DIPLOMARBEIT

TECHNISCHE
UNIVERSITÄT
WIEN
Vienna University of Technology

DISSOLVING STRUCTURES

Wachs als alleinig tragendes Baumaterial für freistehende Strukturen

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Diplom-Ingenieurs / Diplom-Ingenieurin
unter der Leitung:

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E259-02
Interdisziplinäre Tragwerksplanung und Ingenieurholzbau

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ABSTRACT

Diese Thesis erkundet die Nutzbarkeit von Wachs als alleinig tragendes Konstruktionsmaterial für freistehende Strukturen. Für die Sammlung von Wissen wurde ein experimenteller Ansatz gewählt, in dem die Versuche iterativ hochskaliert wurden. Im Laufe der Auseinandersetzung wurden 20 Experimente durchgeführt, die Bandbreite erstreckt sich über Objekte mit einer maximalen Seitenlänge von 10cm bis hin zu Objekten mit einer Höhe von mehr als zwei Meter.

Wachs ist die Bezeichnung für eine heterogene Gruppe an Materialien. Der Großteil der Experimente wurde mit Paraffinwachs durchgeführt, aufgrund der Verfügbarkeit und des niedrigen Preises. Mit Bienenwachs wurde ebenfalls experimentiert um das Verhalten zu vergleichen und eine Alternative zu dem erdölbasierten Paraffin aufzuzeigen.

Die Fokusse lagen auf der Erforschung eines für das Material passenden Produktionsprozesses und der effizienten Nutzung des Materials in der Struktur.

Aufgrund der niedrigen Schmelztemperatur von Wachs bot sich Gießen als grundsätzlicher Produktionsprozess an. Spätere Experimente zeigten, dass eine Textil Schalung die Tragleistung von Wachsen verbessern kann, indem es Brüche des Wachses verhindert und falls diese passieren die Struktur weiterhin zusammenhält. Zusätzlich ermöglichte es Objekte hängend zu gießen , was die Produktion wesentlich vereinfachte, während es Freiform Geometrien ermöglicht. Nach der Produktion wurden Belastungstests durchgeführt, um die Streckgrenze des Hybriden Materials einzuschätzen.

Ein digitaler Design Prozess wurde erarbeitet um die Strukturen zu entwerfen. Die „particle spring“ Methode wurde genutzt um Grundgeometrien, auf der Basis von Liniennetzwerken oder Flächen, zu entwerfen. Die resultierende Geometrie wurde danach mit der Finiten Element Methode von Karmaba3D® analysiert und nötige Elementquerschnitte berechnet.
Danach wurde das Nähmuster generiert, mit dem die Schalung des Objekts erstellt werden konnte.

Die Design, Fertigungs und Testprozesse wurden für jedes Experiment einzeln festgehalten und beschrieben.
Eine Zusammenfassung und Evaluation der Resultate befindet sich am Ende der Ausführung im Kapitel „Results“.

ABSTRACT

This master thesis aims to explore the usability of wax as the sole load-bearing building material for freestanding structures. To aggregate knowledge an experimental approach was chosen, in which the dimensions of conducted experiments were iteratively upscaled. Throughout this research 20 experiments were conducted ranging from small boxes with a maximum side length of 10 cm to objects taller than two meters.

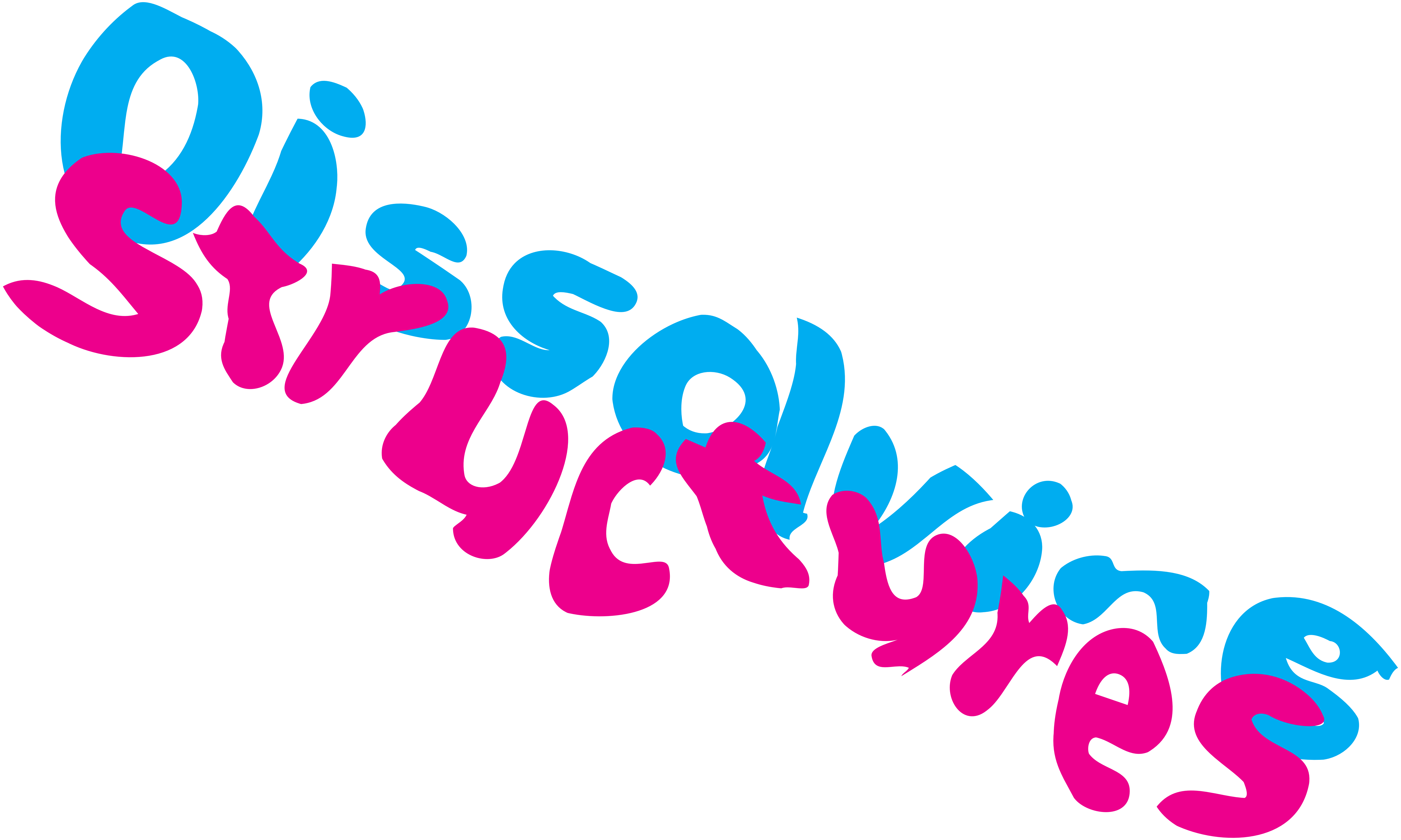
Since waxes are a heterogenous group of materials it was chosen to conduct the largest part of the experimentation with paraffin wax, the most common and cheapest variant. Beeswax was also experimented with for comparison and as a naturally sourced alternative.

Searching for an optimal production process and ensuring efficient material usage throughout the structure were the main foci of this exploration.

From the start casting was explored for the production of structures, which was chosen due to the low phase change temperature of wax. Further experimentation showed, that fabric formwork can strengthen the material performance by preventing and bridging over cracks in the wax.
Additionally it enabled hanged casting, which simplifies the production of larger structures, and the generation of freeform geometries.
After cast stress tests were conducted to estimate the yield strength of the hybrid material.

To support this a digital design process was developed. Using the particle spring method of Kangaroo 2, base geometries were designed from either surfaces or line networks. Then the output was analysed using the Finite Element Method of Karamba3D® and necessary beam-sizes were calculated.
Afterwards a sewing pattern for the designed structure was generated.

The process of design, assemblage and testing are described for each experiment individually. A summary and evaluation of the outcomes can be found in the results section at the end of this thesis.


Dissolving
Structures

ACKNOWLEDGMENT

I want to take a moment to thank the people that enabled me to write this Thesis.

First and foremost I want to thank Dipl.-Ing. Dr. Zeynep Aksöz Balzar for supporting me with her knowledge and experience through the hard times of this thesis. Her ambition was always a great inspiration for me.

I also want to thank DI Lukas Zeilbauer who sparked my interest for algorithm based architecture without which this project would have been impossible.

Without the generous and patient help of the model building workshop team this thesis would have been unimaginable. Thank you for your support.

At this place I also want to thank my family which always supported. I can not imagine being the person I am without them.

I also want to thank my girlfriend Jennifer for being the balance that I needed over this time and her contagious positivity.

Finally I want to thank all my friends who have supported me in thought, in person or in Kleines cafe. Y’all are very special to me.

I. Route to the project

I.A. DERIVATION

Prior to this exploration a project was conducted, in which mycelium, grown on spent coffee grounds, was used as a fully recyclable construction material. Parametric design approaches helped to create geometries which would compliment the material.

Following this idea other materials were researched, which were sparsely used, but had a high potential for recycling. Among other wax was identified, which can be theoretically infinetly recycled, since it solidifies due to a phase change and without a chemical process.

In preliminary tests it was tried to manipulate the physical properties by foaming the material.
To produce it, the heated wax was manually foamed in a bowl and then casted into a formwork.

The result was a material as fascinating as it was fragile.

To make the material more resilient to pressure it was tried to create a protective layer around the material, among others using cotton.

This was a success. The hybrid material was more rigid than wax and stayed in the shape in which it solidified.
For my thesis I wanted to explore this connection of two materials further. Therefore the following premise was set out

Exploring wax as the sole load-bearing building material for freestanding structures, through iterative upscaling of experiment dimensions.

II. Methodology

II.A. PREMISE OF THIS RESEARCH

Aim of this research was to explore the capabilities of the rarely used material wax.

Therefore, the project was set out under the following premise:

Exploring wax as the sole load-bearing building material for freestanding structures, through iterative upscaling of experiment dimensions.

To break down this broad topic, multiple areas of interest were defined and ranked in importance

01. Casting strategies
02. Design strategies
03. Physical properties
04. Ecological performance

Most of the project is based on primary data (numerical values), especially 3. Area 1, 2 and 4 relied mostly on secondary data (experience reports).

Casting strategies

Wax is a phase change material and solidifies quickly at ambient temperature. The casting process was developed throughout this thesis to enable flawless structure generation, while reducing complexity of the process.

These are the parameters on which it was evaluated:

- Does it inherently generate casting deficiencies
- Does it support a uniform filling throughout the whole structure
- Does it reduce the number of actions needed to create a structure

Design strategies

The structure design, later split up in base geometry (macro form) and system (micro form), was dependent on the interplay of casting process and material properties. The high viscosity of wax when casting, its brittleness and its significantly better performance in pressure, than in tension were the defining characteristics.

Parameters on which the design strategy was evaluated were:

- Does it create geometries, in which pressure is the dominant force
- Does it support a uniform filling throughout the whole structure

Physical properties

For this research physical properties of wax, which are closely connected to its structural abilities were needed.

The following values were searched:

• Yield strength	in KN/cm2
• Youngs modulus	in MPa
• Specific weight	in kg/m3
• Volume expansion	as a percentage
• Melting onset	in °C
• Self incineration in	in °C

These values were collected from scientific sources. Their origin is mentioned in the respective chapter of *III. The material wax.*

Ecological performance

The ecological viability is evaluated by the following criteria

- Possibility of reuse of the wax

II.B. DATA COLLECTION

The primary subject of experimentation was paraffin wax (specifically: casting paraffin “356/58C (Sasol Wax 5603)”. Experiments were also conducted with pure beeswax and recycled wax, to compare material properties named in the paragraph above.
Knowledge was generated mostly by conducting experiments. The following steps were undertaken for each experiment.

Defining objective

Objectives were usually defined while reviewing the preceding model and casting process. Often they are assumptions how a better model could be created. For each experiment they are listed in the *“Aim”* section. They are evaluated in the *“Results”* and “Learnings” section.

Reevaluating parameters

After objectives were defined the Parameters of the preceding design were reevaluated and updated. The parameters changed can be found in the section *“Conduction”.*

Design of a structure

Structure design was mostly conducted using digital design tools, such as a 3D modelling program, an algorithmic modeller and a program for a preliminary finite element analysis.
Specifically, the chosen programs were

Rhino 3D, a 3D modelling program

Grasshopper, a plugin for Rhino 3D, which enables to create and execute algortihms

Karamba, a plugin for grasshopper, for structural analysis using the Finite Element Method.

The programs and the used operations are explained in more detail in the chapter *II.E. Digital design*.
The detailed process of model creation is noted in the “Conduction” section of each experiment.

Production

The production process was kept manual. Textiles, heat sources and a sewing machine were used. Information on the production is stated in the “Conduction section of the experiments.
Over the course of the experiment different textiles were used. The experimentation row *V.D.3. Experiment 11 / textiles* gives an in-depth view of the used material and the process of material selection.
Two heat sources were used. In the beginning of the experimentation only an electric stove with a 10l pot was accessible. Later it was expanded with a ~25l self-heating pot.
For the formwork creation a standard electrical sewing machine was used.

Stress testing

The stress tests were conducted by fixing the structure on supports and attaching metal weights to the structure. After a set period, 10min, more weight was applied in 5kg steps. Photos document this process. The load at the first visible deformation, as well as collapse are listed in the *“Result”* section.
For each experiment with a stress test the details of testing, as well as irregularities are listed in the *“Stress test”* section.

Recycling

Models were recycled by removing the fabric and melting the wax. Afterwards the wax was used for new models, the fabric was thrown away.

Type of data

Qualitative data was measured for

- Maximum load without visible deformation
- Maximum load at collapse

In later iterations it was only tested, whether the load, which the model was designed to carry could be applied without deformation.

Additionally, quantitative data was generated, by recording production procedures and their improvements. Depending on them, different geometries are presented, which are also evaluated according to their performance in the areas of interested, stated in *II.A. Premise of this research*.
Furthermore, the process of recycling and observations made throughout the project are also recorded in this research.

II.C. METHODS OF ANALYSIS

Due to the lack of references and research on this topic, a physical prototyping approach was chosen as a general structure.
For that, prototypes are continuously built on the knowledge gained in the preceding experiments. This allows for rapid application and verification of theories.

As a consequence a low-tech approach was chosen for the whole project. Physical prototyping demands, that tools needed for experiment conduction are available on a short notice. This could be only guaranteed for the tools described in the paragraph above.

Experiments were grouped into three segments.

Material experiments

The project was started at a small scale, ca. 20x10x1cm. Here the general casting process was tested and material manipulation was explored.
Wax was whisked to produce a foam-like material structure.
Other experiments explored the usage of cotton as a possible reinforcement for wax.
These experiments were conducted to research general material behaviour.

In this time mostly quantitative data was collected to optimise the casting process. Model behaviour was tested rudimentary by cutting through them and evaluating their sections.
This section consists of exp.1-8.

Hybrid material and element experiments

In the second section of the experimentation was was cast into fabric formwork. It was evaluated by stress testing.
An early focus was to make assumptions on the yield strength of paraffin wax cast into fabric formwork. It was assumed as described in *VI.D.1. Assumptive calculation of Yield strength*, based on the stress tests conducted in this section.
This enabled a digital workflow, in which a base geometry was produced using Rhino 3D and Grasshopper. The designed structure was then analysed with Karamba and beam-sizes were calculated based on the assumed material.

Here, qualitative data on Yield strength was generated. Additionally quantitative data on the digital design process, casting process, textile selection and construction methods was acquired.
This section consists of exp.9-15.

Volumetric design experiments

In the last group of experiments the knowledge created in the preceding experiments was applied to create structures with a height of up to 2m. The increase in scale in this time demanded a further development of the casting process.
The digital design process was also enhanced to approximate doubly curved geometries.

In this section quantitative data was collected on the digital design process, casting process and construction methods.
This section consists of exp.16-20.

II.D. EVALUATION OF THE CHOSEN PROCESS

The central criticism of this method is the lack of qualitative data generated. A thorough testing of wax and its combination with textile could have produced these important results.

Additionally, a more rigid process of experiment design would have been able to produce more robust results.

Nevertheless, this method was chosen, since the projects main goal was to illuminate the possibilities of wax as an experimental construction material.
For this not only material properties, but also a production process had to be created. Especially for the process the number of experiments conducted in this research allowed to encounter many of the challenges of the material, which could be in turn reacted to.
Additionally, a more flexible approach, like the one followed in this discussion, is able to adapt to the project and to focus on areas which needed further clarification.

The repeated conduction of similar tasks lead early on to significant efficiency gains. At the end of the thesis experiments, which took weeks in the beginning for planning and realisation were designed and conducted from the ground in the matter of 5 days.
Additionally the execution quality was improved by slowly increasing the complexity of the designs.

Fig. 1. Experiment 18

II.E. DIGITAL TOOLS

II.E.1. Definition parametric design

Parametric design is a term, coined by Luigi Moretti in 1939. It describes a process in which a design problem is solved by defining logic rules that govern it.
(Tedeschi and Lombardi, 2017, p 20)

Contrary to the traditional drafting, in which this process happens in the mind of the drafter, it is expressed in numeric values (parameters) and their relations to each other. This allows for computers to process these rules, which in turn enables designers to work efficiently with complex design goals and geometries.
(Tedeschi and Lombardi, 2017, pp 17)

Parameters can be defined by demands of the design in relation to its environment, such as gravity, wind forces, rain, etc., can express design goals, for example base shape, size, etc., can be influenced by building law, maximum height, maximum Volume, materiality, etc., and many more.

These parameters are then interpreted and set into relation to each other using the algorithm, which is a set of unambiguous instructions for a computer to process.
(Tedeschi and Lombardi, 2017, p 23)

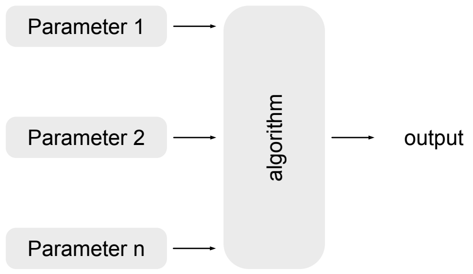


Fig.2. The base principle of algorithms

In this logic the user does not design a specific object, but rather the process out of which the object results.
(Tedeschi and Lombardi, 2017, p 25)

While algorithms can be written in programming languages, like python or C#, a simplified alternative exist in the form of node diagrams. They provide code blocks, which perform specific often used tasks, which are combined by the user to an algorithm. This enables designers without coding experience to pursue this design strategy.

II.E.2. Rhino 3D & Grasshopper

Rhino 3D is a 3D modelling tool produced by Robert McNeel & Associates. It can create and edit geometries, such as lines, surfaces and meshes.

The plugin “Grasshopper” adds the ability to create and execute algorithms within Rhino. These can be created using programming languages like C# or Python, or a node diagram.
The nodes provided can create numeric or geometric data (e.g. numbers, lines or 3D shapes), analyse them (e.g. find points on the geometry, find intersections, etc.) and edit them (move the geometry, scale, etc.).
Especially the wide range of plugins make “Grasshopper” a versatile tool for designers. These enhance existing functions or add new ones for a wide range of topics such as sound design, robot control, structural analysis and many more.

Rhino3D and Grasshopper facilitate the design process by displaying the output of the written algorithm in real time. This speeds up the design process as the result can be directly evaluated by the user.

II.E.3. Particle spring method

The particle spring method is an abstraction of a traditional form-finding method in architecture.

Before computers existed it was complicated to optimise structural performance. One early workaround was the catenary line. To produce it a chain was hung from two supports. In this experiment the chain self-organises into an upside down arc, in which only tension exists in the structural system, like in *fig.3*.

An arc, which approximates this shape upside down, can be built more efficiently as its members are only subject to pressure forces, as long as the principle load-case is gravity, an early example can be seen in *fig.4*.

This principle is still of importance in contemporary form-finding, even though its process has changed.
Nowadays points are defined and connected by the designer. Using a solver program, in this case “Kangaroo”, the connections are interpreted as springs and forces are applied to the points.

To start the simulation the following parameters must be defined:

- Base geometry
- Particle location
- Spring connections
- Spring strength
- Force direction and strength
- Anchor points

Base geometry

The base geometry should be a group of points, which are interconnected. It is often either a set of lines, like in *fig.5* , or a mesh, like in *fig.7*. Using lines and meshes simplifies the extraction of the needed values for the simulation.

Particle location

Fig.3. A catenary line

Fig.4. The Taq-I Kisra in Ctesisphon, Iraq an example of a catenary arc ca. 250-500 AD

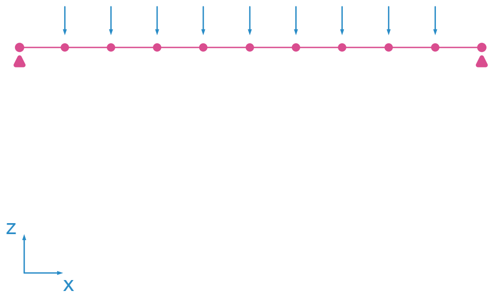


Fig.5. A 2D particle system before application of forces

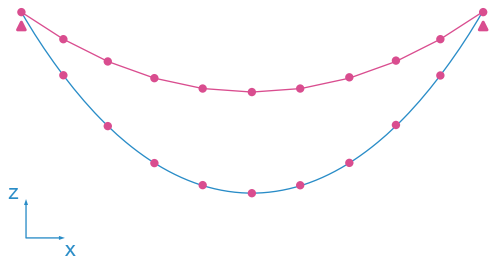


Fig.6. Two simulated results. The pink line has a higher spring strength than the blue line

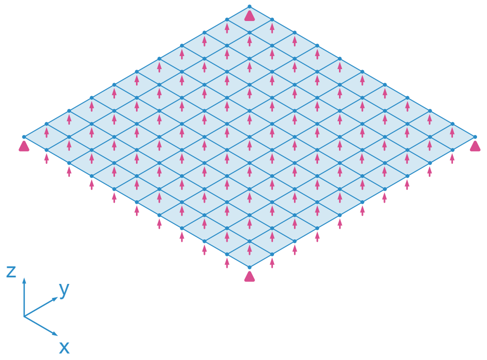


Fig.7. A 3D particle system using a mesh as input geometry

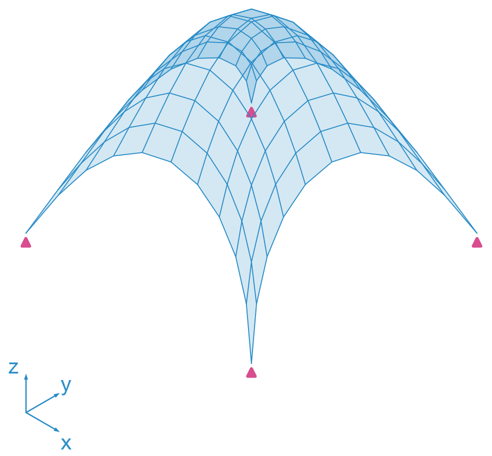


Fig.8. The result of the 3D simulation

Particles have to be defined as points, on which forces will be applied. In *fig.5 & 7* the particles are depicted as points

Spring connections

Here the defined particles will be interconnected by the user. When initial shape was a line or mesh geometry usually the lines or the mesh lines are used respectively. The springs are displayed as lines in *fig.5 & 7*.

Spring strength

This parameter defines the strength of the springs, i.e. how much they will deform under a certain load. If the situation requires it multiple spring strengths can be set in one simulation.

Force direction and strength

The direction of the force is defined as a vector in x, y and z direction. The length of the vector defines its strength.

Anchor points

Anchor points are defined as points that can not move freely. The can be locked in one or more directions. For example an anchor locked in z direction could still move in x and y directions. In the drawings the anchors are locked in all directions and represented by pink triangles.

When these parameters are given the resulting deformation can be simulated. The strength of the deformation can be manipulated by changing the ratio of spring strength to force strength. The weaker the springs and the higher the force applied, the stronger will be the deformation.

Fig.5 & 6 show a 2d particle spring system. A line is created and its endpoints are defined as anchors. Then the line is subdivided into shorter segments. The segments are defined as springs and their endpoints as particles. Then forces in -z direction are applied at the particles, which are not anchors.
In *fig.6* the pink line shows the simulated deformation of the line with a high spring strength.
The blue line is the result when the spring strength was lowered. To approximate the original idea of the catenary line a bit better the second line, drawn in blue, does not represent the springs directly, here the resulting particles were interpolated as a curve.

Fig.7 & 8 show a three dimensional particle spring system. In *fig.7* the light blue coloured represents the mesh, while the lines are the borders of its faces. The outer corners are defined as anchors. And forces are applied in +z direction at the corners of the mesh faces.
The result of the simulation is shown in *fig.8,* a dome like structure, in which its members are only subject to pressure forces.

II.E.4. Finite element analysis

The finite element method is a way of analysing the structural performance of a structure. It focuses on calculating the displacement from which other values, such as support forces and stresses, are derived in a second step.
(Werkle, 2021, p 103)

To conduct it the geometry which should be analysed, *fig.9*, is subdivided into a finite set of elements. These can be lines, mesh faces (like in the example on the right) or solids depending on the base geometry that should be analysed.
Even a mixture of these elements can be analysed, which makes the method versatile.
This process is called discretisation, *fig.10*.
(Werkle, 2021, p 78)

Depending on the discretised geometry, the line endpoints and the corner points of the meshes or solids are extracted and called nodes.
The lines, which connect the nodes, are from here on seen as springs like in *fig.11*.
At the nodes the degrees of freedom are determined. Depending on the geometry there can be a maximum of 6 degrees of freedom at each given point, namely movement in and rotation around the x, y or z axis, *fig.12*.
Each degree of freedom is then interpreted as a spring.
The spring strength is set to approximate the behaviour of the material chosen for this element.
(Werkle, 2021, pp 107)

These informations are then accumulated in a formula based on Hooks Law, which describes the extension of a spring:

$$[K] * \{u\} = \{F\}$$

K the global/element stiffness matrix

u the displacement vector

F the load vector

Fig.9. An element before the analysation

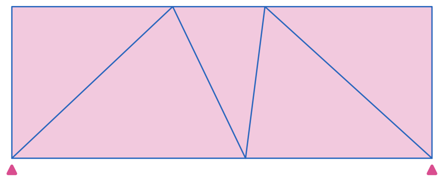


Fig.10. The discretised element

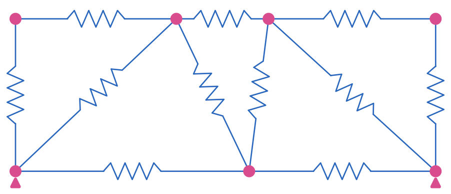


Fig.11. Lines between the nodes are interpreted as springs

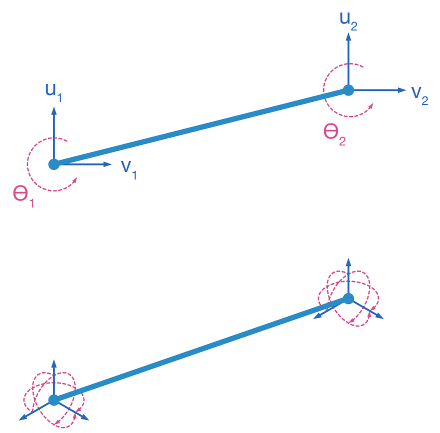


Fig.12. The possible degrees of freedom. Top: 2D geometries; Bottom 3D geometries

$$
\begin{array}{ccccc}
[K] & * & \{u\} & = & \{F\} \\
\begin{bmatrix}
k_{11} & k_{12} & k_{13} & k_{14} & k_{15} & k_{16} \\
k_{21} & k_{22} & k_{23} & k_{24} & k_{25} & k_{26} \\
k_{31} & k_{32} & k_{33} & k_{34} & k_{35} & k_{36} \\
k_{41} & k_{42} & k_{43} & k_{44} & k_{45} & k_{46} \\
k_{51} & k_{52} & k_{53} & k_{54} & k_{55} & k_{56} \\
k_{61} & k_{62} & k_{63} & k_{64} & k_{65} & k_{66}
\end{bmatrix}
& * &
\begin{Bmatrix} u_1 \\ v_1 \\ \theta_1 \\ u_2 \\ v_2 \\ \theta_2 \end{Bmatrix}
& = &
\begin{Bmatrix} f_{x1} \\ f_{y1} \\ m_1 \\ f_{x2} \\ f_{x2} \\ m_2 \end{Bmatrix}
\end{array}
$$

Fig.13. The element stiffness matrix for a 2D beam element

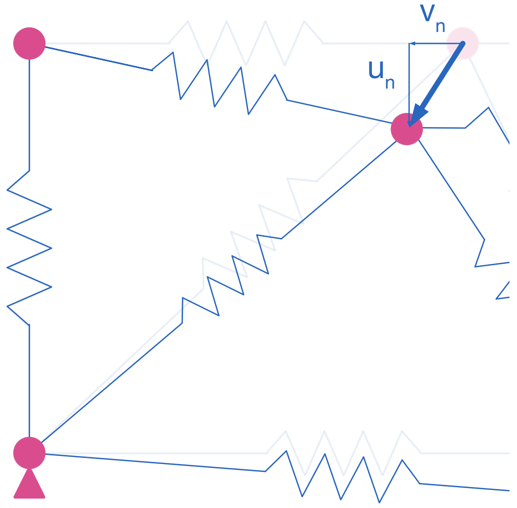


Fig.14. The deformation vectors applied to the geometry

Element stiffness matrices are created for each element (spring) of the discretised geometry, *fig.13*. These are then joined together in one global stiffness matrix based on their connections and positions.
Since the stiffness matrix is quadratic it has the same number of values horizontally as vertically, as visible in D. The amount of values in each direction is equal to the total number of degrees of freedom. The number of values within the matrix therefore is the number of degrees of freedom squared.
Discretised geometries can easily have more than thousand or hundred of thousand degrees of freedom, which make it necessary to solve these equations with a computer.
(Werkle, 2021, p 77-81)

The displacement is calculated by enforcing equilibrium throughout the structure, *fig.14*.
However the finite element analysis is only able to produce exact values for line geometries and very basic shell structures. For more complex structures the displacement vector can only be iteratively assumed and therefore equilibrium is approximated but not fully reached.
(Werkle, 2021, pp 193)

Over the course of this research Karamba3D was used for this task.

II.E.5. Conclusion

The explained methods give a short insight into modern form-finding methods. Through the use of computers and the widely available program options, formerly hard to conduct experiments can be simulated and integrated in a design process. Especially in multi parametric design processes this methods can be advantageous, as it is possible to keep oversight over a multitude of parameters and results.

A built structure is always subject to a multitude of environmental restraints, artistic ideas, etc. These can be translated to parameters in the design phase of an experiment. Later on they can be added, deleted and set into relation with each however needed. This approach can help to find an equilibrium between all of them, while design decisions stay transparent and editable.

Especially for a series of experiments, using an algorithm based design process can speed up experimentation since many parameters, e.g. material performance, chosen system, etc., remain the same.
Gained knowledge can be directly integrated into this process so that the algorithm reflects the current state of the project.

