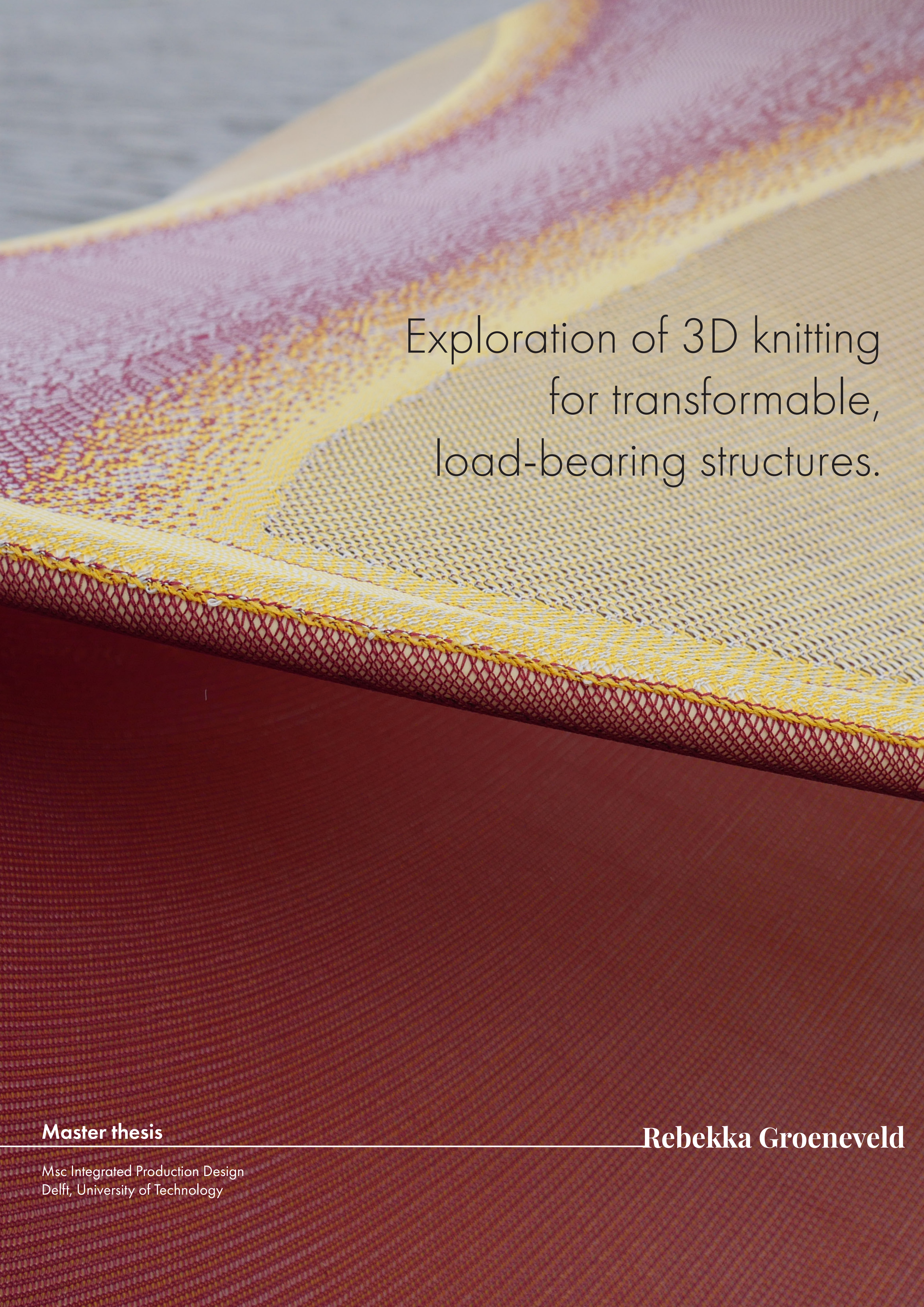

Exploration of 3D knitting for transformable, load-bearing structures.

Master thesis

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Msc Integrated Production Design
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MSc Integrated Production Design
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Preface

Dear reader,

You are about to read about my journey of the past 6 months from a vaguely described assignment to a textile hybrid 'chair'. Textiles have always fascinated me, so I am very grateful to end my academic carrier with this knitting project. It was (is?) me and the machine against the world, and I have quite some people to thank for that.

This project would not have been possible without my amazing supervisors: Holly and Mariana. Holly, eternal gratitude for putting textiles on the agenda of the faculty of IDE. Since the start of my Master's programme you have guided and supervised me throughout various projects, teaching me how to conduct research through design, to find my own path within the academic field, always there with an interesting paper or book for me to read or project to join.
Mariana, you showed me that knitting can be applied and studied from so many domains and that the possibilities are even more endless than I thought. Thank you for letting me be part of the interdisciplinary group of students, where I got to know a whole new vocabulary and met lovely people. I greatly enjoyed our talks about the knits, yarns, and (almost) impossible computational models, and thanks for not holding it over me that I chose STOLL over Steiger.

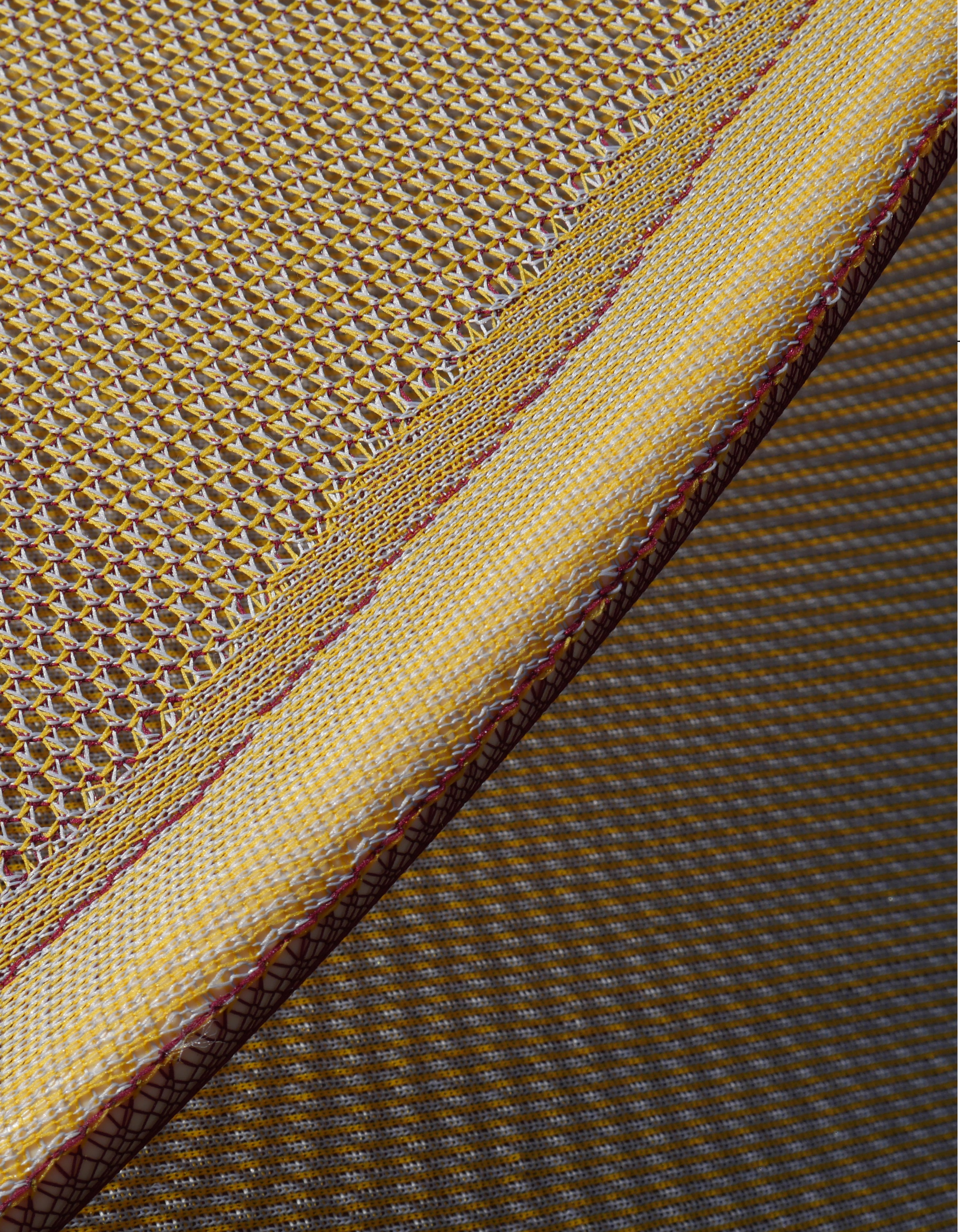
Thank you both for the inspiring meetings and amazing guidance.

I want to thank Linda Plaude for allowing me to play with Günther and not getting mad for breaking an estimated 120 needles. Shoutout to Adam, the technician, whom I video-called multiple times to ask for help on how to fix the machine. And enormous gratitude to the men of the PMB, especially Wiebe, who helped me to finalize my prototype and put bets on how much my chair could hold before breaking. (They lost.)

Last but not least, thanks to my friends, boyfriend and family for supporting me throughout this project, listening to my ups and downs with the machine and discussing at length the 'why' of it. You responded with enthusiasm when I pushed samples under your noses, told me to keep going when I did not see the knit through the stitches anymore, and forced me to enjoy the sun from time to time.

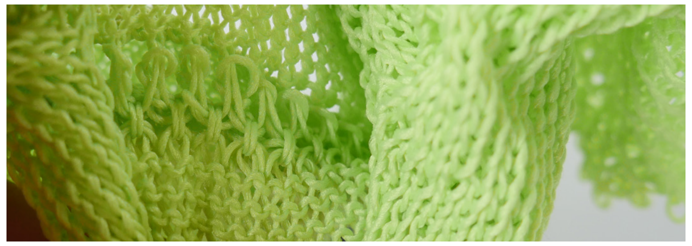
Thank you all for being part of this journey.

I hope you enjoy reading this report.



