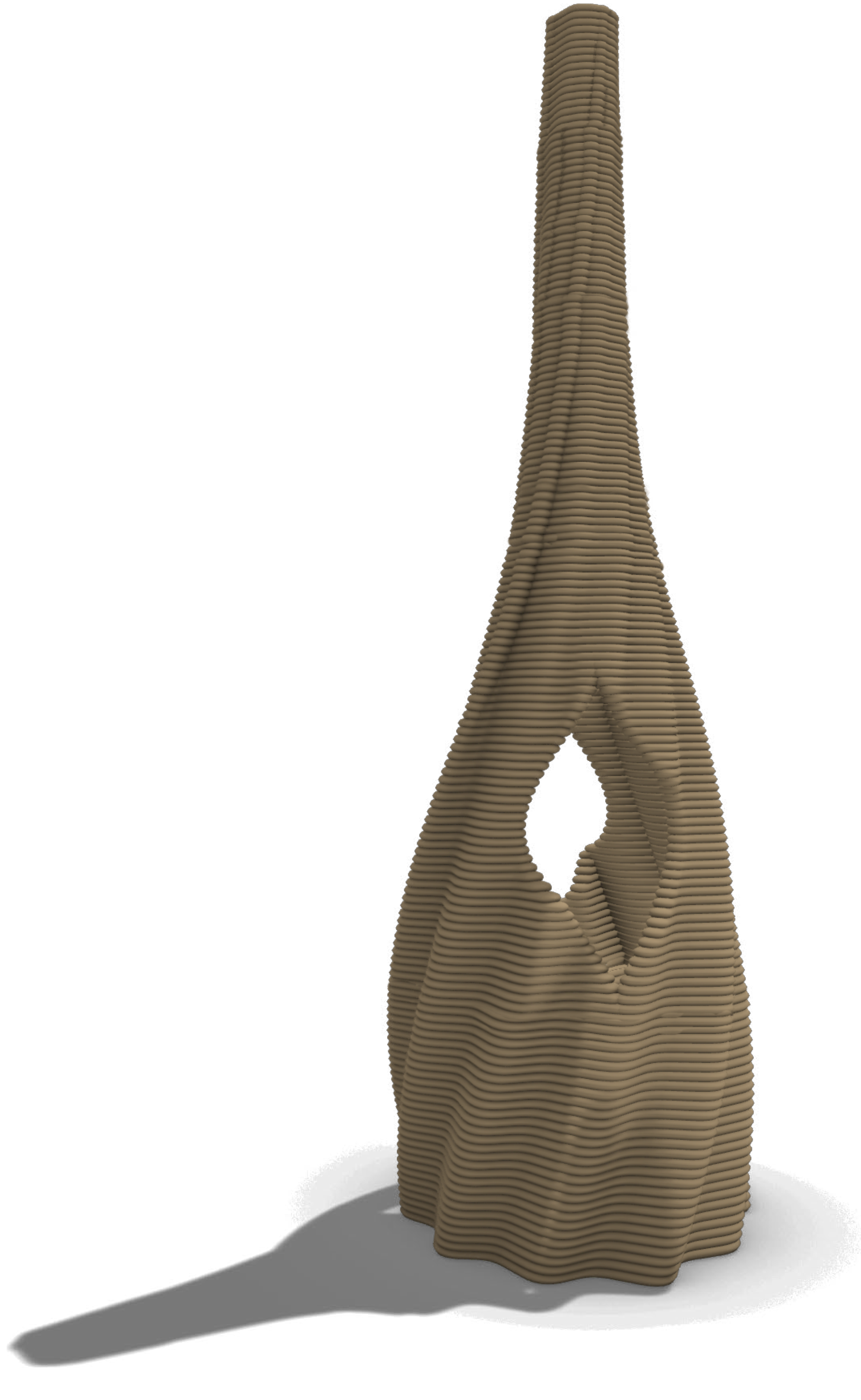
OPENINGS



View of openings from inside

Inside view from prototype

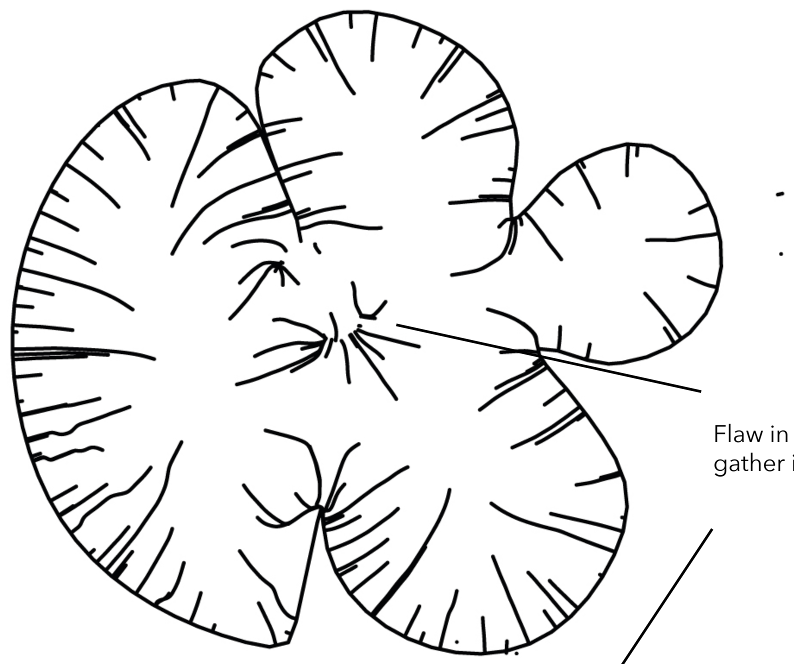
THE CHIMNEY



ORIGINAL RAINWATER SIMULATION

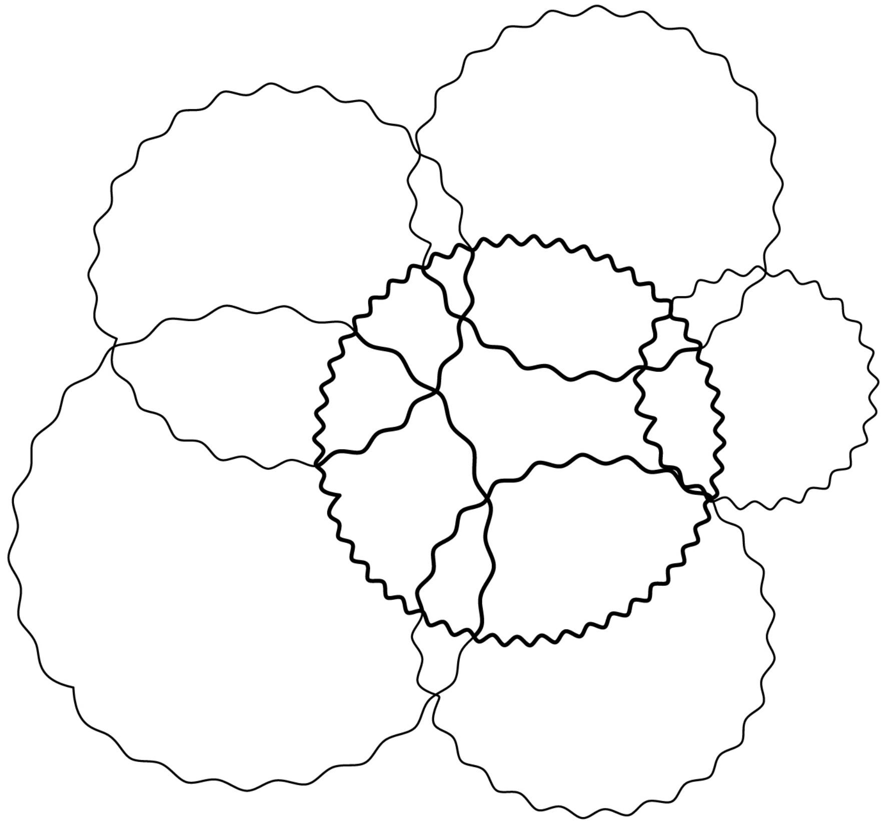
The original plan was to have a central column in the form, which would also act as a chimney for a fireplace, however after running rainwater tests, originally as a possible solution to the rib alignment, It became apparent that this wouldnt be a practical or viable option.

The water would gather and collect, which is something the structural form would not be able to tolerate.



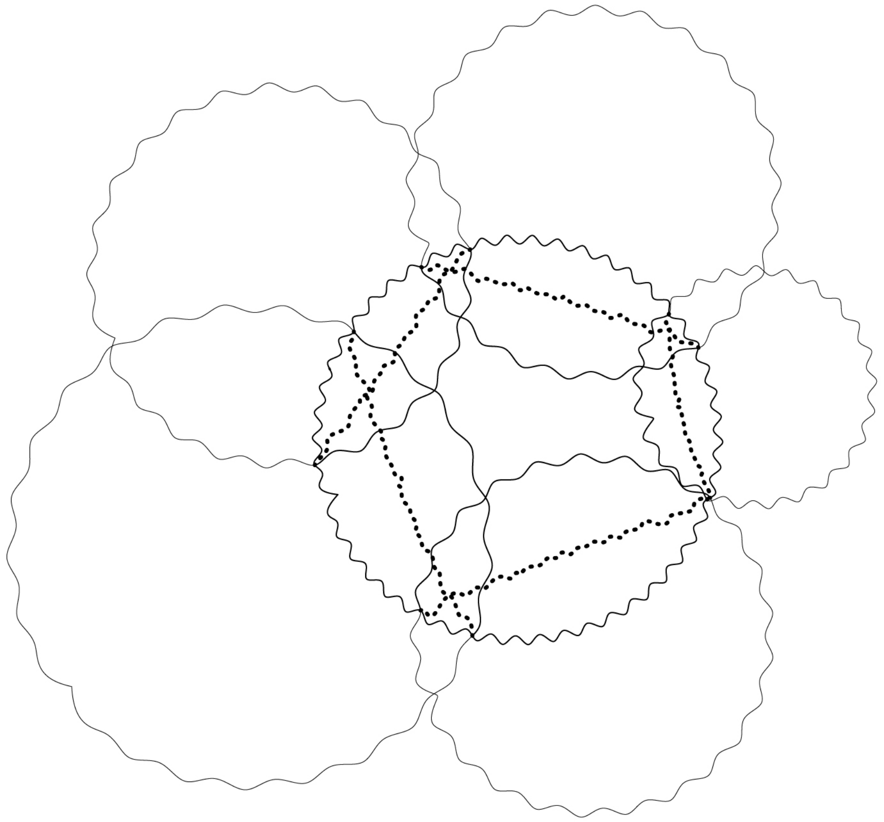
Applying a rainfall simulation to the surface, to get vertical ribs running down building.