Using the particle spring method can simplify working with materials, which perform well in either tension or pressure. This way it can make lower performing materials viable, since they are only used in one load-case.
Another advantage of this principle is that very slim cross-sections can be reached. This is possible, because the size of the material can be optimised for an ideal performance in one load-case and does not have to take into account multiple other load-cases.

The finite element method explained in the last section makes it possible to calculate the performance of a geometry and the ideal material measures. This enables physical prototyping approaches as it gives instant feedback on expected material performance.

III. The material wax

III.A. A BRIEF HISTORY OF WAX

Wax has been used as a Material already by early humanity. Areas of application were not limited to candles or lamps and can be broadly described as “technological, ritual, cosmetic and medicinal” (Roffet-Salque et al., 2015, p 227) The earliest find of beeswax was on pottery in Çatalhöyük, which is situated in the Anatolia region of Turkey. It was dated to approximately 7.000 BC. The earliest finds in central Europe were dated to around 5.000 BC. (Roffet-Salque et al., 2015, p 229)

Around the same time (5.000 BC) the first metal objects were produced using the investment casting process (lost-wax casting). For this method objects (e.g. tools, weapons, jewellery, statues, etc.) are modelled using wax which is, enveloped with clay when finished. Afterwards, the metal, often copper, bronze or gold, is heated and poured into the clay. Due to the heat, the wax vaporises and leaves the clay through small channels. Its place is taken over by metal, which then solidifies in the shape modelled with wax. This process enabled humanity to cast complex geometries precisely and was used all over the world.(Orazi, 2020,pp 280; Pattnaik et al., 2012, p 2333)

One of beeswaxes most prominent early uses was as ingredient in the embalming process in Egypt starting probably in the XVIII dynasty ca. 1580-1340 BC. (Tchapla et al., 2004, p 219)

Early civilisation also used wax to take temporary notes. The earliest find of a tablet can be dated to the 14th century BC and was in a shipwreck close to Ulu Burun in south-west Turkey. (Payton, 1991, p 99)

Another remarkable usage of wax, as a means of communication, were the medical moulages, which were casts of dissected humans, organs and symptoms of diseases for medical education. Being fabricated since the renaissance, these moulages were used most commonly from the 18th to 20th century. (Lutz Sauerteig, 1998, pp 122)

Over time wax was used in many ways and the here mentioned ones are not an exhaustive list but should rather illustrate the versatility of this material.

With the discovery of crude oil and the continuous work on its refining process, paraffin was found by Karl Reichenbach in 1830. (Aronson, 2016, p 1)

In contrast to its strong connection to human culture over the last thousands of years, today usage of wax is mostly restricted to candles and packaging, which make up for 49% and 21% of global wax consumption. (Floros et al., 2017, p 2)

III.B. WAX AS A MATERIAL

The group of wax materials is a diverse collection of materials. It cannot be defined solely by its chemical composition and needs a second parameter, the physical performance, to distinguish it from other related materials.

„They may be branched or linear long chain hydrocarbons […], those derived from fossil petrochemicals or those produced synthetically […]; or, in the case of natural waxes […], they may comprise of lipid mixtures of fatty acids, alcohols, amides, esters, ketones, aromatics, carboxylic acids, triglycerides, and aldehydes [5]. Regardless of their source, however, waxes are industrially classified as materials which are hydrophobic, soluble in hexanes, solid at room temperature, congeal above 40°C, melt without decomposing, and are malleable or polishable at room temperature (20°C) [5]. „
(Floros et al., 2017,p 1)

For this research the most important information can be summarised as the following:

- Waxes can be sourced from petrol, plants and animals
- Waxes melt without decomposing
- Waxes congeal over 40°C
- Waxes are hydrophobic

The market of waxes is dominated by petrol-based and synthetic variants which make up for about 95% of the ca. 3,4 million tons of wax consumed every year. Recently a higher interest is directed towards natural waxes which are largely sourced from plants.(Floros et al., 2017, p 2)

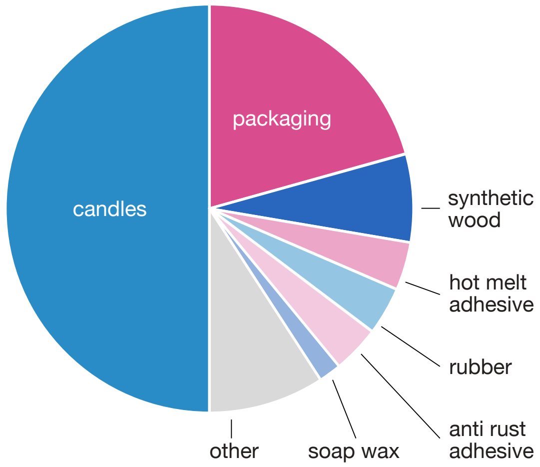


Fig.15. Utilisation of wax in 2012 (Floros et al., 2017)

Even though wax is nowadays largely used to produce candles many other areas of application can also be named, such as cosmetics, rubber, packaging and synthetic wood. This wide variety illustrates the versatility that this material can provide.(Floros et al., 2017, p 2)

III.C. STRUCTURAL PROPERTIES OF WAX

Due to the large diversity of wax, general assumptions about its structural performance cannot be made. Nevertheless, through testing each type in a standardised test, the different performances can be compared.

Below the waxes, which were tested in the following sections, are given a short description.

Fischer-Tropsch (FT) is a synthetic wax. Combining Carbon monoxide and Hydrogen at a certain pressure, temperature and combined with a catalyst, many materials can be produced, among others a FT paraffin wax.(Marchese et al., 2021)
This reaction can be used to recycle organic waste. (Nuss et al., 2013, p 8)

Paraffin is derived from petroleum. It is extracted in the refining process of crude oil. (Tufvesson and Börjesson, 2008, pp 329)

Beeswax is sourced from the honeycombs of bees, which are crushed and heated to extract the wax. (Kast and Kilchenmann, 2022, p 2)

Carnauba wax is a natural wax sourced from the Carnauba palm. It can be extracted from its palm leaves. (de Freitas et al., 2019, p 38)

Soy wax is a derivative of soybean. After its harvest the beans are processed and pressed, which extracts the soy oil. This oil can be treated with hydrogen (hydrogenation) to produce soy wax. (Rezaei et al., 2002, p 1241)

NWA and NWS-55 are both bio based waxes. They are both based on vegetable oil, which is hydrogenated. In the case of NWS-55 it is additionally metathesised, a process in which carbon bonds are redistributed and equalised. (Floros et al., 2017,p 3)

III.C.1. Yield strength

The yield tests were conducted by applying an increasing pressure on a wax disk of the size 3,2 mm height x 20 mm diameter.

Using a differential scanning calorimeter, the phase change temperature as well as its limit values were determined. (Floros et al., 2017, p 4)

In the tables above it is visible how heterogenous the physical properties of the different waxes are. Soy wax (343 N) or paraffin (709 N) are only able to withstand 5% or 11,2% of the pressure at which FT yields (6348 N). (Floros et al., 2017, p 9-12)

In the paper “A toolbox for the characterisation of bio based waxes” the performance in the yield test is connected to the size, morphology and distance of the crystalline structure. It is further mentioned, that the melting onset point can be seen as the closest approximation of its possible performance.
(Floros et al., 2017, pp 10)

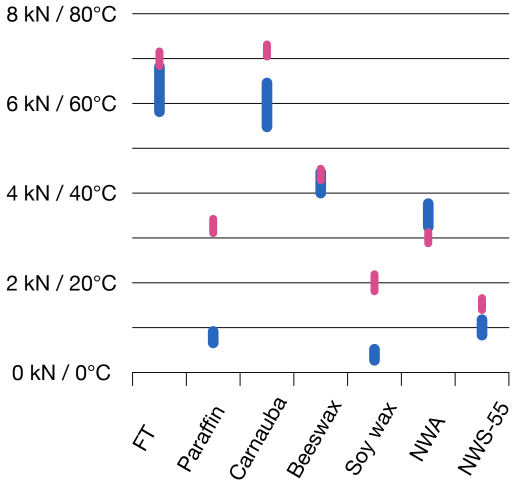


Fig.16. Yield forces (blue) in comparison with Melting onset (pink) for different waxes

However, the performance of the material in tensile strength tests seems to be unconnected to its performance in the pressure test. Here, Paraffin performed better than beeswax. The first yields at 0,102 KN/cm2, the latter at 0,094KN/cm2. (Dubey et al., 2021, p 248)

Based on both stress tests, it can be said, that wax performs considerably better in load cases in which only pressure is exerted on it. In tension it can support in the case of paraffin only ~44% and for beeswax merely ~7% of the same weight.

	Measured Yield force	Yield force in N/cm^2	Yield force in KN/cm^2
Fischer Tropsch	6348 N	2020 N/cm^2	2,02 KN/cm^2
Paraffin	709 N	225 N/cm^2	0,23 KN/cm^2
Carnauba	6002 N	1910 N/cm^2	1,91 KN/cm^2
Beeswax	4332 N	1375 N/cm^2	1,37 KN/cm^2
Soy wax	343 N	109 N/cm^2	0,11 KN/cm^2
NWA	3460 N	1101 N/cm^2	1,10 KN/cm^2
NWS-55	998 N	318 N/cm^2	0,32 KN/cm^2

Chart.1. The Yield force of different waxes

III.C.2. Young modulus

Youngs modulus is an indicator for the elasticity of a material under stress. It can be expressed as numbers or as a graph that shows the performance over time. Both were only found for paraffin and beeswax. They were obtained with tensile tests. The found values were:

Paraffin wax	116.3×106N/m2
beeswax	93.96×104N/m2

The values approximate the slope ratio before a directional change. For example a plateau or a flattening of a curve.
(Dubey et al., 2021, pp 248)

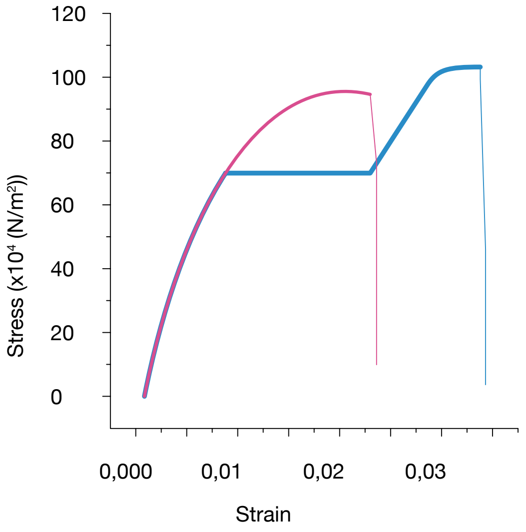


Fig.17. Youngs modulus, Pink: Beeswax, Blue:Paraffin wax

When looking at the graph beeswax and paraffin wax perform very differently. Even though they both begin with a steep curve, beeswax becomes flatter over time until it reverses direction and ends, while paraffins graph shows a plateau and another steep curve which also ends after reversing its direction.

In a graph depicting Young's modulus, the end of a line shows that the material failed at this point.

An interpretation of the Young's Modulus graph of beeswax can show some of its limitations. The first learning would be, that it is a brittle material. This can be concluded due to the missing plateau and the continuous curve of the graph. A plateau would indicate that the material enters an elastic phase when stressed to a certain amount. In contrast to beeswax, paraffin could be observed to be somewhat elastic.

III.C.3. Specific weight

Density is an important material property. It can influence the process and tools that are needed to work with it.

Even though it has already been shown that the physical properties of wax can vary widely, their densities do not. Usually they lie between 900 kg/m3 and 1.000 kg/m3.

	Density
Fischer Tropsch [1]	940-1000 kg/m^{3*}
Paraffin [2]	894 kg/m^3
Carnauba [3]	998 kg/m^3
Beeswax [4]	952 kg/m^3

Chart.2. Density of different waxes

(1) (EVONIK INDUSTRIES, 2022);
(2) & (3) (Cameo chemicals / National Oceanic and Atmospheric Administration of USA, 2022);
(4) (aqua-calc, 2022)

III.C.4. Performance in hot environments

From the performance in hot environments, it is possible to define necessary fire safety precautions. Since wax is used as a fuel, it must not be underestimated how flammable this material is.

The flash point (the temperature starting from which it can spontaneously self-incinerate) of paraffin wax, for example, lies at 193°C, which is very low. (MSDS: Paraffin Wax, 2010, p 2)

Even though this might sound problematic, it can be disregarded in this research. The onset of melting will always be at significantly lower temperatures and will cause the structure to fail sooner.

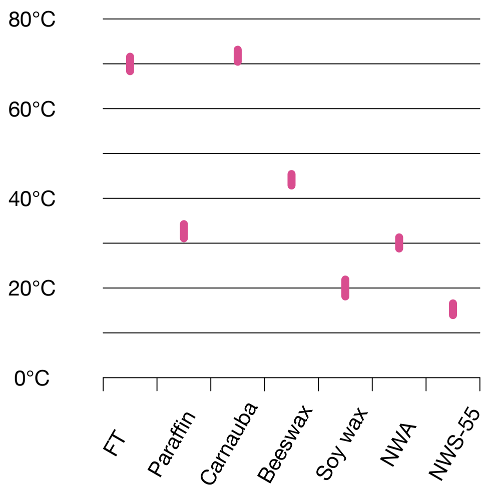


Fig.18. Melting onsets for different waxes

A structure that is intended to be used in a non-experimental environment would need to solve this and other problems that this material faces when exposed to heat.

IV. State of the art

IV.A. RECYCLING IN SHORT-TERM ARCHITECTURE

IV.A.1. Definition of different recycling logics

Even though recycling has become a word that is ubiquitous nowadays, it seems to be used more as an umbrella term.

In the following paragraphs different specific terms will be presented, using the nomenclature laid out in the paper “Recycling concepts and the index of recyclability for building materials” by Luiz H. Maccarini Vefago and Jaume Avellaneda.

At the same time, this serves as a short introduction to reuse cycles and options available today. The list starts with Recycling and is then continued with the next closest term.

For the authors, a material is recycled when its chemical internal structure can be transformed or its physical state can be changed, while its initial properties are maintained. However, it does not have to have the same function as in its previous life cycle.

The examples given are metals, which can be recycled through smelting. Another example are pieces of wood, which, when not treated with toxins, can be recycled by leaving them to natural decay.

A material is Infracycled, when it changes its physical state or its chemical internal structure, but its initial properties decrease. Due to this it cannot be used for the same application anymore.

Petroleum plastics are named as an example here, since they lose their initial properties over the course of their lifecycles.

Reused is the appropriate term, when a materials chemical internal structure or physical state are not changed, and its initial properties remain the same. Although it does not need to be used in the same way as before.

A wooden beam, which is deconstructed and then reattached in another building would fulfil this definition.

Infraused describes a process in which neither the chemical internal structure or the physical state is changed, nor are the initial properties of the material preserved. Therefore, it cannot be used like in the same ways as in its previous life cycle.

Crushed concrete or ceramic brick are given as examples as they are usually reused for street construction.

(Vefago and Avellaneda, 2013, p. 2-3)

These terms shed light on the different varieties used under the umbrella term recycling. It becomes visible that, when following these definitions, Infracycled and especially Infraused are processes which are less advantageous than recycling or reusing, even though they are colloquially called the same.

Naturally, not all these processes can be applied to all materials, which makes the less advantageous processes often the best opportunity for some of them.

IV.A.2. Definition of temporary architecture

Temporary architecture is a work term that will be defined here and used throughout the project.
Since there is no definition of the word in common knowledge the working definition chosen for this project is the following:

“A building which is intended for one use and one main user. It is disposed after this use is not needed or wished for anymore”

IV.A.3. Recycling opportunities for materials used in temporary Architecture

The projects listed are examples to illustrate material usage. Comprehensive data on material usage and choice in temporary architecture was unavailable.

The materials used in the shown pavilions can be grouped in the following way

Wood

Wood is a common material in temporary architecture, due to its availability and ease of use. It can be found as sole material, as in *fig.19*, or as substructure, as in *fig.22*.

	Wood
Recycling	Wood is an organic material, it can be easily recycled, if not treated with toxins. Therefore it has to be composted to return to the natural cycle.
Infracycling	X
Reusing	As long as a new application can be found it can also be reused.
Infrausing	Wood can be infracycled to lower quality products through shredding. The most common new product would be particle boards. (Eisenlauer et al., 2018)

Chart.3. Recycling opportunities of wood

Metals

Metals are most often used as substructure in temporary architecture. *Fig.20* shows a pavilion made of steel and textile and *fig.21* a pavillon made of aluminium, wich are the most common metals in construction.

Metals theoretically all have the same recycling options. The needed energy varies.

In Europe, 2008 about 50% of produced steel was sourced from scrap metals. The share of recycled metals for aluminium was 2010 at 40%.
For both metals demand is continuously rising, so virgin material has to be introduced to the market as well. (Rombach, 2013, p 1017)

Fig.19. Nine wooden cabins from Lake Annecy Cabin Festival, 2021

Fig.20. A pavillon made of aluminium by Nebbia Works, 2021

Fig.21. Steel pavillion by AIRLAB in Singapore, 2020

Fig.22. "pineapple" by Studio Morison in Berlington Hall, 2017

Fig.23. "Leverage" by Rumgehør built from Dunnage bags, 2021

Fig.24. A pavillon of SelgasCano in Cognac, 2017

	Steel	Energy consumed
Recycling	Iron can be melted and separated from its additives. It is fully recyclable.	9–12,5 GJ/tcs
Infracycling	X	
Reusing	As long as a new application can be found it can also be reused.	
Infrausing	X	

Chart.4. Recycling opportunities of steel

	Aluminium	Energy consumed
Recycling	Aluminium can be theoretically melted and separated from its additives. It is fully recyclable.	25,1 GJ/t
Infracycling	Aluminium is infracycled, when impurities or additives are not taken into account. That can result in lower quality aluminium.	
Reusing	As long as a new application can be found it can also be reused.	
Infrausing	X	

Chart.5. Recycling opportunities of aluminium

Textiles

Textile is used primarily as space creating element. *Fig.21 & 23* are a good examples for that. Since textile can be sourced naturally and synthetically a general statement can not be made. In this section only naturally sourced textile, such as from cotton or wool will be discussed. Partly or completely synthetic textile will be discussed in the paragraph “Plastics”

(Sandin and Peters, 2018, p 355)

	Naturally sourced fabric
Recycling	It can be composted to return to the natural cycle.
Infracycling	Textiles are usually infracycled since the fibres, which make it up, have to be partly destroyed, thus resulting in a lower quality.
Reusing	As long as a new application can be found it can be reused.
Infrausing	X

Chart.6. Recycling opportunities of textiles

Plastics

Plastics are used either as finish but rarely as structural material. *Fig.23* shows an installation of Dunnage bags which are usually used to protect cargo on trucks or ships. The structure on *fig.24* uses plastic sheets to crate shadow, as well as plastic pillows.

	Plastics
Recycling	X
Infracycling	Plastics can be reused a limited number of times and it decreases in quality with every new use
Reusing	Plastic parts are usually optimised to for one purpose which makes reusing them difficult.
Infrausing	X

Chart.7. Recycling opportunities of plastic

(Vefago and Avellaneda, 2013, p. 2-3)
(Rudolph et al., 2020, p 13)

IV.A.4. Conclusion

In this discussion different paths for reutilisation of materials were presented. A work definition of temporary architecture for this thesis was given and examples were presented to highlight the used materials in this subfield of architecture.
After a short description of how the materials are commonly used their Recyclability and Reusability was estimated using secondary information.

It became visible, that most used materials have few direct options for reuse.

Only steel and to some extent aluminium can be permanently recycled. Although this requires a considerable amount of energy .

Wood, probably the most commonly used material for temporary architecture, can be reused. Quantitative data on this was not available and suggests that this might occur rather incidental.

Due to the nature of largely one use materials their generation and processing has to be taken more into account, whereas recyclable resources can be evaluated rather by their recycling process.

These three materials, which have the most a advantageous reuse and recycling scenarios show, the dilemma of temporary architecture. Structures are being built with materials that outlast them by a long time.

New bio based materials, such as Mycelium based products, try to bridge this gap, in this case, by being compostable and having very low emissions cost for their creation. In other cases materials are reused to build structures. Nevertheless both of these approaches seem to be rather niche strategies at the moment.

IV.B. FABRIC FORMWORK

IV.B.1. An introduction to casting

Casting is one of the oldest construction techniques used by humanity. It is characterised by its process in which a liquid material, which can solidify, is poured into a negative shape to create the desired shape. Founds show that copper had been casted in the Balkans and Middle East already around 5.000 BCE. (Neukirchen, 2016, p 27)

Nowadays many materials can be casted, for example metals, such as steel, copper, or brass, concrete, plaster, resin, etc.

Traditionally, casting (especially metal casting) can be subdivided into 3 groups based on the details of the process:

01 Casts with lost formwork and a permanent model

02 Casts with lost formwork and a lost model

03 Casts with permanent formwork

The first category describes a process in which a prototype of the desired shape (positive) was already produced and is of a material (often metal or wood) which will not deform when the negative is created.
To construct the formwork (negative) the positive is enveloped with another material (A). In earlier times this was often made with clay. Nowadays it is done with a special kind of sand, which is stickier and can therefore retain the shape, when the positive is removed.
Then the sand parts are carefully removed, and the positive is taken out (C). If the model is supposed to be hollow for its use or to save material, a filling element is now attached to the negative shape (D). Finally, a funnel is carved into the sand through which the metal will flow into the shape, together with some thin air vents to avoid air bubbles in the finished cast.
Afterwards, the negative is assembled as it was before, only without the positive inside.
Now the mould is ready and can be filled with the desired material (E).
When the material is solid, the positive can be taken directly out of the sand without the need to preserve the formwork (F).

The second category can only be used with materials which are very hot when cast. Here a positive is needed, which is destroyed when the model is cast.

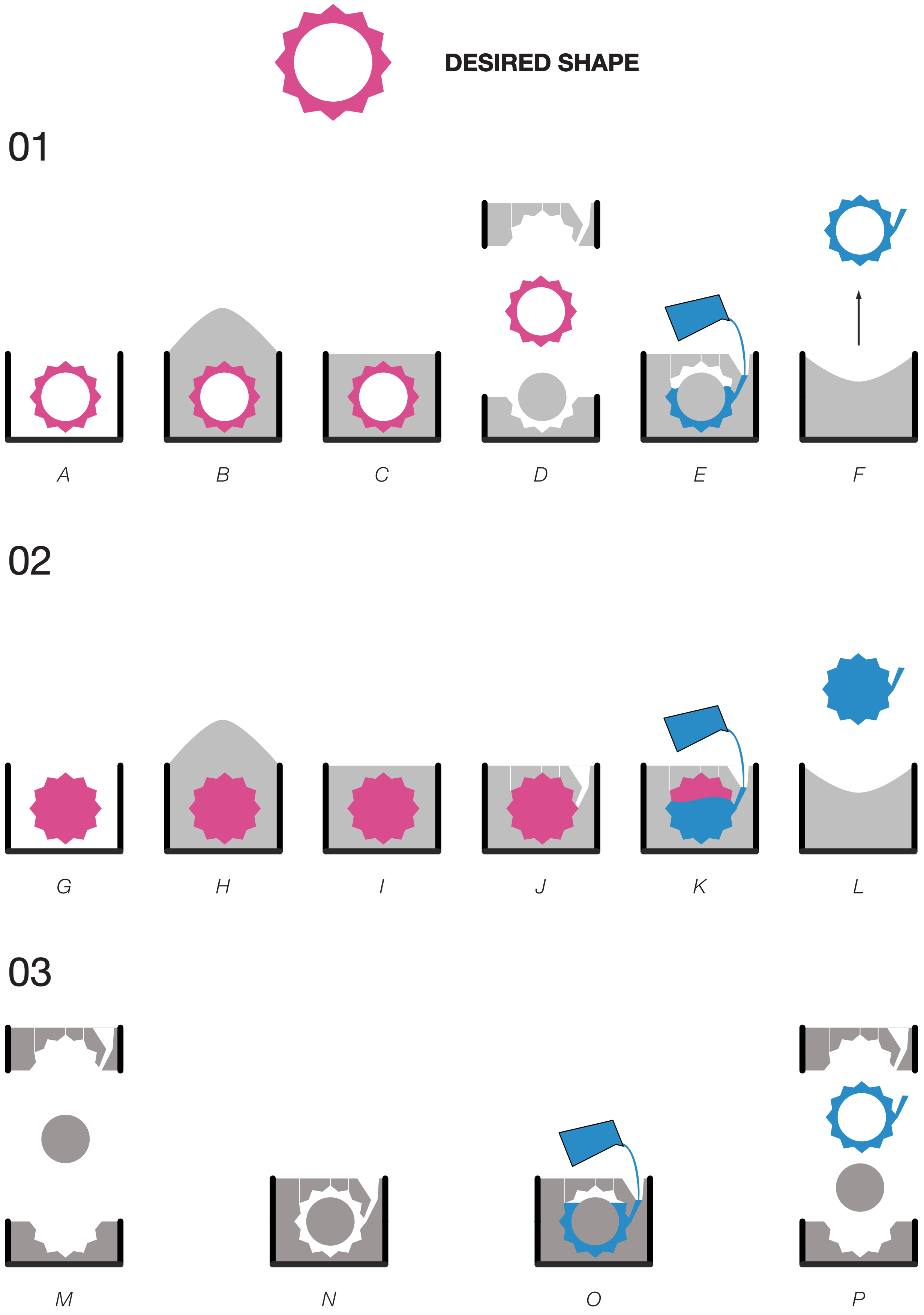


Fig.25. The three main casting methods

For this a model is made from an easily formable material, like wax (G). It is then enveloped in clay or sand (H & I). In this process a funnel is designed and some exhausts created (J).
Then the hot metal is poured into the funnel, because of its temperature, it evaporates the wax on contact and takes its place (K).
To remove the positive, the formwork is destroyed (L).

The last category is optimised for repetitive casting.
Here a formwork is produced which can be reused (M). Therefore, it must be made of a material that remains stable at all stages of the casting process. Additionally, it should be prepared to open easily so that the positive can be removed.
To use it the form would be assembled (N). Then the material is poured into the shape (O). As soon as the positive is solid, it can be removed from the formwork, which is then reassembled for the next casting process (P).
(Klocke, 2018, pp 6)

IV.B.2. Definition and history

Fabric formwork describes a subgroup of casting techniques which use fabric to create the negative shape. Only materials can be cast without special preparation, that don't destroy the fabric in the casting process.

In architecture, the material of choice here is usually concrete.

Fabric formwork can fit into many design strategies. It can be used to optimise cross-sections, create smooth structured concrete finishes and as a lost formwork it can even be used to create base geometries.

Using fabric as formwork is a comparatively new idea. Even though Roman engineering already used a parallel technique, constructing falsework for vaults from woven reeds, the first usage of this technique was recorded by Gustav Lilienthal.

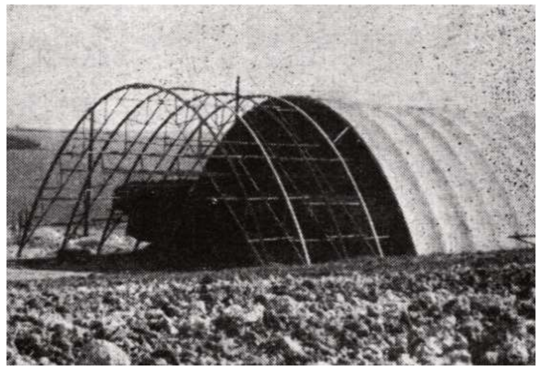


Fig.26. Ctesiphon by James Hardress de Warenne Waller

Directly followed by James Hardress de Warenne Waller, who developed the idea of lost form work casting with concrete. This is a technique in which the desired shape is constructed using only textile. When finished, cement dust is sprayed over the structure which will cause the fabric to solidify.

His “Ctesiphon” system, *fig.26*, a row of catenary-shaped steel arcs which carried this cement fabric hybrid material, was used by Felix Candela for his first shell. (Veenendaal et al., 2011, pp 165)

The availability of synthetic fabric, which was better suited as a formwork due to its strength and the fact that it does not adhere to concrete, drove a rising interest in fabric formwork from the 1960s-1980s, which continues to the present.

Since then, fabric formwork has inspired many engineers.

In architecture the idea of shaping the design with the formwork was further developed. Wallace Neff built dome like houses on pneumatically pressured formworks to save costs.

New attention was drawn to this idea by Heinz Isler, who used inflatables as form-finding models and built experimental large-scale structures following up on these ideas.
(Veenendaal et al., 2011, pp 171)

Until recently this research area has not been well connected with a very limited amount of scientific literature and architects, mostly working on their own experiences instead of building on the ones of others.

Nowadays, fabric formwork gets more attention in architecture, especially through the work of students. Many experimental structures have been erected and are displayed in the next paragraph.

A more widespread application of fabric formwork in built architecture is not yet foreseeable due to its requirements for architects, engineers, and construction workers.

Nevertheless, through modern computer-aided design strategies, the design and planning of these structures is more feasible than ever before.
(Veenendaal et al., 2011, pp 172)

IV.B.3.Fabric formwork today

Nowadays fabric formwork is a research subject of increasing interest. Therefore, many projects using this technique have been developed, mostly in the university context.
In the following paragraph some of which are presented to give a brief overview over recently conducted research.

To structure the projects they were distinguished in two groups. The projects presented first have the structural material cast on fabric.
In the second category the material is cast in fabric.

Casting on fabric

KnitCandela, Mexico City, 2018

The project, developed and realised by Popescu et al. [2017;2018] as a cooperation of Block research group from ETH Zürich and Zaha Hadid Architects Computation and Design Group (ZHCODE), consists of a knitted fabric, onto which concrete is cast, *fig.27*.
The doubly curved surface, which forms the base shape, was translated to a knitting pattern for a CNC Knitting machine.
To stabilise the formwork for the casting process, a scaffolding made of wood and and steel was constructed, *fig.28*. It was used as supports for the structure and otherwise only constructed around the open edges of the formwork. Then the formwork was attached to the substructure and tensed. A steel cable net within the knitted textile was used to keep the shape stable, *fig.29*.
Pouring was subdivided into two phases. At first a coating with Calcium Aluminate Concrete, which hardens fast and should prevent local deformations, was sprayed on the outer side of the formwork. Secondly three layers of glass-fiber reinforced concrete were applied.
After the solidification process the prototype was removed from the substructure and the steel cable net was taken out.