Executive summary

This research-through-design explores 3D knitting for load-bearing, transformable structures using a Material-Driven Design approach. 3D knitting is a low-waste textile production method that allows for highly adaptable designs and an iterative design process. Current literature is studied in various domains, exhibiting the knowledge gap on development of 3D knitted, load-bearing, transformable structures on the scale of a sitting object.
A tinkering phase resulted in a Design Space, demonstrating the range of possible materials, structures, geometries and transformability methods. Multiple concepts are developed to define the relationship between the parameters. The final demonstrator is the ARCHETYPE.98, a sitting object showing the adaptability, load-bearing capacity, transformability, material expressions and streamlined, low-waste production process of 3D knitted, transformable, load-bearing objects. The ARCHETYPE.98 is a bending-active textile hybrid structure. The load-bearing capacity is evaluated through a technical evaluation which exhibited the framework material to require improvement. User research exhibited the novelty of the design. The transformability of the sitting objects allows for eight variations of the aesthetics within one product. The sitting surfaces are highly adaptable through the knitted material, enabling personalization of the aesthetics and ergonomics of the chair.
The development and production process of the ARCHETYPE.98 show the need for modelling software for knit structures and textile hybrid structures to improve the technical performance and reduce the number of required iterations. Further research into the frame material and bursting strength of knit structures related to the yarn materials could improve the load-bearing capacities of the object and bring forward the limitations of the applied rigidifying method.



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0.1 Introduction

Textiles are used to produce a wide range of finished goods: not only for apparel but also for medical purposes, upholstery, transportation, and bedding. Textiles are all around us. We touch it when sitting down, we wear it to protect us from the weather, and we live in and under it.
Textiles are flexible, anisotropic, porous materials with visco-elastic properties. The most commonly used production methods of textile are weaving, knitting, or non-woven textiles.

Production process
The production process of a textile consists of the following steps: (1)growing, harvesting, or mining the fibre or base material, (2) spinning of the yarn, (3) weaving, knitting, or otherwise producing the textile, (4) dyeing, (5) finishing. This is where textile production ends and the manufacturing of the finished good takes over. Most often follows a process of cutting and sewing the fabric, after which the product might be dyed or finished again.

Environmental impact
The scale on which textiles are produced these days has a negative impact on our environmental and social sustainability. To demonstrate this scale, the global textile market was valued at 961.5 billion USD in 2019 and is expected to grow by 4.3% until 2027. (Global Textile Market Size & Share Report, 2022-2030, n.d.)
The greatest environmental impact comes from the so-called "wet" processes, meaning dyeing, finishing, and printing, contributing the most to the water consumption and wastewater emission associated with the textile industry. (Roos & MISTRA, 2015)
The fibre production impact highly depends on the material that is being processed. Cotton has a much larger impact compared to other natural fibres, and even synthetic fibres. Additionally, natural fibre properties vary largely compared to synthetic fibres, and the yarn quality also changes when the quality of the natural material changes. Hence, testing and evaluating tools are necessary for the process as well.

Fabric production techniques
Weaving
Weaving is the interlacement of yarns in mutually perpendicular directions, requiring tension on the warp yarn to insert the weft yarn. The structure can be varied in length and distribution of the interlacement, resulting in a variety of fabric properties.
Woven fabric is mostly used for clothing, such as jeans, furniture, or any application that requires strong, non-stretchy material. Intergrating elastane in the yarn, the fabric can be stretched.
For large-scale production, the fabric is woven on a roll after which it is cut to the desired shape and sewn together to create a 3D form. This cut-and-sew method is labour-intensive and almost always results in waste fabric. Zero-waste System Thinking is needed to develop these woven products without producing textile waste. (McQuillan, 2020) The development of multiple 2D shapes in one field, stacked on top, can be used as the basis for the shape development of the 3D woven structure. Dr McQuillan developed this method to explore the theoretical, aesthetic and technical development of systems and methods for zero-waste textile forms.

Knitting
Knitting is the second most popular production technique of fabric. Knitting is the interloping of one or more yarns and is comparatively faster and more economical to convert yarn into fabric. (Gong & Özgen, 2018) These loops create a stretchable fabric resulting in comfortable fabric for apparel. Knitted fabric can be made by hand, using two needles, or using a domestic or industrial machine, where every stitch requires a separate needle. Different handlings of the loops results in different stitches, and thus different fabric properties.

Knitting can be another zero-waste textile form. 3D knitting means knitting tubular using two or more knitting beds. (Figure 1) Cut-and-sew is avoided by directly knitting fabric into shape, called fully-fashioned knitting. The shape resulting from this technique is quite typical: often rounded, limited by the amount of knitting beds. Shima Seiki developed a knitting machine with four beds, allowing for a larger degree of freedom when designing knitwear. (Shima Seiki, n.d.)
This is a labour, time and cost-saving method of the production of textile products.

The potential sustainable benefits of using knitted structures are explored in other fields of work besides the fashion industry. Dr Mariana Popescu and her team developed a new system of formwork using 3D knitting. (Popescu et al., 2021) The system is a material-saving, labour-reducing and cost-effective solution for the casting of double-curved concrete geometries on an architectural scale. The textile formation technique used, weft knitting, eliminates the need for pattern cutting, sewing and welding, compared to weaving. The technique gives the possibility to integrate openings, and channels, in various sizes and directions.
The knitted structure is made rigid using concrete to keep the structure in form. Consequently, this stay-in-place formwork is completely rigid and thus needs to be set up in the place where it will stay unless the parts are small enough to be transported. It would be desirable if parts of the structure could be left flexible so a foldable construction is created, like origami. An example of this origami technique for architectural scale is Joseph Choma. (Joseph Choma, n.d.)

These are examples of how to apply traditional textile production methods in other domains than would be expected. Textiles are not just planar surfaces with uniform behaviour. Both weaving and knitting allow for personalized local manipulation of the structure, material and form. Knitting even allows for 3D shaping, similar to the 3D printing of multiple materials. This approach is beneficial for the environment for its low energy, low waste and on-demand production possibilities. As this perspective has been demonstrated by Mariana Popescu and Holly McQuillan, this project builds upon it. (McQuillan, 2020) (Popescu et al., 2021)

Figure 1. Industrial knitting machine

This project explores rigid and flexible knitted elements for a load-bearing, transformable structure, further developing our understanding of the benefits of tuning textile-form behaviour via material, structure and form.

The sitting object is chosen as a demonstrator of this knitted textile form which is:

1: Lightweight and flexible - while being able to bear the load of a person sitting.

2: Tunable - the structure can be locally programmed to have property variations (elasticity, rigidity, density, etc)

3: Deployable and transportable - transforming from space-saving folded textiles to 3D form when needed.

4: Able to be produced on-demand, in minimal steps, with low waste.

0.2 Literature research

The project takes inspiration from different domains. The overarching goal can be separated in the following elements: furniture design, knitting, deployable structures, and rigid/flexible materials. The different elements can again be studied through different domains: architecture, furniture design, industrial design, and fashion design.
Following the antidisciplinary hypothesis of Neri Oxman, “knowledge can no longer be ascribed to, or produced within disciplinary boundaries, but is entirely entangled.” (Oxman, 2016) The cartography in Figure 2 visualized this interrelation between the multiple domains. The explorative nature of this research is inspired by this holistic perspective.

Literature research is conducted to explore the scope of the research. Literature on applications of 3D knitting is studied to find possible examples of how knit is used in the beforementioned domains, possibly as transformable, load-bearing structures. Second, methods of controlling the behaviour and form of a knitted textile are explored. Thereafter, transformable structures are studied on different scales, from furniture design to architecture.

This chapter is concluded with a defined knowledge gap.

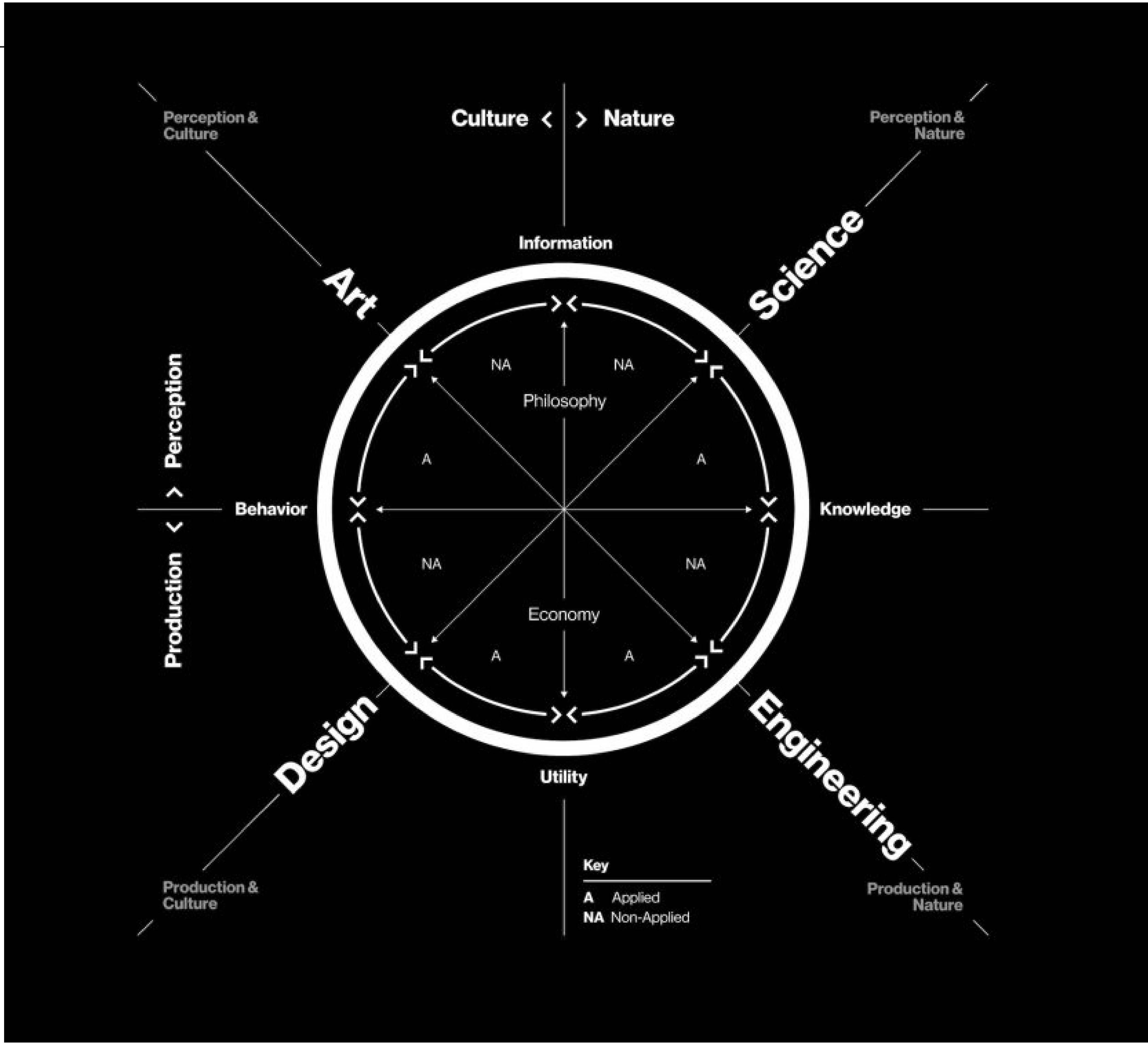


Figure 2. Interrelation between multiple domains (Oxman, 2016)

0.2.1 Applications of 3D knitting

As the largest part of the produced textiles is used for apparel, this is considered a large source of inspiration for this project. Three examples of this are elaborated on whereafter the application of 3D knitting for furniture design is introduced. Applications in the domain of architecture and robotics are explained in the following chapter.