THE FIREPLACE



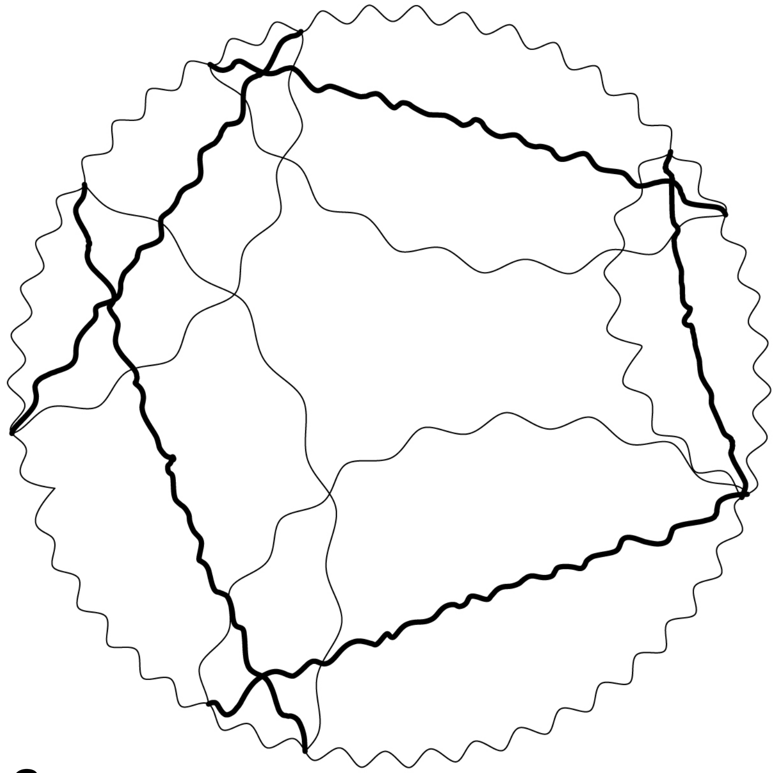
1

take intersecting curves from central dome and surrounding



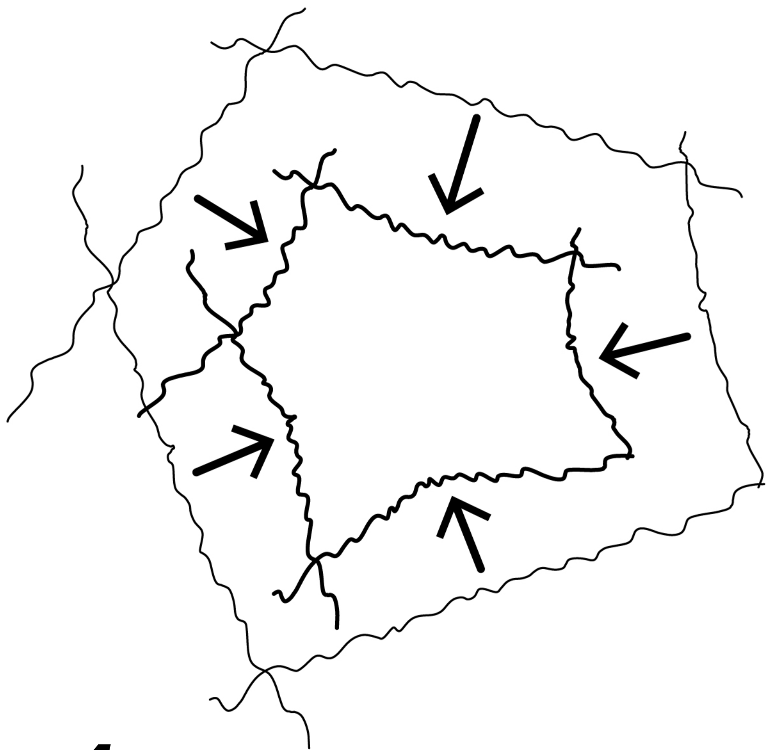
2

Tween between curves



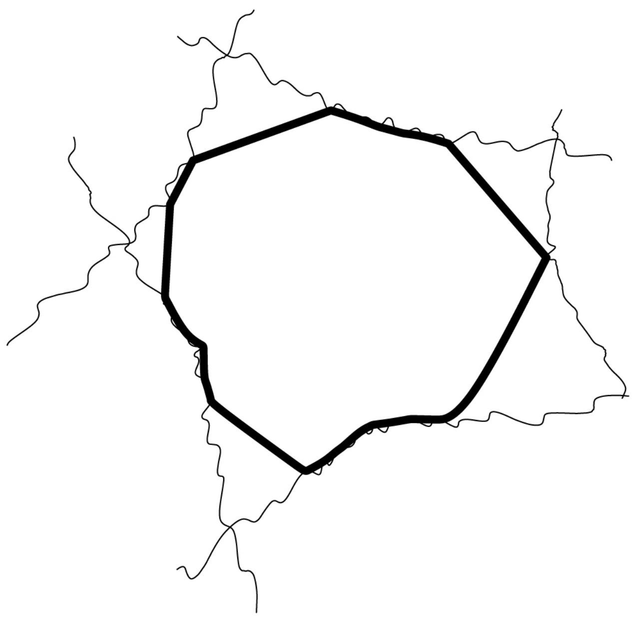
3

Create tweened curve from intersecting points



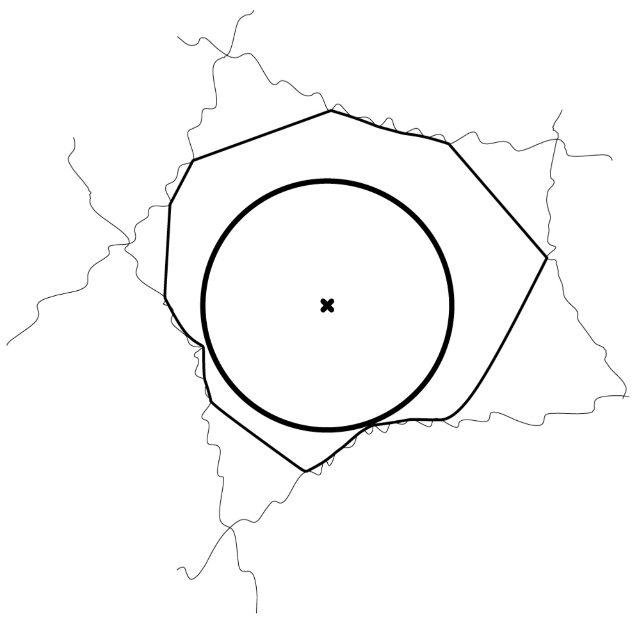
4

Pull curve inwards towards central point



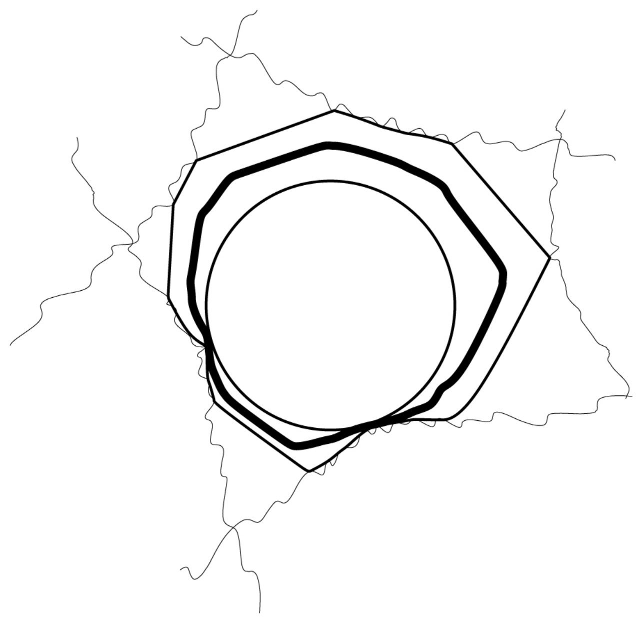
5

Create interpolated curve through closest points



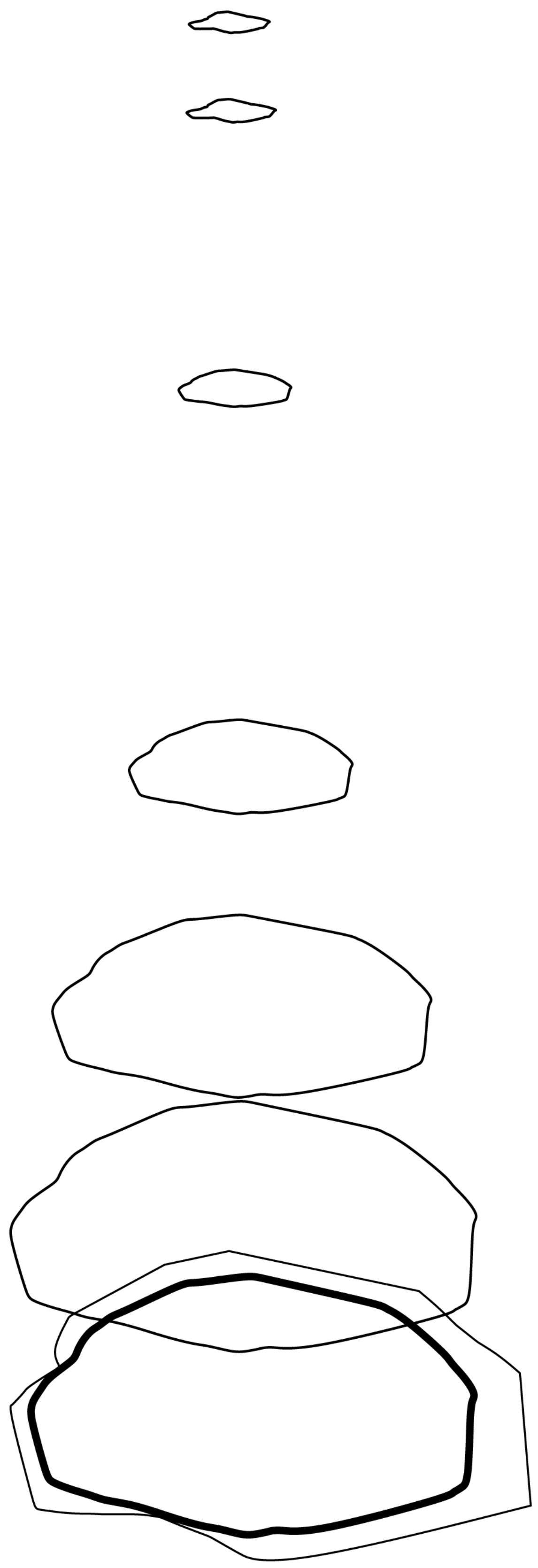
6

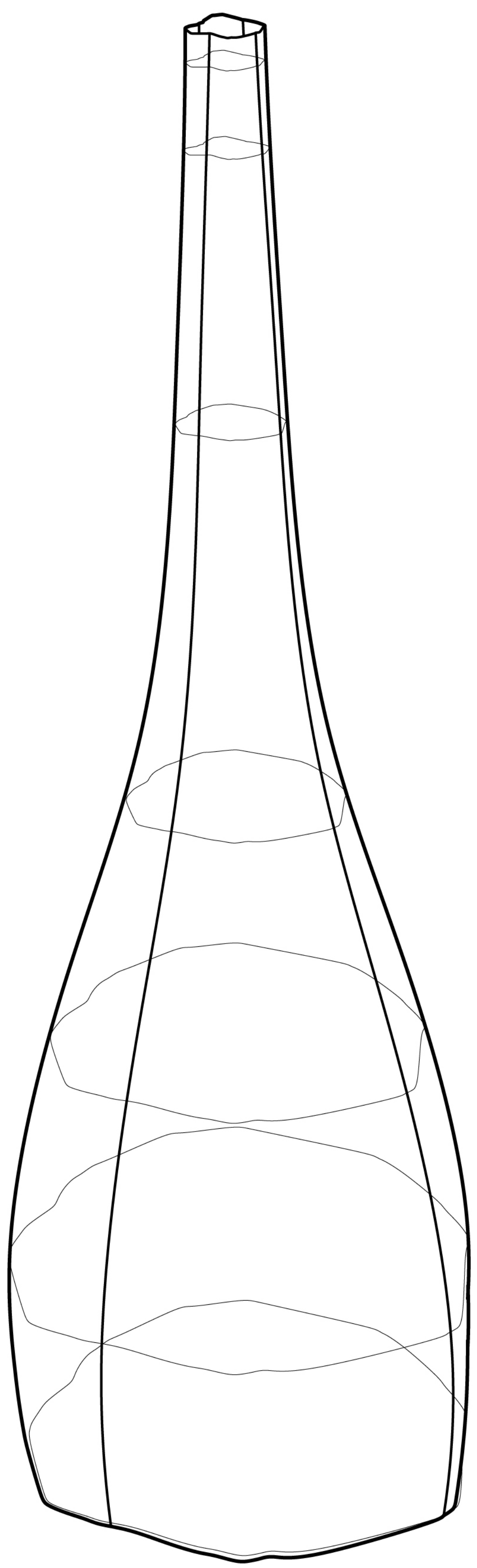
Create curve around central point in dome

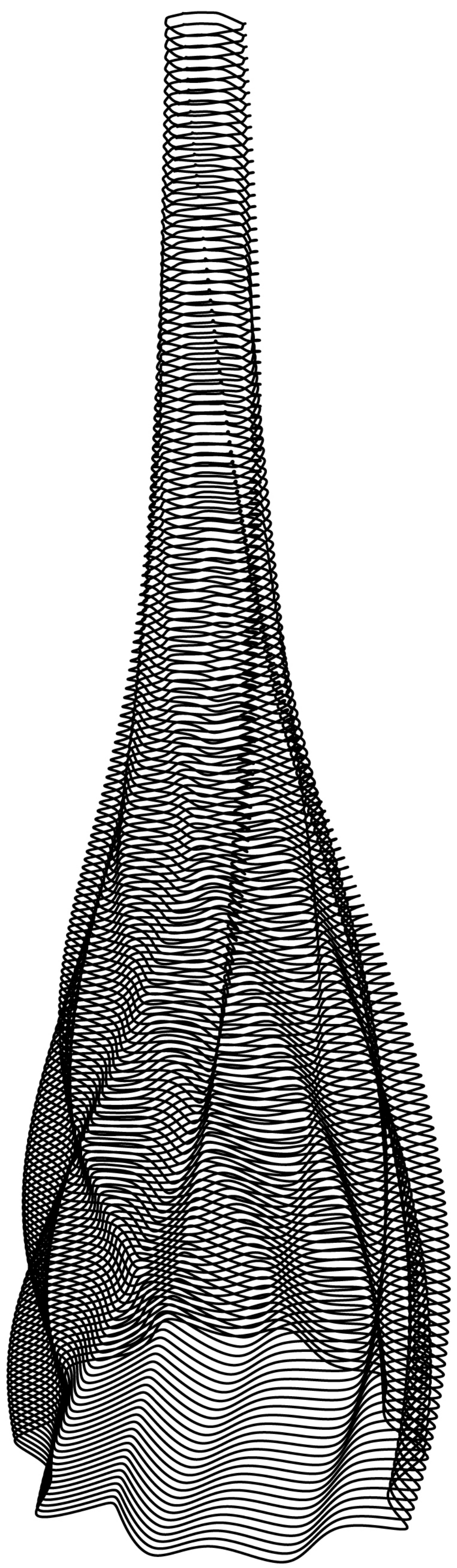


7

Tween between the two curves to create a usable curve on which to form the chimney