The KnitCandela proves, that realisations of doubly curved concrete surfaces can be time saving, the whole project was conducted in three and a half months, and cost effective, the material value was 2.250€, while producing considerably less waste than a more traditional approach.
(Popescu et al., 2020)


Fig.27. The finished KnitCandela


Fig.28. The temporary scaffolding

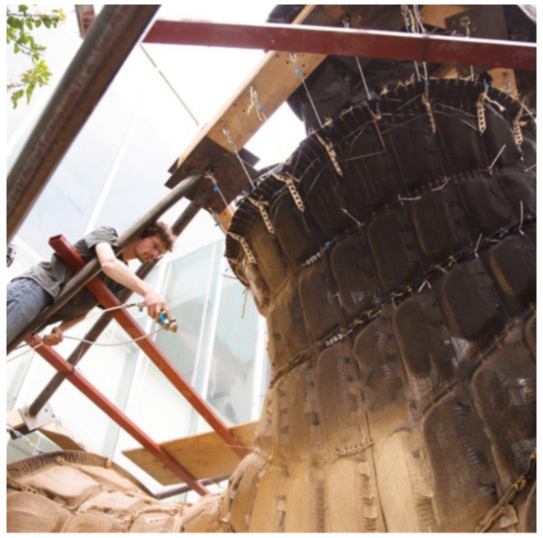


Fig.29. Tension connections & cable net structure

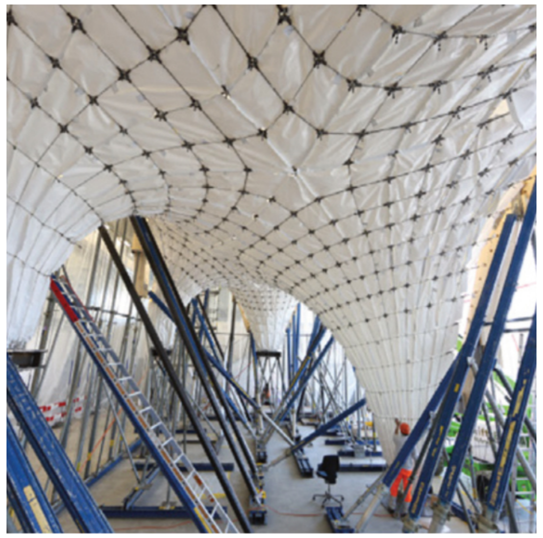


Fig.30. The HiLo cable net structure & fabric formwork

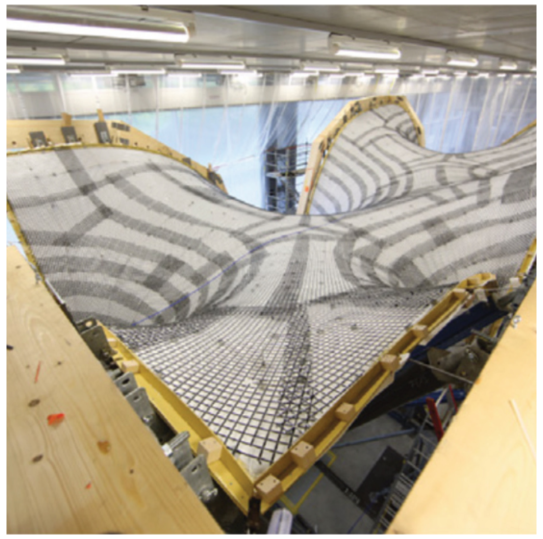


Fig.31. The carbon-fibre reinforcement on top of the fabric formwork

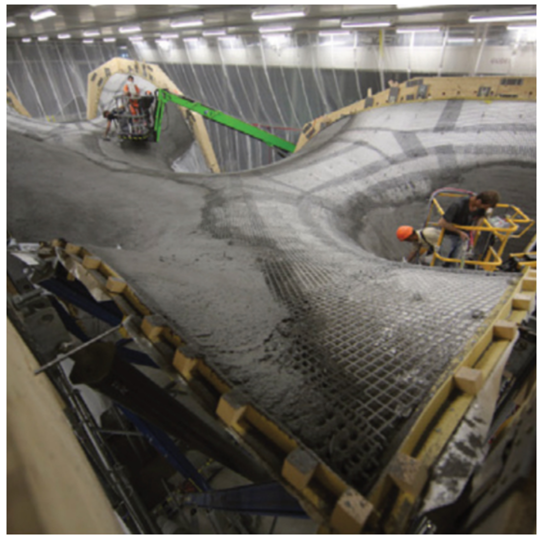


Fig.32. Concrete is sprayed on the structure

HiLo roof prototype, Zurich, 2018

The project was conducted by Block research group of ETH Zurich. Even though it uses approximately the same process as the KnitCandela, it illustrates to a greater extent, how feasible the technology is for application in everyday architecture. It's size, roughly covering an open space of 120sqm, shows the scalability of the process, *fig.33*.
Digitally a doubly curved surface standing on five supports is designed.
To construct the prototype, a scaffolding was created, in which a cable net was clamped, to form the desired geometry, *fig.30*. On it a polypropylen textile was mounted, which was produced slightly smaller than need, to create a higher tension. A higher tension within the formwork prevents the fabric from forming bumps, when the concrete is applied to it.
Afterwards carbon-fibre reinforcement was installed on top of the fabric and at last concrete sprayed onto the structure, *fig.31 & 32*.

This prototype was followed by a realisation as the roof structure of the HiLo NEST building, *fig.34*. (Méndez Echenagucia et al., 2019)

Terramia Drone Spray Project, Milano, 2019

A collaboration of MuDD Architects with Canya Viva, Summum Engineering and AKT II conducted this project, *fig.35*.
Here, instead of concrete, a mixture of wetted sand and clay was used as a binder. Additionally to the focus on renewable resources, many tasks, which would be usually performed by humans, were performed by drones.
For the production of these prototypes, the largest roughly spanning over 27sqm, a substructure made of local bamboo was created. After this drones took over the production process and lifted the textile over the substructure. At first, to stabilise the fabric, a mixture of sand and clay was applied and secondly dried fibres for insulation, *fig.36*. Both were sprayed onto the structure by drones.

This projects show fabric formwork from a different side, than both projects above. It shows, that concrete is not the only imaginable material in this concept.
Especially the use of drones, a unique feature in this list, shows up other option to upscaling of geometries.
(mudd architects, 2022)


Fig.33. The finished HiLo prototype


Fig.34. The built structure in Zurich

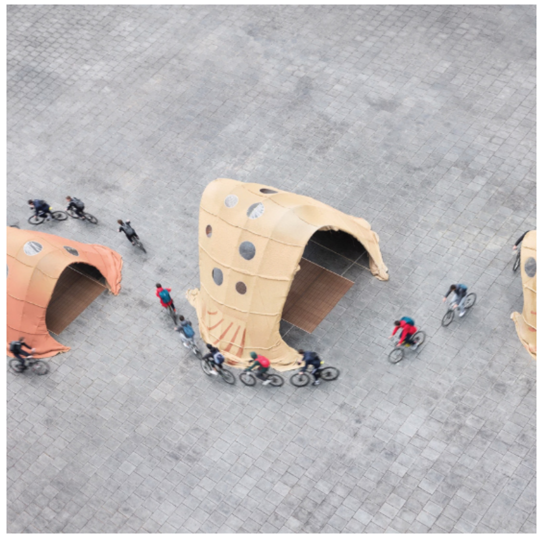


Fig.35. The Terramia Drone Spray Project


Fig.36. Sands and clays were sprayed on a textile with the help of a drone


Fig.37. The substructure was made from bamboo


Fig. 38. An inside view of the Terramia

Casting in fabric

Organica Hyparbolica, Eindhoven, 2016

This student project, conducted at TU Eindhoven, uses a pvc coated polyester as formwork. It was chosen, because it becomes adhesive at low temperatures, which simplifies the production of the formwork.
The shape, a column was designed for optimal material use, hence the pattern.
It was scaled, so that it fit into a cube with a side length of 2,4m, *fig.39*.
Due to the mostly closed fabric formwork, a reinforcement could not be integrated into the structure. Therefore a higher concrete quality was chosen, which was reinforced with 60mm long steel fibres, enabling the structure to withstand small tension loads. Since the use of a vibrator for deaeration of the concrete was impossible a self-compacting product was chosen.
For the production process a wooden structure was erected, as visible in *fig.40*.
The basis was cast traditionally, with exposed steel anchors to connect to the column.
Then the formwork was attached to the basis and clamped to the wooden structure.
Afterwards it was filled with the described concrete and steel mix and left to solidify.

This project shows the hardships of using concrete in a fabric formwork. Especially the difficulties of introducing traditional steel reinforcement into the material show intrinsic problems of this process.
(Coen Smets, 2022)

MARS Pavilion, 2017

The MARS Pavilion was designed and produced by a collaboration of Form Finds Design with Walter P. Moore engineers, *fig.42*. In this project robots help to put fabric formwork under tension to generate module shapes.
To create the project a macro shape was design. It is created with mesh relaxation methods and later approximated with a honeycomb pattern. This pattern is then subdivided into Y shaped nodes, which are all unique. Each of these elements has its own nylon formwork, *fig.44*.
The casting was simplified by having one pouring point and two robotic arms at each side. Each ending of the Y is then connected to either a robotic arm or the pouring point, which always needs to be the highest point of the geometry. Then the arms are moved into place putting the formwork under tension, *fig.43*. Due to the tension it will not bulge when it is filled with twisted micro steel reinforced concrete.

Fig.39. The Organica Hyparbolica

Fig.40. The wooden substructure for the casting process

Fig.41. Wrinkles in the casted shape

Fig.42. The MARS Pavilion

Fig.43. Robots were used to cast the modules

Fig.44. The sown formwork and its mounting on the robot

These shapes then solidify until hard enough to be removed from the robots. The Y shapes are interconnected using triangular steel elements. Theses are connected with screws to the modules.

This project shows an interesting path towards mass individualisation using fabric formwork. Even though in this iteration all elements had their proper formwork it was stated in the paper that, using the flexibility of nylon, only ten formworks could have been sufficient to produce all of the 70 elements.
(Sarafian et al., 2017)

Computational design of fabric formwork, 2019

The process proposed by Zhang, Fang, Skouras et al. [2019] describes a computational framework for the creation of fabric formwork, cast in suspension, which is derived from a user generated desired shape. Later experiment are carried out to verify the validity of this process. In a trial production process the information searched for are described as the following: Set of 2D panels, location of seams, suspension contact points and external supports.
After designing a freeform shape, the optimal hanging direction is determined, by calculating the deformation it would entail, when filled, *fig.46*. The direction with the minimal deformation is chosen. Then the free form shape is subdivided into planar sections using the Variational Segmentation Approximation, as detailed by Cohen-Steiner et al., [2006], *fig.47*. Afterwards, neighbouring patches are joined, as long as the resulting shape can still be planar developed, a process designed by Wang C., [2008]. The edges of these panels are the later seams of the formwork.
Additionally supports, consisting of strings, cables and planes, can be added to the structure for geometries that would not be producible using only fabric formwork, *fig.49*.
For a better approximation of the desired shape material parameters were also researched and integrated into the simulation.
An examination of produced geometries showed a high accuracy of the end shape but many optimisation potentials in detail processes. For example the formwork was still simulated as one piece by the algorithm, which produced inaccuracies in the areas around the seams. Additionally areas with a non-zero gaussian curvature were susceptible to forming wrinkles.

In this project a automated way of formwork design for free form geometries is presented, which is one of the most difficult parts of working with fabric formwork. Simplifications like this have a huge potential to inspire wider use of the technique.
(Zhang et al., 2019)

Fig.45. Steel triangles connect the modules

Fig.46. The target shape was designed

Fig.47. The surface of the shape was subdivided into planar panels

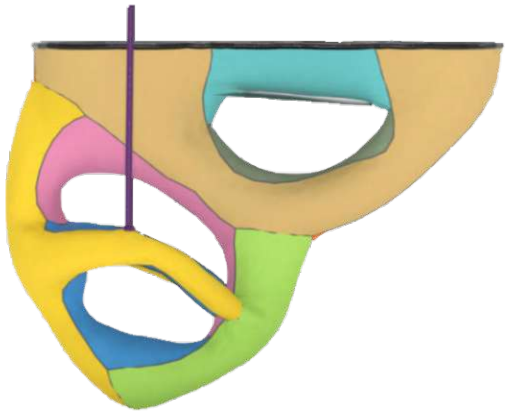


Fig.48. The location of the planar panels on the structure

Fig.49. The realized and filled formwork

Fig.50. The realized structure made of plaster

IV.B.4.Conclusion

The broad overview over the history of fabric formwork and its current use, given in the chapters above, paints the picture of a production process which is at a crucial point between mostly academic use and a possibility of adoption into the vocabulary of architecture.

Projects such as the *“MARS Pavilion”* and the *“Terramia Drone Spray Project”* show new strategies of approaching this topic. The usage of drones and robots is interesting in the context of fabric formwork. It shows new paths to a potential upscaling of structure size. Additionally the minimisation of waste production, which is already an inherent advantage of fabric formwork is advanced.
Lastly the introduction of new materials is important asset, since the production process of concrete, usually the standard material, is very resource intensive. (source)

The perception of feasibility is changed by projects like *“KnitCandela” “HiLo roof prototype“* and *“Computational design of fabric formwork”*. Advances like these reference strategies for computation and execution, which together can have an impact on the risk averse construction industry. Especially the fact that larger scales continue to be more resource efficient compared to traditional processes holds the possibility of a wider application of casting on fabric in built architecture of the next years.

Due to the problems with reinforcement and deaeration of concrete, shown in *“Organica Hyparbolica”*, an application of casting in fabric for structural elements might be further from application. A more feasible application for this technology might be closer to the idea developed after the conduction of the *“MARS Pavilion”*. With this technology non load carrying elements could be produced, using stretchable formwork. A process like this could be extremely resource efficient, while allowing designers to create non repetitive patterns.

The increasing knowledge and interest in complex geometries and the current explorations of more efficient structures and production processes elevate the possibility for wider adoption of fabric formwork. Recent project decrease the complexity of the subject and raise interest through their unique shapes.
Further observation of this topic appears worthwhile, since a breakthrough into the standard vocabulary of architecture seems more and more possible.

V. Experimentation

V.A. AIM OF EXPERIMENTATION

Throughout this thesis experimentation was always necessary to verify material behaviour. At the same time it was also one of the catalysts of development through which alternative practices to achieve higher quality or efficiency became visible.
The main question of this thesis has to be how to make wax a feasible material for construction.

From this most of the aims for the experiments can be derived:

- Defining/Estimation of the strength of the material
- Researching the scalability of the processes and material
- Defining the ideal casting process
- Defining shapes that compliment the given material
- Defining construction principles for the material
- Finding textiles that work well with wax

Due to the limitations of the university facilities the analysis of created experiments could not be conducted in the necessary accuracy. Testing processes, their results and restrictions are listed in the Result sections of the respective experiments.
To reflect this the research was restricted to a low-tech environment.
However this was not seen as a restrictive measure, but rather as an enabler for a process based on a multitude of experiments. Facts had to be proven over the course of multiple experiments which scrutinised the findings more often, but lead to a more wholistic understanding of the material.

Accurate data was, when needed, collected from scientific sources.

V.B. CATALOGUE OF EXPERIMENTS

On the following pages the conducted experiments will be presented chronologically. Failings of the experiments that have to be attributed to the design of the experiment will be explained in the description. Experiment unspecific problems will be discussed in the *"Result"* section.

The different experiments are listed chronologically and grouped by their focus. An introduction will be given for each group.

Fig.51. A part of the wax core of exp.14

V.C. MATERIAL EXPERIMENTS

Since knowledge and and experience were very limited in the start of this discussion only simple experiments were conducted at first. Brick-like shapes were chosen since the needed formwork was readily available and differences in volume or other properties were easily observable.

Later tests focused also on volume increase through whisking.

To summarise the areas of interest:

- Development of a basic understanding of the material
- Physical material modification


Fig.52. Experiment 1

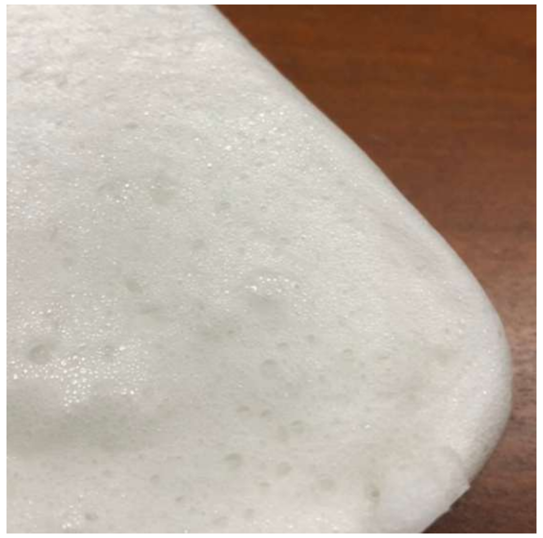


Fig.53. Experiment 4


Fig.54. Experiment 7


Fig.55. Experiment 5


Fig.56. Experiment 6

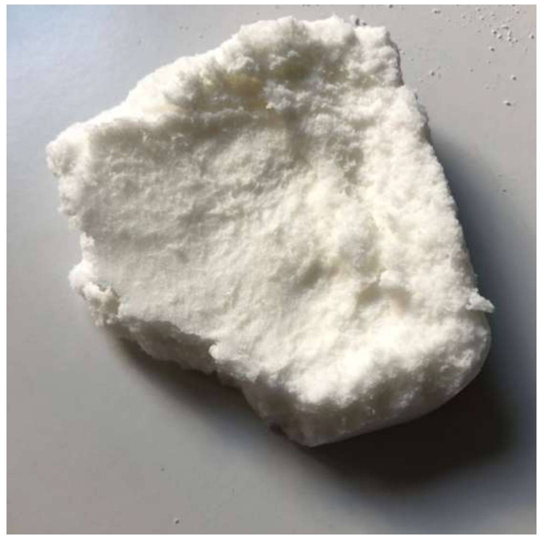


Fig.57. Experiment 8

V.C.1. Experiment 01 / Casting wax

Aim

- Exploring the casting process of wax

Conduction

Wax candles were broken and the wig removed. The broken pieces were put into a metal bowl and heated slowly in a water bath.

As soon as the wax had completely transparent and liquefied it was poured into a small plastic box with a smooth inner finish.

It was left until solid.

To remove the wax the formwork had to be lightly deformed to allow air to enter the space between formwork and wax. Since paraffin wax is not sticky, it can be removed easily afterwards.

Results

The result was a white wax plate. The upper surface was a bit concave since the edges were more elevated than the rest of it.

Learnings

- Wax can be easily cast into plastic formwork
- Smooth formwork finishes and deformability simplify the removal of the casted object
- The current state of aggregation can be visually identified
- The volume of wax decreases when it solidifies


Fig.58. Candles were weighed


Fig.59. The wick was removed


Fig.60. The wax was heated in a water bath


Fig.61. When transparent it was ready to pour


Fig.62. The wax was poured into the formwork


Fig.63. The finished object

V.C.2. Experiment 02 / Foaming wax manually

Aim

- Manipulation of material performance by aeration
- Aeration through manual whisking

Conduction

Like in exp.01 the wax is taken from candles and the wig is removed. Then they are heated in a metal bowl in a water bath.

Before it is cast in the same plastic box it is transferred to a larger plastic bowl where it is whisked using a kitchen whisk. In the beginning the wax did not absorb any air, but this changed when its temperature decreased.

Whisking was continued until the wax became uniformly white and was then poured into the plastic box.

It was left until solid .

For the removal of the cast the same process as in exp.1 was used.

Results

Differences in comparison with the experiment before are the colour and the surface structure. The first one comes due to the higher percentage of air in the wax. The latter is the result of multiple effects.

At first wax cannot be foamed at any temperature. It needs to cool to temperatures around the melting point to be able to develop foam, so around 50C° for paraffin wax. This meant that already solidified parts of the wax exist, which hindered the surface from being as smooth as above.

Another reason is the temperature itself. Since the wax is still hot when its being cast more fluid and therefore hotter parts of the material are denser than the foam and will sink to the bottom. The more hot fluid wax is concentrated at the bottom the higher are the chances to melt the foam from below or to at least weaken it enough that there are small collapses in the material while cooling, forming bumps on the surface.


Fig.64. The wax was heated


Fig.65. Afterwards it was whisked


Fig.66. It was poured into the formwork


Fig.67. Experiment 1 & experiment 2 in their mould


Fig.68. A detail of the surface structure


Fig.69. The finished object

Another effect that adds to this is the volume change of wax. In the process of solidifying it looses about 14% of its volume. This can destabilise the foam even further.

Learnings

- Wax can only be physically modified through whisking around its melting point
- Bubbles will float on the heavier not aerated part of the material
- Waxes can not be uniformly aerated. This gives the material a direction, since it has different properties in different axis.

Fig.70. Experiment 1, 2 & 3

V.C.3. Experiment 03 / lower pressure while cooling

Aim

- Producing a homogeneously aerated element by prolonging the whisking
- Prolonging whisking time by heating all tools involved
- Producing larger air bubbles by lowering air pressure in cooling phase

Conduction

This experiment was conducted basically like exp.02 with changes only applied at two parameters:

The bowl in which the wax is beaten was preheated to slow down the process of solidification. After casting the material is transferred into a plastic bag, which is deflated with a vacuum cleaner as soon as the model is inside.
This was supposed to increase the foamed part of the wax.

Result

Due to the low weight and stability of the cardboard box, the wax was shaken by the movement of it while sucking out some of the air. Resulting of this is a wavy surface, additionally every further movement after the pouring will benefit the separation of aerated and solid part.

Even though this happened it is visible, that the foam is more regular than before with a smoother surface.

Still the aerated part floated on the solid part below.

Learnings

- Reducing air pressure can increase the size of the bubbles

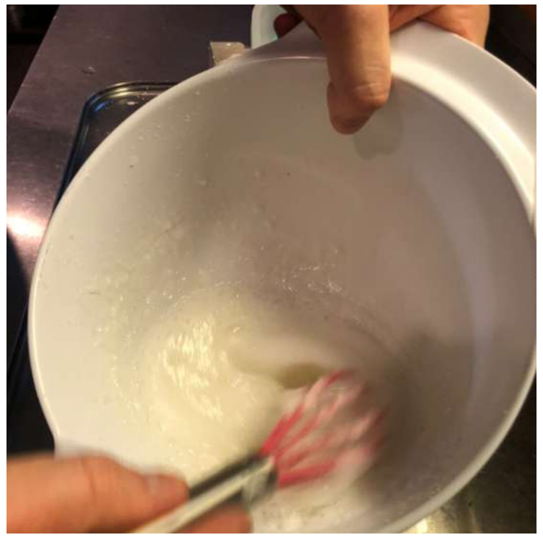


Fig.71. Wax is whisked in a heated bowl


Fig.72. Foamed wax is poured into the formwork


Fig.73. The formwork is transferred to a box


Fig.74. The bag is deflated


Fig.75. The deflated box deforms


Fig.76. The finished object

V.C.4. Experiment 04 / faster cooling

Aim

- Producing a uniform aeration by accelerating the cooling phase
- Creating a more stable casting environment

Conduction

To enhance stability while casting and the speed of the solidification the cardboard box was exchanged with a big steel pot. To cool the environment ice was put into the pot and water was added for more heat exchange surface. Apart from this all the steps were exactly conducted as above described.

Results

The result of this experiment was a foamed wax element with an extraordinary smooth surface. On its side it was visible, that this element had the highest percentage of foam of any of the above.

Nevertheless the foamed part still floated on the solid part. Therefore the higher percentage of air in the element and the preservation of more foamed wax made the upper side (the foamed side) very unstable.

Learnings

- Cooling the element will increase solidification speed
- The higher the solidification speed the more of the aerated part can be preserved
- Wax foam of this quality is very unstable
- The foam and the finish were of the best quality yet achieved

Fig.77. Wax is whisked in a heated bowl

Fig.78. Foamed wax is poured into the formwork

Fig.79. The formwork is transferred to a pot

Fig.80. The bag is deflated

Fig.81. The wax in the box is laying on ice

Fig.82. The finished object

V.C.5. Experiment 05 / protection 01 / unprepared cotton

Aim

- Exploring options to stabilise the foamed surfaces
- Using cotton on the upper and lower surface to stabilise them

Conduction

The formwork was prepared with a layer of cotton on the ground. Wax was prepared, like in exp.04 and poured over the cotton. As soon as all the wax was poured another sheet of cotton was placed on the upper hot wax surface.

Result

The cotton at the bottom did not soak with as much wax, as expected. While the cotton which was put on top of the element destroyed the foam structure and was even less permeated by the wax.

Due to the problems described above the cotton did not produce the wanted protection, while damaging the structures.

Nevertheless, the cotton still provided a tiny increase in stability.

Learnings

- Interaction with fluid wax foam will destroy its structure
- When cotton is soaked with wax it forms a hybrid material that is stiffer than its ingredients

Fig.83. Cotton is placed into the formwork

Fig.84. Wax is whisked in a heated bowl

Fig.85. The foamed wax is poured onto the cotton

Fig.86. The finished object

Fig.87. A sideview of the object

Fig.88. A section of the object

V.C.6. Experiment 06 / protection 02 / prepared cotton

Aim

- Exploring options to stabilise the foamed surfaces
- Using wax soaked cotton on the upper and lower surface for stabilisation
- Using already solidified foam to reduce the impact of the protection elements

Conduction

To create the wax-soaked cotton, two formwork's were prepared with each one layer of cotton on the basis. In the meantime wax was heated in a water-bath. It was then poured into the formwork and on the cotton. Wooden sticks were used to push the cotton into the wax as it floats as long as it is not completely permeated. Afterwards they were left to solidify.

Meanwhile an element was produced as described in exp.04.

As soon as both were completely solid they were taken out of their formwork and another batch of wax was heated.

In one formwork the model was assembled in the following way.

At first one of the protectors was inserted with the smooth side on the bottom. Then wax was poured on it and the exp.04 element was put onto it, with the not aerated side on the bottom. In the end wax was poured on the aerated part of the exp.04 element and the second protection element was put onto it with the smooth side visible from the top.

Results

The resulting sandwich element was the sturdiest yet produced.

When applying point loads from the top the cotton was able to spread the pressure over larger parts of the foam, which remained largely intact.

When cutting this element into two pieces the strength of the cotton became visible. A knife with a wave cut was needed to cut through it since a sharp cutter knife was not able to.

Fig.89. Cotton is place into the formwork and soaked with wax

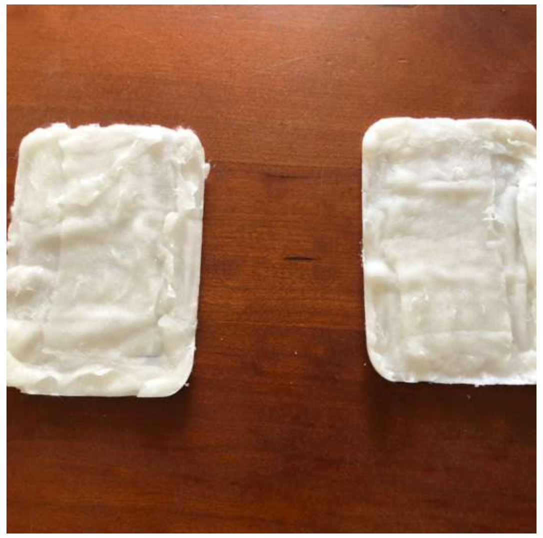


Fig.90. The wax soaked cotton

Fig.91. The finished object side

Fig.92. The finished object front

Fig.93. The finished object

Fig.94. A section of the object

Even when separated the three elements stuck to each other.

Learnings

- Cotton soaked with wax forms a very strong hybrid material
- Solidified foam is not as sensitive as still fluid foam is
- Wax can be also used as glue

Fig.95. A section of the object

V.C.7. Experiment 07 / protection 03 / pure wax

Aim

- Reenabling complete recyclability by using only wax as mono material
- Forming a layer of not aerated wax around the aerated module

Conduction

The wax was foamed and let cool like described in exp.04. Afterwards it was taken out of the formwork.

The green wax, which would be used for the protective layer was heated and without being foamed a small part of it was poured into the formwork, about 2mm thick.

As soon as it was completely solid a little bit of hot wax was poured over it, as a kind of glue, and the exp.04 element was put into the formwork on the solid wax. Then the rest of the heated green wax was poured over the element into the formwork.

Results

The outcome of this experiment is an element with a pure wax surface. While cutting it the strength of this protection was strong although due to its stiffness as soon as it cracked once it broke the whole protective layer.

The hot green wax partly destroyed the upper layer of the foam structure. Therefore the upper protective layer is imprecise and varies greatly in strength.

A significant part of the upper layer would have needed more wax, which would have in turn also destabilised more of the foam.

Learnings

- A not aerated layer of wax can protect the foam yet not as good as the cotton
- The contact of solid wax foam with hot wax should be avoided

Fig.96. The finished object front

Fig.97. The finished object back

Fig.98. The finished object left

Fig.99. The finished object right

Fig.100. The finished object

Fig.101. A section of the object

V.C.8. Experiment 08 / max foam

Aim

- Increasing Aeration of wax through mechanical whisking

Conduction

Basically, this model was produced as exp.04 with only one change before pouring the wax. Until now the wax was always whisked manually. This time it was done by a food processor. It was chosen because it is designed for this process and it could reach higher speeds.
After whisking, the wax was treated as in exp.04. It was filled into a formwork, put into a pot with ice and lower air pressure and left to solidify.

Results

The quality of the foam was very different to the one achievable with manual beating. The air bubbles were smaller, and therefore a multitude of them existed. Of all the experiments, this had the highest growth in volume.

It was also the first element that stuck to the formwork, as some areas of the wax were more connected to the plastic than to the rest of the element. This made it difficult to remove it from its formwork in one piece.

While removing the model, it broke and exposed a cave within the element. This was probably due to a too slow solidification process, even though it was accelerated with ice. This can be seen on *fig.105*.
Even though this experiment showed a new quality of foam it also raised questions about the usability of it. The continuing inherent problems of the process even in favourable circumstances lead to using more granular foam for the next experiments only to stop the process of beating the wax altogether in near future.

Learnings

- Fine foam is hard to work with in a low tech environment
- Foamed waxes have a risk of developing caves inside of the element
- These caves are impossible to find without destroying the module


Fig.102. The wax was heated


Fig.103. When the wax was transparent it was ready to pour


Fig.104. It was whisked by a food processor

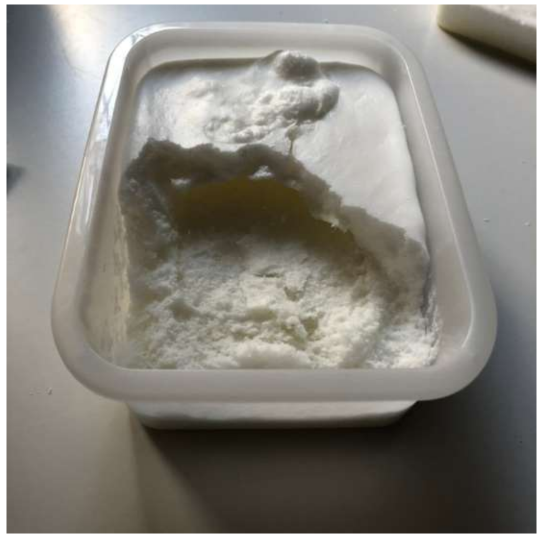


Fig.105. A cave formed in the middle of the object

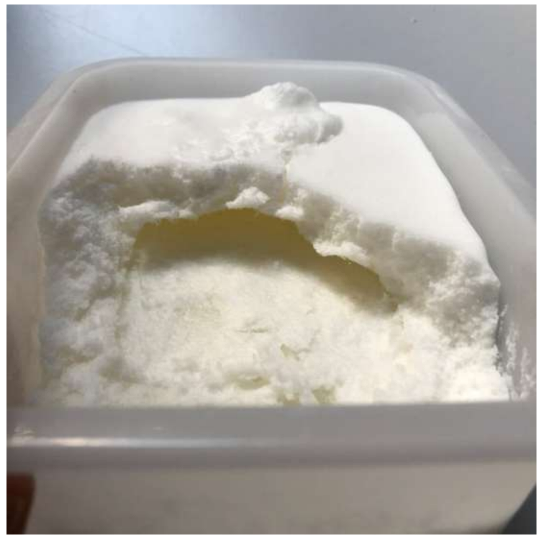


Fig.106. The cave in detail

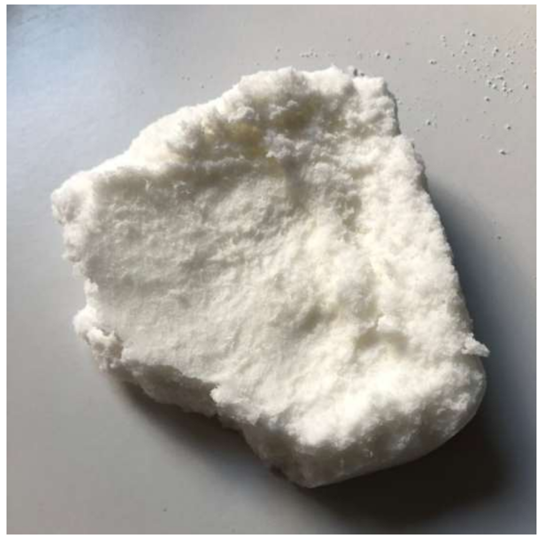


Fig.107. The structure of the whisked wax

V.C.9. Conclusion of material experiments

Due to the lack of knowledge about material performance and handling, these material experiments were supposed to lay the foundation for future experiments.