Textile is the main material to produce apparel. Since more knowledge is gained on the environmental impact of fashion industry, more companies are developing more sustainable products, by for example reducing waste material, using sustainable, biodegradable and recyclable materials, or changing the business model to on-demand production.
This research proposes 3D knitting as a material saving and adaptable production method. Companies base their business model around these characteristics. Two examples of such companies are presented below.

Adaptability as business model

BYBORRE is a Dutch textile innovation enterprise that specializes in the design and development of knitted fabrics with a particular focus on round knitting. (BYBORRE, n.d.) Founded in 2010 by designer Borre Akkersdijk, the company has established a reputation for its thorough understanding of the production process, which is shown by its ability to track and trace all stages of the yarn and fabric production. As a company that primarily specializes in the production of knitted fabric on the roll (Figure 3), BYBORRE has developed a software program called CREATE that empowers designers to design their own fabrics by selecting the yarn and the print. This is in line with their focus on creating innovative and customized fabrics for various applications.
BYBORRE gives insight in the complexity of the production chain of 3D knitted textiles and attempts to brigde the gap between designer and manufactureres by offering a software. The result is a high level of control for the designer over the produced fabric, of which the desirability is questionnable for the amount of parameters is enormous.
The company chose round knitting as production method for their fabrics for the speed of production, which reduces the production costs. The production is on-demand, allowing for small batches to be purchased to prevent waste of textile. The possible knit structures and textures are however limited compared to flat bed knitting, starting with the fact that direct is only possible to a certain extent.

Similar to BYBORRE gives the company Unmade their clients more control over the product they buy. The customer can alter the graphic pattern on the garment and give their size, after which the garment is produced, showing the adaptability of knitwear production process. (Unmade, n.d.) The garment is produced after ordering as attempt to limit overproduction of both textile and garments. Unmade uses flat bed knitting machine, knitting the sweaters in shape whereafter the parts are linked together. Unmade is able to do so because they only adapt the structure, or motif, within an existing design. They limit the amount of parameters that can be adjusted by the customer.

KNITWEAR LAB is a company where all parameters are considered. KNITWEAR LAB is a Dutch company based in Almere that specializes in small knitwear productions on flatbed industrial knitting machines. (KNITWEAR LAB, 2022) They develop the knitwear together with a designer during which the sampling takes place at the LAB itself. If a production of multiple pieces is requested, than this takes place in Istanbul at their production facility. The customer is in direct contact with the knit engineers who program the desired knit shape and structures, but does not have direct contact with any software themselves. KNITWEAR LAB does not directly advertise with the sustainability of their production technique.
The software of STOLL, the industrial knitting machine used at the LAB, is not able to render the exact outcome of the programmed knit, so trial-and-errorb is needed to come to a desired result.

These three companies show different levels of adaptability of knitting, from adjusting all parameters, to limiting it to adapting the motif and colour. In all three, software is used either directed towards the client or the knitengineer, to adjust those parameters and give insight in the consequences of the adjustments to the knit. These examples exhibit the possible production processes and business approaches that 3D knitting allows for.

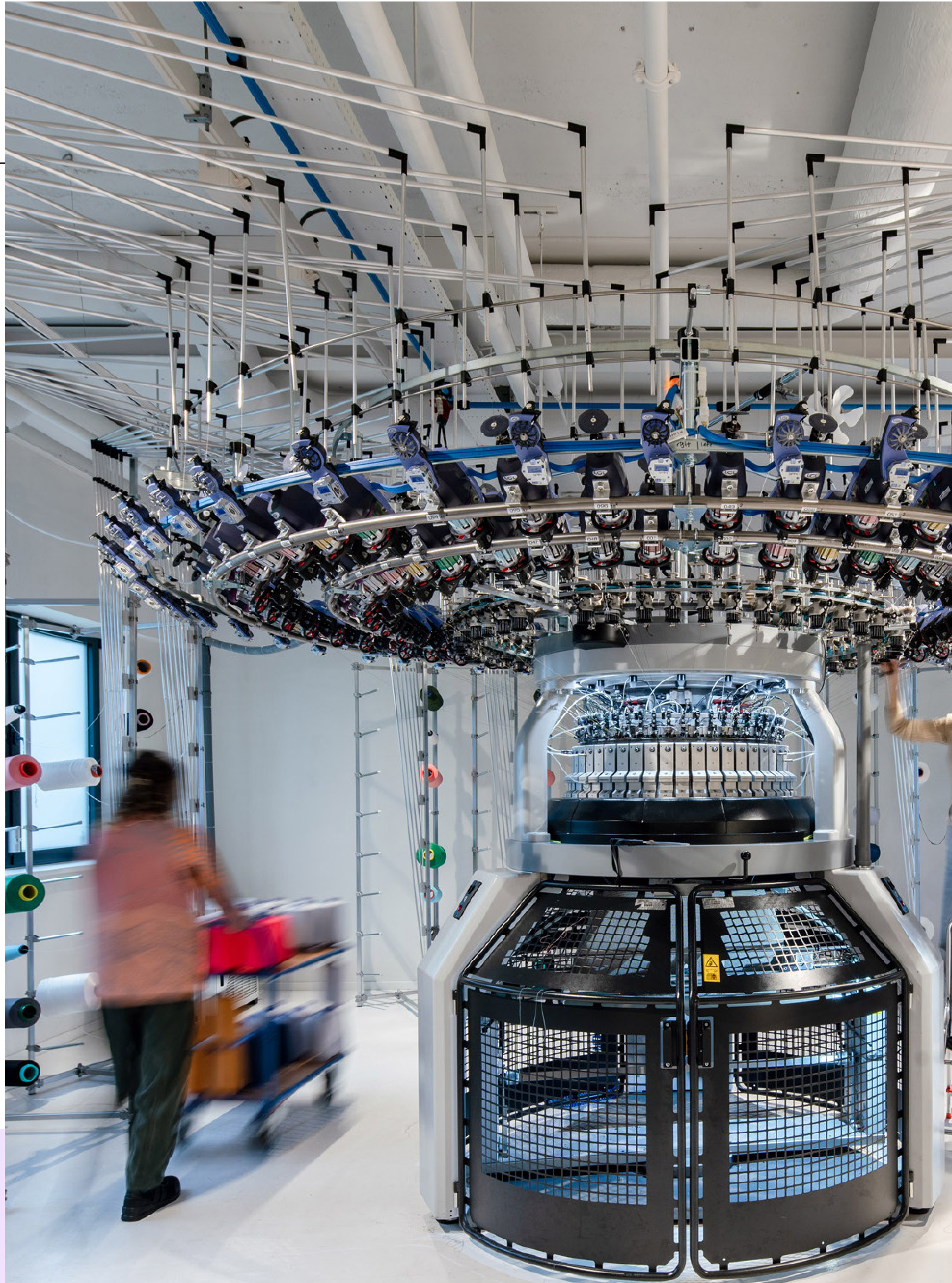


Figure 3. Round knitting machine at BYBORRE (Frearson, 2022)

Furniture

There are examples of 3D knitted upholstry fabrics for furniture, mostly sitting objects.
Studio MLR designs 3D knitted upholstry fabric, in which the cushions are inserted after knitting. A frame is attached afterwards. It is presented as the a zero waste production process because there is no cutting waste after knitting. The sofa is modular because "so is the fabric; you can knit a piece as long as you need with no junktions". (Knitted Upholstery - MLR, 2023)
The knit is still used only as upholstry, not as a structural element of the sofa, see Figure 4.
The 3D knitted upholstry of Studio Skrabanja demonstrates the possibilities of texture in knitting for furniture. (3D Knitted Furniture, n.d.) The knit is produced on a circular knitting machine, not using any direct form making. The knit is not a structural element, nor is the furniture transformable, see Figure 5.
Camira Fabrics 3D knits upholstry fabrics using heat shrinking yarn into a larger dimension than the frame to which it will be attached, after which it is shrunk to the right dimenions, tensed around the framework. (Camira, n.d.) The transformability of the knit through the yarn material and stitch structure is demonstrated, however not using this transformability during other stages of the product life cycle.
Kobleder 3D knits the upholstry whereafter it is tensioned around a frame again. (Kobleder, 2022) The stiff framework gives the knit its final form, there is no interdependence of formmaking visible, see Figure 6.

The Shift Chair is a type of folding chair by which the back rest is 3D knitted, designed by Jonas Forsman for Studio Mooi, see Figure 7. (Forsman, n.d.). The transformabilty, the folding of the chair, is described as existing through the knitted upholstry. It is unclear from visual inspection whether the knit is part of the structure of the chair, or only used as upholstry.
Bejamin Hubert designed both Cradle Furniture and the Tent Chair. (Tent, n.d.) Both are a 3D knitted fabric tensioned over a steel frame, see Figure 8 and 9. The Tent Chair upholstry is knitted in one go, attached to a frame through tunnels and holes. A cord is used to tension a part that suggests an armrest. The shape of the upholstry suggests that the knit is shaping the frame, however knowing the frame is made of steel this is not the case. The seperately presented knitted fabrics suggests the user will transform the knit by inserting the framework, however not explicitely mentioned.

All examples of 3D knitting for furniture design are either a 3D knitted structure tensioned over a rigid frame, or a 3D knitted pocket filled with cushions. Nowhere is the knit part of the structure that creates the form, nowhere is there a codependence with the rigid material to create form.

2D knitting for upholstries is widely used, often knitted on round knitting machines on a roll after which the fabric is cut and sown together in the desired geometry.

Figure 4. 3D knitted upholstry fabric (Knitting Upholstery - MRL, 2023)

Figure 5. 3D knitted upholstry of Studio Skrabanja (3D Knitted Furniture, n.d.)