8

Offset curve vertically based on scale

9

Loft curves

10

Contour, following same Anemone script as domes

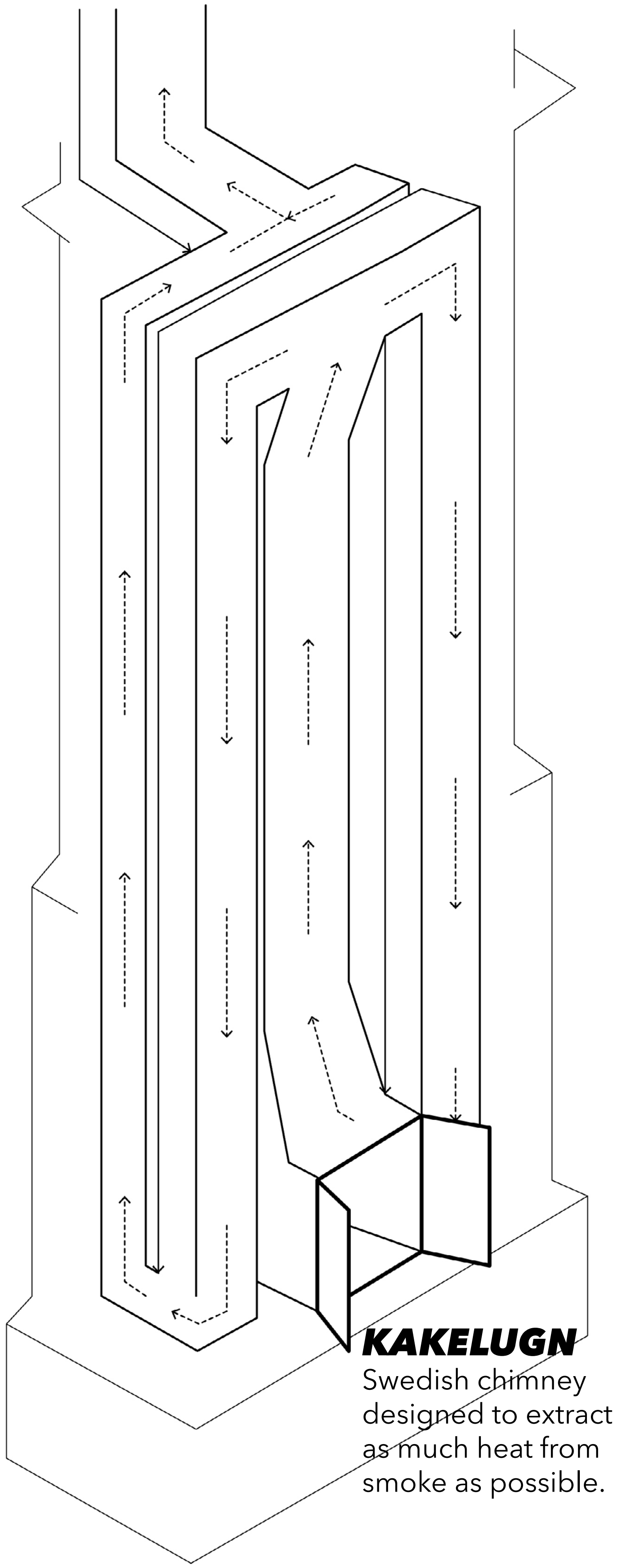
11

Add ribs to chimney, adding a vector force to create a rotated rib

12

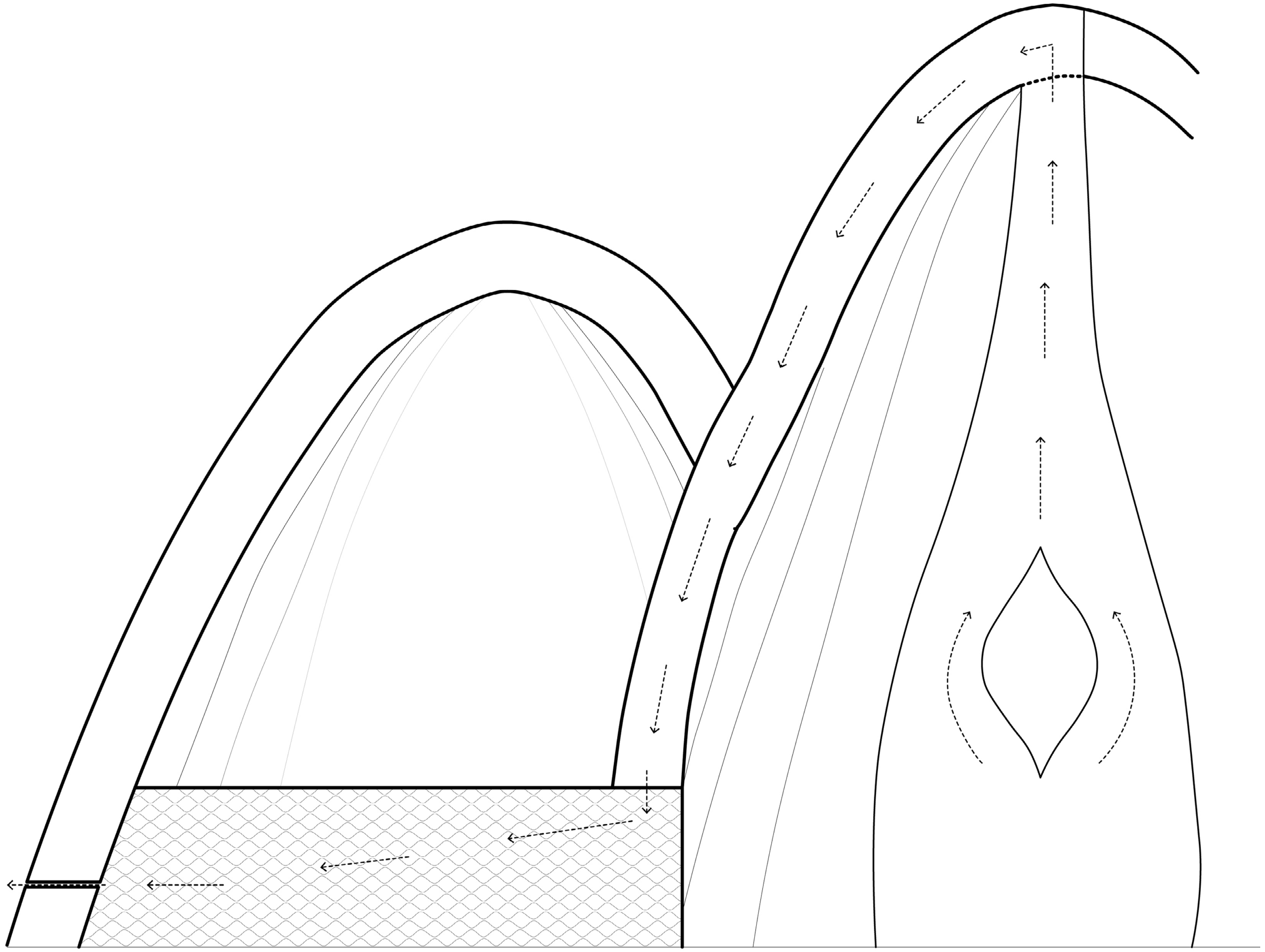
The chimney then channels smoke up along the ribs, creating a smooth flow with little back-draft.

PROPOSAL FOR HEAT TRANSFER OF CHIMNEY



KAKELUGN

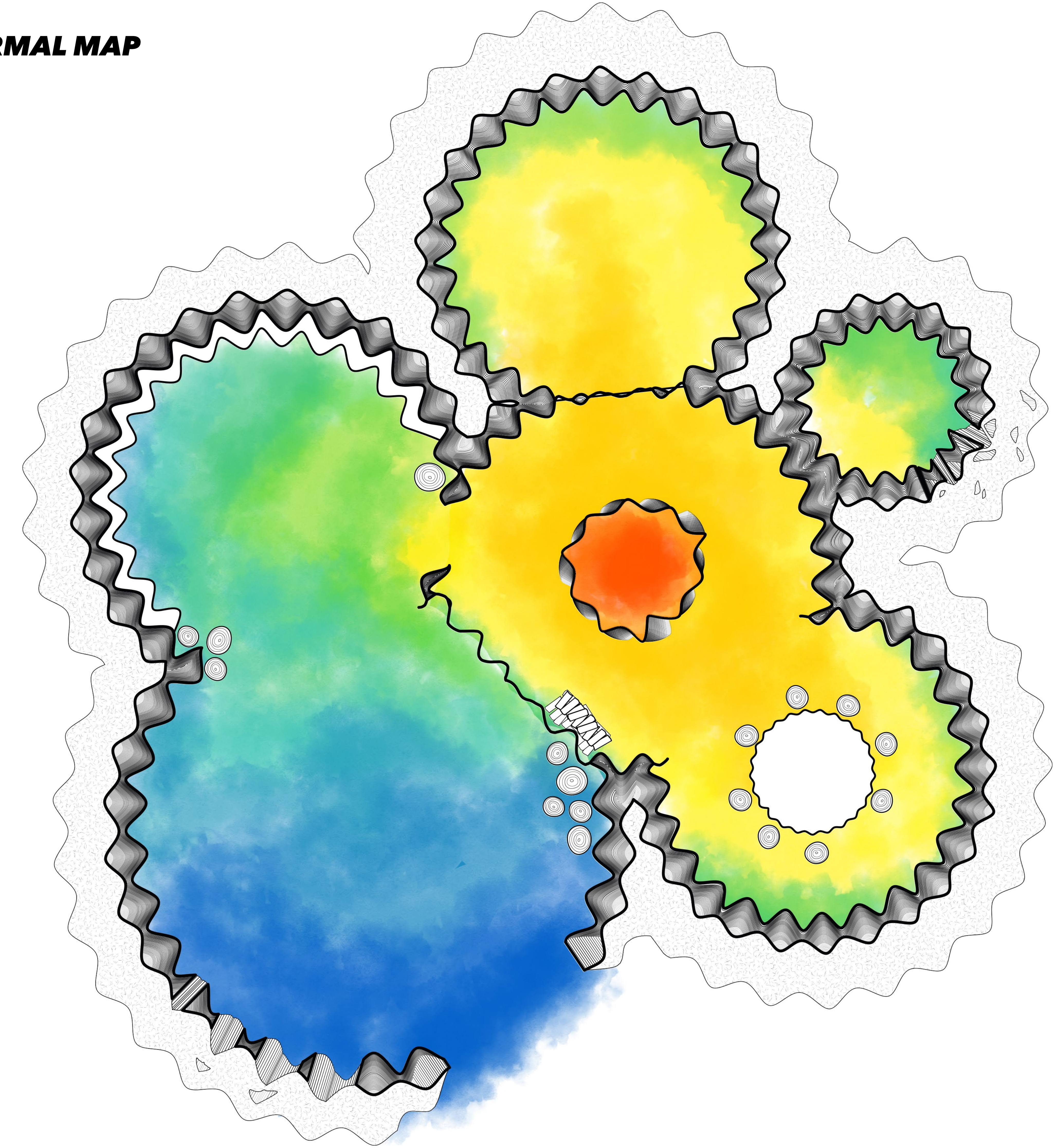
Swedish chimney designed to extract as much heat from smoke as possible.