It was started at a very basic level, a brick, and continued to aerated wax.

However it was not possible to achieve a uniform aeration of the wax. The result was always a block with an upper very aerated part and a lower, rather solid part.
Aerated wax has very different properties than normal wax and can be easily dented.

Since the focus of this work was scaling up the models many questions remained unanswered about the usage of aerated wax.
How to move the aerated wax reliably to the areas where it is needed?
How to preserve the aeration of wax when casting larger models?
How to aerate larger amounts of wax?
These basic questions could not be answered in a satisfactory way, which is the reason aerated wax left the focus of this dispute.

However, the experiences made to protect the foamed wax reaped many benefits. Even though foams were discontinued, cotton stayed in the project due to its synergetic behaviour together with wax. When combined they form a strong connection which practically freezes the textile in its shape.

Additionally, it protects from scratches and makes for a reliable and easy to produce formwork.

The conducted experiments raised the following questions:

- Does fabric synergise with wax as well as cotton does?
- Which qualities of fabrics synergise well with wax?
- How to create formwork from fabric?
- Which geometries would compliment wax the most?

	No.	name	date of cast	temperature	Design methods				production process				stress test		
					2D only	Particle spring method	Finite element analysis	applied loads	mould casting	fabric formwork	hanged casting	injection moulding	max applied loads	max loads before deformation	shape retention grade
exp	1	Casting wax	12.03.21	20 °C	X				X						
exp	2	Foaming wax manually	12.03.21	20 °C	X				X						
exp	3	Lower pressure while cooling	12.03.21	20 °C	X				X						
exp	4	Faster cooling	12.03.21	20 °C	X				X						
exp	5	Protection 01 unprepared cotton	15.03.21	20 °C	X				X						
exp	6	Protection 02 prepared cotton	15.03.21	20 °C	X				X						
exp	7	Protection 03 pure wax	15.03.21	20 °C	X				X						
exp	8	Max foam	27.03.21	20 °C	X				X						

Chart.8. A summary of exp.1 - exp.8

V.D. HYBRID MATERIAL AND ELEMENT EXPERIMENTS

In this line of experiments, the new hybrid material wax with a textile outer layer is further explored.

Multiple new geometries are being tested. Many of them are stress tested to get a better understanding of the properties of the material. With this, the foundation for later experimentation with 3D geometries is laid out.

Additionally, in this timeframe the process of creating sewing patterns is developed from paper drawings over vector drawings to automated generation of sewing patterns with optimised beam sizes.

New methods of casting were also explored. Most of the experiments in this section were filled using an injection casting method. The strategy was to pump hot wax into the fabric formwork. Ideally, this was supposed to enable the desired shape to self-organise through the inner pressure of the formwork.

Scaling increases were the most drastic in this section. Starting with a shape that was merely ca 30x10cm, the last models grew to ca 160x70cm. Many lessons were learned in this episode and are explained in their respective experiments.

Fig.108. Experiment 10

Fig.109. Tools of the injection moulding process

Fig.110. Experiment 12

Fig.111. Experiment 13

Fig.112. Experiment 14

Fig.113. Experiment 15

V.D.1. Experiment 09 / columns

Aim

- Exploring fabric as stay in place formwork
- Testing the scalability of moderately aerated wax
- Testing the protection that wax soaked fabric can provide

Conduction

Unlike all former models, these two elements were cast in a stay in place fabric formwork. Fabric was chosen because many of the qualities that cotton had in connection with wax are also true for this combination (exp. 07).

This structure was designed as a column. For a better load transfer and stability the top and bottom were given a larger cross-sections, than the middle. Since wax is a weak material it was chosen to have a linear reduction of the cross-section.

In this early experiment the foundation for the workflow of larger models was established. The shapes were designed digitally, printed and transferred onto the textile.
Afterwards the textile was sown, soaked in wax and hanged with the open side on top for later filling.

The wax was heated in a pot and then transferred to the food-processor, where it was beaten. For these elements the whisking was slower and longer, so that the foam was much more granular as visible on *fig.115*. This was decided to prevent holes from forming as in exp. 08.

Then the beaten wax was poured into the formwork. Where it was left to solidify over night.

Stress test

After solidification of the material, a preliminary stress test was conducted to help assume the strength of the material visible on *fig.120-123*.

The stress test for this model was repeated for all of the medium-sized models.

Two wooden trestles were positioned next to each other and the model was fixated

Fig.114. Wax was whisked with a food processor

Fig.115. The quality of foam reached in exp.2 was aspired

Fig.116. Each element weighed around 700g

Fig.117. Both elements next to each other

Fig.118. At its widest point it was 7cm deep

Fig.119. The element viewed from above

on them using one screw clamp on each end. In the first tests, the screw clamps were still attached directly to the model itself. In later experiments, when the model was stable enough on the trestles, they were only used to prevent the model from sliding.

When the model was fixed the stress test could begin. Using a drawstring a load of 5kg was attached to the middle of the element. In this case the element span about 25 cm.

Each 10 minutes an additional 2,5 kilos were added to the loads until the element would collapse.

Based on photo documentation deformations can be detected easily.

Later on the experience collected in these experiments were used to create a material in Karamba which was used to estimate beam sizes for the large scale models.

This method of testing is not able to generate a wholistic overview of the material qualities. As mentioned in the introduction the whole project took place in a low-tech environment. Tests and through tests generated informations can only be seen as approximations and not as exact values.

Results

While casting, problems with scaling already became visible. Because of the low temperature when pouring, often under 50°C, the beaten wax was sometimes already too solid to flow uniformly into the formwork. While in this case the process was repeated until both forms were filled, pauses between castings of one model will be problematised later (*VI.A. Analysis of commonly occurring casting problems*).

Nevertheless, the stress test showed a performance of the material that was higher than expected. The observations that could be made in the test are the following.

The element failed when loaded with 33,4 kg.

The element was visibly deformed at around 20kg.

While testing it could be observed that before any deformation of the shape could be identified the textile became white in areas around the bearings and the load points. Due to its location it was assumed, that these are areas in which the textile became separated from the wax. Wax and textile have contrasting load bearing qualities, wax performs better in pressure textile in tension.


Fig.120. The stress test setup front


Fig.121. The object was fixated with screw clamps


Fig.122. The first deformation at 20kg


Fig.123. The object failed at 33,4kg


Fig.124. The fracture in the structure


Fig.125. One side of the fracture in detail

The textile became brighter than before due to cracks in the wax. At these points the textile was the predominant structural member.

For the rest of the experimentation white spots on the surface are seen as light failings.

Another impression that had to be noted was that the final collapse happened when the textile teared apart.

When looking at *fig.125* it can be seen, that the wax inside of the element already broke down into little pieces. This probably happened when the first deformations took place. Wax in its solid form is an inelastic material which will not bend but only brake. Especially in the models of larger size this became obvious.

Before exp.09 it was unsure whether wax was at all able to resist pressure forces that were a multiple of its own weight. This concern evolved now into the question of how wax would perform the best.

Learnings

- Fabric formwork builds a synergetic connection with wax
- Fabric formwork simplifies the production of complex shapes
- Moderately aerated wax can carry more loads than expected

Fig.126. The object after testing

V.D.2. Experiment 10 / hexagons

Aim

- Scaling up the size of the resulting model by using modules
- Exploring casting processes for more complex geometries

Conduction

To design a modular system with the hybrid material, a hexagon pattern was chosen. The regularity and the ease with which these shapes can be combined were seen as advantages. Due to their joints at which three beams meet hexagon structures distribute loads very well. Since wax is a weak material it would theoretically benefit from lower maximum loads.
Three elements using the double hexagon were produced together with two using only a single hexagon.

The designed pattern was printed out, transferred to fabric and then sewn. When finished the unnecessary fabric was removed.

To stabilise the formwork it was soaked with hot wax and then inflated to simplify a future filling.

To fill the formwork it was hanged with a cord. It was lead though the hexagon which was directly connected to the open branch used for filling.

The wax was poured into the formwork and as soon as it was filled sufficiently the open branch was closed and the shape was laid flat on a horizontal surface to ensure planarity.
Like this they were left to solidify.

Later on they were plugged into each other and then fixated with a cord. Many combinations are possible, but the structure visible in *fig.131 & 132* seemed the most promising.

Stress test

After solidification, preliminary tests were conducted researching the possibilities of combination and to estimate the strength of the geometry.

Fig.127. The finished formwork

Fig.128. The formwork was soaked in wax and inflated with air

Fig.129. The wax was poured into the formwork with a funnel

Fig.130. A finished module

Fig.131. A structure built of the models top

Fig.132. The same structure side

There was a wide variety of possible combinations using the given geometry. For the preliminary stress test the modular structure seen in *fig.131 & 132* was chosen and a total load of 23kg was applied. It was carried without even minor failures, like white spots, which was the prerequisite of further testing.

Stress testing the geometry was conducted exactly like the tests of exp. 09.

Results

While casting the new shape generated some problems, especially regarding uniform filling of the formwork. Another problem was the insufficient hanging of the textile. Through shifts of the centre of mass while pouring the material, the textile would sometimes fold, making the uniform filling of the element close to impossible. Even though this was likely to happen while casting sometimes it occurred later on, too.

Other problems were more connected with the chosen geometry. For example, the branches were usually very difficult to fill, especially when they were not in the flow direction of the wax. For this experiment granular beaten wax was also still used which amplified this.

The plank between both of the hexagons was usually not completely filled because of tensions in the textile.

As a quick fix the element was laid on a flat surface as soon as the wax was too solid to spill out of the textile. This was a solution for most of the problems mentioned above.

The observations that could be made in the test are the following.

The element failed when loaded with 51,2 kg.

The element was visibly deformed at 38,8 kg.

As mentioned above the first visual signs of failure are usually white spots on the surface. These spots formed, how it could be expected around the corners on the sides on which the bearing was and in the middle, where the load was applied.

Again here the final reason of failure was that the textile was teared apart.

Learnings


Fig.133. The stress test setup for one of the modules


Fig.134. The setup was the same as in exp.10


Fig.135. A detail of the screw clamps


Fig.136. The first deformation at 38,8kg


Fig.137. The object failed at 51,2kg


Fig.138. The object after testing

Modular approaches have the following drawbacks:

- Wax is a weak and flexible material which makes connection points harder to design
- When forces can’t be completely determined before the production the elements might easily bend or brake
- While casting the formwork it usually deformed which complicates joint design even further
- Textile can prevent a complete failure of the wax model in the stress test
- The hybrid material performed better than expected

Fig.139. The object failed when the textile tore

Fig.140. The upper tear in the textile

Fig.141. A detail of the lower tear

Fig.142. The object developed white spots in heavily stressed areas

Fig.143. The object was left outside in the sun for one day

Fig.144. The maximum surface temperature reached was 36,8°C

V.D.3. Experiment 11 / textiles

Aim

- Identification of fabrics that work well with wax
- Identification of properties that are needed to work well with wax
- Exploration of filling the formwork with a pump

Conduction

The tested textiles were:

- Velvet (brown)
- Twill (white)
- Darkening textile (pink)
- Satin (blue)
- Felt (white)

Qualities of interest were:

- Density, of the textile, to keep the wax in the formwork
- The strength of the connection between fabric and wax
- The performance in a stress test.

The design, a single slab spanning over about 60 cm had a basic design to get quick and comparable results.
Another beam was designed with a textile tension element on the base of the beam. The lower half of any beam usually is subject to tension forces and the upper half to pressure forces. Since wax performs better in pressure and textile in tension, it was tried to split up these forces and apply them to the material best suited for them to reach a better performance.

For the rest of the chosen materials a new way of casting was build up. Instead of pouring the wax into a hanging formwork it was now pumped into the textile.

Pumping the wax was a step taken to explore the possibilities of generating 3D shapes by creating a formwork that would expand into a 3D geometry when inflated

Fig.145. Wax used in exp.09 was recycled

Fig.146. The wax was cooled down to have a higher viscosity

Fig.147. The heated wax was mixed to generate a uniform consistency

Fig.148. The formwork was filled using the injection moulding process

Fig.149. A drill pump was used to fill the formwork

Fig.150. The wax was transferred from the heat source to the formwork with a hose

with wax.

Due to this added complexity the process of casting became even more turbulent and closely timed.

Stress test

For the stress test, a different construction was chosen. The elements were not fixated directly to the trestles anymore. Instead on each trestle an auxiliary construction was attached which would only keep the elements upright.

Also the general way the stress test was conducted was changed. Instead one load being attached to the middle of the element now two equal loads were attached at 1/3 and 2/3 of the length of it.

Results

Felt was disqualified in the beginning. It was chosen due to its natural high stiffness and its thickness. When the process of casting was tested, the wax poured out of the formwork because of the textiles high porosity. Since keeping the wax within the formwork is a key criterium, this material was directly discarded.

While testing the material, it became clear that the designed geometry performed worse than the ones before. The highest weight carried by any of these structures was 10kg.

While the sub-spanned elements generally had a better performance, the difference was miniscule.

The best performing materials were satin and twill. Darkening textile and velvet were significantly weaker.

When cutting open the elements and separating the textile from the wax, the last needed quality could be checked. Here it took a significant effort to detach the white textile from its core. The brown was the second hardest to remove, while with blue and pink it took hardly any effort at all.

Overall, the twill performed the best out of all the five. From now on, with one exception, only textiles that were, like white, densely woven cotton textiles were used for the formwork.

From the start there were some problems with this way of casting. At first, pumping

Fig.151. Three formworks with subspanning

Fig.152. Three formworks without subspanning

Fig.153. In the new stress test setup the load was applied at 1/3 & 2/3 of the length

Fig.154. The beams were no longer clamped but flexibly mounted

Fig.155. The pink formwork was hardly attached to the wax

Fig.156. The white formwork was as if glued on the wax

a material that could solidify meant that in the tubes small patches with residues would build up until it was completely clogged.

Also, the mechanism in the pump was very maintenance intensive as it had to be cleaned after each casting process.

Here another quick fix was implemented. After each casting process the pump was cleaned by pumping boiling water through the system. This helped for about half of the casting processes. When the tubes were already clogged it was not helpful anymore.

Opening the elements and removing the textile also made problems with the new casting method visible. A uniform filling was only rarely achieved. Sometimes air bubbles were only small and local, but often they would stretch over large areas of the element. This not only reduced the cross-section but also reshaped it into a less efficient geometry.

The formation of bubbles was aided by at least two factors.

The first being the low amount of wax that could be heated at once. As soon as most of the wax was pumped into the element, the entry of the hose of the pump would be close to the surface of the wax, sometimes also sucking air into it.

Secondly the pump system, even though controlled and cleaned carefully, probably had some leaks. This is assumed because, when the hose connecting pot of wax with the pump was already clogged and the pump left on, air was still flowing into the element.

Learnings

- Using a pump to fill up formwork’s can create air pockets
- Twill works well as a formwork material in connection with wax

Fig.157. The injection moulding process produced many air bubbles in the formwork

V.D.4. Experiment 12 / monolithic framework

Aim

- Creating nonplanar shapes with inner pressure
- Exploring casting processes for 3D geometries

Conduction

This experiment was designed together with exp.13 to compare monolithic with modular strategies. A simple 3D geometry, a framework beam was designed. It was chosen because of its simple geometry, of which a sewing pattern could be easily created.
In this experiment the monolithic approach was tested.

To create the formwork, the pattern was transferred onto a textile. The second textile, which was to be sown on top was then prepared in such a way, that for all the beams a bit of extra textile was provided. This was done, so that the textile would not be under too much tension. A textile under tension hinders the flow of wax and would have prevented the beams from forming cross sections as voluminous as they became in this experiment.
After sewing the rectangular pattern both of the long edges were sown together to form a tube. At this point the sewing process was concluded and the textile was soaked with wax and let cool like usually.
For the process of casting the wax into its formwork a pump was used like in the experiments above. Due to the size of this element, it weighed around 3 kg, multiple casting processes were needed to fill it with the appropriate amount of wax.
As stated above the casting process takes some time and between the several processes the model was hanged to prevent deformation.
In the end the element was hanged like it would be tested, visible in *fig.159*. On this picture some of the problems of this casting can be seen. Firstly one of the seams broke which led to a field that should have been empty being full of wax.

On the same picture the leftmost beam is not fully filled, which led to it braking even before the stress test. Another issue is the middle vertical beam. Due to tension in the textile it ended up not being filled.
The asymmetrical base shape visible in *fig.160* also has to be noted here.

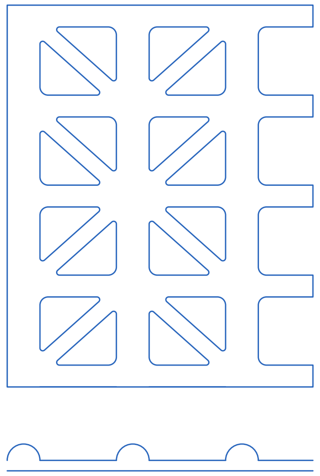


Fig.158. The sewing pattern. Below: At the horizontal beams one textile was folded in to form natural corners when filled.

Fig.159. The object had to be hung to solidify to preserve the geometry

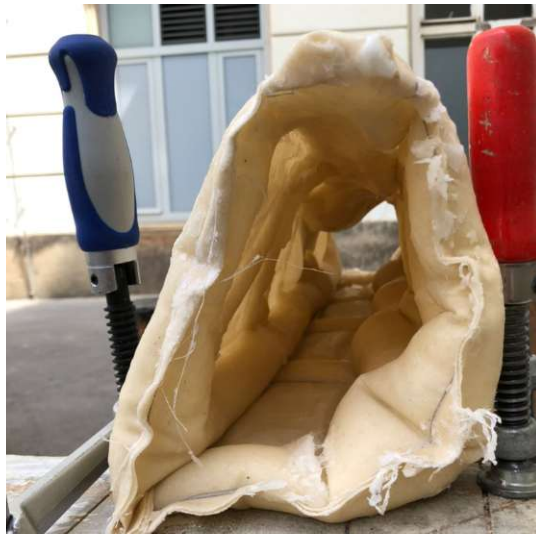


Fig.160. A view inside the object

Fig.161. The stress test setup front

Fig.162. The object failed and deformed at 51,8kg

Fig.163. The object after testing

Stress test

The stress test was conducted like in exp. 11, with equal loads at two points of the element and a span width of about 60cm.

Results

The observations that could be made in the test are the following.

The element failed when loaded with 51,8 kg.

The element was visibly deformed at 51,8 kg.

While stress testing the element the most unusual observation was, that it did not deform in a visible way before it collapsed. Also the collapse was interesting as it broke the upper beam exactly where the loads were applied, while all the rest of the structure remained mostly intact.

Since this element and exp.10 carried about the same loads it could be asked to what extend these are comparable. Though due to the change of many parameters of stress test and element the comparison will stay inexact.

In general it can be said, due to the less uniform way of casting, the longer span width and the lesser deformation over the course of the stress test, that exp.12 performed better overall and therefore must have a geometry that works better with the hybrid material, than exp.10.
When taking the model apart flaws of the casting process like in exp.10 could be detected. On *fig.168* one connection was documented in which the beam coming from the right is fully cast, while the one from below was too hollow to take loads. While this problem existed over the course of this whole project, this severity was only encountered when the formwork was filled with a pump.
Due to the problems with the uniformity of the material due to the contorted structure of the formwork another formwork was designed, which consisted only of planar elements.

Learnings

- The pump injection of wax creates air bubbles which are hard to spot
- Creating 3D shapes through inner pressure is not possible with the given setup
- Despite the inaccuracies the closed shape was very stab

Fig.164. The deformed object before removal of the textile

Fig.165. A detail of the areas which failed

Fig.166. The formwork was removed

Fig.167. A common casting mistake

Fig.168. A very severe casting mistake

Fig.169. The upper truss

V.D.5. Experiment 13 / modular framework

Aim

- Finding a way to connect wax modules to a larger structure
- Comparing the strength of a modular approach to a monolithic approach

Conduction

This experiment together with exp.12 was designed to compare monolithic with modular approaches.
In this case the modular approach was explored.

A slightly different geometry, with knots exactly where the loads will be applied, and the modular style, which enabled planarity of the elements. Also two different kinds of connections were proposed. On top the elements were bound together, while on the bottom there was a plug connection to the base.

The process of casting was conducted exactly like in all the experiments before in which the pump was used to fill the formwork. Though now, to ensure, that the wax had exactly the viscosity needed for processing the temperature was measured.

While conducting the experiment it was concluded, that the best results are usually achieved with paraffin wax at a temperature around 51°C. At this temperature there are small particles that already have solidified. When filled in the formwork they will build a thin layer on the inside of the formwork which prevents fluid portions of the wax to spill out of the textile.

After cast the elements were laid flat until solid. This ensured their planarity.

Then the model was assembled and to start testing.

Results

The observations that could be made in the test are the following.

The element failed when loaded with 40 kg.

The element was visibly deformed at 35 kg.

Even though this element performed worse when looking at the loads it was able to

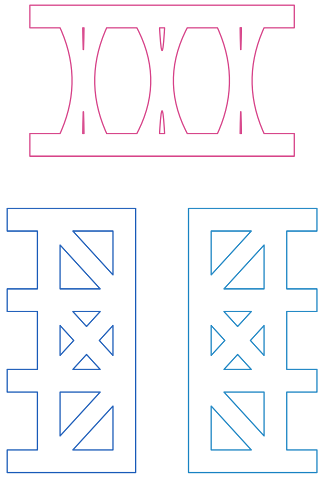


Fig.170. The sewing pattern

Fig.171. The stress test setup front

Fig.172. The stress test side

Fig.173. The first loads were applied

Fig.174. The first deformation at 35kg

Fig.175. The object failed at 40kg

carry the element was cast more precise and uniform.

The connections were not working as planned and left the element too many possibilities to move. This is most probably one reason for the early failure of the test.

While comparing exp. 12 with exp.13 it was concluded, that connections of multiple elements have not yet worked sufficiently, but that the planarity of exp.13 was able to provide a significant increase in accuracy.

Learnings

- Joints with a small connection area (cords & plugs) seem to be unfit for this material
- The modular approach performed worse in stress testing than the monolithic

V.D.6. Experiment 14 / wall

Aim

- Increasing the scale of the model
- Reintroducing the hanged filling of formwork
- Exploring a new geometry

Conduction

After comparing both of the framework geometries, it was decided to scale up another time. This time a planar element with a size of 180x80 cm was designed. Since the pump injection seemed unreliable the hanged casting approach, already used in earlier experiments, was tried another time. Due to the drastic increase in size a planar base shape was chosen. This should ensure the flow of wax through the whole formwork.

For this new size a different approach towards design had to be taken. The geometry was designed in grasshopper, then tested in Karamba, with which also a beam optimisation was conducted based on the estimated material qualities of wax. The base system was also changed, a detailed description can be found in *VI.C.3. The selected system.*

After the calculation, the sewing pattern was automatically generated.

On the lower end there was extra material left to create a kind of natural funnel to simplify pouring.

The sewing process remained the same and at its end the textile was again soaked in hot wax.

Because of its future weight and size the casting process had to be adjusted. The empty formwork was now hung from a scaffolding, with the integrated funnel side up.

At the same time the wax was heated to around 51°C . As soon as it reached this temperature and was of a uniform consistency the whole pot was poured into the formwork. This process was repeated many times as the volume of the formwork was considerably larger than of all the ones before.

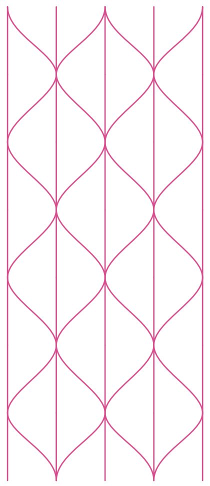


Fig.176. The planned line geometry

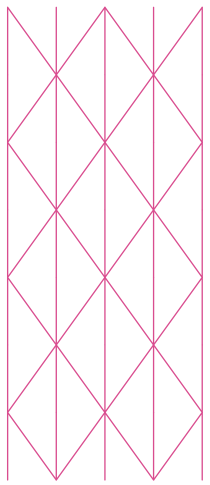


Fig.177. The target geometry was simplified

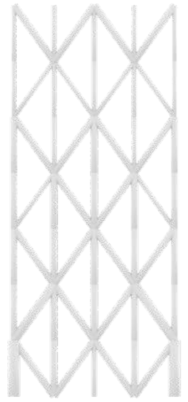


Fig.178. A rendered image of the structure with optimised beam-sizes

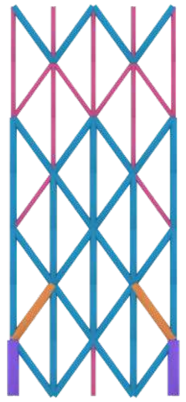


Fig.179. The different beam-sizes in different colours

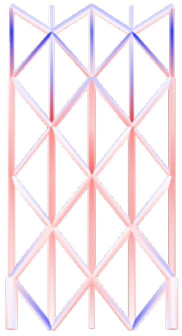


Fig.180. The analysed deformation and utilisation of the structure

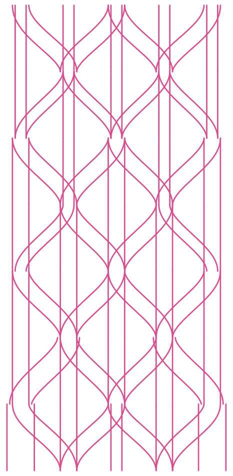


Fig.181. The resulting sewing pattern

As soon as the formwork was filled it was left to solidify for some hours. When solid it was carefully removed from the scaffolding to be erected later on.

Stress testing

Since the model was only designed to be able to hold its own weight, it was later set up and bound to a box which was supposed to have hindered it from falling. While standing not required textile was removed from the sides and since it was a pure pressure model the unfilled triangles within the element were also removed.

For testing it was left standing as it was only supposed to carry its own weight. After a short period of time it collapsed, not because of the heavy weights, but because of its footing and the way it was fixed to the box. It did not stand exactly upright but rather leaned a little forward. Because of its planar geometry it was not able to withstand the leaning which became stronger and stronger. When the bending got too strong local fractures appeared. These fractures were easily identified, since they are highlighted by white spots on the surface of the model.

Attempts to raise it again were unsuccessful since the general leaning could not be corrected and the parts which already broke remained unstable.

Results

Having multiple casting processes also came at a cost. The wax flowing from the funnel to the lower parts of the formwork always left a layer of wax inside the formwork. When the air temperature would get to low or the pauses between casts too long these layers solidified. Often this was not a big issue but sometimes the inner walls of the formwork would then stick together or form “balloons” within a beam. These problems will be thoroughly discussed in the chapter *VIA. ANALYSIS OF COMMONLY OCCURRING CASTING PROBLEMS*.

Another difference of this casting process is that no direct or indirect effort was taken to beat the wax. Starting from this model only solid wax fillings were developed.

When opening the formwork to recuperate the wax for later models the difference in casting quality was observed easily. The wax was uniform and without destabilising air bubbles.

Since this test was not able to provide the information needed to continue the work a second slightly different model was prepared


Fig.182. The pattern was printed and assembled


Fig.183. The pattern was cut out and transferred onto the textile


Fig.184. The sewed pattern


Fig.185. The formwork was hung from a scaffolding


Fig.186. A detail view of the funnel


Fig.187. The structure about half filled

Learnings

- Hanged filling of formwork can deliver a higher material uniformity
- Hanged filling of formwork can be scaled up easily
- The estimated strength of wax was too low
- Planar geometries encounter bigger problems to sustain equilibrium the higher their scale

Fig.188. The structure about half filled

Fig.189. A detail of the filled formwork

Fig.190. The structure about half filled

Fig.191. The structure was removed from the scaffolding

Fig.192. The structure erected and removed from redundant textile

Fig.193. The structure failed due to its 2D geometry

V.D.7. Experiment 15 / arc

Aim

- Increasing stability through curvature

Conduction

This experiment is a variation of exp.14. Due its planar base shape it was very susceptible to crack and fall over. The curvature introduced in this experiment was intended stabilise the geometry.

This time pressure connections on top were added to the model, so that the model wouldn't fold with the wind but would lean against a wall. For the general structure, a chain line was approximated to form a small arc.

Again the model was calculated to only withstand the loads of its own weight. In general the process until casting was the same as above.

After hanging the upper side into the scaffolding the lower edge was attached to a wooden bar. This bar was fixed with ropes horizontally to one of the sides of the scaffolding as visible in *fig.196 & 197*.

The casting process was now conducted with another heating element to grow accordingly with the size of the wax models. Now a theoretical maximum of up to 40l could be heated at the same time. Even though multiple casting processes were still needed to fill the whole model it were significantly less than before.

The simplification and quality improvements resulting from this change can not be underestimated. As described later on the volume of wax that can be heated up at the same time is one of the most important parameters for this material combination.

Stress test

Like in exp.14, this structure was only designed to carry its own weight. After solidifying it was erected and fixed to wall, so that it couldn't fall over.

The unused textile was removed, so that only the filled beams would remain.

Leaving it outside for a night it became clear that it would not collapse by itself. To

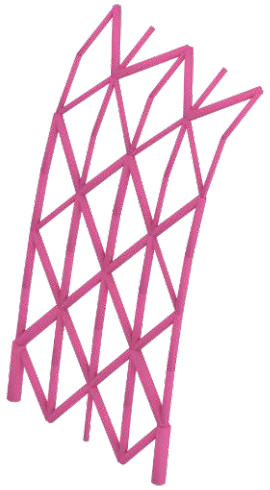


Fig.194. An isometric view of the planned structure

Fig.195. The wax was mixed to generate a uniform consistency

Fig.196. The filled formwork front

Fig.197. The filled formwork rearview

Fig.198. The structure erected and removed from redundant textile

Fig.199. The finished object side

test the structure further it was loaded with a significant weight for a short time. This stress test was also completed successfully.