Figure 6. 3D knitted upholstry of Kobleder (Kobleder, 2022)

Figure 7. Shift Chair by Jonas Forsman for Studio Mooi (Forsman, n.d.)

Figure 8. Cradle Chair by Benjamin Hubert (Cradle, n.d.)

Figure 9. Tent Chair by Benjamin Hubert (Tent, n.d.)

0.2.2 Controlling behaviour and form of knitted textile

The behaviour and form of a knitted textile can be controlled from different levels: on micro scale through the yarn and knit structure, on meso scale by coating the knit, or on macro scale by shaping and tensioning the knit through a structural material.
The different methods are elaborated on in this chapter.

Yarn material and stitch structure

The yarn material and knit structure are the basis of what makes a knitted textile a knitted textile. The behaviour of the knit means the elasticity, dimensional stability and possible transformability in terms of elasticity and form.

Figure 10. Heat shrinking yarn (Active Textile Tailoring, n.d.)

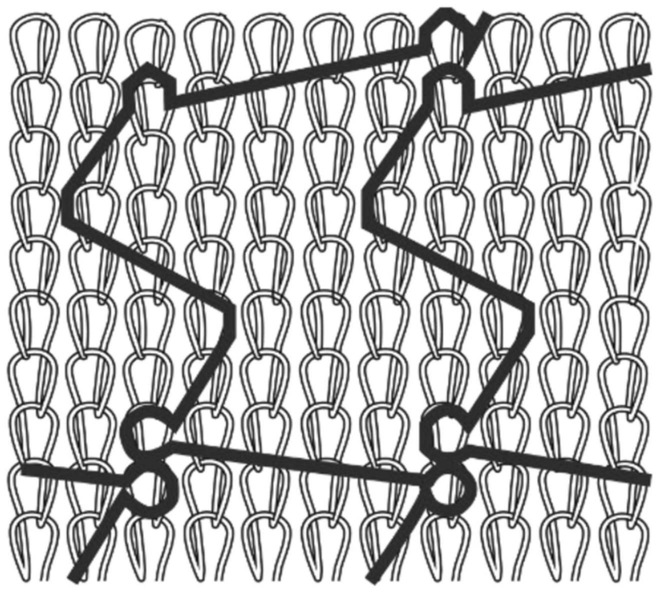


Figure 11. Auxetic inlay warp knit structure (Granberry et al., 2019)

Heat shrinking yarn

Yarns with shape morphing properties are used to transform the 3D shape of a garment or product. Using heat shrinking yarn in knitted structure allows for adjustment of the shape of a garment to the body size of the user. (Active Textile Tailoring, n.d.) Heat shrinking yarn can be combined with a non-shrinking yarn to create textures after applying heat, see Figure 10.

Shape Memory Alloy

Shape Memory Alloys (SMA) are alloys that can be deformed when cold but will return to a pre-deformed shape when heated. This 'memory' can be used to give knitted textiles for example auxetic behavior, or be used as an actuator. (Eschen et al., 2020) When a knitted fabric is stretched in the X or Y direction, the fabric will elongate first because of the structure of the knit (the loops are elongated in the direction of the force) and then because of the properties of the material (when elastic is used, this will result in more stretch in the direction of the force). The sides of the fabric in the direction of the force will curl inwards, reducing the width. (Minapoor et al., 2013) Warp- and weft-knitted plain structures have a positive Poisson's ratio.
Auxestic behavior appears in structures with a negative Poisson's ratio: when stretched, the material becomes thicker perpendicular to the force applied. This behavior is expressed by auxestic materials integrated in non-auxetic structures, or by non-auxetic material configured into auxetic structures. (Granberry et al., 2019) Shape-memory alloys (SMA) can be integrated as warp-inlay to create this behavior in knitted structures, see Figure 11.

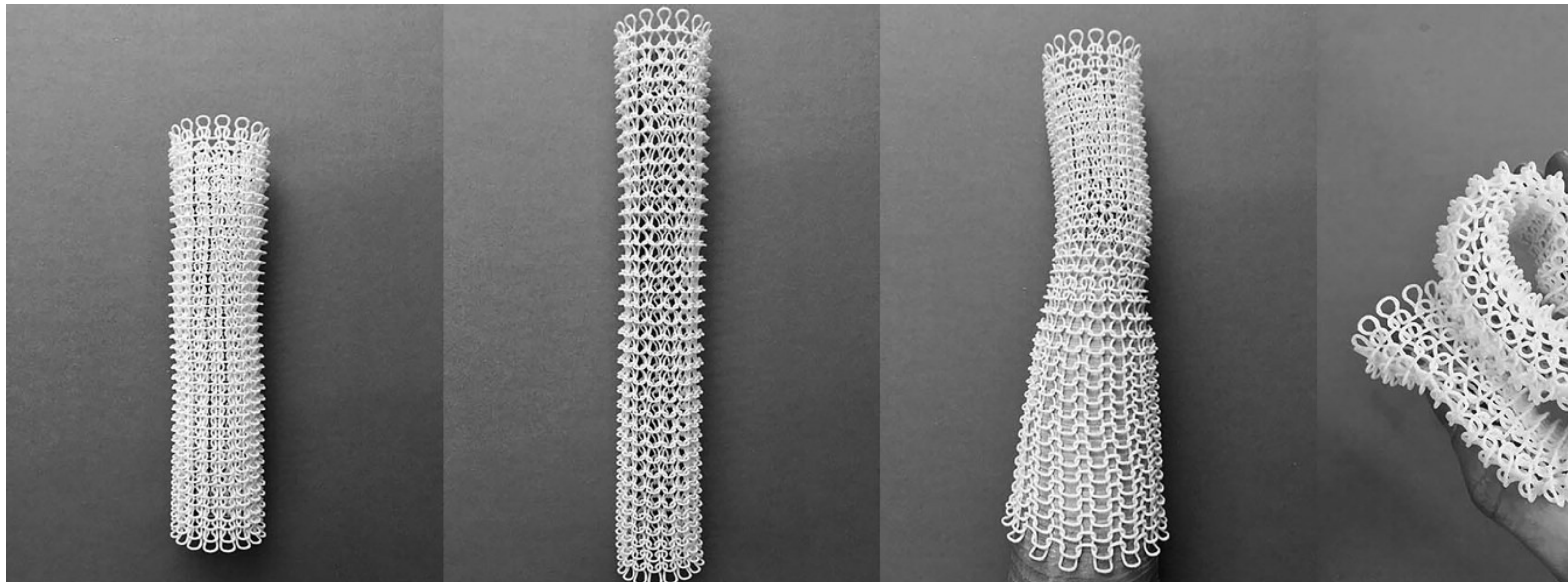


Figure 12. 3D printed knitted structure (Beecroft et al., 2019)

3D printing of textiles

3D printing is a rapid, efficient, adaptive production method based on a computer-aided design (CAD). It can produce complex 3D geometries in a short time and at low cost compared to traditional manufacturing processes. It is applied in a wide range of domains, including electronics, biomedicine, architecture and aerospace. (He et al., 2020) It is used to mimic textiles by fully printing flat surfaces, or to alter the behaviour or aesthetic of a textile by printing on top of a textile surface. The first are presented here, the latter in a separate section.

Printing flexible structural units is explored by Beecroft et al. (2019) amonst others, see Figure 12. A flexible, tubular textile-based structure is printing using selective laser sintering (SLS), which exhibited traditional knitted structure properties and mechnical properties of the printed material.
Similar to the above, Wang et al. (2021) SLS printed a structural fabric that, when pressure is exerted on the boundaries, results in the interlocking of the modules and thus an increased bending resistance.

3D printing a textile, or surface with similar application and function to a textile, are stiff compared to traditional textiles. Therefore printing fiber, printing flexible structural units or printing on top of textiles are proposed as methods to maintain the inherent flexibility of textile. Printing on top of textile is considered a form of coating, see section 'coating' for examples.

The presented methods of controlling the behaviour and form of a knitted textile on a micro scale demonstrate foremostly the behavioural impact of the (yarn) material. Most research focusses on this one variable consistent over the whole textile. The methods could be applied in segments of a textile to locally control the behaviour.

Surface treatment

A textile surface can be altered by applying another rigid or flexible material that will adhere to the surface and therefore alter the behaviour of the textile. Examples of these are 3D printing, coating with resin, and coating with concrete. Both allows for local manipulating of the textile behaviour.

Figure 13. Knotted Chair by Marcel Wanders (Knotted Chair, n.d.)

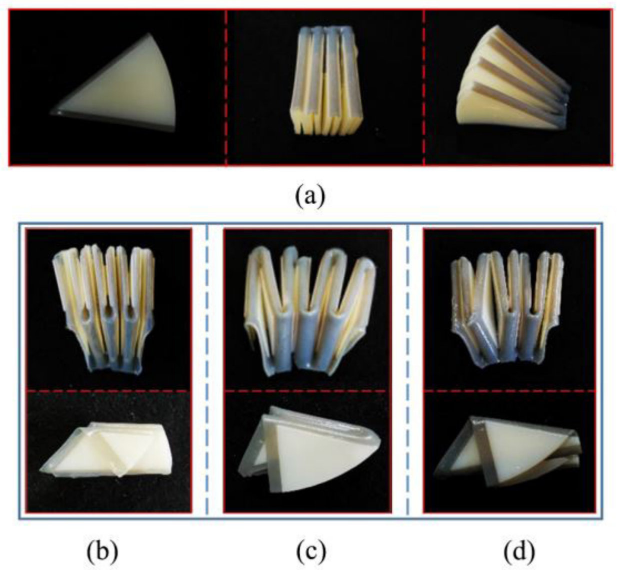


Figure 14. 4D printed self-deploying circular structure inspired by origami. (S. Liu et al., 2020b)

Coating with resin

Coating, a chemcial substance applied to a textile surface, can be applied for different purposes. Coating is a common post production step to make a textile hydrophobic for example. This maintains the flexible nature of the textile. Another example of coating is epoxy which makes a textile fully rigid, as demonstrated by Marcel Wanders' "Knotted Chair", see Figure 13. (Knotted Chair, n.d.) The range of possible chemical substances and applications is wide.