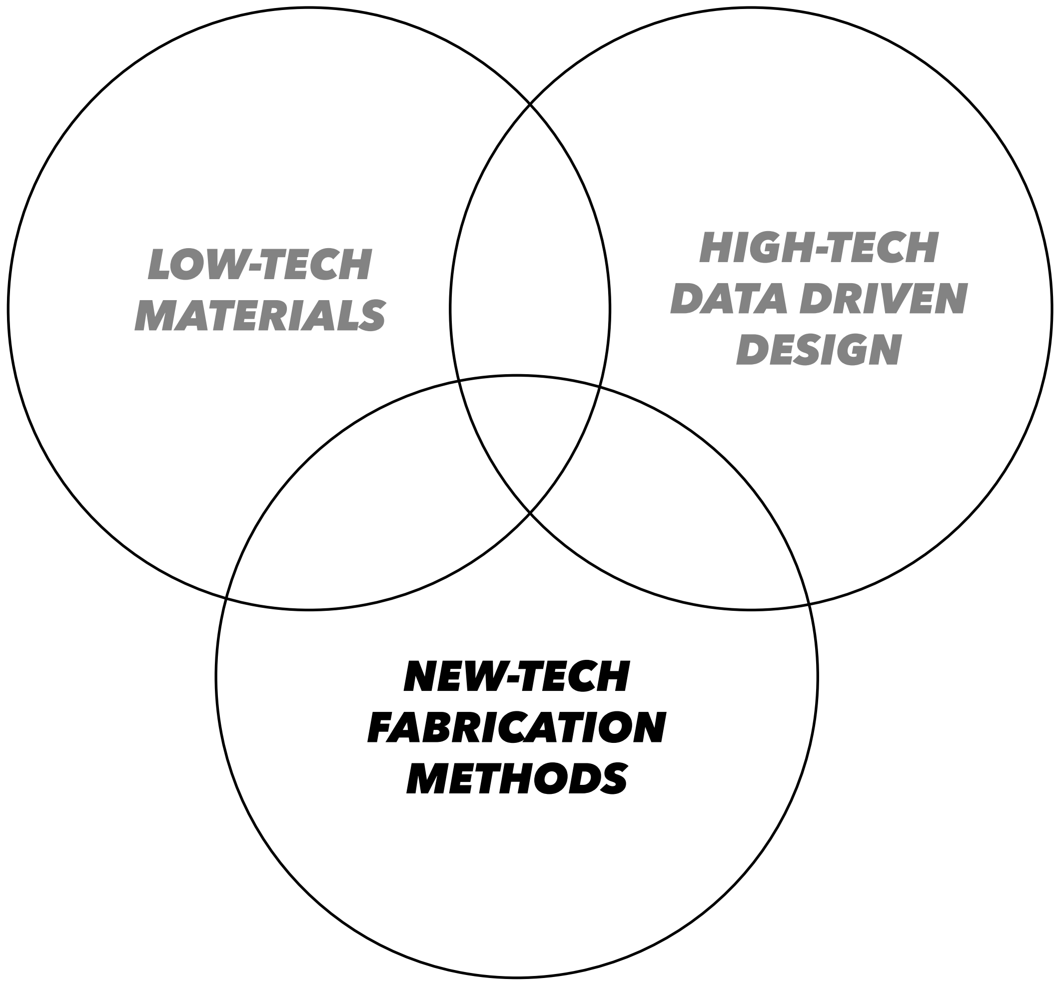


ADAPTED THEORY APPLIED TO BUILDING

Hot air passes along ribs created by inner and outer walls, passing down through infill of sleeping area and out small outlet.

SUGGESTIVE THERMAL MAP

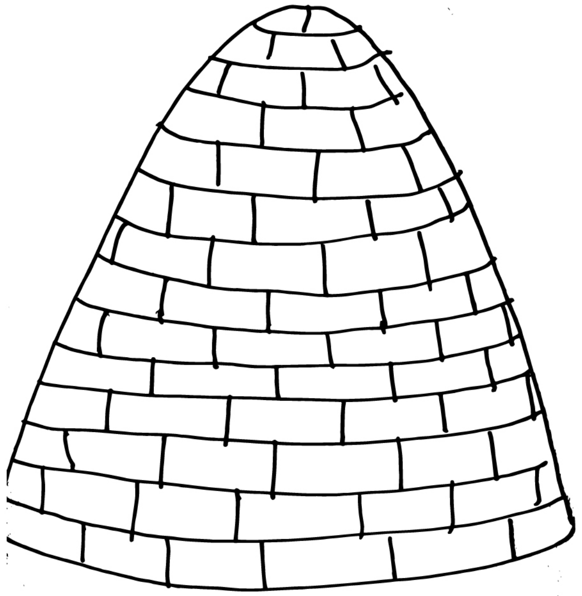




LOW-TECH MATERIALS
HIGH-TECH DATA DRIVEN DESIGN
NEW-TECH FABRICATION METHODS

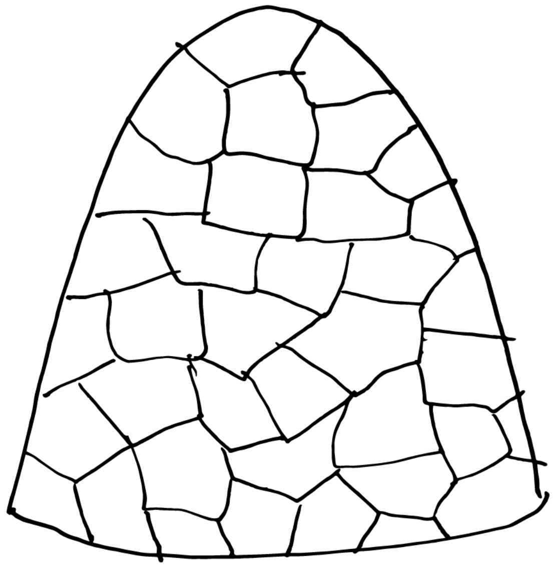
PRINTING SCALES

Deciding on the scale to work on the project: pros and cons of each scale.



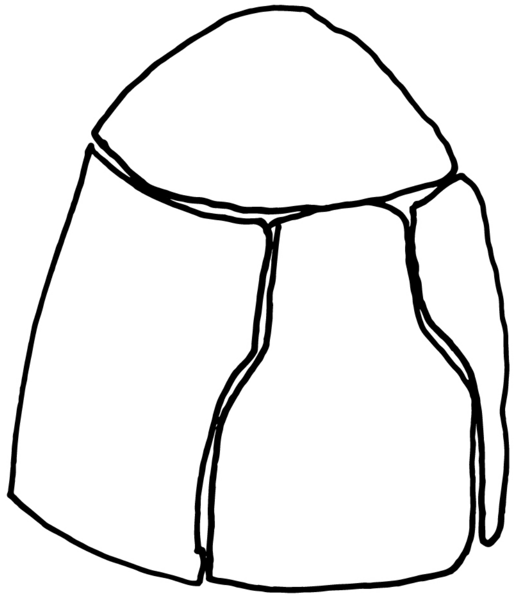
AS STANDARDISED ELEMENTS

- Limits forms to what can be produced with element.
- Requires further consideration of how bricks are placed.
- Goes against principal advantages of 3D printing in that it can produce unique and non-standard forms.



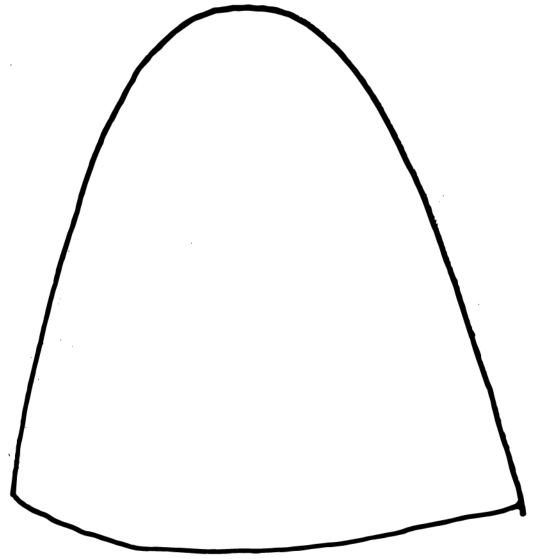
AS UNIQUE SECTIONS

- Issue of joining each element
- How to hold form during construction: it will most likely need secondary supports such as scaffolding added.
- Time between producing sections, positioning them then felting on-top is too tight



AS PARTS

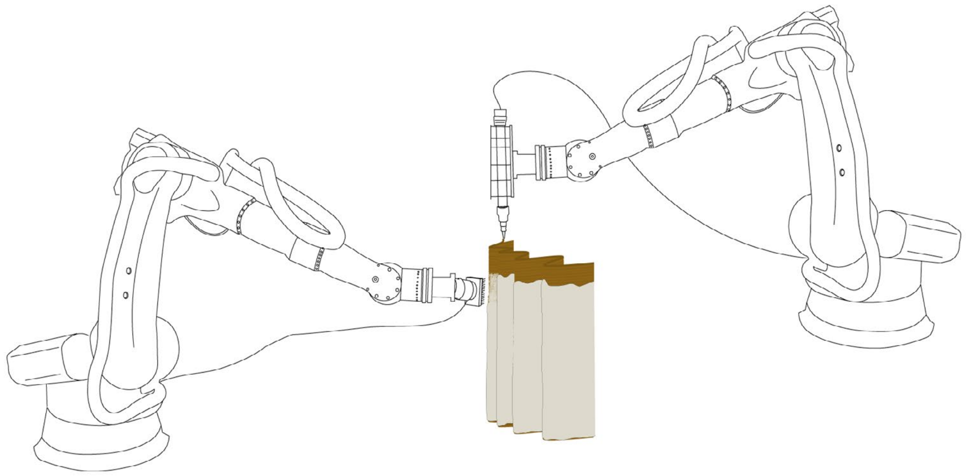
- Reduces risk of collisions between felting and printing.
- Increases geometry possibilities for overhangs.
- Issue of moving and joining elements.
- Large parts would be difficult to position correctly, with a high possibility of misalignment.
- Similar to as one, but with more risks and almost no advantages.



AS ONE

- No joints to overcome
- Limits geometry to what can be printed as one: no overhangs.
- Printing in situ reduces risk in misalignment between form and felting arm.

DIFFERENT FABRICATION OPTIONS



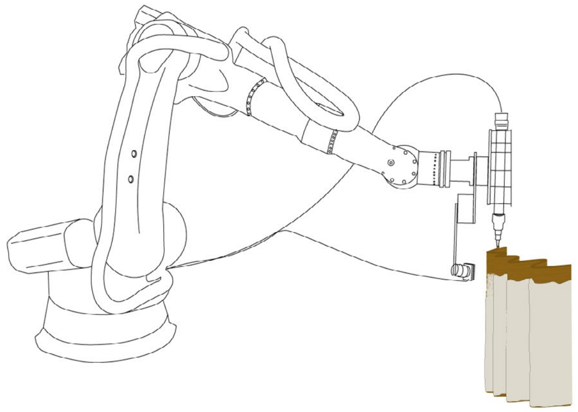
TWO ARMS

- One arm prints the clay extrusion
- The other felts the wool onto the outside

ADVANTAGES:
- Fast
- Could increase complexity of form as one supports the pressures from the other
- As the workspace is the same for both, there is low risk of them getting misaligned

DISADVANTAGES:
- Increased risk of collisions
- More expensive
- If one fails, the whole print is ruined
- Harder to run tests (availability of using 2 arms in a busy university workshop)

A developed version of this is what is proposed for the **full scale construction** of the shelter.



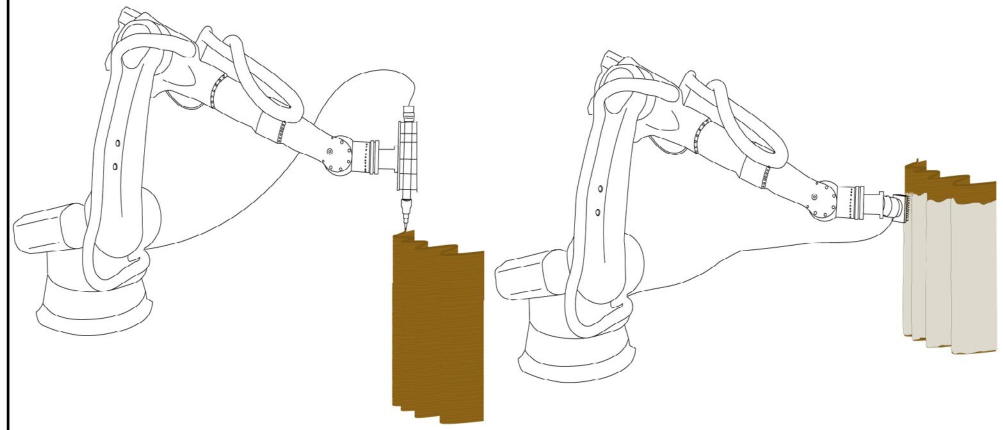
ALL AT ONCE

- Print wool and felt at the same time dual
- Extruder/ needle felting arm.

ADVANTAGES:
- No risk of misalignment
- Fast

DISADVANTAGES:
- Could limit form as matching paths needed.
- Complex design of tool head needed

This was considered too complicated to design and program, whilst also severely limiting the form the shelter could take.



ONE AFTER THE OTHER

- 3D print clay with extruder nozzle attached to arm.
- Once finished, change end piece to felting tool and
- Begin felting process.