Results

The approximation of a chain line was largely successful even though the curvature was not as round as expected. This was most probably because the wax in the lower areas was already solid when the upper side wasn't yet filled. Due to this, the structure couldn't fully self-organise into the desired geometry.

After stress testing the material, the reaction to higher temperatures was also to be evaluated. At first the model was placed in front of a hot air fan for up to one hour, at a distance of 10 cm.

While testing it was seen that in the areas where the hot airstream touched the model slowly liquified wax was visible on the surface. Periodically, the beam was pressure tested with a finger to see how far the wax had become liquid or soft. Even after a long time (30-40min) the portion of the wax which had softened was a very shallow area facing the hot fan. On its backside the wax was as solid as before. This can also be estimated when having a look at the energy transmutability of wax.

Secondly, the model was heated using an infrared panel at a distance of 20cm.

The results of this test were even weaker than from the one before. It took longer for the wax to heat up which consequentially meant that the heat was not reaching the same material depths as in the experiment before.

These short experiments could show, that the structure continues to react to heat, but due to size and shape of the structure it takes a considerable time or energy to heat the structure in a way that would let it collapse.
Nevertheless a weak point was created and cracks occurred later on more often in the heated areas, than anywhere else.

Learnings

- Curvature can increase stability of a geometry
- Wax is only slowly reacting to a hot environment
- Wax is stronger than previously approximated


Fig.200. An improvised stress test


Fig.201. A long time stress test


Fig.202. A heat test using a heating panel


Fig.203. A heat test using a heating fan


Fig.204. The loss of wax due to heating was negligible

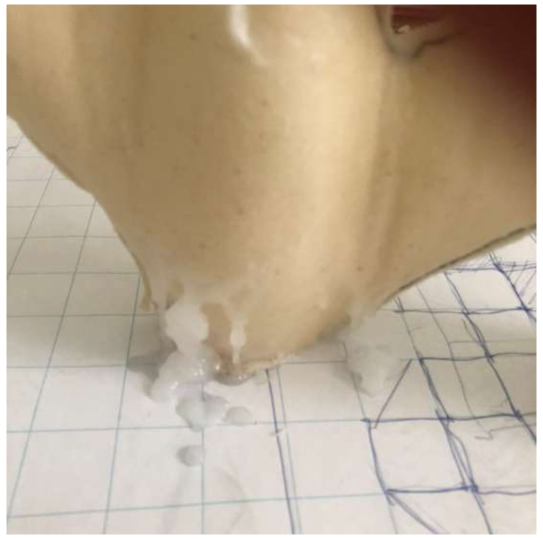


Fig.205. A detail of the lost wax due to heating

V.D.8. Conclusion of hybrid material and element experiments

During the experimentations in the chapters above much knowledge was acquired about the material.

Stress tests allowed to designate a yield strength to the material which was later used to optimise the beam strengths of models in the next chapter. Even though this number was always taken as an estimate and not as a proven fact, it helped to stay material efficient.

Another test that laid the foundation for the models to come was comparisons of textiles. Before it was assumed, that most textiles would perform equally, which was proven wrong by it. The material chosen based on the parameters laid out before was one of the most readily available textiles. Its connection with the material was very strong and it was used until the end of this thesis.

The geometries, which started with a simple column and advanced to a framework like structure, broadened the view. Ultimately, the system of exp.14 & 15 was chosen. Since this system is very regular and does not have any horizontal connections, it meant that beams would split of the major vertical beams at a lower angle, thus being more naturally accessible for the wax.

Models with this pattern usually had less wax distribution issues. Since this thesis explores mostly monolithic designs casting quality throughout the model was a defining parameter.

Between exp.14 and exp.15, a new heating vessel was acquired. Therefore, exp.15, which was conducted alone, was significantly easier to cast, than exp.14, which was cast by two people. Based on this experience it is recommended many times in this thesis, that heating capabilities should always be appropriate to the volume of the model.

Injection casting, which was seen before this section as a possibility to cast large volumes of wax, was discontinued. The main reason was that the pump could not be stopped to also push air into the model. These could not be seen or otherwise recognised which magnified the problem.
Since wax is already a very weak material, the possibility of air bubbles would have made the next experiments unimaginable. The experiments with injection casting were therefore discontinued.

No.		name	date of cast	environment temperature	Design methods				production process				stress test		shape retention grade
					2D only	Particle spring method	Finite element analysis	applied loads	mould casting	fabric formwork	hanged casting	injection moulding	max applied loads	max loads before deformation	
exp	9	columns	30.03.21	20 °C	X					X	X		33,4 kg	20,0 kg	
exp	10	hexagons	05.04.21	20 °C	X					X	X		51,2 kg	38,8 kg	
exp	11	textiles	07.06.21	25 °C	X					X		X	10,0 kg	5,0 kg	
exp	12	monolithic framework	11.06.21	25 °C	X					X		X	51,8 kg	51,8 kg	
exp	13	Modular framework	15.06.21	25 °C	X					X		X	40,0 kg	35,0 kg	
exp	14	wall	02.08.21	22 °C			X	self-weight		X	X				Full
exp	15	arc	23.08.21	21 °C		X	X	self-weight		X	X		85 kg	no deformation	Full

Chart.9. A summary of exp.9 - exp.15

V.E. VOLUMETRIC DESIGN EXPERIMENTS

During this final experimentation phase of the thesis the previously gained knowledge was applied to build larger scale structures, which could carry more weight than all the previous models.

In this phase the geometries became more complex than before. Therefore, automated sewing pattern generation became a central focus of this time.

Additionally, it was tried to simplify pouring, through adjustments to the funnels. Generally, it became clear, that the larger the models become, the better organised and simplified the pouring process should be.

The environment became also more important, since models reached a scale at which anchor points, from which the model should be suspended, needed to be significantly stronger, than before.

With beeswax, a new kind of wax was also tested. Due to its higher melting point, it was suspected to be a bit stronger and more resistant to heat.

Likewise, a new geometry was tested and multiple small improvements took place.

Fig.206. Experiment 16

Fig.207. The casting of experiment 17

Fig.208. Experiment 17

Fig.209. Experiment 18

Fig.210. Experiment 19

Fig.211. Experiment 20

V.E.1. Experiment 16 / beeswax chair

Aim

- Exploring the production of freeform geometries
- Increasing stability through multiple curvatures
- Exploring the capabilities of beeswax

Conduction

Taking the system, first used in exp.14, which seemed to have synergies with the material, a new model was developed. As a test for taller structures and as an experiment with bees wax (instead of paraffin) a chair was designed.
As a chair it had to have a seat and a lean. A chair was chosen because it has to be able to carry a vastly higher load than any experiment until now did.

Unlike before, the base shape of this model was designed as freeform surfaces in rhino on which a beam pattern was projected. This pattern was extracted and then processed further using line relaxation. For this a load scenario was created with gravity applied to all lines and another force at a lower angle *fig.215* only applied to the seat, to enlarge the seating area and to consider the forces when someone is sitting down.

Additionally, there was another load scenario applied to the seat to simulate a person weighing 100kg sitting on the chair. This new load resulted in the bulkiest beams designed yet.

Before only gravity was simulated which made this process unique.

When the desired shape was found the beam sizes were optimised and the preparation for realisation could begin.

The code was further developed to be able to calculate patterns for double curved surfaces. Since surfaces with two curvatures can not be unrolled onto a planar field, the model had to be divided into multiple smaller parts.

For this the line model was converted to a polysurface, which was then unrolled and exported to the viewport.

Due to the design of this model, the unrolled elements were two aggregations of

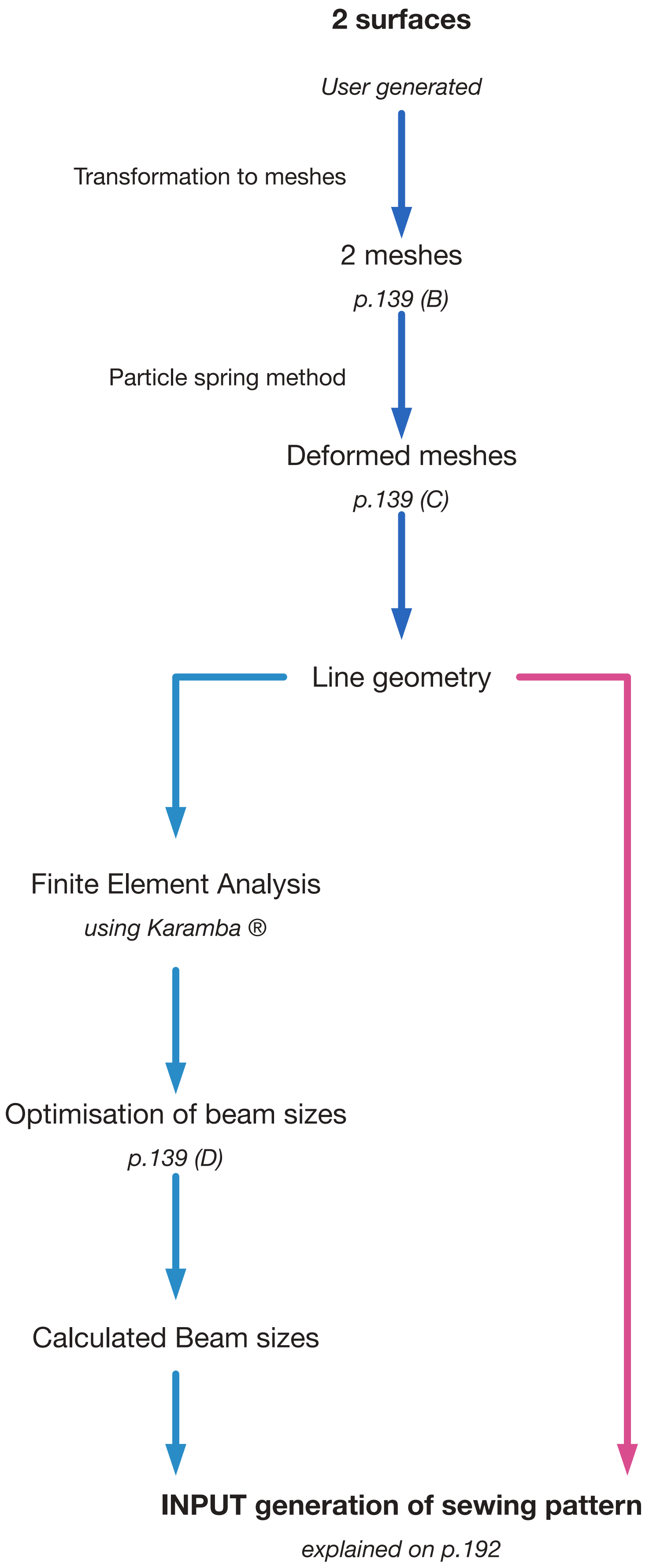


Fig.212. The digital design process of experiment 16

triangles. In each aggregation each triangle was connected at least on one side to the rest of the agglomeration. They also intersected with each other.

Here the user could move groups of elements which did not intersect each other out of the agglomerations and form subelements which were planar.

It is advantageous to form the biggest and lowest number of groups, since planar elements can be produced fast. The connection of two planar elements to a curved shape, on the other hand, is more prone to error and unwanted gaps in the seam.

However, other parameters, such as skill, size of production site and process of production, can make smaller groups an interesting compromise.

While searching for the preferred solution, the beam sizes were kept up to date in the viewport. As soon as the user was content with their choice, the plans could be exported and processed.

The sewing process could be described as the digital process only the other way round. The grouped patterns were transferred onto the textile. Then the closed triangles were sown at first, so that the textiles were fixed on each other. Then the connection beams of the groups were sown and at last the complete outer seam.

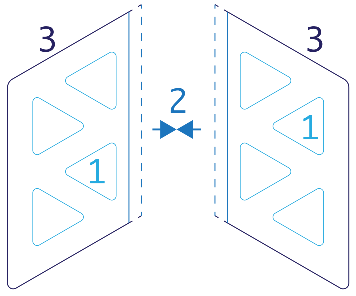


Fig.213. The sequence of assemblage of the formwork

After the sewing process was finished new problems for casting this geometry were encountered. The shape of the seating area was produced by applying multiple load cases instead of one in the mesh relaxation tool of kangaroo. Models before had only one load case, gravity, which allowed for a simple hanging

Due to the new situation a more complex hanging would have been needed. Connecting each extreme point of the formwork with two or three points of the scaffolding could have helped to keep the shape even when filled unevenly.

However this was not prepared and the shape was only hung from above, as with the models before, too.

As a result the shape was deformed and not anymore close to its design.

The cross-sections were calculated without a minimum, which led to very slim beams, especially in the lower part of the lean. Due to the viscosity of wax it became impossible to fill the lean appropriately and it was discarded.

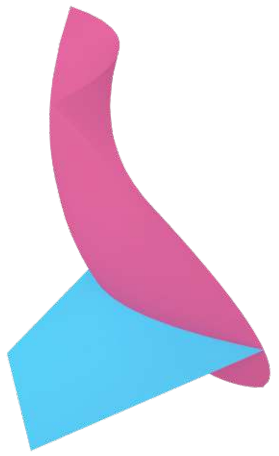


Fig.214. Two surfaces were generated by the user

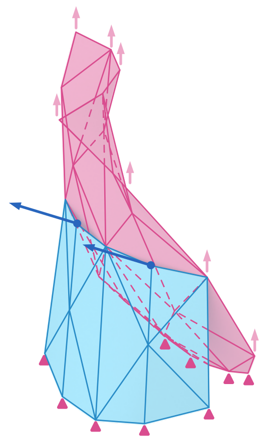


Fig.215. A mesh was created and deformed using the particle spring method

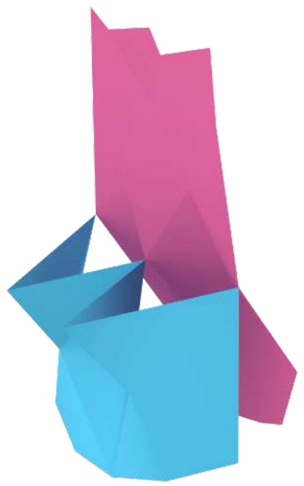


Fig.216. The mesh in its final shape; the design was split into two elements

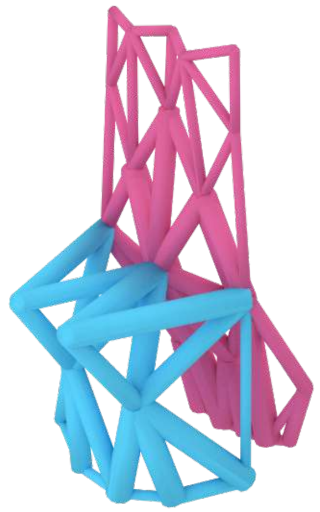


Fig.217. The needed cross sections were calculated with Karamba ®

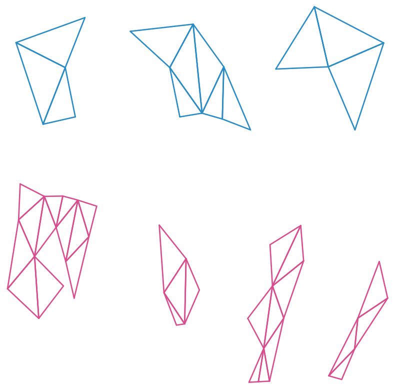


Fig.218. The meshes were unrolled and grouped to smaller panels

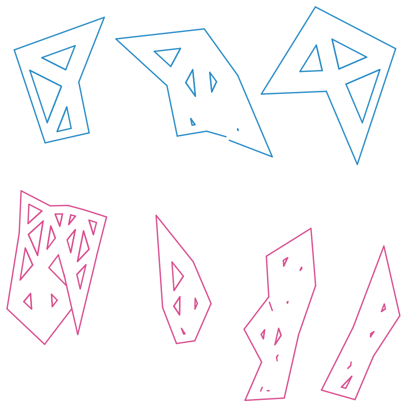


Fig.219. A sewing pattern was generated for each panel

In the end only the seat was filled up. As soon as the wax was not fluid anymore but still soft the hanging was changed, so that the two front points of the seat were hung from above. This was done to approximated the lower angle force described in the paragraph above.

The seat was then taken down as soon as solid and the unused textile was cut out. Afterwards it was attached to a table to prevent it from falling over.

Stress test

When loaded in the stress test the model had no visible signs of deformation or cracks. Stress test were not continued until collapse because of the limited time and the lack of weights in this scale.

This encouraged the construction of a better planned model of bigger scale.

Results

Many problems were encountered while creating this model which will be listed here.

The most critical error was made while optimising the cross-section of the beams. This was conducted to only fit one parameter set namely the structural integrity of the system. The outcome was that many of the beams, especially in the lower section of the lean, were not voluminous enough to supply the whole formwork with wax through them. Additionally, due to their small size, they would clog easier reinforcing the problems.

Because of this, future beam optimisations had a minimum diameter size of 5cm, whereas this model had some beams with the size of 3,5cm.

The process of self-organisation while casting was also more difficult this time since the desired shape is only reached when both form-works are filled up completely. In the given setup multiple pouring processes were needed to fill the whole volume. In the time between these the equilibrium of the model was not the designed shape. Since wax continuously solidifies some parts already hardened in an undesired shape before the formwork was filled. This resulted in more shape imperfections.

Due to the complex shape and the problems with the hanging system, some beams ended up only partially filled.

The newly used material, bees wax, had some notable differences to the usually

Fig.220. The pattern was transferred to the textile

Fig.221. A seam connecting two subelements

Fig.222. The textile was soaked with wax

Fig.223. The formwork was hung from a scaffolding

Fig.224. The finished object

Fig.225. The finished object left

used paraffin. The surface of this material is moderately sticky. It also seemed to be a bit more flexible and had a stronger odour.

While all of these differences are mostly positive, there is one which is in this set up clearly negative and hindered further models from being made of this material. The melting point of wax is at around 62°C-65°C, while paraffin melts at around 50°C. This difference of 15°C might seem small, but due to the low tech approach chosen in this thesis, it matters. While touching hot paraffin around its melting point is surely hot and hurts a bit, the same happening with bees wax hurts incomparably more.

When skin comes into contact with temperatures over 45°C, it can be damaged. (onmeda, 2022) Since there was no sufficient protective gear at hand, tests with this material were discontinued.

Learnings

- Free form geometries need an appropriate and more complex hanging system
- The model was stable but it can’t be said with certainty that this is due to the curves in the base shape
- Beeswax is more stable than paraffin wax
- Beeswax is less safe in a low-tech environment due to its higher melting point
- Beeswax seemed to be less brittle than paraffin
- A minimum beam size to ensure a certain flow rate has to be defined

Fig.226. A detail of the object

V.E.2. Experiment 17 / modular structure

Aim

- Scaling up the geometry
- Exploration of recycling capabilities of wax
- Exploration of construction methods
- Simplifying production by reducing the load-cases to only gravity

Conduction

This model resulted of an upscaling of exp.16. Due to the experiences made the minimum beam-size was increased and the structure was designed with only one load-case resulting in a more vertical geometry.

As in exp.16, the base shape was created using surfaces, on which a pattern was projected, to create the base shape. The modular approach was adhered to. Three elements were supposed to come together to form the structure.

The mesh relaxation, in which 3 different load-cases were simulated last time was simplified by only simulating the forces of gravity. In this case the structure was designed to carry only its own weight.

After experiencing the problems with the beeswax chair in exp.16, a new minimum strength was set for the optimisation of beam sizes to ensure a high flow-rate throughout the model.

The design and production of the formwork was otherwise exactly as described in exp.16.

Before the cast the textile was soaked in wax, inflated with air and then left to dry.

The three elements were attached to each other using cords.

Ideally for this size of a model a scaffolding would be erected with a space for the formwork in the middle. It should be tall enough, that the model, when hung, levitates around 50cm above ground to accommodate for the stretching of the textile when loaded.

In this case the scaffolding which was used for the earlier experiments was not tall

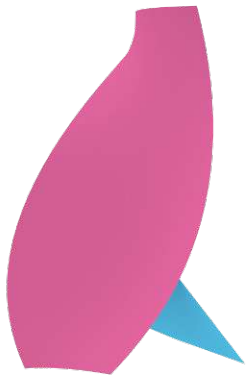


Fig.227. Two surfaces were generated by the user

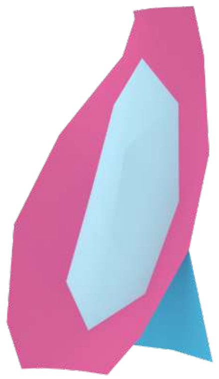


Fig.228. The surfaces were transformed to meshes

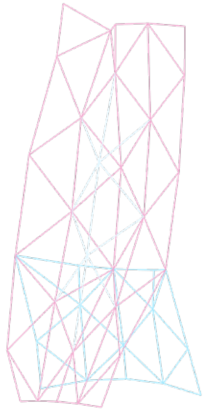


Fig.229. The meshes were transformed to a line geometry

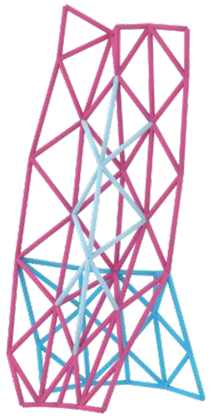


Fig.230. The needed cross sections were calculated with Karamba ®

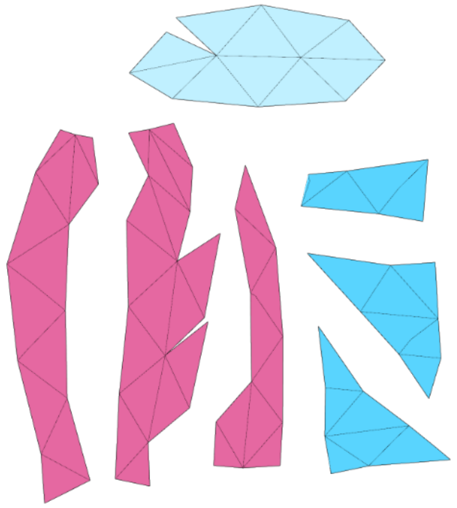


Fig.231. The meshes were unrolled into smaller panels

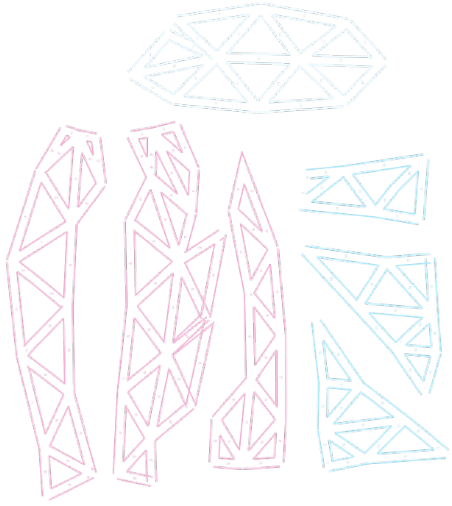


Fig.232. A sewing pattern was generated for each panel

enough, so a different location had to be searched. A tall arc was found and the cast was then conducted there.

Since the new casting area only offered a line as support, the hanging of the model had to be adjusted.

The primary element, which had its support on a very short curve was converted to a point support.

The secondary element was suspended from a wooden bar, which was itself suspended form the arc. This solution was not available for the primary structure because of its bigger size and therefore higher weight would risk breaking the available wooden bars.

Wax was recycled in this experiment by removing the fabric, breaking down the pure wax beams into small pieces and reheating them with the new wax.

Even though these fixes changed the structure, it could still self organise into a shape close to the designed one while being cast.

One row of beams was undersupplied with wax because of a kink in the textile. Luckily, this was found while the casting process was ongoing and it could be partially counteracted.

Due to the fast solidification speed of wax, it was decided to fill up at first the primary, then the secondary and at last the tertiary model.

Casting the structure took eight hours. After finishing the casting process, the structure was left to solidify and later removed and put on the floor.

As usual, the unused fabric was removed from the structure.

After finishing the post-processing, the elements were prepared to be assembled. For this a cord was used to bind the respective areas together as a first test. Later, they were supposed to be sown together for a stronger and less visible connection.

When it was tried to connect the elements it became visible, that the joints had a too high tolerance. As a result, the model could not be assembled and could only be used in single parts.

Stress test

Even though the stability of the whole structure couldn't be verified due to the stated problems partial performance could be again observed.


Fig.233. The casting site was prepared


Fig.234. Old models experiments were recycled in the process


Fig.235. The formwork was hung on from a beam


Fig.236. The primary element was suspended with yellow belts, the secondary with orange ones


Fig.237. Recycled wax was used in the process


Fig.238. The structure half filled

The primary element which still had a size of 2,3m height was erected and due to the missing support element leaned against a wall. In this position it was left standing and was later on removed without signs of deformation.

Results

In general it has to be summarised, that due to the scale of the object this casting process was one of the most difficult to control.

The realised object merely resembled the designed structure. All elements deviated from the designed shape in such a way that the construction was no longer possible and could only be improvised.

The lack of sufficient heating capabilities was at its most visible point of the project. Due to the large difference between the maximum volume of heatable wax and the total demand for wax by this structure it took 8 hours until the whole formwork was filled. As a result, the primary element was already mostly solid when casting of the secondary begun. Therefore, the primary element became more planar than designed. This was due to the lack of counterweight of the secondary element.

The simple attachments of the formwork with cords did not lead to elements which could be easily combined later. It proved to be to inaccurate, especially for a material that was already hard to connect, like wax.

Secondly, when bound together, the elements were rubbing against each other producing forces that were not foreseen in these areas. Because of this, many more cracks emerged.

This was the reason for which after this model only monolithic designs were created. The bigger scale of this model amplified problems that were already encountered before. Whenever the supports changed or forces where applied for a short time, there was a growing possibility for cracks in the wax.

Even though the fabric was still holding the elements together, the whole element became more shaky and therefore more prone to losing balance or forming more cracks.

Learnings from this encounter were plenty. To use this material at a larger scale it is recommended to not only design itself and the casting process, but also the transport to its place of use.

Ideally, a model of this size is cast on site. The post-processing would then be done

Fig.239. The structure completely filled

Fig.240. The structure was removed and placed on the ground

Fig.241. The primary element

Fig.242. The secondary and tertiary element

Fig.243. The finished primary object

Fig.244. The finished primary object from the right

either when it is still hanging from a scaffolding or when it is already standing in its final position. In the time between that, the process of turning it around and moving to the final position should be holistically designed.

Learnings

- A sufficient joint design for modular structures could not be found
- Wax remains stable at this scale
- Formerly used wax can be heated and used again
- Using only gravity as load-case simplifies the casting considerably
- This scale demands more than one person for the casting process
- The scale of the project should be limited to the amount of heatable wax
- Transportation of wax elements should be considered in the design process
- The minimum size of beams guaranteed a high flow-rate throughout the formwork

Fig.245. The finished primary object

V.E.3. Experiment 18 / Dome

Aim

- Exploring basic doubly curved base geometries
- Exploring a new sytem
- Focussing on quality of execution instead of upscaling
- Exploring point suspensions
- Exploring loops to connect to the suspension

Conduction

The object was thought of as a possible substructure of a table. It was about 90 cm tall and had a dome like geometry with four supports. After exp.17 it was realised, that modular structures have inherent drawbacks, as a consequence this structure was planned in a monolithic concept.

The base geometry which was used until this point was disregarded to produce this object. Having a new shape the design was still triangulated but for the pattern the base geometry was also taken into account, so a radial geometry was developed. The pattern was designed on a planar ground. Afterwards the line structure was relaxed using a single load-case in z direction.

In the usual process of beam optimisation this model was designed to withstand a load of 80 kg, which was applied on the uppermost ring.

Subsequently the sewing pattern was created. Here, it was decided to split up the structure into four quarters when seen from above. Even though a dome like structure can be theoretically unrolled without any self intersections, this was decided to safe textile material. The pattern was exported and transferred to the textile.

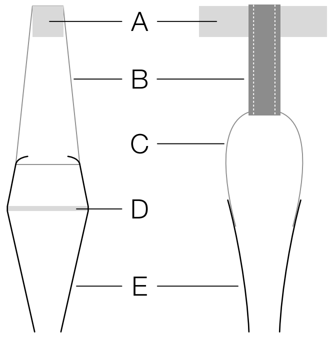


Fig.246. Suspension of formwork. Left:prev used method; Right: new method, loops;
(A) scaffolding, (B) tension band, (C) Loop, (D) prev. used opening element (e.g. wooden sticks),(E) formwork

One of the key differences was that this time, for the funnels, loops were designed. These kept the funnels and the formwork open and simplified pouring.

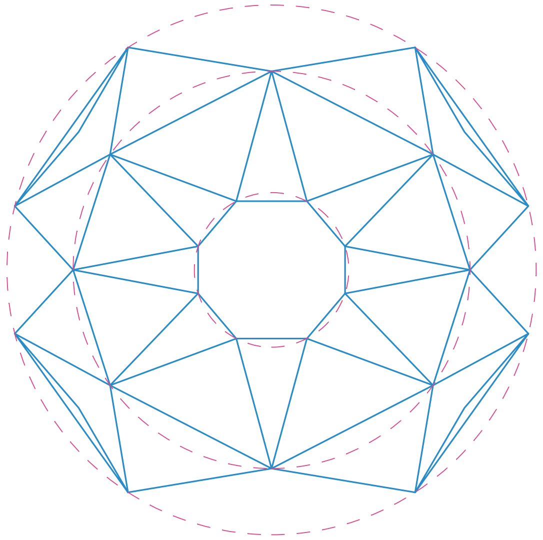


Fig.247. The designed planar pattern

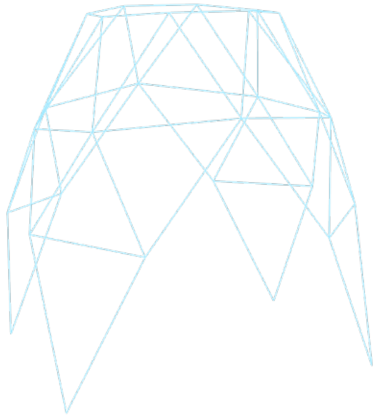


Fig.248. The pattern was deformed with the particle spring method

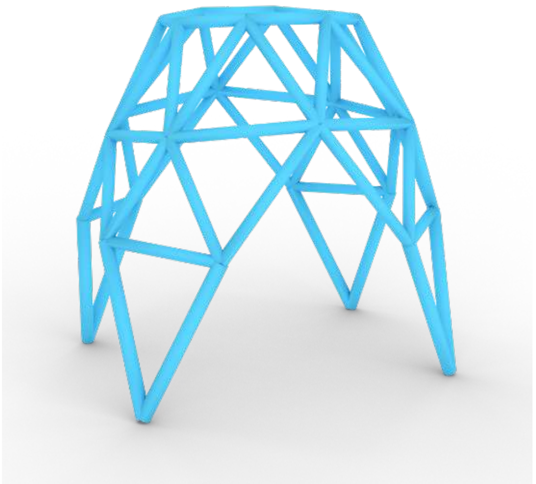


Fig.249. The needed cross sections were calculated with Karamba ®

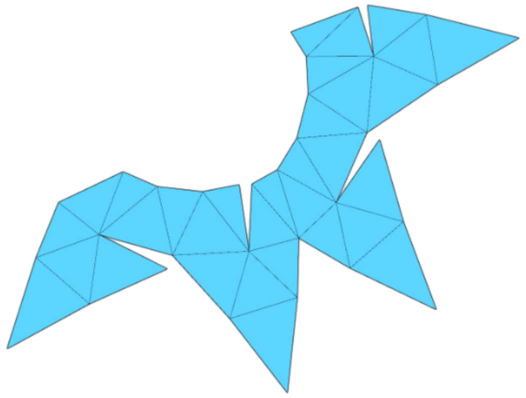


Fig.250. The mesh was unrolled

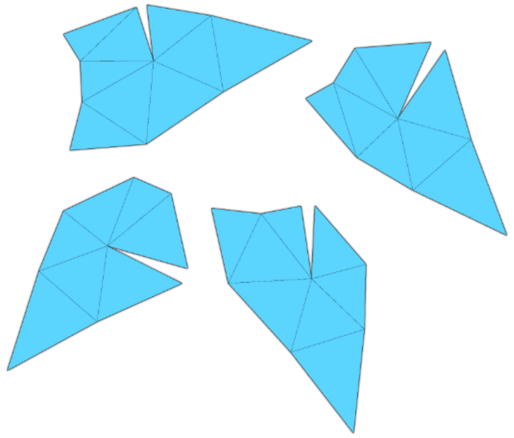


Fig.251. Panels were grouped

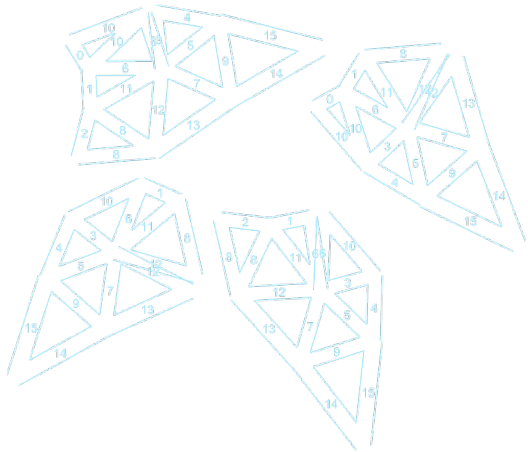


Fig.252. A sewing pattern was generated for each panel

Ideally enough hot wax would have been at disposal, but due to the lack of sufficient heating capabilities multiple casting processes were needed for this model. This might have been also a catalyst for the problem described in the result section.