3D printing on textile

A textile surface can be decorated with 3D printing on top of it, without the need for adhesives. Iris van Herpen, a Dutch Haute Couture designer located in Amsterdam, started using 3D printing in her collections in 2010. Since then many designers have explored the possibilities and limitations of either combining additive manufacturing with regular textiles, or just using 3D printing to create a fashion object. (VanderPloeg et al., 2017)
3D printing on top of a textile to add a fourth dimension to it: time. The 3D printed PLA for example can transform shape when for example pressure or heat is applied, using Shape Memory Polymers (SMP). Figure 14 presents a 4D printed self-deploying circular structure inspired by origami. (S. Liu et al., 2020b) Both flexible and rigid materials, TPU and PLA or ABS resp., are tested. (Tolmaç & İşmal, 2023) The textile is transformable on a meso scale.
3D printing leads to control of the behaviour and transformability of the knitted textile, but no example is exhibited of a load-bearing construction.

Figure 15. KnitCandela (Popescu, 2018)

Coating with concrete

An examples of fully rigidified textile throguh surface treatment on architectural scale is the research of Popescu et al.(2018) Mariana Popescu developed a method for the use of 3D weft knitting for doubly-curved concrete shells, to eliminate the need for a falsework, see Figure 15.
These doubly-curved surface require patterning of the textile, which is possibly with weft knitting without waste through offcuts. To construct the formwork the knitted textiles is tensioned into shape using hybrid methods: bending-active elements, inflatable segments and a cable net. Coating the textile with a cement paste stiffens the textile for using it as a mould directly.
The inflatable balloons are inserted into pockets controlling the final size, through the loop size and density.

To create the designed 3D geometry, Popescu et al. developed an algorithm in which the loop geometry of the desired knitted textured is used as input to computes the input for the knit software connected to the industrial knitting machine. Consequently, the accuracy of the final knitted geometry is highly dependent on the accuracy of the input. As indicatedby Popescu et al. (2018), creating various patterns to control the density or other desired parameters is not possible yet. The machining instructions are still a manual process, after the code is transfered to the knitting machine.

The presented methods exhibit the range of flexibility and rigidity that can be achieved by applying various materials. The method of applying greatly impacts the production process of a product. All examples apply the surface treatment over the whole surface of the textile. Examples of partial application are found in the fashion industry but only for decorative purposes. Partial rigidifying through surface treatment of a knitted textile for load-bearing and transformable purposes is not found.

Structural material

To create a load-bearing structure with a knitted textile, different structural materials can be added to form various degrees of load-bearing capacities. Examples of different structural materials and form-making methods are presented.

Figure 16. Knitted robot hand (MIT, 2022)

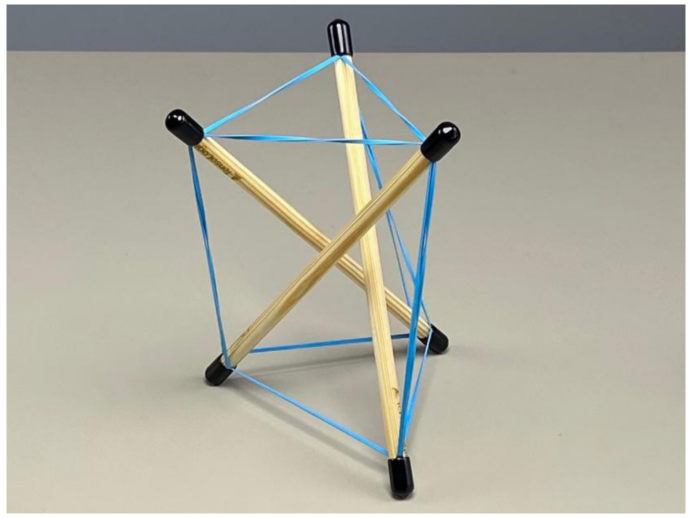


Figure 17. Prismatic tensegrity structure (Tensologic, 2020)

Figure 18. Isoropia: bending-active structure using knit (Isoropia, 2023)

Inflatable

According to Yiyue Luo, a PhD student at MIT CSAIL and the lead author of a recent research paper, digital machine knitting is a widely used manufacturing method in the textile industry today. It allows for "printing" a design in a single process, making it highly scalable.(MIT, 2022) When the knit is tensioned by the inflatable element inside of it, the stitch configuration determines the geometry of the inflatable element, see Figure 16. Conventional robots are composed of rigid elements and structures, resulting in high rigidity, precision and fast speed, but poorer result in flexibility and adaptability. (Liu et al., 2022) Soft robots, such as presented by MIT, have a great flexibility and adaptability, but the load capacity is then again limited. This demonstrates the need for a balance between rigid and soft elements. A promising solution is to combine the two.

Tensegrity

Tensegrity, tensional integrity or floating compression is a structural system which comprises of parts which are in compression or tension, often strings in tension and bars in compression. The compression elements do not touch each other and are held in place by the prestressed tensioned elements, see Figure 17. This result in a light weight, deployable yet strong structure used in both civil and architectural engineering mainly in dome structures, towers, roofs of stadiums or temporary structures such as tents. (K, 2021) Research is conducted in how tensity can be used in robotics, where it combines the advantages of both rigid and soft structures. (Liu et al., 2022)

Characteristics of an tensegrity structure are the following:
- high flexibility: the shape of the structure can be altered by changing the length of any compression or tension member
- high compliance: high degrees of freedom so easily folded
- adjustable stiffness: the tensional and compressive elements can be adjusted to alter the stiffness
- large strength-to-mass ratio: the lightweight and flexible tensional elements wil retain the load capacity of the rigid compression elements
- high redundancy: any element can adapted to adjusted to deorm the structure
- self-balancing: the geometry is balanced through the structure of the internal forces.
- force distribution: external loads are distributed to the entire network, where in more traditional mechanical structures the stresses would be concentrated on the joints. (Liu et al., 2022)

Bending-active structures

"Bending-active" is a form defining strategy through elastic deformation. It describes curved beam and surface structures resulting in a geometry based on the initially straight or planar elements that deform elastically. (Knippers, 2015) The load-bearing capacity of these structures is largely dependent on the topology and geometry of which a wide variety is possible.
Plants are a source of inspiration for their movements that demonstrate high elasticity and flexibility of their structures. (Poppinga et al., 2010) (Lienhard, 2011) These movements can be classified as autonomous or non-autonomous movements. Autonomous meaning that the movement is caused by internal factors, where non-autonomous movements are actuated by external factors, based on reversible deformation, such as the application of force. The use of bending principles in main structural components allows for the creation of different shapes that can be stabilized through pre-stressing. Fabrication of these structures can be limited to the flat components because bending is introduced during assembly of the structure. This simplifies production and transportation.

Knitted textile is used to create bending-active structure, see the example given in Figure 18, which is elaborated on in the next section.

Figure 19. Textile hybrid (Ahlquist, 2015)

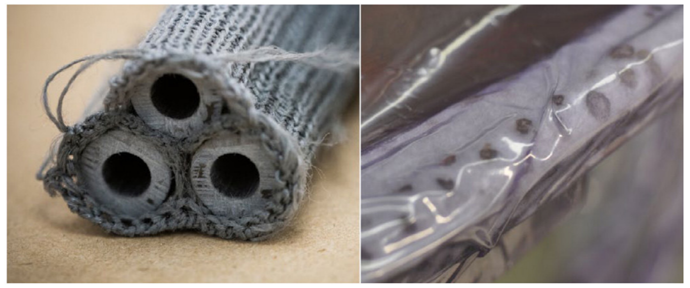


Figure 20. Glass fiber reinforced polymer rods (Alquist, 2016)

Figure 21. Textile hybrid (Ahlquist, 2016)

Textile Hybrids

Heino Engel provides a definition of a hybrid structural system as a system that integrates multiple types of structural action to achieve stability. (Engel, 2007) The structural types together has improved properties compared to each seperate element, a synergetic effect. (Fangueiro & Soutinho, 2011)
In the context of textile hybrid systems, form is achieved through a balance between tensile (form-active) surfaces and arrangements of elastically bent (bending-active) elements, based on textile material behaviour, see Figure 19. (Ahlquist, 2015) (Lienhard, 2015) Examples of textile hybrid systems are the Hybrid Tower, the prototypes of responsive environments of Ahlquist, and the Isoropia. All are examples on architectural scale.

The ideal materials for such systems are those that combine high strength with low bending stiffness. Bending these rods into shape utilizes the material's ability to deform elastically. Textile hybrids require a balance to withstand external impact and to deform elastically to create a deployable structure. This balance requires stiffness and rigidity, and flexibility and softness. (Thomsen et al., 2015)

For both constructions of Ahlquists work shown in Figure 19 and 21, and for the Hybrid Tower (Figure 22), glass fiber reinforced polymer (GFRP) rods are used, bundeling three seperate rods using a knitted structure to increase stiffness, see Figure 20. (Lienhard et al., 2014)

The presented works have been designed using computational design modelling as most textile hybrids are. (Suzuki & Knippers, 2017) The workflow for the design of the Hybrid tower is the following: first the variables are defined, the design, the constant and flexible geometric parameters and material properties. A Generative model thereafter produces the possible geometries based on the set parameters. Finally the Analytical Model provides data on the performance, and the Design Instance translates the data to the elements that need to be produced to actually make the tower. The study Thomson et al. (2015) recognizes the difficulty to design a hybrid interaction of a bending active system and a knitted structure functioning as a membrane. Bi-axial testing and physical experimentation through prototyping is conducted to establish the characteristics of the knit to adjust the design.

Figure 22. Hybrid Tower by CITA (Thomsen et al., 2015)

All describe the balance between the rigid and flexible materials that are essential to the behaviour and characteristics of the structures. The computational workflow as described in the section 'textile hybrids' shows the fine balance between the materials. The textile element tension a rigid of flexible structural element, either an inflatable segment, beam or plate. The attachement of the structural material is transforming the textile from a mostly flat to a 3D form. The materials can be considered form-making methods. The load-bearing capacities of the presented examples are not quantified.

0.2.3 Transformable structures

Transformable structures are designed not in end state but in a transition state. (De Temmerman et al., 2012) Transformable structures allow for adaption to changing environments and user preferences by altering the shape and/or function. In that sense, a fourth dimension to the 3D structure is taken into account during the design process: time. Transformable structures are relocatable, reusable, demountable, removable, reconfigurable. These transformation can take place during any stage of the product's life cycle: during production, use, after use, after a decade.

Transformability can take place on the levels described in the previous chapter.
Different forms of transformability are described here, starting with architectural structures, followed by textile hybrid structure and furniture.