ADVANTAGES:
- Both can run at once- speeding up production times
- If one fails, does not affect the path of the other
- No risk of collisions

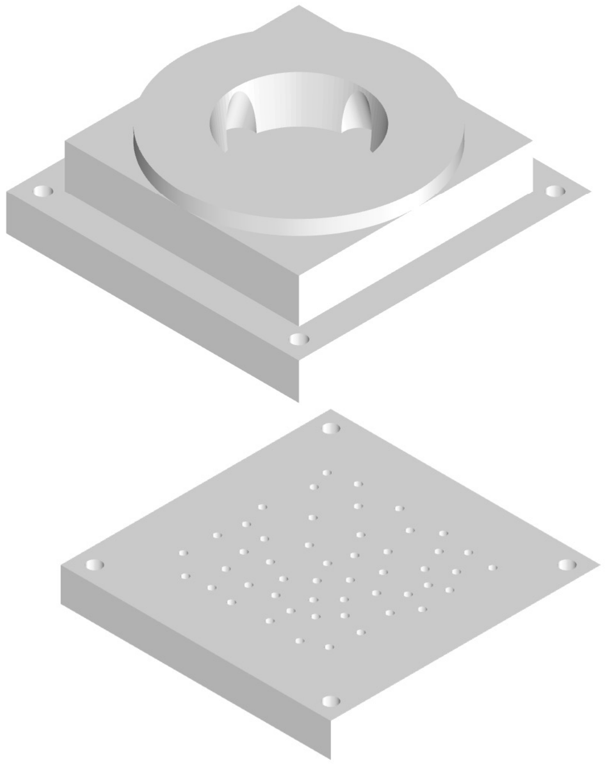
DISADVANTAGES:
- Aligning of workspaces when moving between machines will have to be carefully measured
- Timings between, as clay must be wet to felt onto

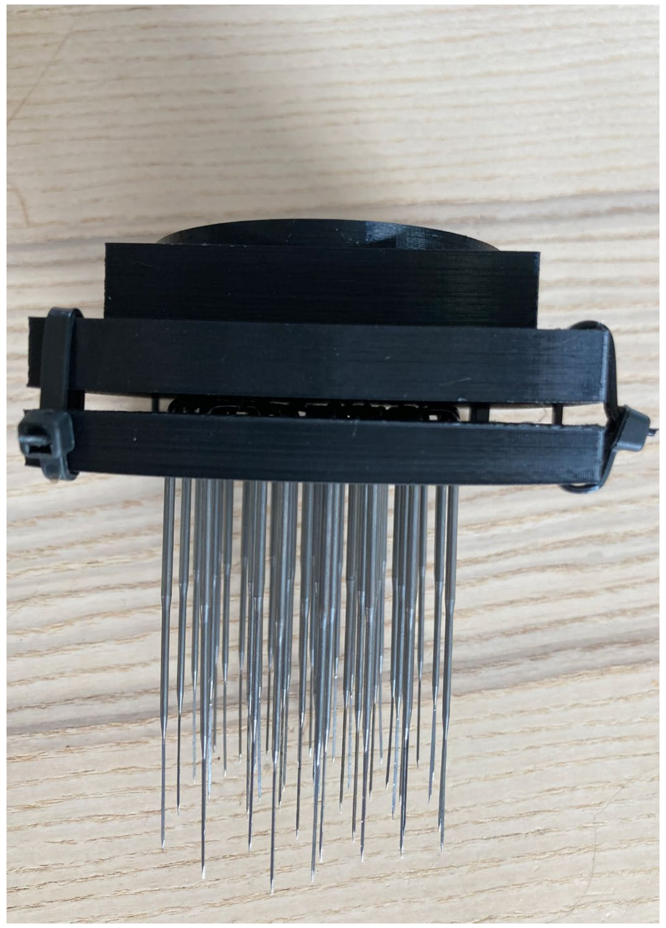
This is the process which was used for creating the **prototype**, as it is the most practical and flexible in terms of timings, access to the machines and development of form.

TOOL HEAD DEVELOPMENT

ORIGINAL HAND-HELD NEEDLE HOLDER

- Has 4 holes for felting needles to be inserted.
- Needles held in place by screwing top part of handle together.





DESIGN FOR ROBOT ARM

- 50 holes for needles means larger area will be covered, at faster rate.
- Top part connects directly to robot arm.
- Two parts held together by pressure (screws or cable tied).

ABB 160
Set-up for robotic felt test 01

ROBOTIC FELT TEST: R01

Using Robotstudio software, a RAPID code was developed to produce a motion similar to that done when felting by hand.

The 'woodpecker' motion was coded to follow a horizontal path with repeated passes, felting 4 layers of wool together onto the surface of the clay.

In this test, the wool was felted onto flat slab, as a proof of concept that it is possible automate the process of felting wool onto clay.

R01: OBSERVATIONS

- Repeated passes were necessary to begin to felt.
- At the start it was also necessary to hold the felt in place.
- Adapting RAPID code and woodpecker motion to a non-flat surface
- How to accurately align printed form to tool path

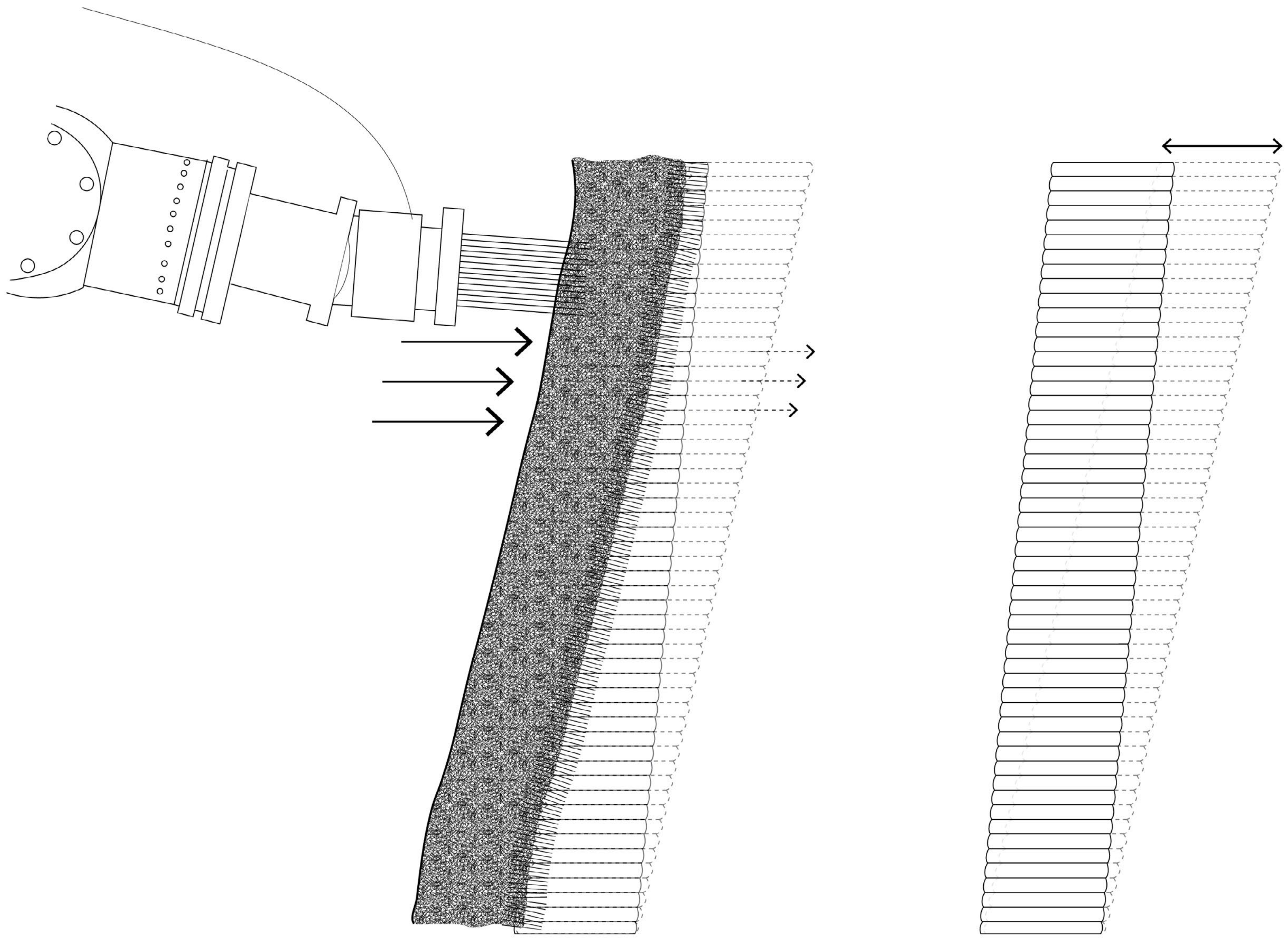
FABRICATION TEST 02

Test 02 showed that print is stable, however the print wall was very thick.

At a real scale, this would make the printed extrusion ~25mm wide. Whilst this increased the adhesion between print layers, the stability was not greatly improved for the quantity of clay being used, and overhangs were consequently heavy.