After the process of solidification, during which the model was suspended, the model was left to stay on its four legs for seven days.

Stress test

After the seven days a stress test was conducted. The model was loaded two times, once with a load of 60kg once with 85kg. Both of the tests lasted for 5-10min.

An interesting observation was, that the structure was not breaking, even though it deformed a bit when being loaded. The more weight was mounted on it the more it would lean to one of its longitudinal sides.

Results

In the end the model did not collapse even when loaded with more than it was supposed to carry. In an analysis of the surface as well as while dismantling it neither cracks nor breaks could be found. This was especially surprising since the other models were usually so stiff, that they would break immediately when the system was moving. Nevertheless a movement within the system has to be seen as a failure of the design, since it was expected to not deform at all.

The reason for this movement without breaking is difficult to assume. Most probably a combination of multiple factors added up to this result.

- Some of the junctions were not properly filled. Therefore they were able to use the flexibility of the textile to bend.
- The horizontal connections were so malformed, that they can be largely ignored. This converted the pattern from a triangular into quad geometry, which is less stiff and more susceptible to shearing.
- Due to its long legs it this design has only one row where all 4 subelements connect. Therefore more space can be used for individual movement. Previous designs had a more tightly woven network of connections without free standing legs.

Even though motion without cracks in the material was an interesting discovery, no further experiments on this subject were conducted, since it would leave the scope

Fig.253. The hanged model

Fig.254. Funnels were attached at each support

Fig.255. The filled formwork left

Fig.256. The filled formwork right

Fig.257. The structure was removed

Fig.258. The erected structure

of this research.

A negative development of this design were the horizontal beams. These did not completely fill up, because of tensions in the textile at their connection points. This can be identified in fig.262 on this side of the model all not horizontal beams and junctions were filled, while the horizontal ones, apart from the upper row, were filled, but had kinks on their edges rendering them largely useless to take up pressure or tension forces.
This had never been observed before, because the pattern used before only had diagonal elements. Due to the problems caused by this change of geometry the horizontal elements were not used anymore for further designs.

Due to the tension in the textile there was also a lack of wax in the lower junction on the sides. At this point multiple seams met, some even with multiple layers of textile which were probably too stiff to be completely filled.
Sewing the model out of one piece of fabric might have been helpful here. As mentioned above it was decided against that for material efficiency reasons.

Due to the geometry now 4 funnels did exist, through which different areas of the structure could be accessed by the wax. Especially the direct connection from the funnels to the base of the model simplified the pouring.

On the basis of this experiment a return to the former pattern was planned since many problems encountered here were already solved in the previous one.

Due to many efficiency gains over the course of this experimentation this model was built in 4 days from design to solidified model.

Learnings

- Basic double curved shapes are very easy to fill
- The new pattern was stable but introduced many new shortcomings
- Due to the smaller scale no new problems were encountered while casting the model
- Problems which were encountered with previous models could be reacted to, which led to a higher quality of execution
- Point suspensions simplified the casting process
- Point suspension might have also introduced some tension into the model, a


Fig.259. The finished object front


Fig.260. A detail of a leg


Fig.261. A detail of a connection joint


Fig.262. Horizontal beams were hardly connected to the structure


Fig.263. The casting quality of diagonal beams was substantially better


Fig.264. The joint on the side were insufficiently filled

spacers in between the funnels might be able to prevent this

- Loops worked perfectly and were used in all following models
- Free standing legs made the structure more flexible than before
- This flexibility prevented the model from forming cracks
- Horizontal beams should be avoided
- When possible tensions in the model should be anticipated and prevented

Fig.265. A view of the object

V.E.4. Experiment 19 / tower

Aim

- Exploring a new base geometry
- Exploring stability of closed shapes
- Exploring the feasibility of this scale

Conduction

This is the second experimentation with a large scale design. In the end it was planned to be 2m tall and should be able to carry 100kg of load on top.
At this point exp.18 was seen as the most successful iteration in terms of shape retention. This experiment built on these experiences and like before a planar system was designed, which was then deformed with the particle spring method to create the design. Another learning from exp.18 was that three-dimensional systems seemed to have a higher internal stiffness, compared with the planar designs from before. The tube-like structure of this experiment should explore this concept further.

It was tried even though the circumstances remained the same as in exp.17, causing foreseeable problems in the casting process. For example, the issue of too many needed casting processing which leads to early solidifications of lower areas, while the model is not yet completely cast.

In this casting process, another issue inherent in a low-tech approach also became visible. Since a dedicated casting space could never be established, areas in the courtyard of the university were used temporarily. Especially for the larger designs, it was vital to find a location and then tailor the design to it since there were only a handful of places in which casting was possible. The parameters on which the situation was chosen were:

- Stability of the elements from which the model would be hanged
- Accessibility of these elements
- Distance from frequently used areas
- Sufficient height so that the hanged model levitates about 50cm above ground

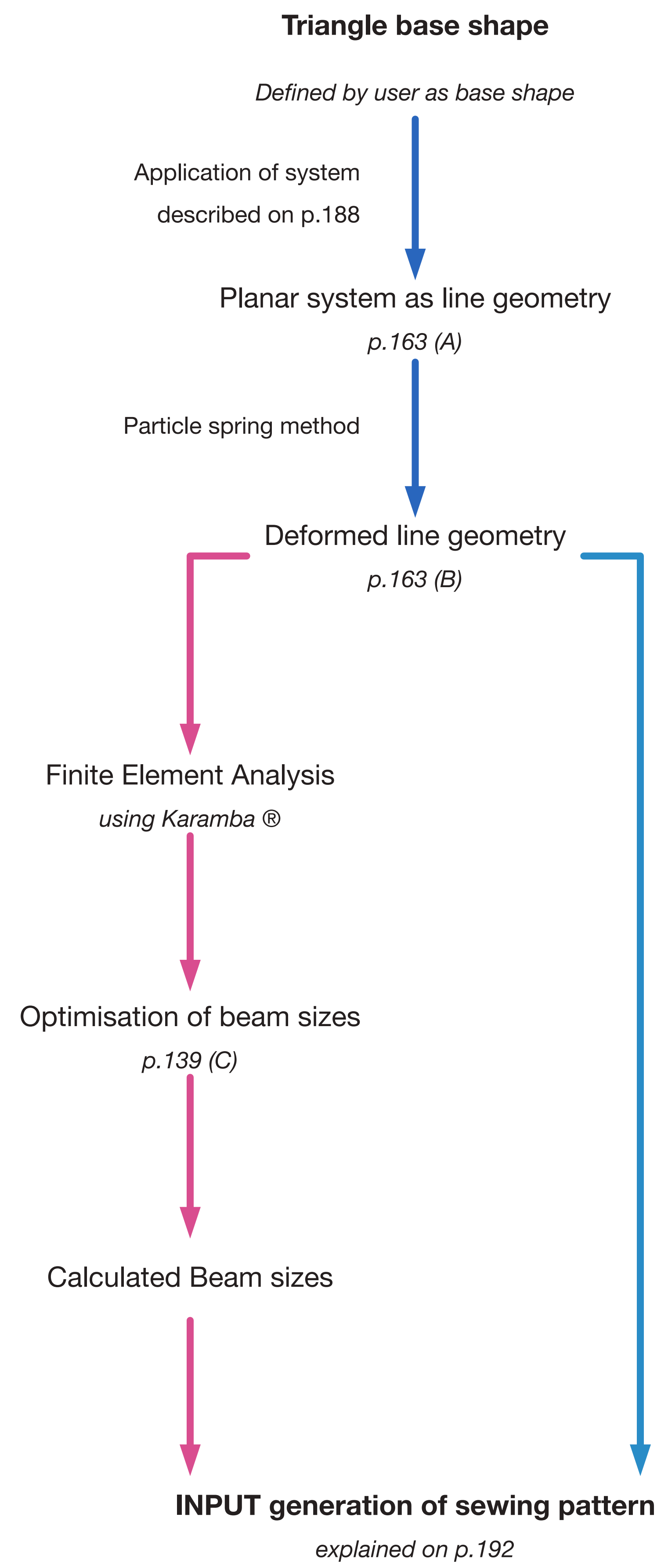


Fig.266. The digital design process of experiment 19

For this experiment an area was chosen that fulfilled all these criteria. After the preparation was finished and the casting process was about to start, the experiment had to be relocated.

The new location did not have a sufficient height to hang a model of this size. While in the other space it would hang at a height of 40cm, there it scratched the floor already before the casting process was started. The weight of the wax which is cast into the formwork causes the textile to further stretch a bit, which magnifies this issue during this casting process.

At this point the situation was reevaluated. The result was, that, excluding the creation of a new design, the best option would have been to shorten the model by sewing a horizontal seam at a height of about 1,60m. In this moment it was only a theoretical thought, since the textile was already soaked with wax, and further sewing would either come at the cost of an imprecise seam and a possible unusable formwork when sewing by hand or the sewing machine might become damaged or clogged with wax.

In the end the process was continued knowing that the model would be deformed and possibly too weak to carry the loads it was designed to withstand due to that.

Additionally, to the foreseen problems mentioned above, another issue resulted from their combination together. After the first casting process, one of the subelements was almost halfway filled. Due to its connection to the ground, the stiffness of the wax-soaked textile together with this element kept reorganising itself so that it would bend inwards of the model. This would create kinks on the sides of the filling which kept the wax from filling the formwork in a more uniform way, and stabilised this form. This bending is still visible on the finished model. It can be seen as the outcome of the relocation, and most of the other smaller deformations can be seen, at least partially as a reaction to this deformation.

Due to this deformation, the usual casting process was also changed.

Since self-organisation would not work now, the formwork was filled by casting one subelement after the other. The reasoning for this was, that the connection from the top to the ground was given a preference. Even though the subelements could not be filled with only one casting process, the wax of consecutive processes connects better.

It can not be said with certainty wether all the above stated reasons have an impact on the stability of the system.
Like before, after casting this model, it was left to solidify and on the next day the

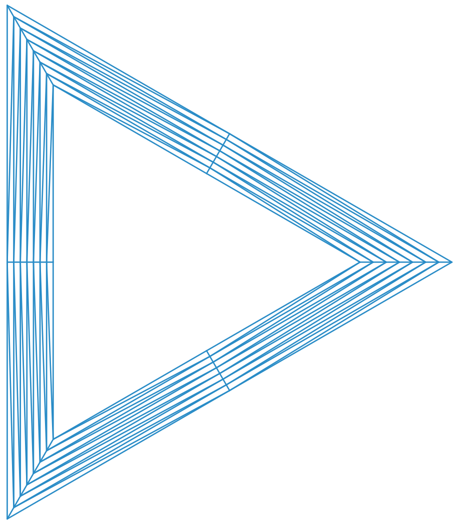


Fig.267. The designed planar pattern

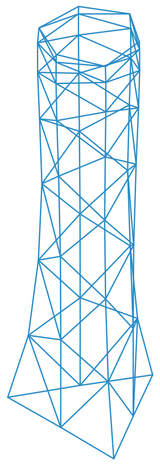


Fig.268. The pattern was deformed with the particle spring method

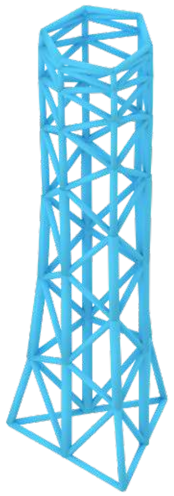


Fig.269. The needed cross sections were calculated with Karamba ®

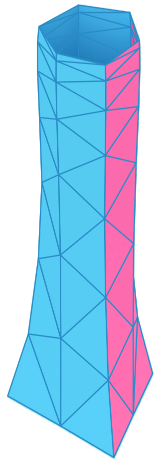


Fig.270. The mesh of the target shape before it was unrolled

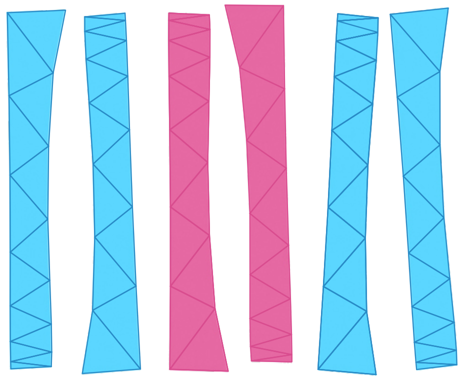


Fig.271. The unrolled panels

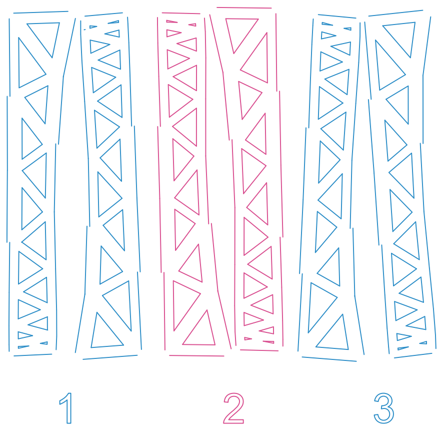


Fig.272. The sewing pattern

usual post-processing was conducted.

Stress test

Before stress testing, a superficial survey showed some few more inaccuracies of the cast object. While overall the formwork was filled quite uniformly, there were some beams that were not filled at all. This was possibly due to a solidification that had already started in this area before the problem was found. Additionally, the deformed base geometry might have produced kinks or high tensions around these beams, since they are only appearing in one small sector of the model. Due to the deformation, the stress test was conducted as safely as possible. Next to a scaffolding the model was erected so that people sitting on it could always touch the ladder and escape a possible collapse.

While stress testing, the model turned out to be more stable than expected. Despite all the weakening factors mentioned in the paragraphs above, the model carried 80-90kg of load for about 15 minutes without any visible deformations or cracks. Even a more thorough investigation while disassembling the model, didn't show any signs of local failures.

Results

In this case the result of the particle spring method was not as convincing as in exp.18. Many beams were concentrated at the top, the area of the structure with the least loads. This created an unnecessary weight concentration.

Like many of the formerly made experiments, this model also leaves a difficult conclusion. It is far from being a perfect cast for its geometry and still has multiple smaller issues.
However, since the structure could carry the weight, it was designed to hold up without any signs of collapse. Also it cannot be described as totally unsuccessful. The stress test, which was conducted in a low tech environment, as with all the stress tests of this project, has to be taken with the typical disclaimer, since it does not fit the criteria of a holistic material test.
However, one effect of this way of casting was most probably, that the deformation of the first cast element became that strong. A more uniform way of casting, as in trying to have about the same percentage of filling over all the elements, could have produced a structure with more but smaller deformations.

Especially when comparing the casting process of this model to the one of the


Fig.273. The suspended formwork, left side filled, right side empty


Fig.274. The formwork mostly filled


Fig.275. The suspension system of the formwork


Fig.276. The finished object


Fig.277. A detail of a deformed area


Fig.278. A detail of the fold

model before, the improvements are clearly visible. Even though the large deformation took place, there are no beams as systematically unusable as the horizontal beams were. The geometry of having only vertical and diagonal beams supports the casting process, and with a material that has such high demands towards its pouring, it is of paramount importance to use every measure that simplifies this process.

Overall, leaving aside the problems described in the paragraphs above, this experimentation was another step towards a higher degree of efficiency due to a better understanding of how the two heating elements could be used together.

Having the small pot always on the highest level to heat the maximum amount of wax as fast as possible, the big pot was now used at low power to ensure only that the wax in it would never be under 50°C to keep it from solidifying. Whenever the level of fluid wax in the small pot reached a height of about 5cm, it was transferred to the bigger pot leaving the still solid wax in the smaller pot. The bigger pot functioned as a sort of storage before casting. Since the wax coming from the small pot usually had a much higher temperature, than the aimed for 50°C, it had to be cooled down. This was simplified because usually the wax coming from the small pot had only a fraction of the volume of wax which was already in the pot. To further accelerate this process, small solid wax elements from earlier cast models were put into the big pot and served as a kind of ice cube. During this experimentation this was the fastest way to generate fluid wax at a temperature of 50°C using the setup at hand.

Learnings

- Closed geometries seem to be more stable
- The old pattern created fewer pouring problems
- The influence of the casting location should not be underestimated
- The availability of a sufficient volume of hot wax is one of the most crucial prerequisites for a successful casting
- This scale is not feasible in the existing environment

Fig.279. The casted wax did not form a uniform material

Fig.280. A detail of a casting issue at a joint

Fig.281. Many layers in a casted beam

Fig.282. An enclosed air bubble in the middle of the beam

Fig.283. The wax was reheated and cast into large boxes

Fig.284. In this shape the wax was stored for later use

V.E.5. Experiment 20 / small tower

Aim

- Reaching a higher quality by scaling down the model
- Verifying the previously given statements

Conduction

In this experiment, conducted after most of this report was written, all the summarised checkpoints for a successful casting process were followed as well as possible.

Using the base design of exp.19, a new smaller model was created. Since the concentration of beams on the top of the structure was seen as one of the main design problems of exp.19 this structure was not planned as a planar pattern, but as 3D line geometry. As a consequence the beams were better distributed over the whole design than before.

The model was designed to use only so much wax that it was heatable at one time. A second reason for the downscaling of the model was that it had to be adjusted to the smaller scaffolding utilised in this iteration.

For the beam optimisation a load of 30kg was applied on top of the geometry.

The sewing process is executed as above, only with a small modification. The leashes used to hang the model were now attached at the same height to guarantee an upright hanging.

These leashes were hung on wooden bars, which helped to keep them on one line and at the same height, enabling a correct shape also at the bottom of the model.

After the process of sewing was finished the unnecessary textile triangles were removed. As described in a later chapter, leaving the textile would result in more tension within the textile, which results in more elliptical beams.

Like in the experiments before, the formwork was soaked in wax.

The base of this model was in a triangle shape. To connect the bars to the scaffolding, a loop was attached at each edge of the triangle and in the middle of the line.

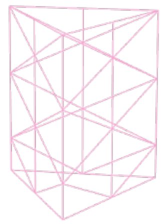


Fig.285. A line geometry was created by the user

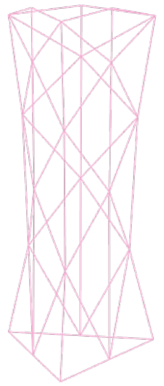


Fig.286. The geometry was deformed with the particle spring method

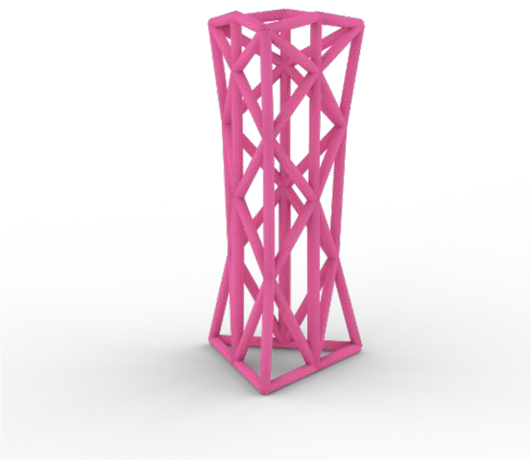


Fig.287. The needed cross sections were calculated with Karamba ®

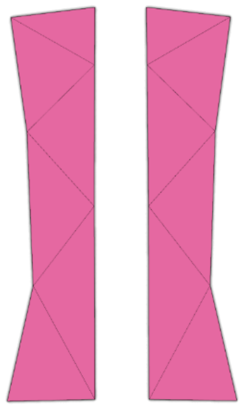


Fig.288. The unrolled panels

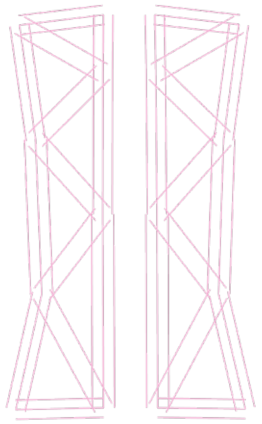


Fig.289. A sewing pattern was generated for each panel

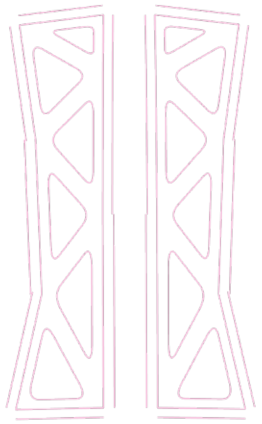


Fig.290. The refined sewing pattern

After the hanging was finished, casting could start when the wax reached the desired temperature.

While casting the significantly lower ambient temperature had its impact on the process of solidification. It happened now at an accelerated speed, and problematic areas, like described in the next chapter started to form faster than before. This was tested by moving the still fluid wax in the formwork after it was filled.

After this verification process, the model was left to solidify for an hour.

Later it was taken down and as usually, the unneeded textile elements were removed.

Results

As a short resume it can be said that the scale of the object fitted the available working environment better than exp.19. As explained above, most of the criteria that set out for a successful casting process were realised. Even some aggravating circumstances were neutralised due to the preparation.

Another upside of this scale, in contrast to exp.17 and exp.19, was that all of the steps in the casting process could be performed alone in a sufficient quality.

Because most of the wax needed was directly available many problems as described in earlier experiments could be avoided. The lower end of the structure needed a second casting and therefore

The shape of this model, in comparison to the 3D planned object, is only mostly retained. The top became round, due to the weight in this area of the design. Therefore the sides are mostly precise.
A more detailed discussion of its shape retention can be found in *VI.E.4. Level of accuracy.*

Learnings

- This model has reached a higher accuracy than most of the models of larger size
- The round shape has advantages in the self organisation process while casting
- Many of the given statements could be at least partially verified
- For the given environment this size seems to be ideal

Fig.291. Wax from previous experiments was recycled

Fig.292. The textile was soaked with wax

Fig.293. The formwork was hung from a scaffolding

Fig.294. The suspension system of the formwork

Fig.295. A view of the object left

Fig.296. A view of the object right

V.E.6. Conclusion of volumetric design experiments

During this final stage of the experimentation many efficiency gains could be recorded and many more problems were encountered.

Most of the issues encountered in this time frame were connected to issues with scaling. The biggest of them all was, that heating capabilities were not added in a sufficient way to accommodate for these sizes. This problem became so dominant, that most other encountered difficulties could be connected to it.

Due to this, the last phase is very ambivalent. On the one hand, the largest models were created. On the other, most of them deviated visibly from their target geometries.

However, imperfections are minimised in the smaller scale models of this period. A possible conclusion of this could be, that the ideal scale for the environment in which this thesis was conducted lies between exp.18 and exp.20.

Smaller improvements to the casting process were made. Adding loops to the funnels helped speed up the cast and less wax was wasted through overflow. Removing the excess fabric, inside the triangles of the pattern, reduced the overall stress in the model and helped the diagonal beams to take their shape. Pouring of hotter wax, than usually, was used to free up clogged beams.

Even though the models had many imperfections, they still withstood the loads they were designed to carry. This was quite surprising and strengthens the these, that wax can be a viable material at this scale.

No.		name	date of cast	environment temperature	Design methods				production process				stress test		shape retention grade
					2D only	Particle spring method	Finite element analysis	applied loads	mould casting	fabric formwork	hanged casting	injection moulding	max applied loads	max loads before deformation	
exp	15	arc	23.08.21	21 °C		X	X	self-weight		X	X		85 kg	no deformation	Full
exp	16	Beeswax chair	06.09.21	20 °C		X	X	100kg		X	X		85 kg	no deformation	Local
exp	17	Modular structure	13.09.21	25 °C		X	X	self-weight		X	X				Insufficient
exp	18	dome	20.09.21	15 °C		X	X	80kg		X	X		85 kg	no deformation	Full
exp	19	tower	13.10.21	8 °C		X	X	100kg		X	X		85 kg	no deformation	Insufficient
exp	20	Small tower													Insufficient

Chart.10. A summary of exp.16 - exp.20

V.F. INDEX OF ALL EXPERIMENTS

	No.	name	date of cast	environment temperature	Design methods				production process				stress test		shape retention grade
					2D only	Particle spring method	Finite element analysis	applied loads	mould casting	fabric formwork	hanged casting	injection moulding	max applied loads	max loads before deformation	
exp	1	Casting wax	12.03.21	20 °C	X				X						
exp	2	Foaming wax manually	12.03.21	20 °C	X				X						
exp	3	Lower pressure while cooling	12.03.21	20 °C	X				X						
exp	4	Faster cooling	12.03.21	20 °C	X				X						
exp	5	Protection 01 unprepared cotton	15.03.21	20 °C	X				X						
exp	6	Protection 02 prepared cotton	15.03.21	20 °C	X				X						
exp	7	Protection 03 pure wax	15.03.21	20 °C	X				X						
exp	8	Max foam	27.03.21	20 °C	X				X						
exp	9	columns	30.03.21	20 °C	X					X	X		33,4 kg	20,0 kg	
exp	10	hexagons	05.04.21	20 °C	X					X	X		51,2 kg	38,8 kg	
exp	11	textiles	07.06.21	25 °C	X					X		X	10,0 kg	5,0 kg	
exp	12	monolothic framework	11.06.21	25 °C	X					X		X	51,8 kg	51,8 kg	
exp	13	Modular framework	15.06.21	25 °C	X					X		X	40,0 kg	35,0 kg	
exp	14	wall	02.08.21	22 °C			X	self-weight		X	X				Full
exp	15	arc	23.08.21	21 °C		X	X	self-weight		X	X		85 kg	no deformation	Full
exp	16	Beeswax chair	06.09.21	20 °C		X	X	100kg		X	X		85 kg	no deformation	Local
exp	17	Modular structure	13.09.21	25 °C		X	X	self-weight		X	X				Insufficient
exp	18	dome	20.09.21	15 °C		X	X	80kg		X	X		85 kg	no deformation	Full
exp	19	tower	13.10.21	8 °C		X	X	100kg		X	X		85 kg	no deformation	Insufficient
exp	20	Small tower													Insufficient

Chart.11. A summary of all experiments

VI.Results

VI.A. INTRODUCTION RESULTS

On the following pages the creation process of a experiment is described in detail, naming the tools and their exact use. This represents the knowledge gained over the course of the thesis and summarises all experiments.

The chapters are in a chronological order spanning from design of the structure over casting to recycling.

Not only techniques are explained, which were used at the end, where possible also discontinued processes are explained to give a better insight into the project.

VI.B. CREATION BASE GEOMETRY

Starting with exp.14 it is distinguished between base geometry and system.

The base geometry, often also called Macro form, is defined as the basic shape the experiment has. For exp.15 for example this would be an arc.

The system, also called Micro form, is seen as how the material is approximating this shape. Later the system is thoroughly discussed. For exp.15 the pattern would be interconnected straight lines.

During this project the base geometry was for a long time synonymous to the system. From exp.1-13 distinguishing them was not needed and therefore not done.
Most shapes had either no system or had an intrinsic one, like the frameworks.

Later distinguishing them became important, since, at larger scales, base shape and pattern were subject to different demand profiles. Even demands that were congruent had different consequences for the two.

Fig.297. Base shape and system

Pink: Base shape
Blue: system

VI.B.1. Manual creation

Manual creation of base shapes was the process mostly chosen in the beginning of the thesis. Here the focus was on rapid experimentation to explore the strengths and weaknesses of wax. Shape was important, but without knowledge of the material there was no framework to evaluate them.

Therefore already known shapes were approximated. This can be best seen by the two framework designs exp.12 and exp.13, but also the columns exp.09 is a good example. With this rapid change of shapes it was hoped to build up a framework for shape evaluation in the future.

Over time information could be collected, so that these parameters could be set out:

- In the geometry pressure should be the dominating force
- It should be at best one surface
- The surface should be curved in at least one direction

VI.B.2. Particle spring method

The particle spring method was applied in this thesis to all experiments since exp.15. An explanation of this method can be found in *II.E.2. Particle spring method*, this section will only discuss the results of its application.

Since wax is not able to withstand tension forces it had to be ensured, that the predominant fore in the structure is pressure. The particle spring method was introduced to the digital design process due to its ability to deform geometries until this is the case.
Additionally it enabled hanged casting, since the model, when filled completely at once would self-organise into the designed shape.

Nevertheless results of using this method were not always positive.

In exp.15, which was only slightly deformed, the application of this process increased the quality of the design which had a vastly higher inner stability than exp.14.

However in exp.16 two load-cases were used. This made it impossible to use the conventional hanged casting method without additional restraints. Since these were not installed the quality of the realised structure was visibly decreased.

Exp.17 showed another problem of this method. Since it was impossible to fill all the modules at once the structure could not self-organise. Additionally, the anchors of the formwork were not similar to those in the simulation, which caused folds in the formwork.

The best application can be seen in exp.18. Here a designed planar system was deformed to the final shape. Its four point supports were reproduced with four independent towing ropes. Further restraints were not needed. In the realisation only minor deformations were observed.

Exp.19 was designed exactly like exp.18 only that the desired shape was different. The application of the particle spring method caused many beams to concentrate in the top of the structure, where they are not needed. Even though the realised structure proved to be stable it was nevertheless a deficit.

In exp.20 the input structure was already a 3D geometry. This prevented the beams from concentrating as in exp.19. Due to this the application of this method can be seen as more successful.