Figure 24. Classic camping folding furniture using hinges

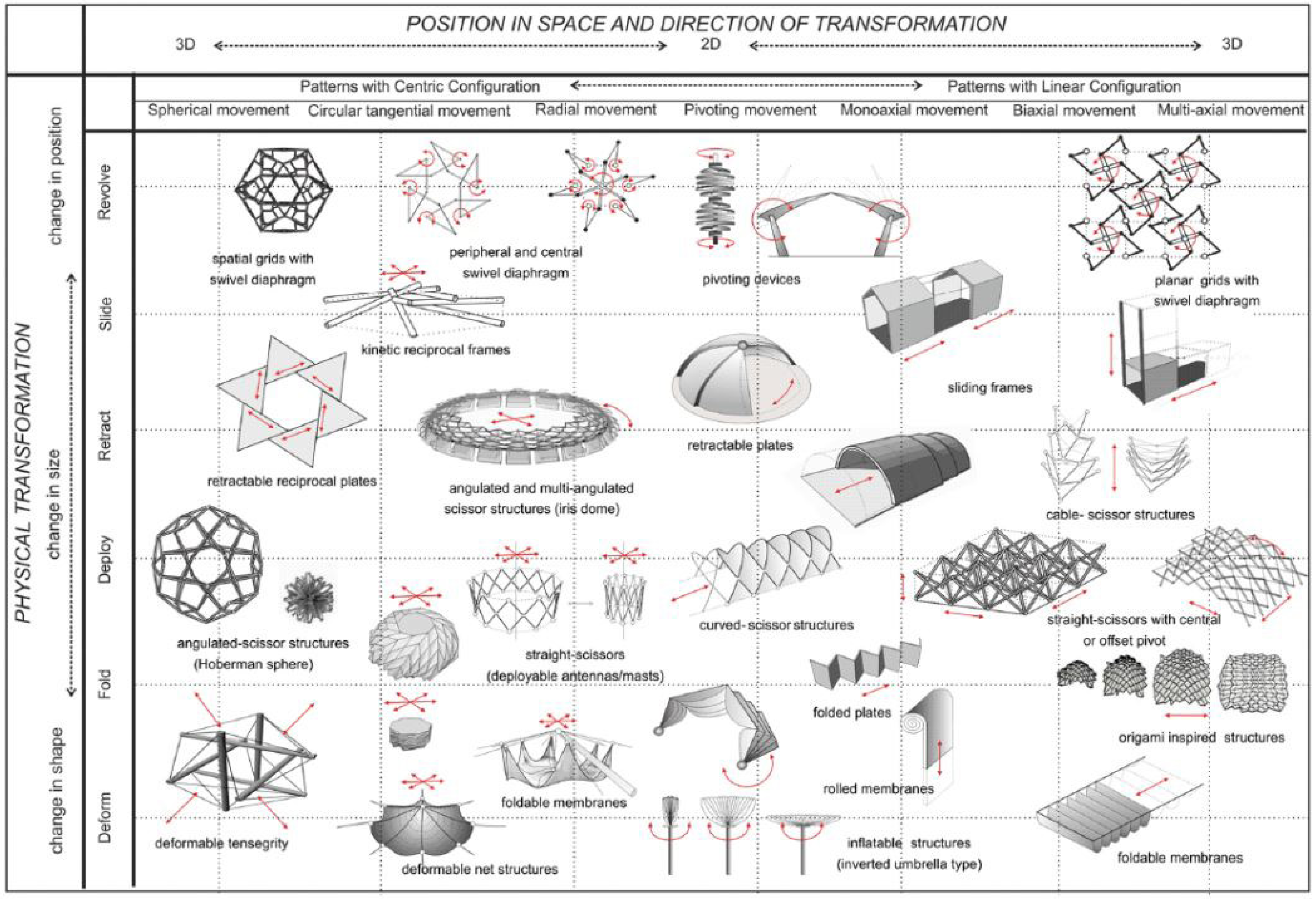


Figure 23. Classification of deployable structures (Stevenson et al., n.d.)

Architectural structures

Transformation in architectural and structural engineering are distinguished in two groups: (1) incorportaing a kinematic mechanism, meaning a deployable structure that can transform from compact to expended configuration, or (2) designing the structure as a 'tool kit' with parts of the system with reversible connections between components, enabling disassembly and reconfiguration, as well as replacement or re-use of parts. This kit-of-parts system allows for re-assembly in different geometries, where deployable structures do not necessarily allow for this. Deployement however allows for transformation in a minimal amount of time without the need to dissassembly and re-assembly.

Deployable structures are classified by Stevenson et al. (n.d.), see Figure 23.

Key principles of tranformability are reducing the complexity of the connections and structural system for easy and rapid assembly. Not only is this beneficial in terms of assembly and adaptability, it also allows the user to assemble, maintain, reconfigurate and deconstruct the product or structure. (Brancart et al., 2017) The desirability, costs and material usage should be kept in mind as equally important requirements to consider during the design of a transformative, deployable structure.

Textile hybrid structures

The bending-active structure in a textile hybrid can be used to create a deployable mechanism in which the textile locks the deployement. This avoids the need for complex joints and thus possibly reducing weight and assembly time. According to Brancart et al. (2016), the deployable structure within the textile hybrid system should not be fully self-equilibrated in the final deployed state to allow for this membrane restrained bending. As mentioned before, the final deployed state is the result of an equilibrium of forces which is defined by the bending-active geometry and the textile geometry and behavioral characteristics.

A self-restraining systems is an efficient method to employ stress-stiffening effects, through shortcutting the bending forces internally by coupling bending elements or adding cables, membranes or rigid elements.

However, to avoid permanent deformation of the bending-active structure, the internal stress needs to be limited, otherwise the bent material will fail.

Furniture

Transformable furniture has great advantages due to its ease of transport.
Conventional designs are mostly based on linking mechanisms using deployable structures with joints and hinges, see Figure 24. Deployability can also be based on the buckling of curved material by Mhatre et al. (2021)
The largest application of tranformable furniture is in camping and outdoor furniture, see Figure 24 for an example. A light weight aluminum frame connected with crews to create joints is combined with a woven fabric upholstry for comfort. The arm rests do seem to keep the structure in upright position, so the fabric is part of the structure and thus codependent with the frame for the final geometry.

Transformability can be incorporated in a design in different stage of the product life cycle. Deployement described for architectural purposes takes place through the structure, where textile hybrid transformation occurs through both the textile and a bending-active structure. Furniture is foremostly transformable through joints.

0.2.4 Results

The results of the literature study are summarized.

Current applications of 3D knitting show the adaptivity of the textile production method and the opportunities for sustainable business models. The application of 3D knitting for furniture is mostly for the sitting surface of a sitting object, not making the knit a crucial part of the construction or a necessary element for the transformable nature of the object.

To control the behaviour of a knitted textile, parameters on different levels can be adjusted: yarn material and stitch structure on a micro level, surface treatments on a meso level, and shaping of the knit combined with another 3D-shaped deployable and/or rigid element to tension the knitted structure on a macro level. Examples are presented in the form of heat-shrinking yarn, SMA, inflatables, tensioning frames and cables, and coatings.
The research demonstrates the possible applications, however, the load-bearing capacities of the developed materials are not quantified. Most methods are applied over the whole textile, no examples are found of partial applications, nor combinations of different methods.
The presented textile hybrid structures demonstrate the potential of 3D knitting as a load-bearing, transformable structure. The development process through computational modelling shows the starting point of the design is a known knit structure, yarn material and structural material of which the technical characteristics are quantified.

Transformable structures can be categorised in two categories: deployable and kit-to-part structures. Both are of transformative nature and are of interest for further exploration within this study, for the methods can take place at various stages of the product life cycle.
The potential of kit-to-part is in the fact that the knitted structure can be the connection between structural elements, creating a co-dependent relation between structure and knit that exhibits the transformative nature.
The transformability of deployable structures is co-dependent when the knitted textile and the rigid and/or flexible deployable structure termine each other's 3D geometry, which describes a textile hybrid structure. This co-dependent relationship is considered an element to explore further in this research.

0.2.5 Discussion

The potential of 3D knitting combined with a rigidifying method -meaning yarn material, surface treatment, or structural material- is demonstrated. However, no examples of combinations of various methods are found. The research led to no example of a 3D knitted sitting object from which the transformability and load-bearing capacity is derived from the fact that the structure is 3D knitted. To conclude, the knowledge gap is exposed in the use of 3D knitting for load-bearing, transformable structures on the scale of a sitting object.

0.3 Introduction

The aim of this project is to explore 3D knitting for load-bearing, transformable structures, by experimenting with various methods of rigidifying a knitted textile. The literature research showed a knowledge gap on the development of such structures, specifically on 3D knitted structures of which the load-bearing and transformable capacities are manifested through the properties of the knitted material. If this co-dependent relationship exists, one could describe the knit as a structural material. The explored methods in literature most often start with a known material, of which the characteristics and technical properties are defined in advance. That will not be the case during this study. The only starting point is the textile production method. The exact characteristics of the resulting material are still unknown.
This project will explore possible combinations of the presented materials and methods to develop our understanding of the benefits, limitations, and opportunities of using 3D knitting as a structural material.

0.4 Methodology

The research is structured according to a Material Driven Design (MDD) approach. The approach supports the design of novel material applications with the material itself as starting point. In this case, the 'material' is knitting. Knitting is a production technique with which a material, a knitted textile, can be made. In this research, it is considered a 'material' to allow for explorative research for the relatively novel application.

The MDD process is described by Karana et al. (2015) and is the guideline for the methodology of this study. The process will include the framing and reframing of the complex design problem to gain an understanding of the parameters that play a role. The development of prototypes plays a crucial role in the process. Each phase of the research entails playing with the material and reflecting upon the process of making and the resulting prototype. In this way, research is conducted through design. (Stappers, 2017)

The process is structured in four phases: analyse, define, develop, and evaluate, see Figure 25. First, the 'material' is analysed through tinkering with it. Multiple rigidifying methods will be explored, and the samples will be reflected upon in order to distill the parameters of 3D knitted, load-bearing, transformable structures. These parameters form the design space. In the second phase, 'define', the requirements for the demonstrator, the sitting object, are set up. Various concepts are explored to gain an understanding of the relationship between the parameters within the Design Space. In the third phase, this knowledge is used to develop a prototype of a 3D knitted, transformable sitting object. The process is tracked throughout the Design Space, and evaluated on the requirements in the fourth phase. This last stadium concludes the research with a discussion and recommendations on the future development of the method and object.