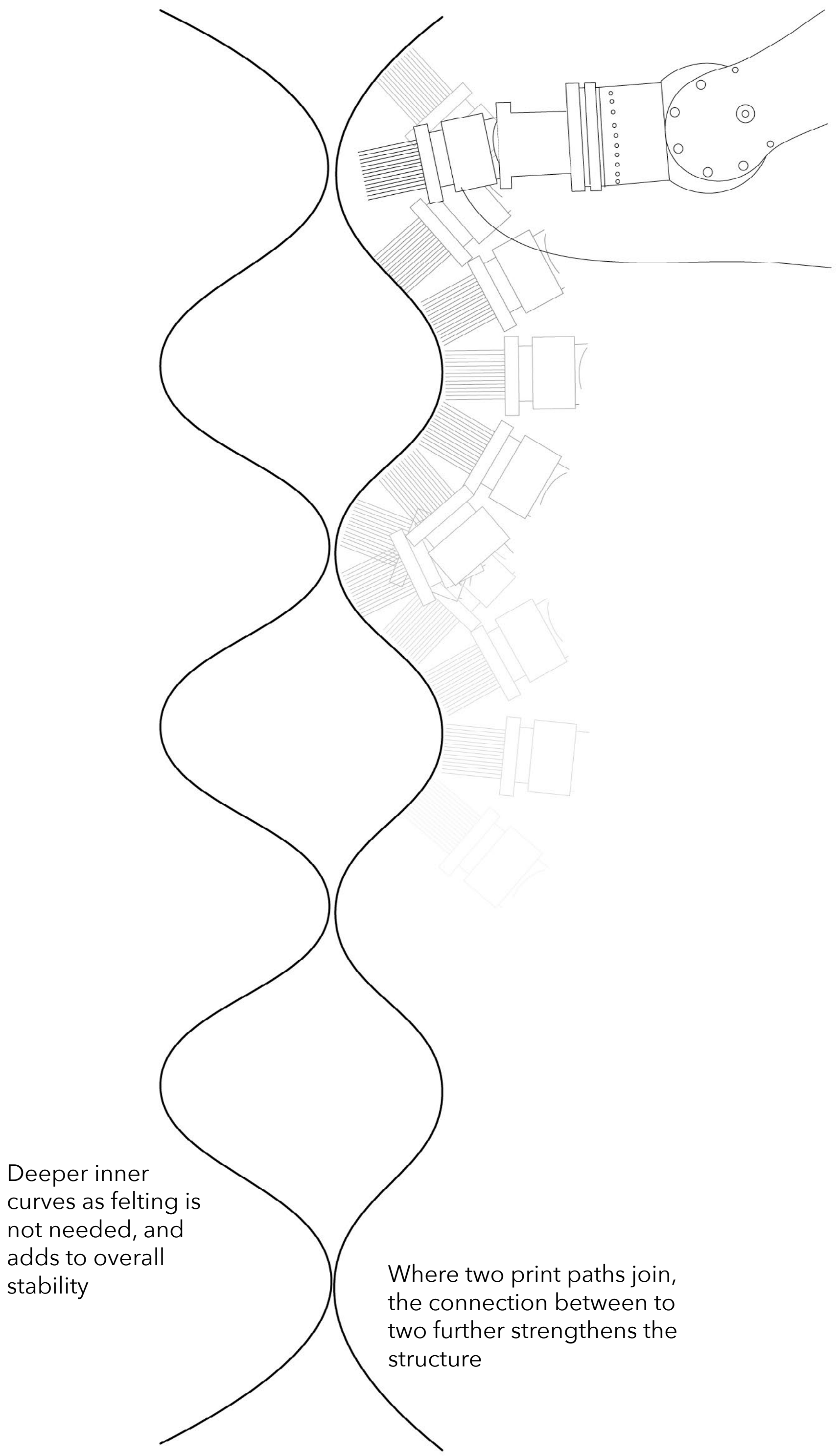
FABRICATION TEST 02

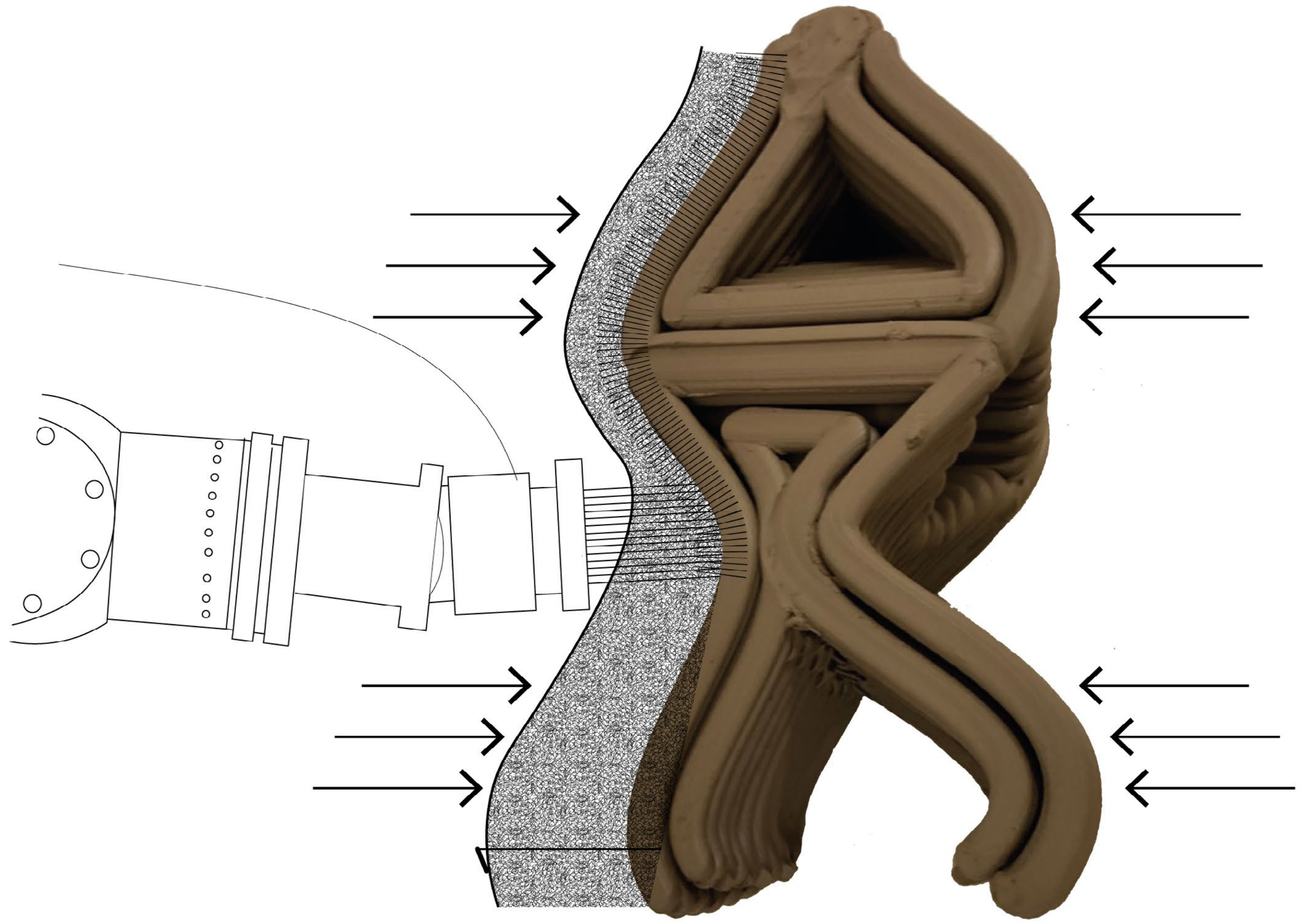
Large print width unrealistic at full scale

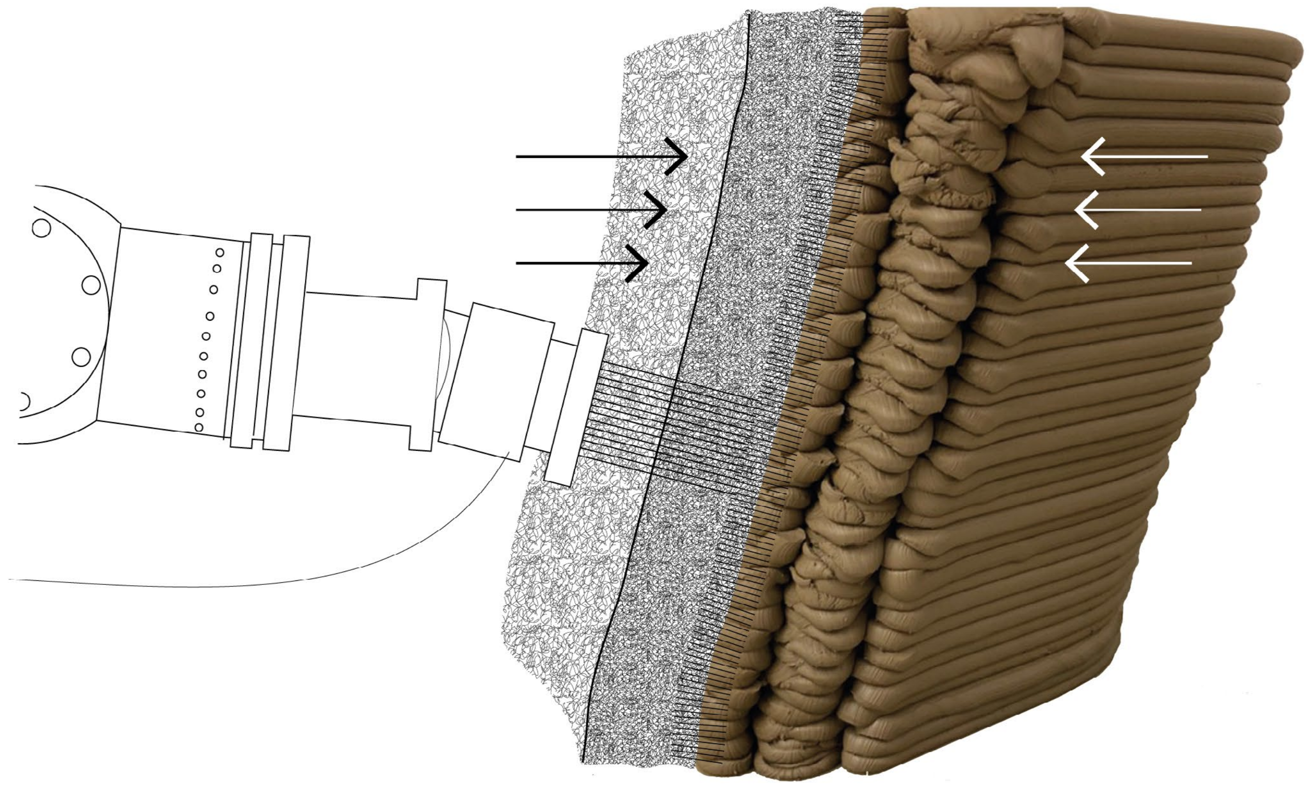


Single walled structure has high risk of deflection due to deflection from felting needle