VI.B.3. Construction principles

From the start, multiple ways of assembly were considered. Experiments were conducted to test modular (exp.10, exp.13 & exp.17) and monolithic approaches.

The modular experiments were either bound together (exp.17), plugged into each other (exp.14) or a combination of both was used (exp.10).

Especially the plugged connections illustrate the problem of modular design approaches very well. As soon as the pins fail locally, a total collapse can be imminent. Because of this the quality of the production process has to be guaranteed, which can be difficult with this material as described in the chapters above.

Additionally, in the experiments conducted here, problems occurred also with the sizes of the connection points. Often these were designed too small and the fact that wax is a weak material should have been considered more.

Another limitation was, that models were designed usually as monolithic and afterwards split up.

Due to the low accuracy achieved in this experimentation, a transfer of forces from one module to the next was impossible to design. As a result, an uneven distribution of forces led to some collapses.

Furthermore, most of the connections were not stiff enough which introduced unforeseen forces by sliding away from its designed point.

Based on all of the reasons given above, a satisfactory connection design was not found in this experimentation. Tests using other materials than wax or fabric for the connections were disregarded due to the focus of this thesis.

Contrary to the modular approach, monolithic designs were usually successful.

Many of the geometries could sustain a higher weight than what they were designed to. Problems which appeared at the connection points in modular designs such as inner movement cannot occur here, while an uneven distribution of forces or casting errors appeared but rarely translated into collapses.

Therefore, a monolithic design comes with its own problems. As explained in “The ideal casting process” the needed volume has to be made available at once. Local casting problems can render larger structures unusable and force a repetition of the cast. Additionally, the whole casting environment always has to be at par with the size of the design, and especially larger structures require a design for turning over the structure and for the transport to the final site.

In the end, the monolithic approach was chosen as it was more fitting to the general scope of this fundamental experimentation. Due to the problems encountered when working with modular strategies, it was concluded, that it would add more sources of errors which would have diluted the validity of the experiments.

VI.C. SYSTEM CREATION

VI.C.1. Early used systems

Over the course of this exploration multiple geometries have been tested.

In the beginning these choices were made rather on aesthetic criteria. The first models, shaped like columns, exp.09, or hexagonal structures, exp.10, were largely designed to test the overall performance of the material.

In the first experiments both of them had their own distinct strengths. While the column was easy to fill it lacked the strength of the hexagonal shape, which was in turn very hard to fill.

The learnings of these experiments can be easily summarised. A geometry was needed, which could distribute forces to compliment this weak material. Already in the first tests it became visible that even though a hybrid material consisting of textile and wax could take up tension forces, the wax core of the element would break while doing this. Efficient geometries would be in conclusion those, which are dominated and optimised for pressure forces.

While testing the different fabrics in exp.11, it was experimented with long beams with and without a tension element on the underside of the beam. The results showed no big differences between those geometries and the most important lesson learned was rather, that the longer a wax beam would become the more unstable it got.

The following experiments using a framework aesthetic, exp.12 and exp.13, were strongly influenced by these thoughts. The new geometry helped to keep beam lengths very low while also offering a tall cross section of the geometry as a whole. The main point of interest in these models was how a uniform and a modularised construction would compare with each other. As stated above in the experiment description the monolithic approach seemed to be overall more successful.

Apart from the points mentioned in the paragraphs above, optimisation for pressure forces, distribution of forces, short beam lengths and uniform design the ease of casting was also an important factor. In exp.11-13 casting was conducted using a pump which turned out to be unreliable.

For further exploration into larger scales a new way of casting was experimented with in exp.14. Due to its success, casting into hanging formwork became the new standard procedure. Therefore a geometry was needed, which was able to distribute the wax throughout the model.

However exp.18 was created without using the system as explained in the following chapters. Since it was only used for this iteration the process of system generation is explained at length in its own chapter: *V.E.3. Experiment 18 / Dome*.

VI.C.2. Criteria for systems for models of larger scale

Before exp.14 many different systems were used as described in the chapter above. Most of them were selected out of curiosity for the waxes behaviour in this shape.

Due to the strong up-scaling of size, a new way of model design had to be conceived. To account for this, base geometry and system were separated.

For the system, the following parameters were deemed important:

- Must be 2D
- Ability to take up pressure forces
- High Stiffness
- No horizontal elements
- Beam lengths don't vary widely
- Has continuous elements from top to bottom
- Simplicity is preferred

One of the most important parameters was dimensionality. Three-dimensional Systems were excluded from the search, since the generation of formwork, and with it the general progress would have been slower.

Since a third dimension is needed for stability of the model, it was decided to utilise a 2D system with a curvature in the base geometry.

As concluded in the first experiments, wax is a material that performs well under pressure and poorly under tension. Even though the fabric improves tensile performance a bit, it is not the ideal load-case for this hybrid material. The system is supposed to compliment the material. Therefore it needs to be performing well in pressure scenarios.

One of the biggest problems with working with already solid wax models is, that slowly small cracks are formed through movement of the wax. To minimise the potential for this, a high stiffness was needed.

For the pouring process, a geometry that lacks horizontal elements works best. Diagonal beams are naturally closer to the flow direction, which makes them easier to fill. Especially with a highly viscous material like wax, this is important.

In exp.11 it was concluded, that wax performs worse, when beam length crosses a certain threshold. Through observation it was assumed that the perfect length, for wax beams of the used size, is around 30-40cm and should not be higher than 50cm. Due to the small field, in which it was assumed, that the beams would perform well, the system needed beams of similar lengths to always stay close to the optimum.

Wax performs best in pressure situations and can break easily. Searching for systems, which have continuous elements from top to bottom, was important, since these elements would be able to bring forces, which are inserted into the system on top directly to the supports.

Simplicity was not a direct criteria, but only a preference. A simple system is easier to program, to sew and to spot mistakes in. All of these improved the speed at which models could be produced, which was very important to gain knowledge quickly.

After defining these criteria, the search for a system began. The chosen one is presented in the next section.

VI.C.3. The selected system

The selected system was a simplification of the Sclerenchyma skeleton of an opuntia cactus. The Sclerenchyma skeleton, which is responsible for the stability of the plant, consists of an intricate web of main and secondary beams.

The main beams are directed towards the main load and parallel to each other. A secondary structure forms a sinus like curve connecting always two main beams. Interestingly, the structure builds knots at which the main beam connects with the secondary structure from both sides, visible in fig.298. (Nachtigall and Pohl, 2013, pp. 220)

This base system was then simplified to a line geometry before it was applied in the models.

According to the parameters set out in the chapter above, the system was evaluated the following way:

The selected system is a 2D geometry.

The system can absorb pressure forces. Long beams, which connect directly to the supports help with that. The connection between the beams helps to share load throughout the structure.

Triangulation is one of the most efficient ways to distribute forces in a geometry and greatly increases its stiffness. Since this system is based on triangles, it can profit from this effect.

The selected system has no horizontal elements.

Due to triangulation, the beam lengths can also be kept very similar to each other. The system can be scaled in one direction to build up equilateral triangles, if needed.

The selected geometry has continuous elements from the top to the supports.

Solution chosen starting from exp.14, a new system was applied combined all of these features in an aesthetic way. Another system was experimented with in exp.18, which will be discussed later.

Due to the simple construction of the system, it is quite simple to spot mistakes or inaccuracies.

Fig.298. The sclerenchyma skeleton

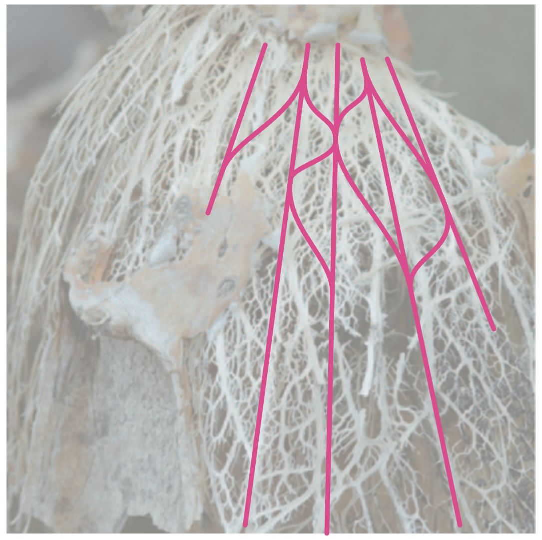


Fig.299. The principal structure of the sclerenchyma skeleton

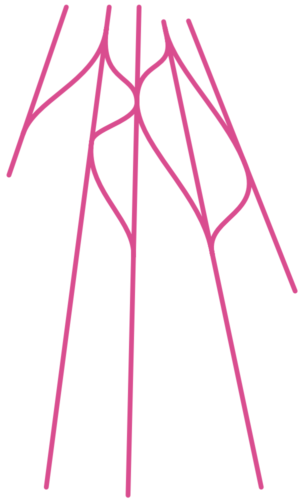


Fig.300. The pattern of the principal structure

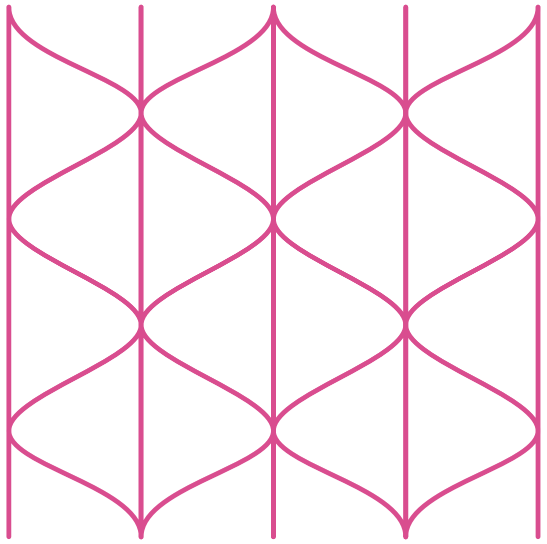


Fig.301. The abstracted system

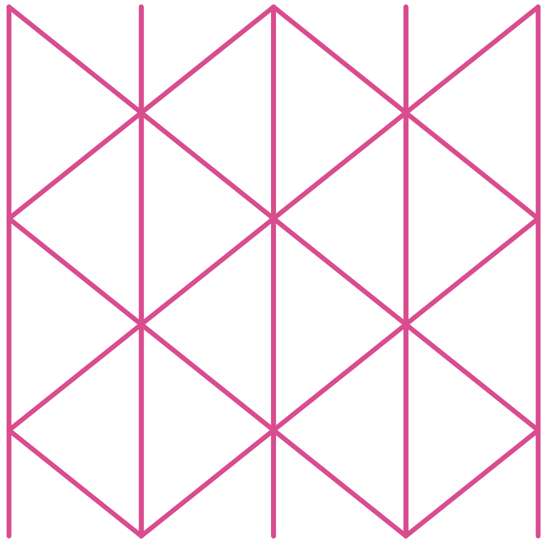


Fig.302. The system only represented with straight lines

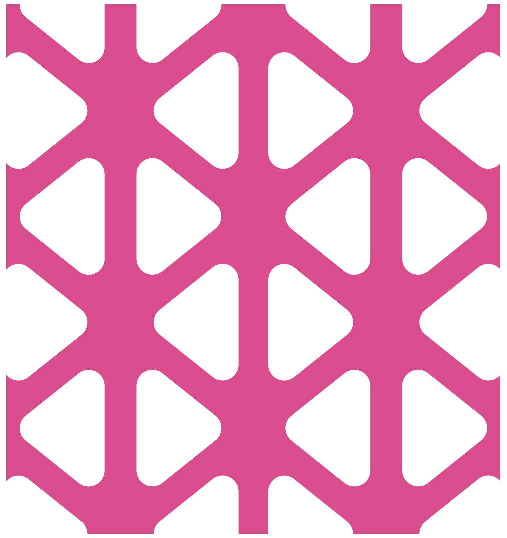


Fig.303. The basic system of the experiments

VI.D. SEWING PATTERN GENERATION

VI.D.1. Assumptive calculation of Yield strength

An Assumption on the performance of this material was needed when between exp.13 and exp.14 the step was taken to also optimise the beam sizes. This became necessary since the new models were of a larger scale, which meant that the lower beams would need to carry a significantly higher load compared to the upper ones. To respect this basic principle the beams needed to have different sizes.

Fig.304. Exp10 after stress testing

The low tech environment in which this exploration was conducted did not allow for professional material testing, especially not on such a short notice as needed. The possible strength of this material was assumed based on the performances in the stress tests before exp.10.

It was done in the following way:

Average beam size: 4 cm * 2 cm = 8 cm^2

No. of beams reaching to load: 4

Max load before signs of displacement: 40 kg

Load per beam 40 kg / 4 = 10 kg

Load per cm^2 10 kg / 8 cm^2 = 1,25 kg/m^2
~ 0,012 KN/cm^2

Additional security value 0,012 KN/cm^2 / 1,4 = 0,0087 KN/cm^2

Yield strength $_{\text{Assumption 01}}$ = **0,0087 KN/cm^2**

Even though this way of calculation is not able to provide exact material properties it was sufficient for a basic calculation process.

The cautious calculation of the material lead to an early underestimation of its capabilities. Later on with further testing the value was significantly increased.

After exp. 15, which was as described calculated to only support its own weight additional stress tests were conducted without a failure of the structure. Afterwards these experiments were replicated and analysed with Karamba. Beam sizes of comparable measures as executed in the original model were reached around a factor of 30.

Yield strength $_{\text{Assumption 01}}$ * 30 = 0,261 KN/cm^2

Yield strength $_{\text{Assumption 02}}$ = **0,261 KN/cm^2**

Starting with exp.16 the new value was used in all experiments for the beam size optimisation.

The stress tests continued to be successful, even though many casting problems occurred, as explained in the experimentation review. This leads to believe, that the material might be even stronger than assumed here.

Especially since the final model was to be exhibited it was important to generate safe values.

It has to be mentioned that the beams also need a certain diameter to allow a uniform flow of wax while casting. Often this minimum diameter was applied to the majority of beams in the structure which makes it highly probable, that these were never fully utilised.

An appropriate testing of the material was not within the scope of this project due to the low tech approach.

The study, mentioned in the chapter *II.C.1. Yield strength*, tested among others also paraffin wax. In their tests they defined the Yield strength at 0,23 KN/cm^2 , which would be 0,031 KN/cm^2 lower than the estimation.

VI.D.2. Generation of a sewing pattern

Parallel to advances in the search for a geometry, demand grew for a suitable generation process for the sewing pattern of the formwork.

The first experiments, exp.9-13, were only vector drawings of simple geometries. A line offset was used to generate a beam structure in which all beams had the same strength. This was mostly done as a vectorised drawing because higher accuracies could be achieved in a shorter time. Theoretically, this process could have also been done completely analogue.

The resulting patterns were then transferred to the textile and later sewn. This part at the end of the process stayed the same during this project.

Starting from exp. 14 this process changed in a fundamental way. The aim was no longer to only generate a pattern with a certain accuracy, but rather to generate larger scale complex patterns with differentiating beam sizes. This was not achievable anymore when using a largely analogue way of designing.

To digitalise this process, the first step was to abstract the geometry explained in the chapter above into a line geometry. The resulting pattern was adjusted to complement the experienced material behaviour, e.g. the scale of the pattern was modified until the longest length of a beam was under a certain threshold.

Afterwards, this line structure was analysed using karamba and the beam strengths were optimised based on assumed material qualities.

Since this process only generated the final structure, another intermediate step had to be designed to allow for the creation of the formwork. Due to the low tech environment of this research, only a very basic way of sewing could be efficiently used to produce the formwork. This way, sewing two textiles laying on each other together, is not optimal to create a perfectly round cross-section and will always tend to build up elliptical ones. For the aims of this project it still turned out to be good enough, especially since the larger the cross-section gets, the less elliptical it will be.

Due to the restrictions mentioned above, the main challenge for developing the pattern was the translation from a 3D model (generated by karamba) to a 2D pattern for later use.

This process was done in a very simplified way.

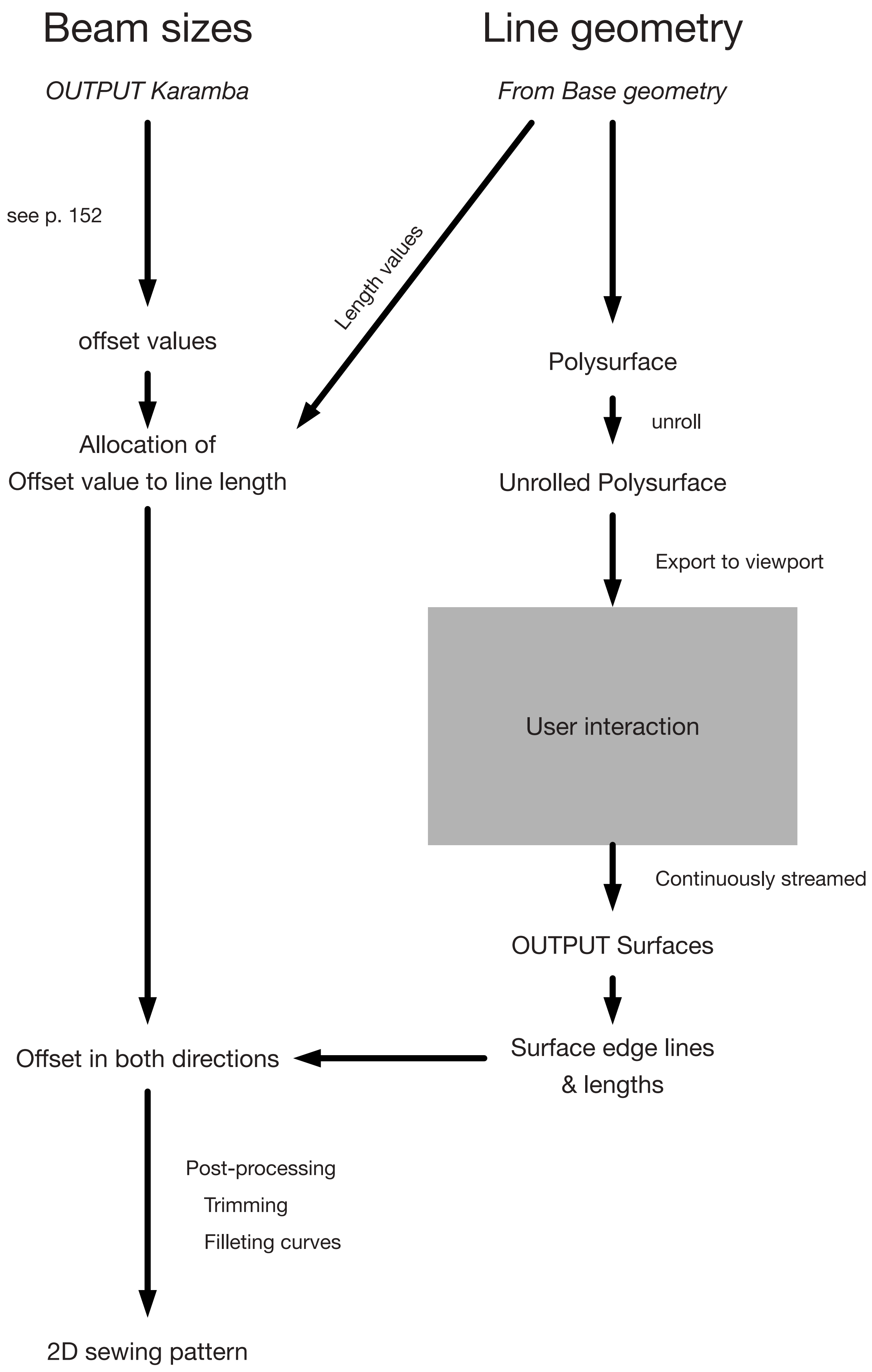


Fig.305. The design process of the algorithm that calculated the sewing pattern

The 2D line structure, which was the input to the optimisation in Karamba, was already prepared in such a way, that lines only span from one connection point to the next. These lines were then offset automatically with the calculated size. Since the size was measured in diameter in 3d and the needed value was a 2D distance, the following equation was used to translate the sizes:

Circumference of a circle = d * Pi

$\text{Offset}_{\text{total}} = d_{\text{karamaba}} * \text{Pi} / 2$
$\text{Offset}_{\text{one direction}} = \text{Offset}_{\text{total}} / 2$

$\mathbf{Offset}_{\textbf{one direction}} = \mathbf{D}_{\textbf{karamba}} \mathbf{* Pi / 4}$

Using this equation as translation back to a 2D manufacturing process turned out to be sufficient for the scale of this project.

Later, more modules were added to the pattern generation.

Using the particle spring method base geometries were created that would guarantee, that only pressure forces would become significant in later stress tests.

This opened the door to the exploration of doubly curved surfaces and freeform geometries.

The code was edited so that the geometry would be unrolled and exported to rhino. There the user could easily merge multiple, not overlapping mesh faces to create sub elements for the formwork. The decisions taken were informed, since the resulting sewing pattern was automatically updated with each movement of a mesh face. User interaction in this area is important, since available textile sizes, size of the workspace and skill level of the person sewing are the most important parameters in this operation.

Complimenting these larger modules, multiple smaller parties of the code were continuously updated to ensure that the correct values were assigned to the beams and to further develop the pattern e.g. with curved edges to spread out the tension in a seam from a point to a longer line.

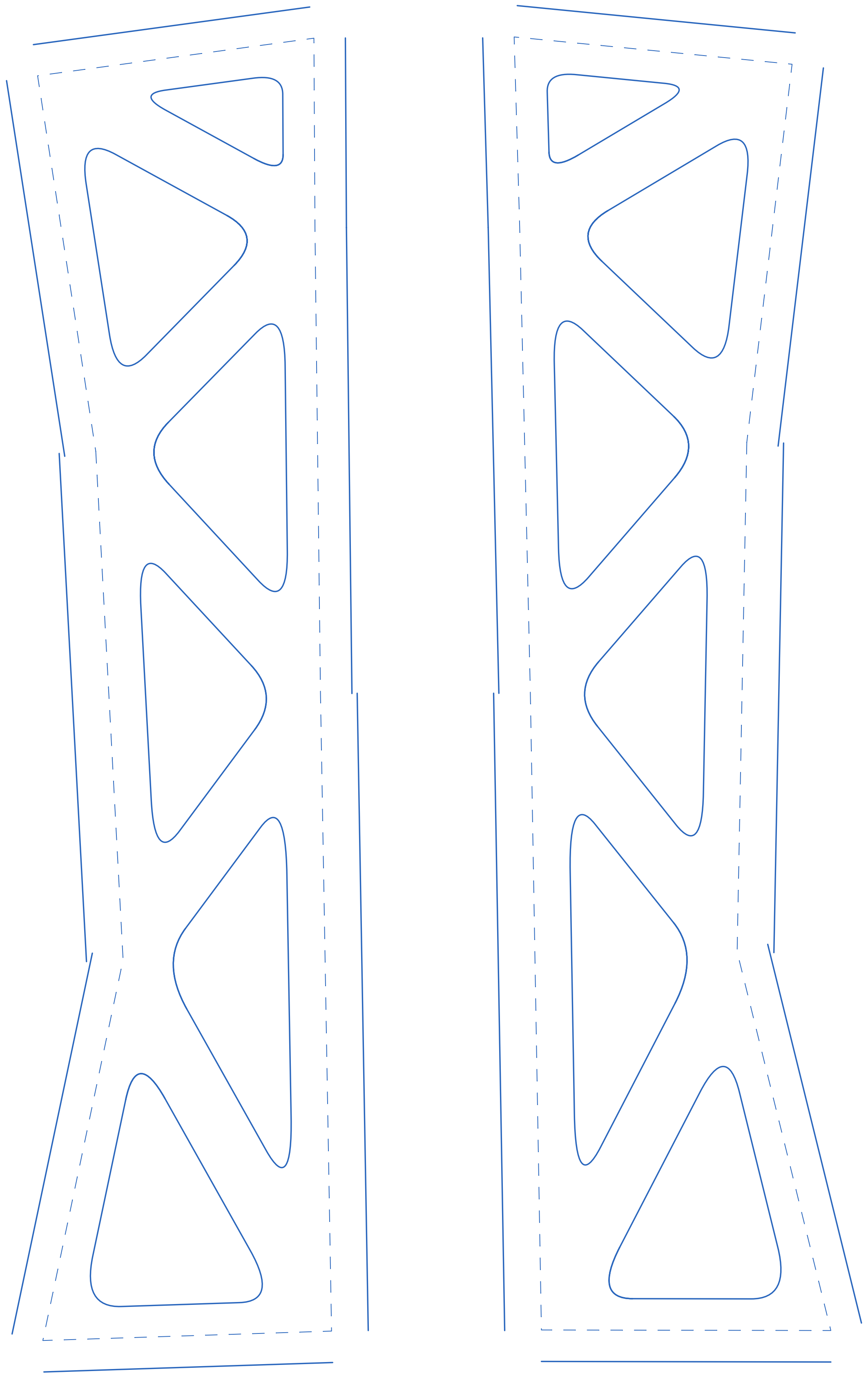


Fig.306. The sewing pattern of exp20

VI.E. CASTING

VI.E.1. The ideal casting process

In the last chapters the problems of casting wax in comparison with other materials were highlighted. A special focus was given to the problems which occur when scaling the model while leaving the casting process as is.

To speak about further developments, it is necessary to first understand the ideal casting process. Apart from casting, every other manipulation of the design or textile was less closely timed so that the other processes were always designed with it in mind.

In the following paragraphs the environment necessary for this is described.

For the ideal casting process, the first thing that is needed is a free space at best indoors. This is quite simple but already generates the advantage of leaving ambient temperature and other possible influences like wind or worse rain out of the equation. Only this way can it be guaranteed, that solidification velocity will not change over the course of a year.

While heating wax, it can be important to have sufficient ventilation. Wax fumes, especially from paraffin, can be poisonous. While a European equivalent could not be found the National Institute for occupational and safety health sets the recommended exposure limit at 2 mg of paraffin fumes per cubic meter of air.

Given that all of the sewing and quality control of sewing was done in a different space, two areas are needed to guarantee a successful casting.

Firstly, a space is needed in which the wax can be heated. This should happen in a vessel of the appropriate size. Appropriate in this context means it should be able to hold and heat at least 10-20% more volume than what is needed for casting. This is a safeguard to account for the loss of wax while casting.

The vessel also needs to be heatable to a temperature which is at least 10°C higher than the melting point of the chosen wax. If a low tech approach is followed in the experiment, it should be chosen mostly by searching for the lowest melting point.

After selecting the material, the needed heat protection should be considered and made available.

Additionally, some smaller heatable vessels could be used to accelerate the process.

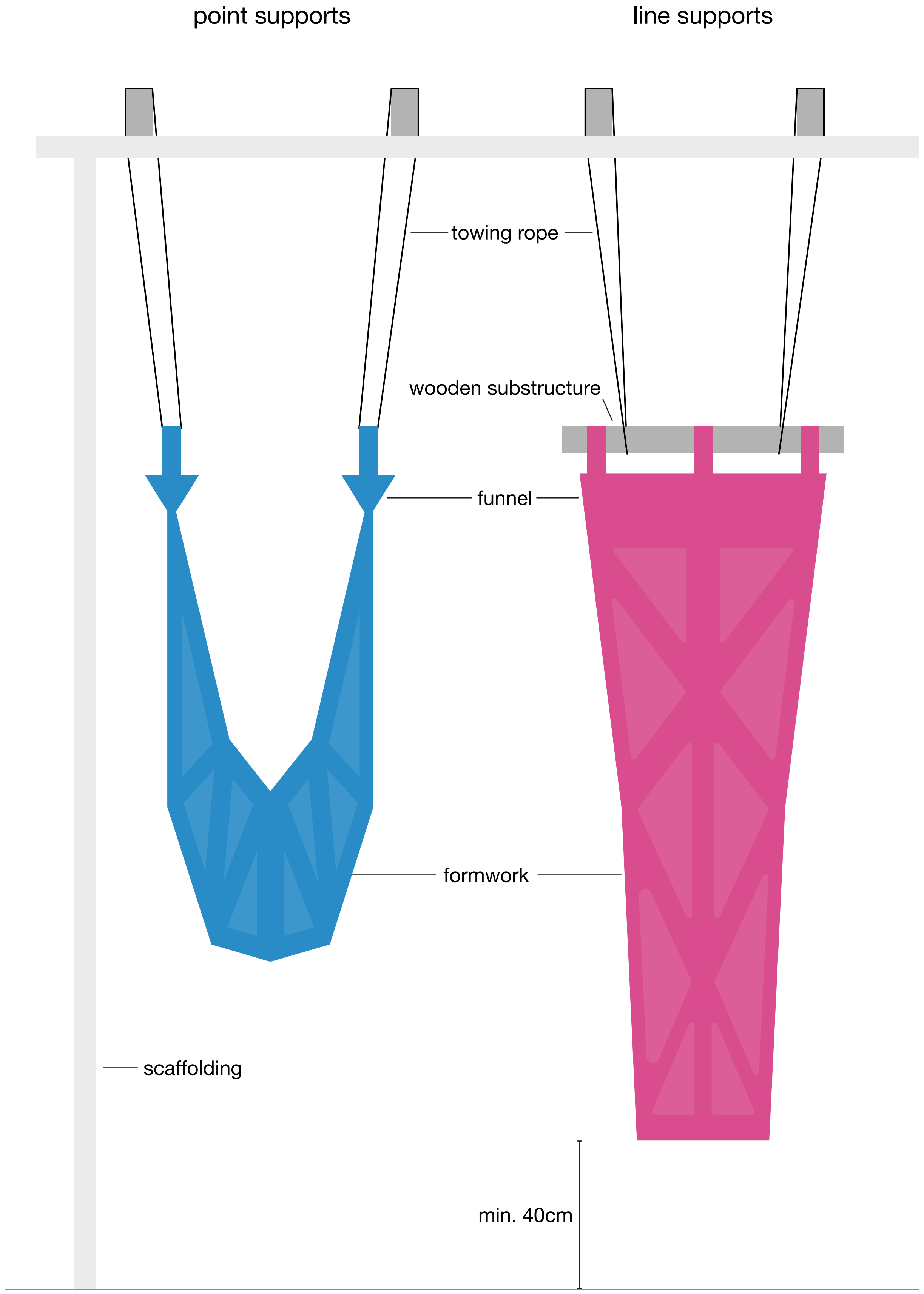


Fig.307. The two developed variants of hanged casting

To generate a uniform fluid, a stirring rod is also needed. In the experience of the author wood is a good material for it due to its availability, strength and its low thermal conductivity.

If no rod is used the heating process will be fragmented, which means that pools of liquid wax will be created, while other parts remain solid.

Secondly, a place for casting the models is needed. For this a scaffolding is recommended because of its modifiability. The scaffolding should be chosen based on the available space and the maximum size of the models that should be casted.

It is also recommended to lay out a protective layer over the floor and to have protective suits available for everyone involved in the casting process.

This concludes the requirements for the environment and will be followed by a detailed description of a cast.

First, all the needed wax should be calculated with a markup of minimum 10% better 20%.

This quantity of wax should be put into the heating vessel and heated to 10°C higher than its melting point.

If additional smaller vessels are available, it is best to heat them to the highest possible temperature. In this case the wax should be split up between both kinds of vessels. The ratio is dependent on the difference of heating power and the relative volume of the small vessels.