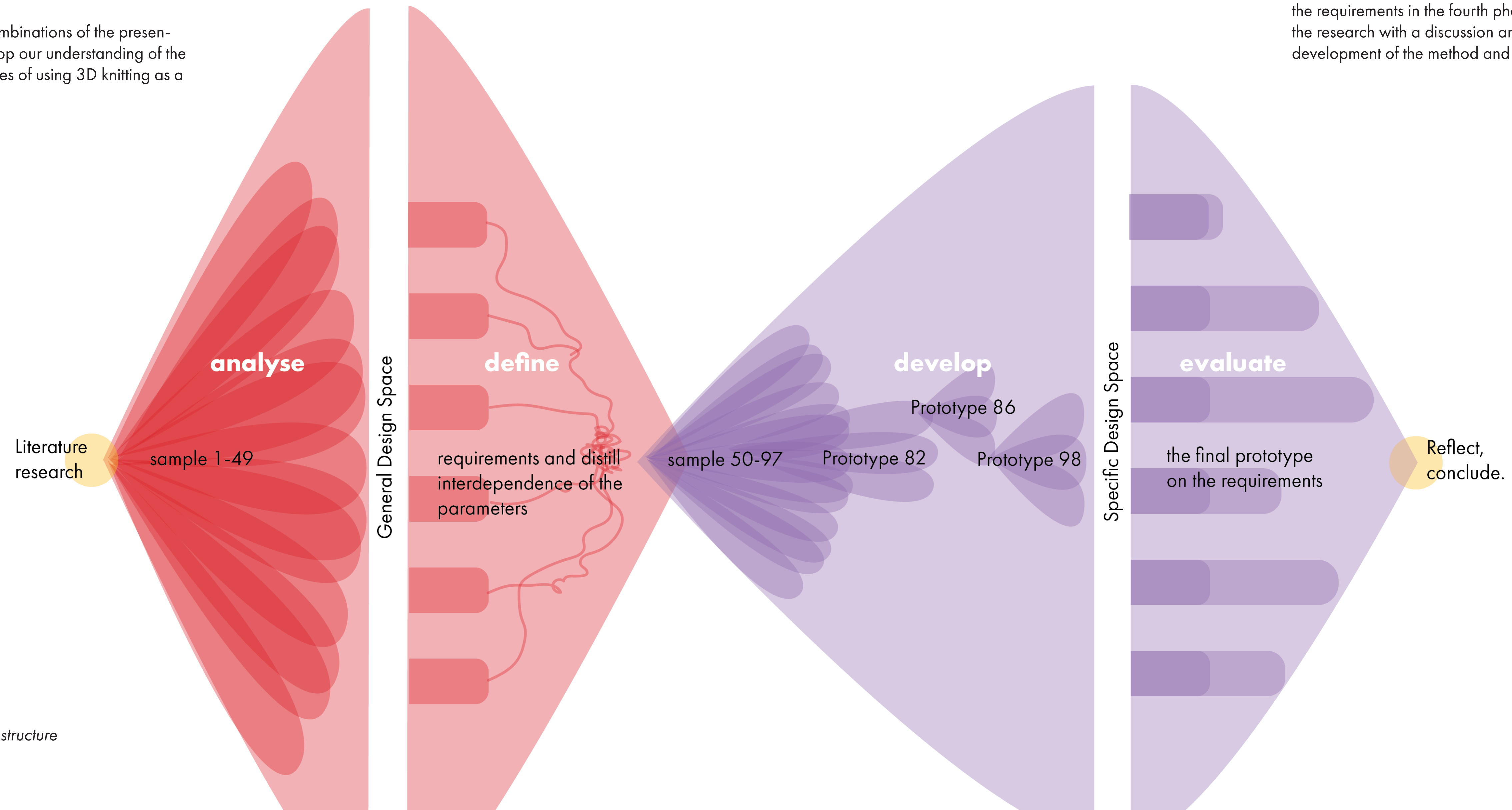
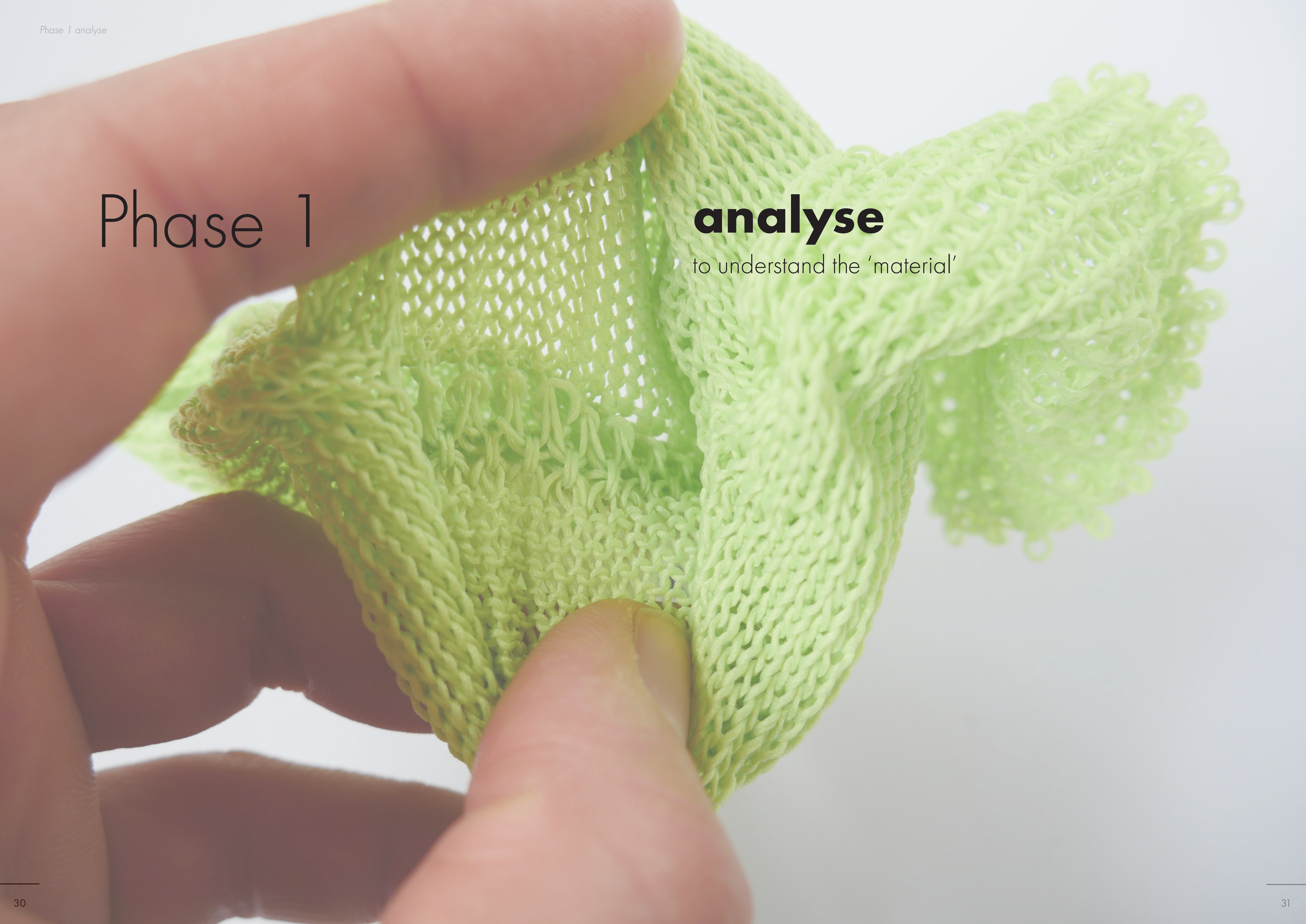


Figure 25. Research process structure



Phase 1

analyse

to understand the 'material'

1.1 Introduction

The ‘material’ and the different rigidifying methods are to be understood. The main properties, constraints and opportunities, possibilities for form and structure-making are explored through experimentation. To introduce the first phase, the known parameters are explained.

Known parameters
The behavior and mechanical performance of knitted textile is strongly affected by many parameters: the stitch length, needle thickness, gauge, yarn thickness, yarn material, tension, and stitch configuration. (Hasani et al., 2016) Adjusting the parameters results in different densities and levels of stretch in one or more directions of the knitted fabric.
Increasing the stitch length results in larger loops and thus more stretchability of the fabric. The gauge is the number of stitches per square inch, which is influenced by all the beforementioned parameters. The gauge of a knitting machine is the number of needles per inch. The domestic knitting machine used in this phase of the research has thicker needles and fewer needles per inch compared to the industrial knitting machine that will be used in a later phase.

There are four basic weft knit stitches: plain, purl, tuck and float. All stitch structures are derived from these four stitch tyeps. The structures differ widely in physical and mechanical properties and are therefore used for different applications. (Assefa & Govindan, 2020)

Plain means to knit a stitch of which the front of the stitch faces the front of the fabric. Purl means to knit a stitch of which the back side of the stitch faces the front of the fabric.

Tuck stitches appear thicker than knit stitches because the yarn accumulates on the tucking points, see Figure 26. The tuck stitch thus increases the areal density, thickness, and width of a fabric. The tuck loops reduce the fabric length and elasticity in length because the increased yarn tension on the tuck loop robs the adjacent loops from yarn, making the adjacent loops smaller. This results in greater stability and shape retention. (Spencer, 2001)

Float stitches, or miss stitches, are materialized when a stitch is not knitted, and a straight segment of yarn appears, see Figure 27. The wales are drawn closer together because of these floats, which reduces the width-wise elasticity, which again improves the stability of the fabric. (Assefa & Govindan, 2020)

Comparing the bursting strength of the tuck and float stitch demonstrated that fabrics containing a tuck loop have lower bursting strength than fabrics with float stitches. (Uyenik, 2017)

Knitting all stitches with plain knit stitches results in a so-called single jersey stitch structure. Alternating plain knit and purl stitches is called a rib structure.

1.2 Methodology

Experimenting in this project means an iterative process of making and reflecting. After creating a sample, the following four questions are asked:

Purpose: why is the sample made?
Process: how is the sample made?
Variables: what are the variables?
Takeaways: what are the learning points of this sample?
Next step: what is the next step?

The results of the first phase are processed by grouping the samples to distill the parameters of 3D knitting for transformable, load-bearing objects.

Tools
During the tinkering phase of this research, a domestic weft knitting machine is used, see Figure 28. The knitting machine allows for hand manipulation of the stitches. It is used both in the single bed and double bed configuration. Utilizing the double bed, double-layered structures and rib structures can be knitted.
The behaviour of knitted textiles is also explored through sample making with tricot fabric, which is warp-knitted fabric bought from a fabric store. The essential property is comparable to weft-knitted fabric: stretchable in X and Y directions.