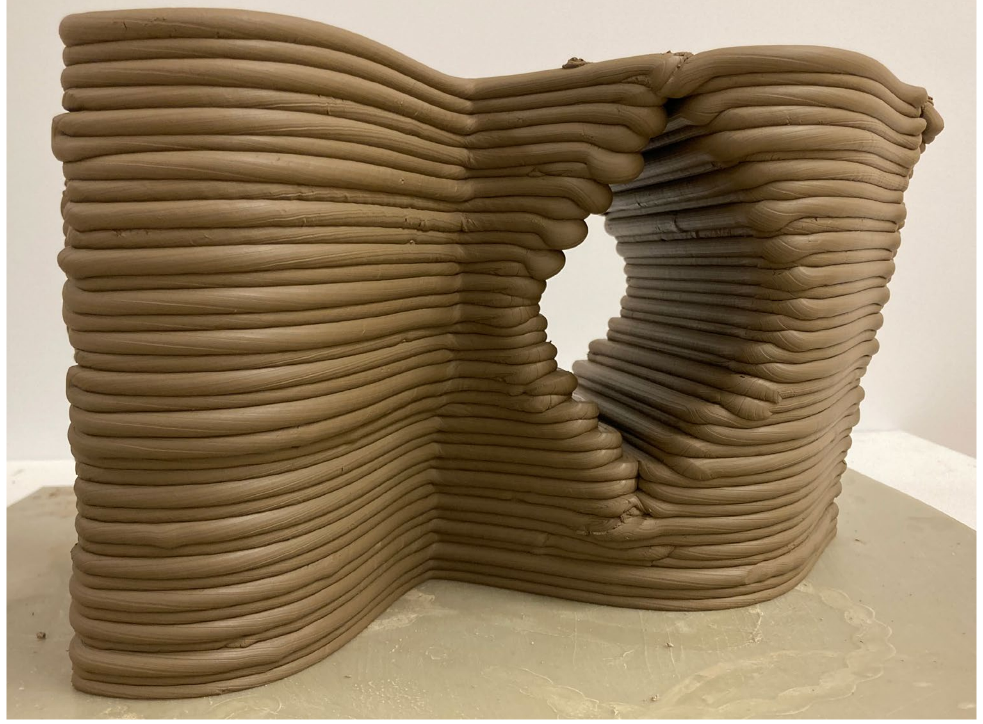
SOLUTION: DOUBLE WALLED

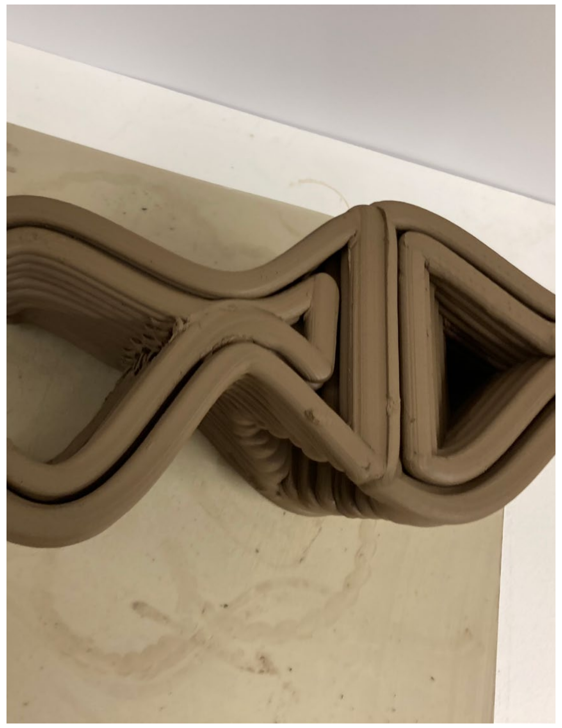


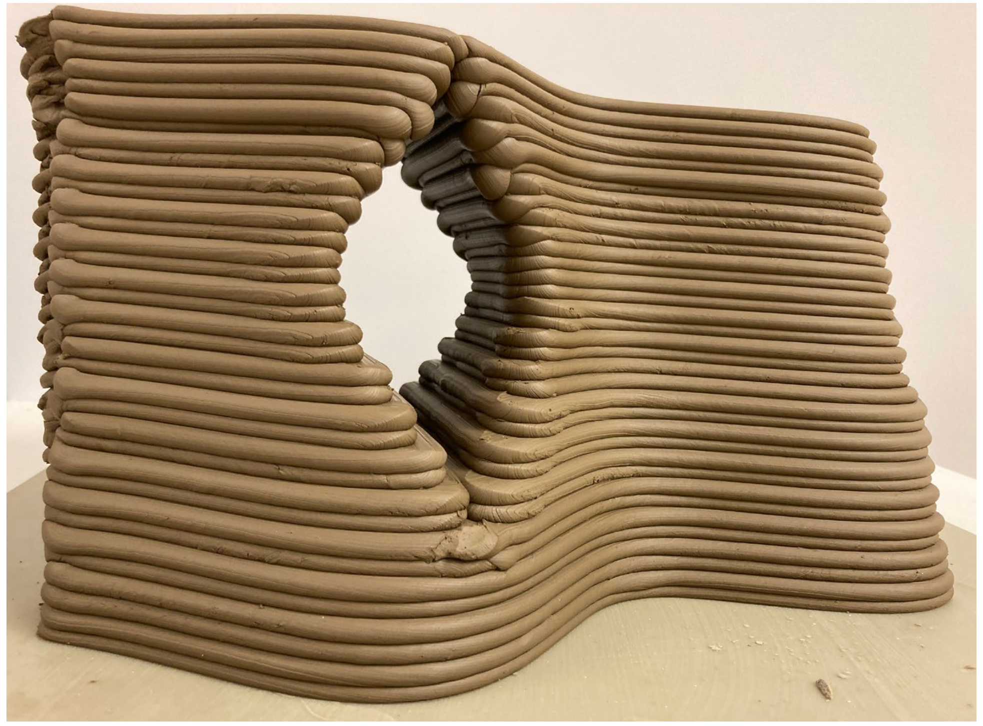




PROTOTYPE PRODUCTION

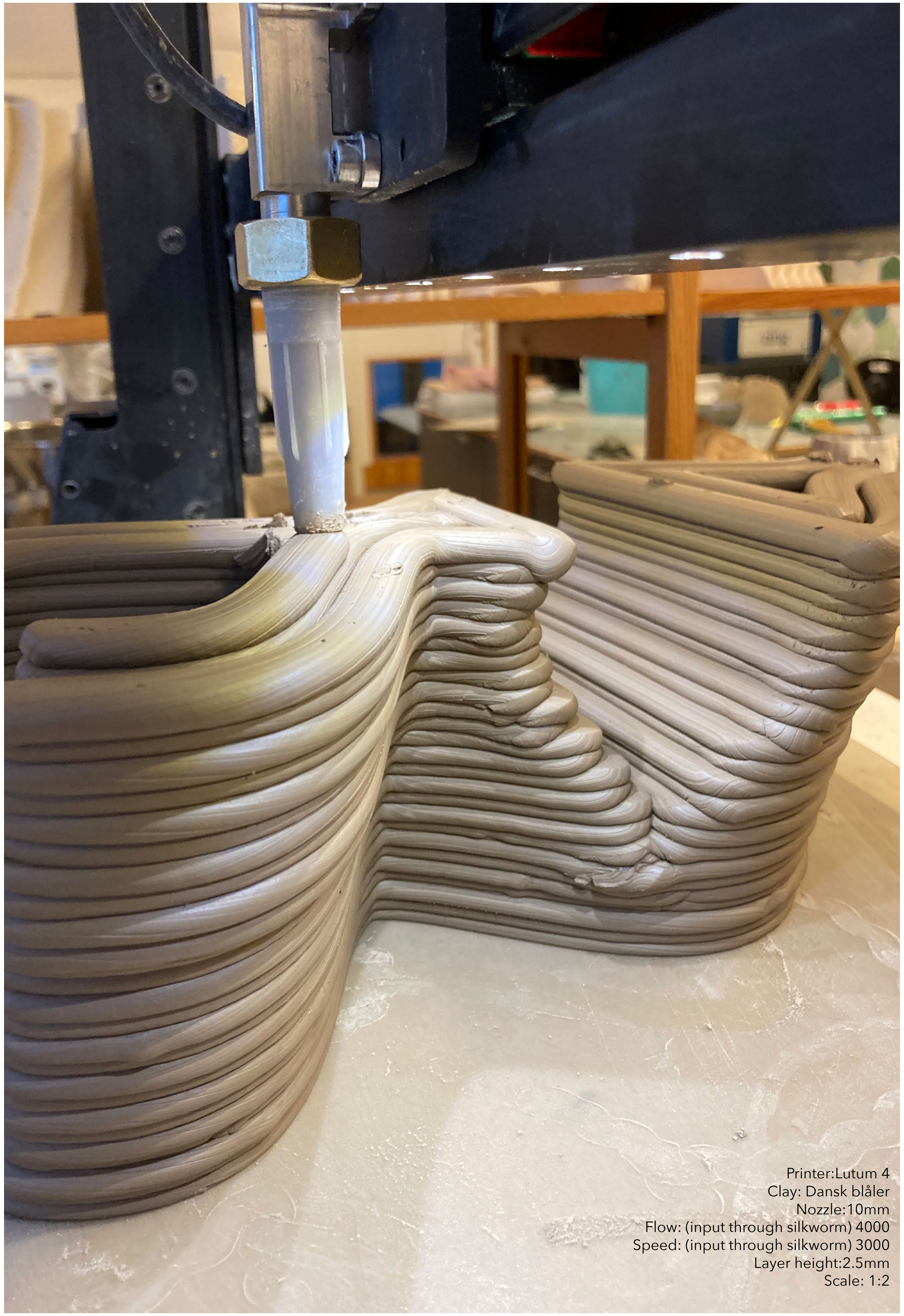


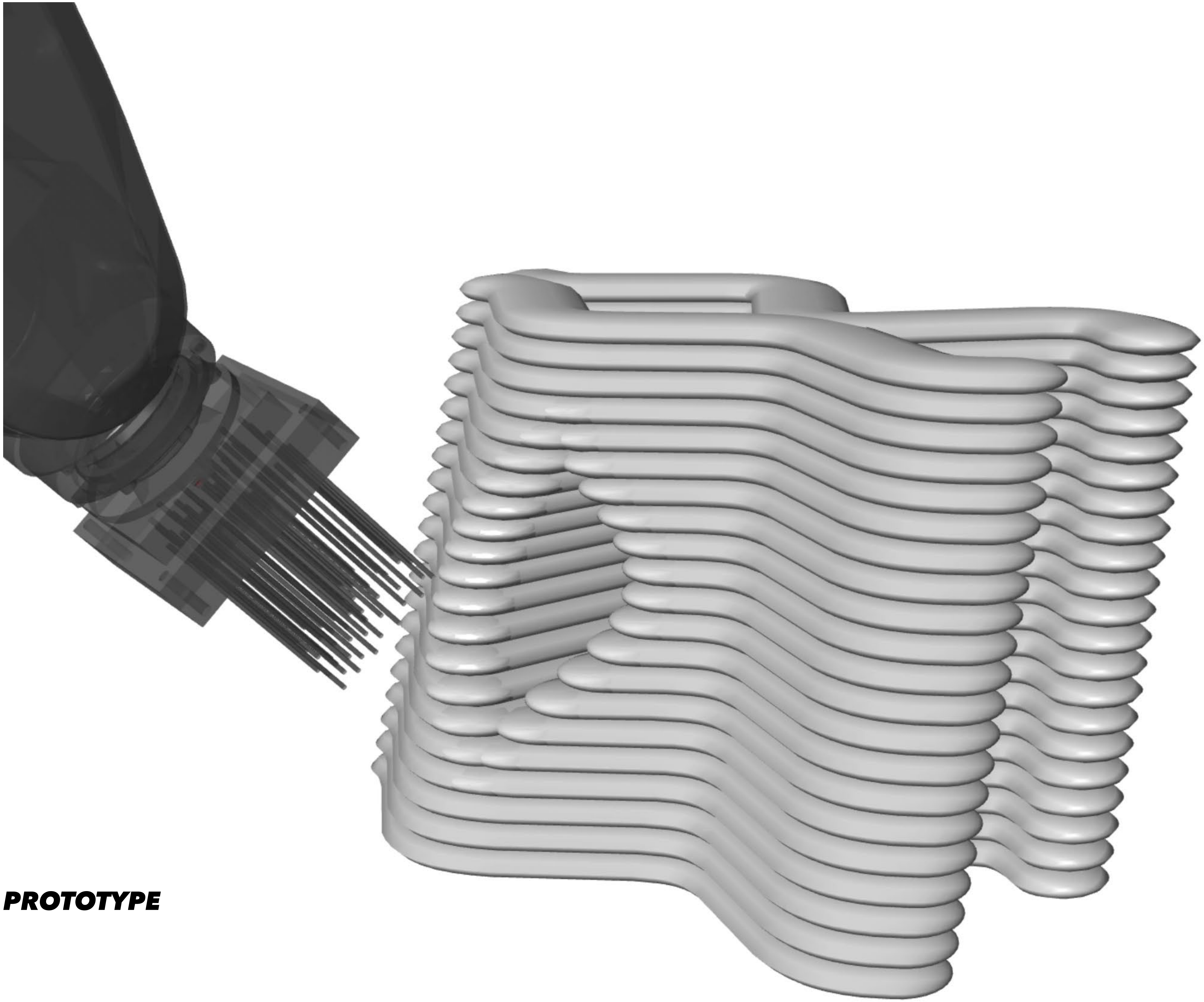




When printing the prototype, it became apparent that the positioning of the openings would have to be positioned to be at the the narrow point in the walls, where the two print paths meet.

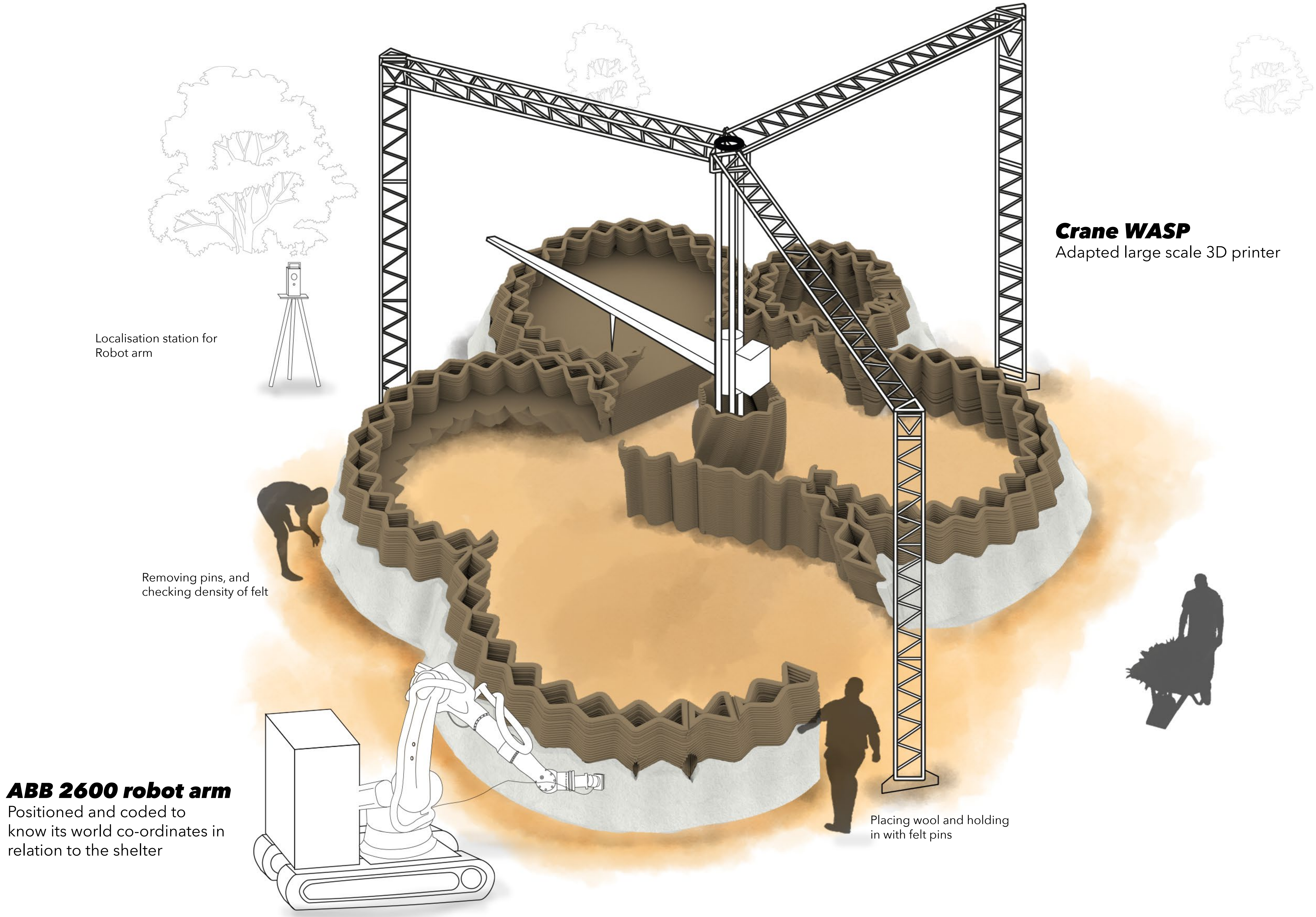
This means that the print extrusion would not have to span the wider gaps with no support below, which would increase the risk of the print path failing.