When the wax is completely liquid at 10°C over the melting point, the textile formwork should be sunk in it until completely soaked with wax.

When it is taken out, protection for the hands is needed.

If pressured air is available, the model should then be inflated to separate the two inner surfaces of the formwork. Even though this can create problems with air inside the module, it is still recommended as an open formwork facilitates a uniform casting.

Nevertheless, pressured air is not generally recommended since the larger a model becomes and the bigger a funnel it has, the less usable pressured air becomes. For the big scale models in this experimentation, it could only inflate a small section of roughly 1x1m of the whole model.

If no pressured air is available, the model is simply hung over a rope in the


Fig.308. The formwork is soaked with wax


Fig.309. The formwork is suspended


Fig.310. Wax is heated to a temperature slightly above the melting point


Fig.311. While casting the wax is continuously stirred


Fig.312. After casting the formwork is left hanging until solid


Fig.313. When solid, unnecessary textile can be removed

scaffolding until cold.

The temperature of the large vessel should now be changed to either exactly the temperature of the melting point or a bit below.

As soon as the formwork has solidified, it can be taken down. Now most of the not used textile should be cut out of the formwork. Leaving the inner triangles will expose the horizontal or vertical beams to tensions in the formwork, which results in elliptical cross-sections.

Especially when a curved geometry was designed, additional textile can result in tensions in unforeseen directions which might deform the whole geometry.

The only exception here is the unused textile at the borders of the subelement. They will come in handy later in the casting process.

When all the post-processing is done the model can be hanged on the leashes.

From this point on the casting can start as soon as the wax has reached a temperature around its meting point. It should be mixed heavily because there will be small parts of it that have already started solidification. These little parts should be present, but as small as possible to not clog the formwork. This viscosity is needed, since too hot wax will only run through the textile.

When the wax is at this point, the casting should start.

In an ideal scenario the large vessel carrying the wax would be lifted and would be completely emptied into the formwork using a hose with a large cross-section.

The rather low-tech approach would be to use smaller vessels to fill the formwork by hand.

The ideal point to fill the formwork is at the end of a beam on which two subelements of the formwork connect. Due to the left over textile it is easy to pull it from both sides to open the formwork. Additionally, sometimes casting problems can occur when the wax crosses from one subelement to the other. Here the wax can easily access two subelements.

If there are multiple qualified beams, it is recommended to choose the one which ends the closest to the later top of the model.

If there are still multiple beams worth considering, its best to use the one with the largest cross-section.

If the designed base geometry is not shaped like a pipe, a special consideration should be given to the beams in the middle of the formwork.

When the ideal beam to start filling was decided, it should be verified, that it is open enough for the filling.

If that’s done the casting can start and it is recommended to cast wax into the formwork until it is full. This sounds trivial but especially when there was no opening process with pressured air, or it worked only poorly, this can happen quite fast since most of the formwork will stick to itself not leaving the wax through.

The more wax was filled into the form, the more likely it will open the lower formwork by itself, due to the higher pressure in these areas.

If it stops completely at a point, it is recommended to deform the not filed area with the hands. This breaks the connections of the wax inside the formwork and will let the liquid wax progress through the form.

Whenever this is done more wax should be added into the funnel, so that more pressure can open more of the formwork.

This process is repeated until the formwork is full.

If the upper parts of the formwork are not uniformly filled the identified spot for pouring most of the wax can be abandoned for funnels that are closer to these areas.

When the pouring is finished the model can be left to solidify. The appropriate time for cooling depends on many factors as stated above. In this ideal setting, the author would recommend leaving it for a whole night.

After this time models of a comparable beam size and scale as produced over this thesis should have solidified securely.

When the model is taken down, the last bits of unused textile can be removed. It is highly recommended to then move the object carefully and directly to the place of use.

VI.E.2. Scalability of the proposed production process

A central interest in this examination always was to find a way to increase the scale of the produced objects.

In the beginning this was achieved regularly, especially due to the overall small scale at which the experimentation took place.
Since no way of modularisation could be found for this material, the only way to produce large scale models would be to cast them in one piece. Therefore, some problems are elaborated upon which were encountered when scaling up the models.

As stated in the chapter *V.E.2. Experiment 17 / modular structure*, an increasing scale comes with many new challenges:

- Necessary protective gear should be considered
- Tensile performance of the textile should be evaluated
- Seams should undergo the same tests
- Sophisticated scaffolding is needed for larger models
- All elements of the suspension should be appropriate to the structure
- The path of wax through the formwork should be designed
- Enough hot wax should be accessible
- The pouring method should be appropriate to the model size
- Transport to the destination should be considered in the planning process
- Ideally, larger models are produced onsite

For further successful scaling, these points should be considered.

Protective gear should not be neglected when working with this material. As already specified in *VI.E.1. The ideal casting process*. Heat protection should always be considered, especially when working with waxes with high melting points.

Depending on the scale of the model, it should also be considered which usual construction site protection could be needed.

Performance tests of textile and seams are important, so that tears can be prevented. Most probably these tears would occur while casting the wax. During this exploration only once a larger tear occurred, which happened in *V.D.4. Experiment 12 / monolithic framework*. In this experiment wax was still injected into the formwork, which might have been a reason for the seam to tear.

In the hanged models however, there were only minor tears that did not impact the casting process by much. Although no data was recorded it seemed like wax spills resulting from teared seams became more probable with a larger model.

Scaffoldings are the simplest and most versatile structure from which to hang a formwork. They can be easily modified in size and shape. Therefore, it can be designed to fit the needs of the current model. Especially models that require a more intricate hanging than a line will profit from this.

The items which are used for the suspension should be checked to see whether they are sufficient for the load that they are supposed to carry. Usually this can be done very quickly by exporting the support forces out of Karamba and comparing them to the product data sheet.

In very large models the path that the wax will take through the model should be designed. This can ensure, that the whole formwork is completely filled. While increasing the scale of the models, it was recognised, that one of the best ways to ensure a uniform filling is to design large beams which will take the wax directly to the lowest point of the formwork. As soon as the base is filled the resting beams will be filled either from the side or from below..

It also helps against suspending wax within the model. This usually leads to problems explained in *VI.F. Analysis of commonly occurring casting problems*, or worse, it clogs parts of the formwork for good.

The reasons for having enough hot wax at disposal and choosing the right pouring method were encountered in exp.14 and are discussed in *VI.E.1. The ideal casting process*.

Transportation becomes more important, the larger the model. At a comparable size to exp.14, transportation should be holistically designed and integrated as a secondary load-case into the beam optimisation. Even though this will probably not be able to prevent cracks from eventually appearing, it might help to delay them. If models should be larger in size than exp.14, a production on site should be considered. Even though in this case the model only has to be turned around, this process should be integrated into the design of the structure as well.

VI.E.3. Level of accuracy

Even though testing the strength and scalability of this hybrid material was the main concern of this experimentation a review on the achieved accuracy can show further axis of improvement for the code as well as the production process.

This was done mostly by comparing the structure to the 3D designed model after cast and via comparison of pictures to renderings. Only the last model exp.20 was digitalised after cast using photogrammetry.

This comparison will start with exp.14 since it was the first which was completely designed digitally.

The here analysed and graded into the following categories:

A. Full shape retained
B. Local shape retained
C. Insufficient shape retention

Models without visible deformation will be sorted in the category “Full shape retained”.

“Local shape retained” will be given to the models which partially retained the designed shape

The label “Insufficient shape retained” will be given to models that deviated so severely, that the majority of the structure deviates from the design.

Experiment 14 // wall

Full shape retained.

Experiment 15 // arc

Full shape retained.

Experiment 16 // beeswax chair

While casting exp.16 severe problems were encountered. The hanging was not adjusted to the shape that was desired. Additionally, it was not possible to fill the lean formwork due to the size of its beams. Therefore the structure gets the label Insufficient shape retention.

Due to this it is more informative to view the seat in isolation. Here a higher accuracy was achieved, although it was only possible due to the change in hanging halfway through the solidification process.
Here the label Local shape retained fits.

Experiment 17 // modular structure

In exp.17 multiple factors caused the the deviations from the designed structure:

- Too few supports to hang the structure from
- modular approach
- size

The location for the cast only had one steel slab to hang the structure from. Therefore it was difficult to create hanging 3D shapes. A quick fix for the smaller secondary element could be found, but the big element had only a point support instead of the designed line support.

Due to the modular approach the self-organisation process of the structure could only happen successful, when the whole structure would be filled completely at the same time. This was due to its size not possible, as a consequence large parts of the structure solidified in deviating shape.
Therefore the bigger element has not reached the curved shape as it was designed, but was rather flat.

Since the model could not be assembled, due to the issues with modularisation, the accuracy of the whole structure can only be assumed.
Judging from the individual elements the assembled structure would most probably get the label insufficient shape retained, since most of the structure is deformed.

Experiment 18 // dome

Full shape retained.

Experiment 19 // tower

This model deviated severely from its designed shape. Main reasons for this are:

- Insufficient height of the scaffolding
- size

It was not possible to cast this model at the place for which it was designed. The new scaffolding was too small, so that the formwork already touched the ground before it was filled. While casting the textile stretches, due to the added weight of the wax, which led to even more deformation.

Due to its size it had to be filled with multiple casting processes. The approach chosen, to fill one side up and then fill the rest, generated an imbalance in the formwork which in turn created even further deviation. Additionally, as in exp.17 large parts of the structure were already solid before the casting process ended. This made it impossible for the structure to self-organise properly.

Therefore the grade is Insufficient shape retention.

Experiment 20 // small tower

For this experiment a 3D model was created, using photogrammetry, to analyse its shape retention.

As visible in the renderings, the shape has two areas of deformation.

It has a rather round top in comparison with the triangular one of the model. This was most probably due to the pressure within the formwork. At the top the pressure in the formwork is at its highest, stretching the textile more than everywhere else. Additionally the formwork was created without an inner or outer side. To reduce this issue, the inner formwork would need to be shorter, than the outer to not deform into a circle.

The second deformation is at the base. Here an issue with the supports must have created this problem. In this casting a substructure was used to align the supports properly, here it must have failed. Due to this one of the sides is bowed in, which resulted in a general leaning of the element into one direction.

Therefore the grade is Insufficient shape retention.

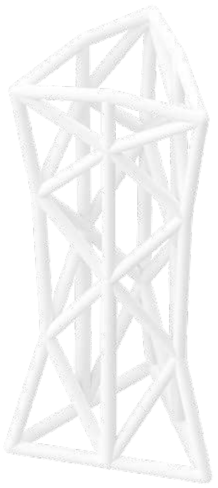


Fig.314. The designed structure

Fig.315. The realised structure

Fig.316. The design and realised object side

Fig.317. The designed and realised object front

Fig.318. The designed and realised object top

Fig.319. The designed and realised object bottom

VI.E.4. Stress test

Due to the lack of research and references, stress testing was one of the most important ways of gaining knowledge early in the project. With it assumption on the yield strength were made, which allowed to use beam optimisation for the larger models. This together with the ability of estimating model performance before building it was vital for the desired increases in scale.

The stress testing conducted in this research can be separated into three phases.

01. Initial testing

02. Stress testing to assume yield strength

03. Stress testing for verification

Initial testing

The initial testing phase started with the beginning of the project and continued until exp.9. In this phase a strong emphasis was on the general viability of wax as a construction material. Basic performance was tested and compared with material manipulations. One of the most important founds was the huge performance improvement achieved when soaking textiles with wax.

Stress testing to assume yield strength

Fig. 320 Models were loaded at 1/3 and 2/3 of their length

The second category includes exp.10-13. In this phase stress testing, sometimes one geometry multiple times, was conducted, to gain knowledge about the material performance. Aim was to make an assumption for the yield strength of the material. For the stress test the model was attached to wooden racks on both of its extremities. Then, in exp.9 and exp.10, a strap band was hung from the middle of the model, with which the load was applied. In exp.11-13 the load was applied using two strap bands, each at one respectively two thirds of the length of the system.
When this system was built up, weights were added to the strap bands. Usually it was started with 10kg as starting weight, adding 2,5kg for the single strap and 5kg for the two straps every 10 minutes. The whole process was documented with photos and loads were recorded when the first deformation happened and when it collapsed. Using these informations the yield strength was assumed as described in VI.D.1. Assumptive generation of Karamba a material. With this assumption the project could proceed to the third phase.

Stress testing for verification

The third and final phase of stress testing started with exp.14 and continued until the last, exp.20. Here the assumption already existed and was used in the design process of the experiments. Therefore models were generated that would be able to sustain a certain load-case. To verify the assumed material strength from now on it was mostly checked, whether the model was able to perform in the designed load-case without deformation.

Exp.14 and exp.15 used the assumed material strength found in the section above. Although after casting exp.15 it seemed, that the material was much stronger, than expected. Through another stress test a factor was calculated with which the yield strength was multiplied.

Afterwards the resting designs were all created using the updated material performance.

VI.F. ANALYSIS OF COMMONLY OCCURRING CASTING PROBLEMS

Fig.321. The exemplary filling process of one structure, dark blue first cast; light blue second cast; pink last cast

Fig.322. The exemplary filling process backside

The casting process of wax differs from widely used castable materials such as concrete or gypsum. While in the latter materials a chemical process is responsible for the solidification, the casting process of wax as described in this research is only a change of aggregate state. This process without any chemical reaction makes it easy for the wax to be completely reused without significant quality losses.

On the other hand, it is also responsible for the problems described in the sections below. Temperature is the only direct parameter which triggers phase change. For this series of experimentation it meant, that the speed of solidification was closely connected to the ambient temperature and could also be influenced by other factors, such as wind.

Additionally, how temperature changes happen in materials is not uniform. The coldest temperature will usually be on the surface of the material, preserving the heat inside. For wax this can mean, that while the interior is still fluid, the surfaces might be already solid.

Thirdly, with the change of phase the density and with it the volume is also altered. Solid wax has about 14% less volume, compared to the same mass in a fluid state.

All of these issues become decisive as the pouring temperature for wax which worked the best in this low tech environment was as close as possible to its phase change while still mostly fluid.

VI.F.1. Layers in casting

Fig.323. The casted wax had multiple layers which were only loosely connected

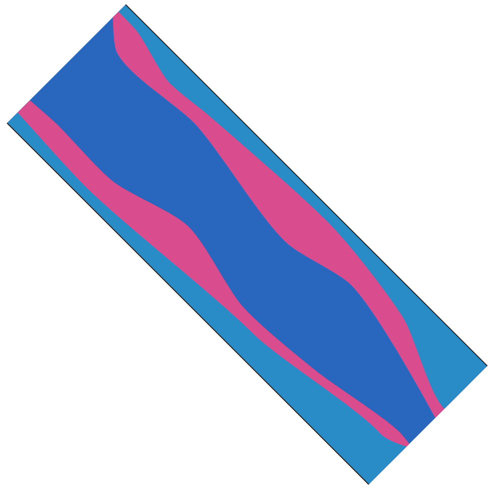


Fig.324. A section through a beam with layers. Each color represents one casting process.

Having layers in a beam section is the least grave of this list of commonly appearing problems. The ideal circumstance to replicate this problem would be a wax which is poured at a very low temperature, while the delay between the multiple fillings is too long in combination with the speed of the solidification.

This issue also occurs naturally more often the closer the element is to the funnel. Each filling will create a new layer as wax sticks to the inner surface of the formwork and solidifies rapidly between casting processes.

Additionally, the fact, that surfaces of materials which are cooling down are usually their coldest areas supports the forming of layers. Later poured wax would need to be hot enough to heat up the surface and connect to the hotter core.

Due to the stay in place fabric formwork, this problem can be partially compensated. While stress testing the materials, this kind of casting issue never was responsible for a collapse of the system.

Still, the stability of this beam is most probably not as reliable as a monolithic one.

The volume change of wax while cooling could theoretically also lead to cracks in some of the layers, although this has not been observed.

VI.F.2. Not monolithic junctions

Fig. 325 A junction without a uniform cast. The beams on the left side are only loosely connected to it

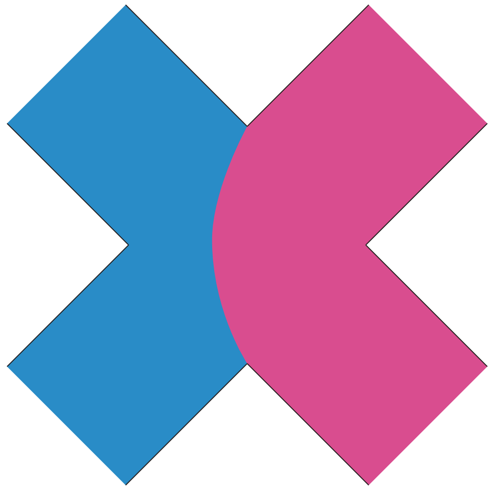


Fig.326. A section of an unconnected junction

This issue could be described as a variation of the layered casting. The formation of it is increased with the size of the formwork and a subelement by subelement approach as chosen in exp19.

Here the formwork was filled one quarter at a time when looking from above. This meant that when the last quarter would be filled in, the wax of the first quarter was already completely solidified. In this area most of the junctions looked like this.

To generalise the ideal formation process could be summarised with having very long delays between the different casting processes.

This inaccuracy has never led to a systematic collapse.

Nevertheless, when these were found in the process of recovering the wax, there were already small cracks between the two elements. This will automatically lead to a different behaviour of the geometry compared to how it would react as a monolith.

Even though it has to be mentioned, that the textile surrounding these elements partially compensates for this problem, it still has to be seen as a local failure.

VI.F.3. Air pockets within the beams

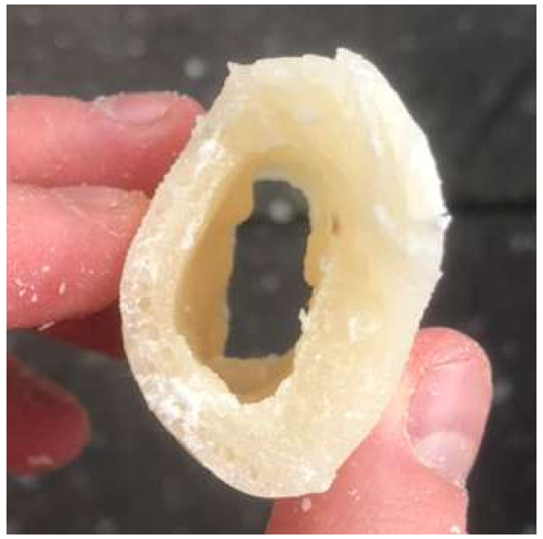


Fig.327. A trapped air bubble in a beam

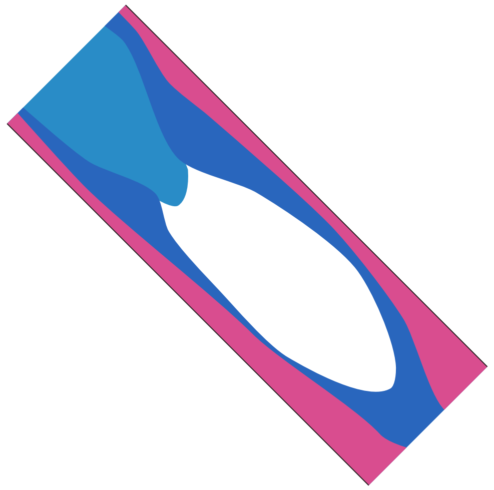


Fig.328. A section through a beam with an air bubble. Each color represents one casting process.

The most consequential problem is the formation of air pockets within the formwork.

This happened especially often when still using the pump to fill wax into the formwork. Here the problem was a mechanical one. The pump was not completely closed and sucked air into the element as soon as there was no more wax.
But even when casting wax with a hanging formwork, this problem kept appearing, but less frequently.
It starts to form with building layers of wax on the inside of the formwork. Only in this case, at some point new wax arrives at this location so viscous that the air cannot escape the formwork anymore. It is then trapped inside and can form pockets that can be as long as the whole beam.

The ideal circumstances for these bubbles to form are when wax is used at temperatures that make it very viscous. Small cross-sections, a delay in pouring and a deformation of the formwork can also higher the probability of this.

What makes this problem even more complicated, is that these pockets are hard to find, as long as the air is not directly next to the textile. Usually they are only found when they burst while stress testing or afterwards when dismantling.

These pockets were already responsible for many premature collapses, especially while researching the right textile. They were also found in later models where they never collapsed, but are clear weak points in the geometry.

VI.G. RECYCLING PROCESS OF WAX

The possibility to recycle wax entirely with low energy consumption after its usage was always seen as a cornerstone of its viability. Even higher melting points, around 100°C, can be reached in a low-tech environment, as standard heat sources, for cooking for example, are designed to reach these temperatures efficiently.

As explained in the chapter *VI.F. Analysis of commonly occurring casting problems* the casting process of wax does not involve a chemical reaction but is only a phase change from solid to fluid and back. Theoretically, this process can be repeated infinite times without losing material quality as long as the following points are adhered to.

To not loose track of the specific properties of the wax used, a combination of different wax types should not be mixed. In a low-tech environment, it is close to impossible to separate two different waxes, again as long as one of those doesn't have a significantly higher melting point. Even then it is discouraged and should be avoided.

For the recycling process in this project the textile formwork was always removed first and then the wax was reheated in a heating element. If a larger heating element is available, the models could be recycled with formwork still around it. Theoretically, there could be a higher chance of fires, when the formwork acts as a wick. Anything connected to flammability was not tested in this research. For these kinds of experiments scale is always important and due to the lack of knowledge of fire safety combined with the unavailability of security measures, a safe experimentation was not possible.

While using a structure, there is always a small risk of dirt accumulating in the wax. This can be counteracted by filtering the wax after each cast.

While experimenting, this turned out to be even easier than thought. If it is acceptable for the user that the wax is mostly but not perfectly pure, another procedure can be recommended. For this most of the wax should be poured into another clean vessel and only the last 10% should be filtered. Due to its weight, the large majority of the dirt gathers at the bottom of the heating vessel and can be removed easily like this.

Generally it is best to keep all the heating elements closed during the time in which they are not needed. This prevents dust from accumulating in them.

If these three points are considered the wax can be used repeatedly without quality losses. This special property is not commonly found in construction materials.

Its recyclability makes wax an ideal material for temporary small scale structures, as long as its weaknesses and the conclusion are kept in mind.

VII. Conclusion

In the beginning of this dispute, small scale experiments lead to the following proposition:

Exploring wax as the sole load-bearing building material for freestanding structures, through iterative upscaling of experiment dimensions.

To explore this field a methodology was designed, which focussed on experimentation. Process design, material behaviour and formwork design were designated as key areas.

The material wax was thoroughly introduced. At first with its usage over time and then with its relevant material properties. It was seen, that wax is a weak material, which is too brittle to perform in tension. However its theoretically infinite reuse potential, since it solidifies at low temperatures due to a change of phase, raised interest.

In the state-of-the-art relevant practices and existing knowledge was discussed. A focus was set on casting ranging from its history up to contemporary examples for fabric formwork. It was shown, that the usage of fabric formwork is a relatively recent concept, which has become more approachable through the utilisation of algorithmic design.
Additionally temporary architecture as a possible area of application was analysed. Material choices in this environment were noted, and their recycling potential analysed. Here it could be seen that most of the materials outlive their time of use by far. Even completely recyclable materials, such as steel or wood, often have significant drawbacks. The recycling process of wood takes a very long time, since it has to be returned to the natural cycle (i.e. rotting), while recycling steel is very energy-demanding.

In the first stage general material behaviour was tested, as well as possibilities of material manipulation. The discovery of the symbiotic relationship of wax and textile was the main learning in this phase. Fabric stayed an integral part throughout this research and was later also used as the forming element.
Secondly the focus moved to fabric formwork and its design. In this phase many stress tests were conducted as well as a research on fabric qualities to lay a foundation for later objects of larger scale.
The approximation of yield strength values enabled a digital design process, which was the basis for all further experimentation. In it models were designed with the help of the particle spring method to create structures in which the predominant force would be pressure. Using the approximated yield strength, beam-sizes were calculated to reach a high degree of material efficiency.

An algorithm was designed to calculate the sewing patterns of the needed elements. This process allowed for more complex geometries to be present in this research. Using the particle spring method to design the structure also enabled hanged casting, which was introduced as a low-tech production process, especially for larger models.
In the last section the scale was enlarged, and material properties were updated based on the performance of these objects.
Additionally freeform structures with doubly curved geometries were realised to prove the versatility of the design approach.
Since a feasible way of joining multiple elements to a larger structure could not be found, most of the experiments followed a monolithic approach. It appeared, that tube or dome-like structures have a higher inner stability, since the number of cracks observed was notably lower, compared with the more planar structures of the early experiments.

The execution of the research proposition given at the beginning of this thesis demonstrates the capabilities of wax as a construction material. Keeping its weaknesses in mind it has unique qualities, especially in the context of temporary architecture. Its energy efficient recyclability has been tested throughout the thesis by reusing the same wax for multiple models. Its structural performance is elevated when using fabric as formwork and outer layer of a hybrid material.
The possibility of hanged casting simplifies the production process and reduces the need for material to construct a mould drastically.

For wax to become a safely usable material, there are still many obstacles.

In the area of material strength, professional testing is needed. Especially interesting would be a comparison between pure wax and the proposed hybrid material. This experimentation could also lead to a more in depth look at the performance of different textiles and waxes. Additionally, switching from cotton to metal fabric might benefit the structural performance, as well as its recycling options.

Further increases in scale of this design approach are of interest. Throughout this thesis this was a central way for the generation of knowledge and increases in efficiency of the design process.

It was mentioned, that waxes with higher melting onsets have higher yield strengths. Experiments with these were impossible due to the safety issues when working with a material in this temperature.
In an environment which accounts for that it might be possible to realise structures, with a significantly better structural performance, compared to paraffin structures.

Automated production of the formwork, or at least of its planar subelements, might be able to reduce production times drastically. Using a CNC sewing machine could automate the production process laid out in this thesis. The exploration of automatically custom knitted textiles might be able to reach a higher realisation accuracy since it is able to produce non planar fabrics.

It was not possible to find a way of joining multiple wax elements to a bigger structure. It is believed, that monolithic structures perform better with this material, due to its weakness. Further research in this topic would nevertheless be of great interest.

For a safe use of the material ways to elevate the melting point and incendiary temperature of wax could greatly improve the fire safety. At the moment this is one of the most important issues with the material, since its performance in these areas disqualifies it from anything but experimental uses.

Nevertheless the prospect of a completely recyclable resource for temporary structures would open the door to new concepts and ways to interact with architecture.

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VIII.B. TABLE OF CREATED & EDITED FIGURES

VIII.C. TABLE OF QUOTED FIGURES

Fig.19:	Nine wooden cabins from Lake Annecy Cabin Festival, 2021; https://www.dezeen.com/2021/09/30/nine-cabins-lake-annecy-cabin-festival-philippe-burguet/; © David Foessel; downloaded 23/02/2022
Fig.20:	A pavillon made of aluminium by Nebbia Works, 2021; https://www.dezeen.com/2021/09/17/nebbia-works-v-and-a-london-design-festival/; © Ed Reeve; downloaded 23/02/2022
Fig.21:	Steel pavillion by AIRLAB in Singapore, 2020; https://www.dezeen.com/2020/01/06/airmesh-3d-printed-pavilion-steel-airlab-singapore/; © Fabian Ong; downloaded 23/02/2022
Fig.22:	"pineapple" by Studio Morison in Berlington Hall, 2017; https://www.dezeen.com/2017/07/12/studio-morison-origami-pink-pineapple-pavilion-berrington-hall-18th-century-garden-design-architecture-england/; downloaded 23/02/2022
Fig.23:	"Leverage" by Rumgehør built from Dunnage bags, 2021; https://www.dezeen.com/2021/08/27/chart-art-fair-2021-five-architecture-pavilions/; © Joakim Züger; downloaded 23/02/2022
Fig.24:	A pavillon of SelgasCano in Cognac, 2017; https://www.dezeen.com/2017/07/05/pavilion-selgascano-cognac-fondation-dentreprise-martell-france/; © Iwan Baan; downloaded 23/02/2022
Fig.26:	Ctesiphon by James Hardress de Warenne Waller; Veenendaal et al., 2011, pp 166
Fig.27:	The finished KnitCandela; Popescu et al., 2020, p 195; © Angélica Ibarra
Fig.28:	The temporary scaffolding; Popescu et al., 2020, p 200; © Mariana Popescu
Fig.29:	Tension connections & cable net structure; Popescu et al., 2020, p 198; © Mariana Popescu
Fig.30:	The HiLo cable net structure & fabric formwork; Méndez Echenagucia et al., 2019, p 79
Fig.31:	The carbon-fibre reinforcement ontop of the fabric formwork; Méndez Echenagucia et al., 2019, p 79
Fig.32:	Concrete is sprayed on the structure; Méndez Echenagucia et al., 2019, p 79
Fig.33:	The finished HiLo prototype; Méndez Echenagucia et al., 2019, p 81
Fig.34:	The built structure in Zurich; https://brg.ethz.ch/hilo; © Block Research Group - ETH Zurich; downloaded 19/01/2022
Fig.35:	The Terramia Drone Spray Project; https://www.muddarchitects.com/dronesprayterramia; © Studio Naaro; downloaded 19/01/2022
Fig.36:	Sands and clays were sprayed on a textile with the help of a drone; https://www.muddarchitects.com/dronesprayterramia; © Studio Naaro; downloaded 19/01/2022
Fig.37:	The substructure was made from bamboo; https://www.muddarchitects.com/dronesprayterramia; © Studio Naaro; downloaded 19/01/2022
Fig.38:	An inside view of the Terramia ; https://www.muddarchitects.com/dronesprayterramia; © Studio Naaro; downloaded 19/01/2022
Fig.39:	The Organica Hyparbolica; https://www.tektoniek.nl/innovatief/tektoniek-university/praktijkcase-fabric-formwork; © Robbert de Smet; downloaded 19/01/2022
Fig.40:	The wooden substructure for the casting process; https://www.tektoniek.nl/innovatief/tektoniek-university/praktijkcase-fabric-formwork; downloaded 19/01/2022
Fig.41:	Wrinkles in the casted shape; https://www.tektoniek.nl/innovatief/tektoniek-university/praktijkcase-fabric-formwork; downloaded 19/01/2022
Fig.42:	The MARS Pavilion; Sarafian et al., 2017, p 523; © Sarafian, Culver, Lewis
Fig.43:	Robots were used to cast the modules; Sarafian et al., 2018, p 524; © Sarafian, Culver, Lewis
Fig.44:	The sown formwork and its mounting on the robot; Sarafian et al., 2019, p 525; © Sarafian, Culver, Lewis
Fig.45:	Steel triangles connect the modules; Sarafian et al., 2020, p 523; © Sarafian, Culver, Lewis
Fig.46:	The target shape was designed; Zhang et al., 2019, p 1
Fig.47:	The surface of the shape was subdivided into planar panels; Zhang et al., 2019, p 1
Fig.48:	The planar panels on the structure; Zhang et al., 2019, p 1
Fig.49:	The realised and filled formwork; Zhang et al., 2019, p 1
Fig.50:	The realised structure made of plaster; Zhang et al., 2019, p 1
Fig.298:	The sclerenchyma skeleton; Nachtigall and Pohl, 2013, p 220

VIII.D. TABLE OF CHARTS