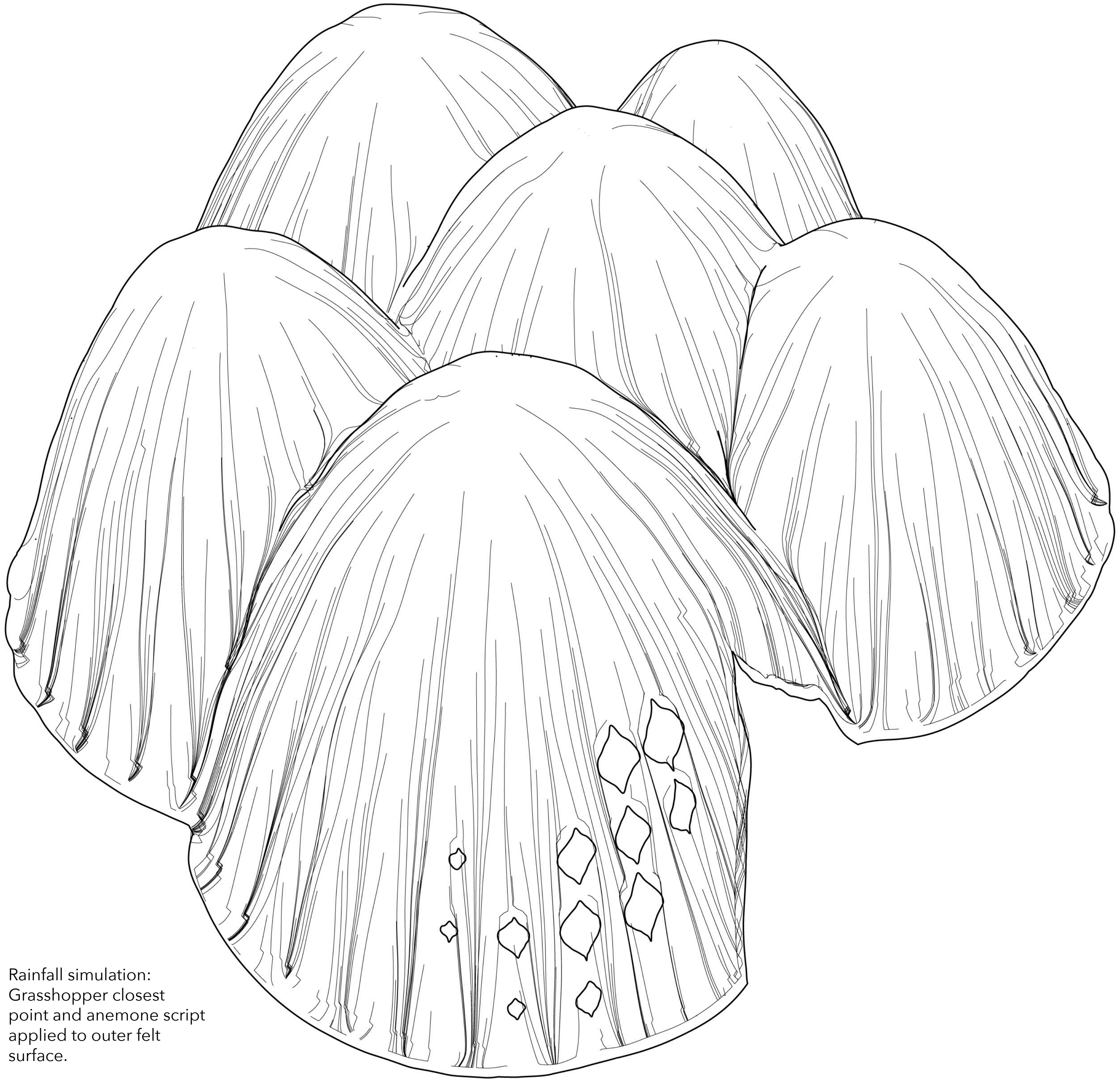


FELTING ONTO PROTOTYPE (SIMULATION)

FABRICATION STRATEGY

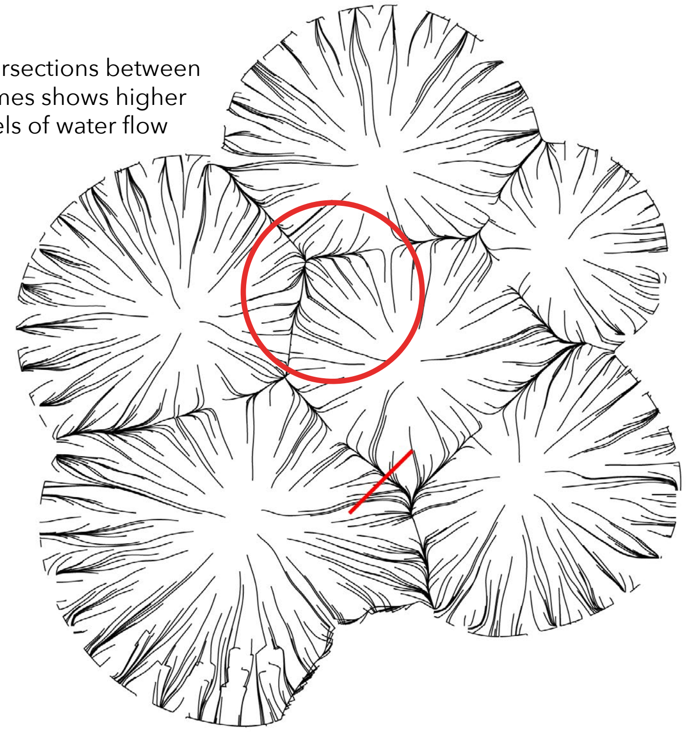


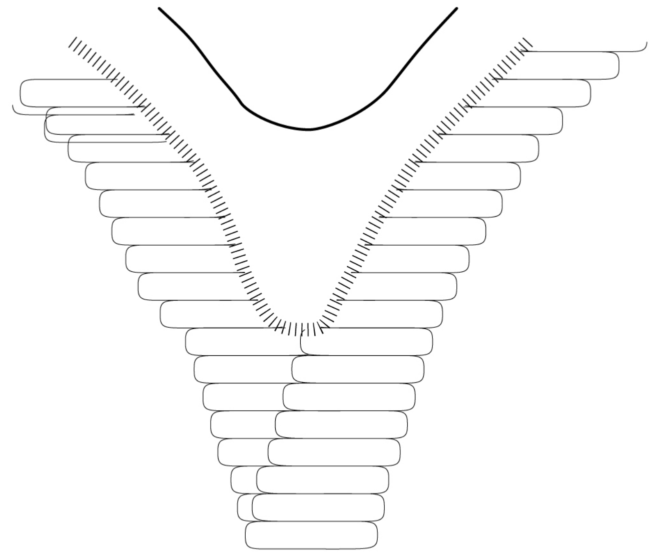
RAINWATER SIMULATION



Rainfall simulation:
Grasshopper closest
point and anemone script
applied to outer felt
surface.

Intersections between
domes shows higher
levels of water flow

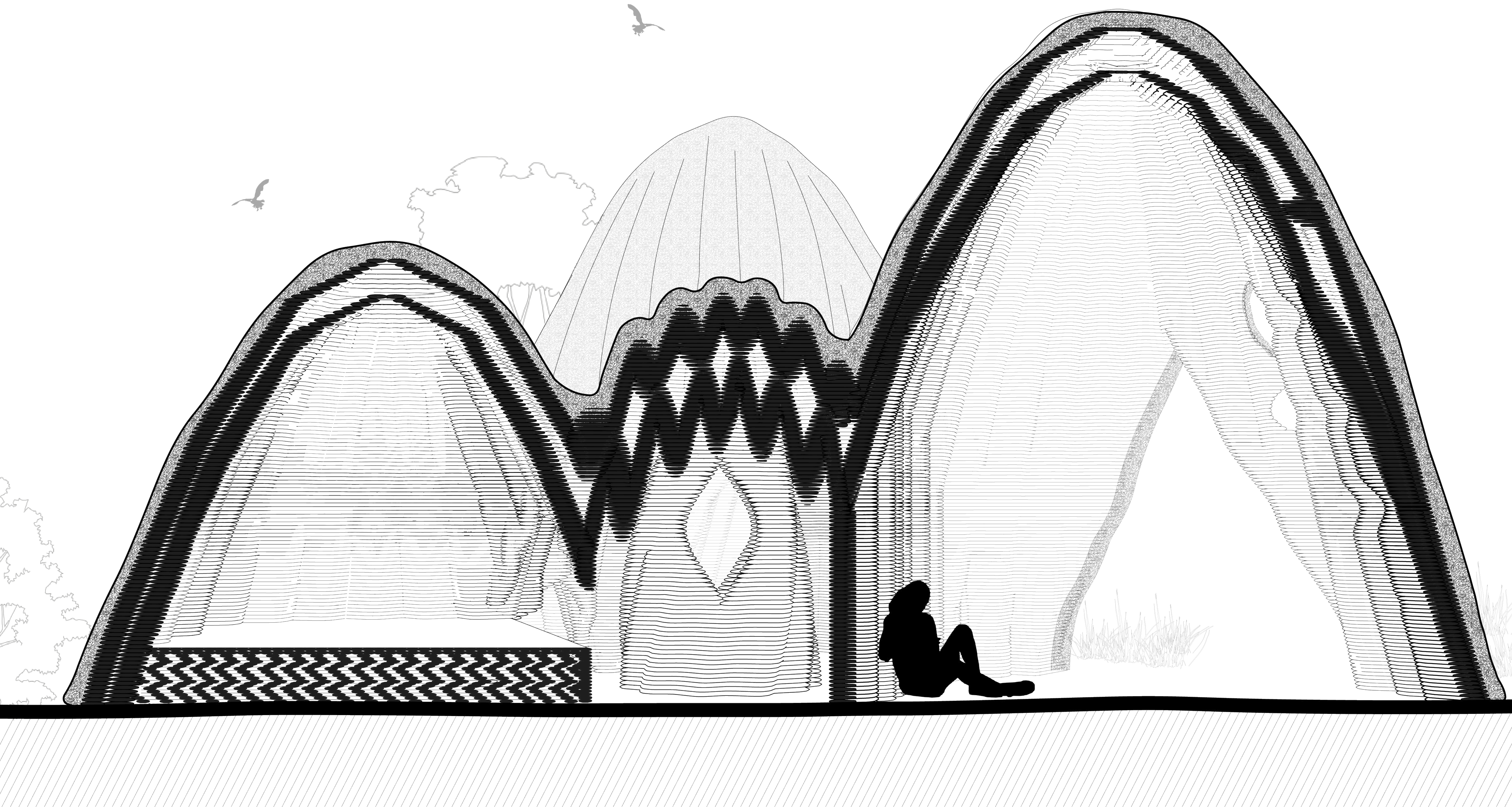




Density and layers of felt are increased where higher levels of water gather on felted surface.

The standard number of layers will be 5, however where higher levels of water flow are found, the layers will be increased to 8, with the path passes doubled.

SUGGESTIVE SECTION



CONCLUSIONS

Throughout this thesis, there have been some discoveries, and many challenges. Whilst these helped to develop the project, they also provide areas to reflect on, as well as bringing up possible further areas of research for the future.

One of the biggest challenges was in scaling up: Even scaling from hand sized tests to the prototype brought a lot of unforeseen results, particularly with material behaviour. As clay does not shrink uniformly, it is extremely hard to predict, and the larger the form, the more noticeable these deformations are.

This also brings up the tolerances. I find it really interesting working with such a loose material such as clay, which sort of has a mind of its own and never performs how you first expect, especially when it comes to 3D printing. This unprecise nature is an amazing juxtaposition with the precise nature of robotics, and trying to compensate for both creates some interesting results and could be really beautiful.

Furthermore, it would be really interesting to investigate further how the felted clay affects the structural properties of clay. From the experiments made during this thesis, it is clear that it does help control the cracking, but whether it creates a more even shrinkage, and wither it even adds strength in tension would be an interesting avenue to follow.

Finally, the big question is whether this really would be durable long-term, and whether its really needed. As discussed at the beginning of this booklet, this project aims to be embedded within the ideas of circular design. That this shelter is constructed only out of clay and wool could mean that, in time, as the shelter does deteriorate, the impact on the environment will be minimal.

The felt on the outside of the structure certainly acts as a protective barrier to slow this down, but I don’t believe we should be designing buildings to last forever, and so I find it interesting to consider how long it would actually last, and what would happen afterwards.

ACKNOWLEDGMENTS

Before I started this Masters course, I had almost no experience and limited knowledge about the world of 3D printing within architecture, and if someone had asked me what my Grasshopper knowledge was, I would have looked at them blankly and thought they were asking about the insect, rather than the computer programme.

However, thanks to the amazing masters programme, set-up and run by David Andreen, within two years I was able to carry out a research thesis rooted in these topics, so I must thank him for introducing me to this world, and guiding me and my peers through this ever-developing area of architecture.

I would also really like to thank Ana, my main supervisor. The invaluable support and guidance I recieved throughout this thesis from Ana helped me to develop a project I was proud of. Supporting me through the upheaval of a global pandemic, always being available, and leaving me after every chat feeling motivated and inspired.

Thanks also to my second supervisor, Anders. Without his incredible patience with me as I stumbled through a crash course of learning how robots work, I would not have been able to work on this subject for my thesis.

Also thanks to the amazing community of digital design and fabrication. Both online and in LTH, students, teachers and friends were all so helpful with their time, offering small nuggets of wisdom and insight.

Thanks also to the friends and family outside this community for the moral support. Joe for the patience as I took over the flat with all my experiments, and to my parents, who although I still dont think they fully understand what this thesis is about, have still been my biggest fans. I seriously wouldnt put it past them to move into a structure made of clay and wool, with no doors, just so they could live in something I designed...