The following pages show the produced samples accompanied by the written reflection. Additional information on all samples can be viewed in Appendix A.

Figure 28. Domestic knitting machine used in Phase 1

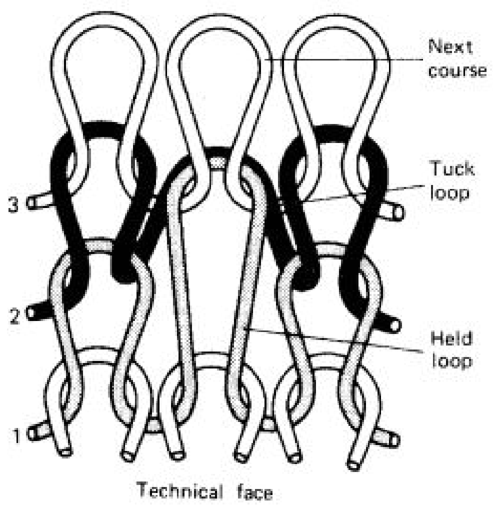


Figure 26. Tuck stitch (Spencer, 2001)

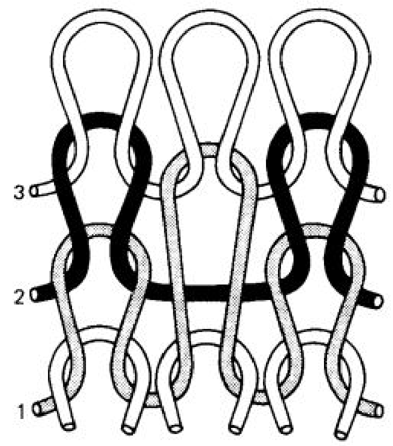


Figure 27. Float stitch (Spencer, 2001)

1.3 Samples

3

Purpose
As first thought on how to use hard plate material inside knitted pockets, where the knit functions as a hinge and is tensioned to keep the plates in place.

Process
Using the overlock machine to connect squared pieces of tricot fabric, see Figure 28. Using pins to enclose cardboard inside the pockets. The pockets and panels overlap approx. 2 centimeters.

Variables
- Relative size of pocket and plate material determine the pre-stretch of the knit and thus the tension when the configuration is altered
- Placement of the pockets and panels in a larger knit structure
- General knitting parameters: tension, yarn material, stitch type

Takeaways
The stretch of the fabric works well to keep the panels at a 90 degrees angle when placed as such. This works both ways, when left is over right or right over left.

Next step
Knitting a three-layer structure to create the overlapping pockets

Figure 28. Sample 3

7

Purpose
Inspired by the work of Victoria Salmon, looked like a hinge function or a directed fold line. (Salmon, n.d.)

Process
Knitting 2x2 rib structure on the domestic knitting machine for approx. 20 rows. Transfer all needles to the other bed, creating the opposite rib pattern, again knit 20 rows, repeat. (Figure 29)

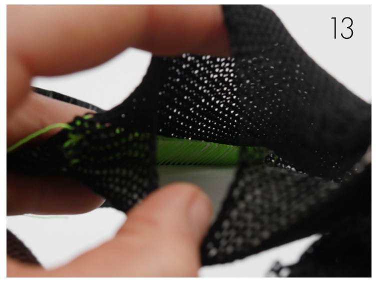
Variables
- Width of rib
- Using a stiffer yarn might make the angle stay in shape more
- General knitting parameters: tension, yarn material, gauge, etc.

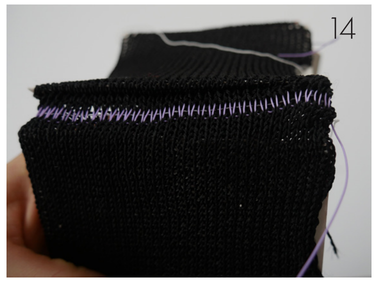
Takeaways
Where the rib is changed, a wider fold is created. When the knit is stretched out in the course direction, the ribs fold into each other, creating an angle in the fabric. It does not undo itself.
Potential hinge or guided fold line to assemble a product.
Still very flexible and soft, although the word 'hinge' suggests it is made of metal.

Next step
Creating this 'hinge' on a line that should be folded combined with pockets tensioned with plate material, to test if the fold then still stays in place despite the weight of the plates.

Research into these so-called self-folding structures is conducted by Amanatides et al. (2022)

Figure 29. Sample 7





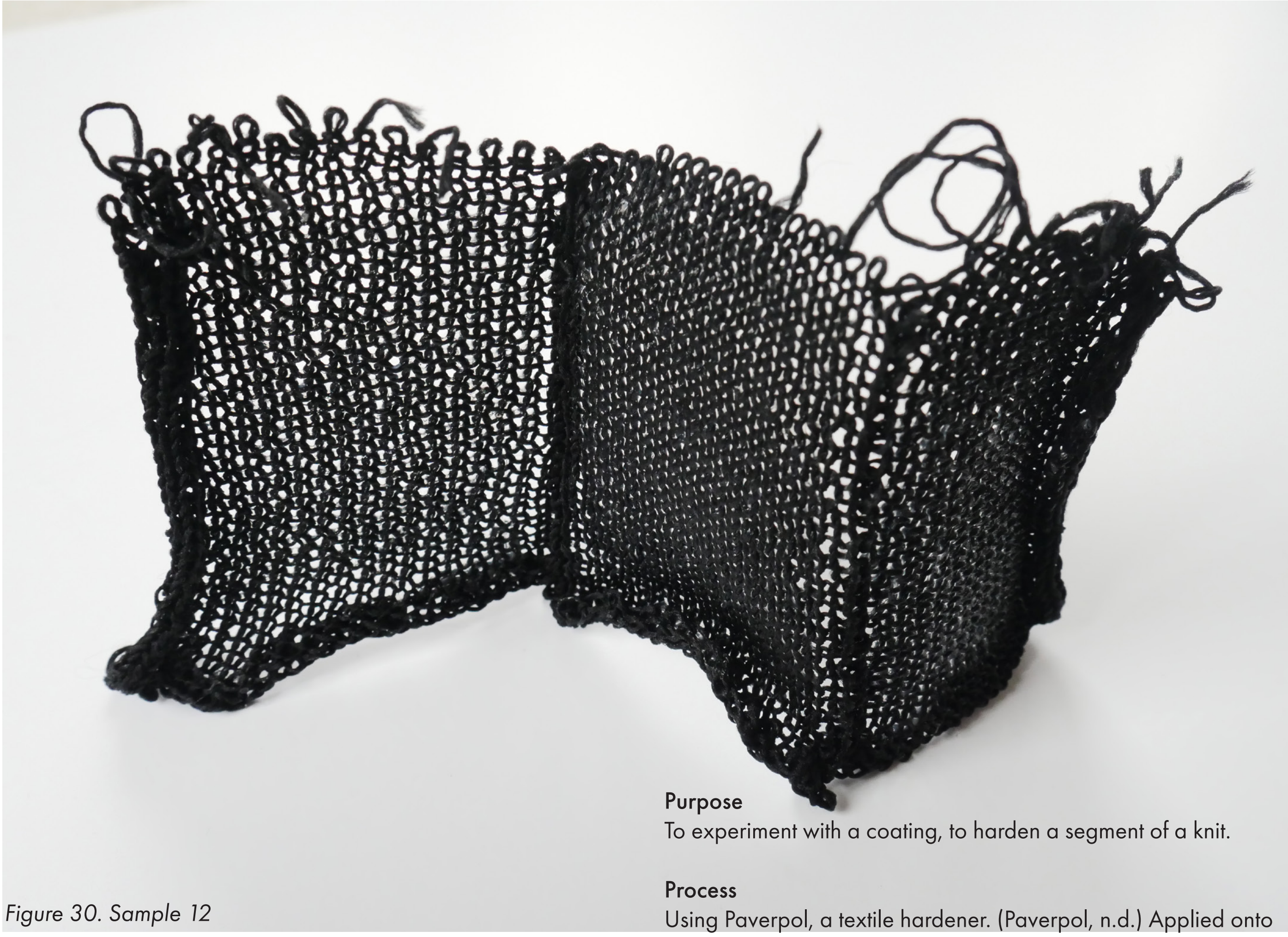


Figure 30. Sample 12

12

Purpose
To experiment with a coating, to harden a segment of a knit.

Process
Using Paverpol, a textile hardener. (Paverpol, n.d.) Applied onto the knitted sample (plain and a rib) and regular tricot fabric, see Figure 30. Multiple methods of applying are attempted: pour it over, dip it in, and brush it onto the surface.

Variables
- Size and shape of the coated part on a knitted part, only coating a strip or the whole area, or even a corner or tunnel shape.
- Amount of coating: using a thin layer leaves the material flexible.
- Type of coating: possibly dissolvable with heat or water, stronger coating that makes it even more stiff.
- Stitch structure: a porous knit structure becomes more rigid because the holes can be filled with coating.

Takeaways
The rib structure that was soaked into the Paverpol is very stiff, still flexible, and not brittle at all. It is stronger than the plain knit since the rib creates a thicker material that can absorb more hardener.

Next step
Apply it onto a 3D sample of a box to evaluate the stiffness on larger scale, to be knitted with the industrial machine which has a smaller gauge than the domestic knitting machine.

Figure 31. Sample 18

18

Purpose
To explore how form can be made with small pockets with filling

Process
Made of tricot fabric and lock machine, creating pockets that are filled with polyester filling material, see Figure 31.

Variables
- Size of the pocket relative to the amount of filling material
- Distance between the adjacent pockets

Takeaways
The pillows can hold each other, enabling different positions and different forms.
The sample shows how many sewing seams are required to make this type of pillow while knitting ottomans can create these pockets without needing any seams.

Next step
Knit it on the industrial knitting machine, try another filling material, and specify the distance between the pillows and the size, to make them 'grab each other' more strongly.

19

Purpose
To try to create a sitting object using the stretch of the fabric as tensioner and structural material.

Process
Made using tricot fabric and the overlock machine, and three cardboard panels cut out to a slightly bigger size than the pocket, see Figure 32.

Variables
- Stretch of the knitted structure: hold the panels in place and determines how much the panels can move when a force downwards is applied
- Size of the panels relative to each other and to pocket size
- Connection points of the fabric to each other

Takeaways
The downward force from 'sitting' on top, releases the tension on the sides, while more tension on the side is desired to stabilize the structure. Upside down works better: by sitting down, the cardboard is pushed outwards and the fabric is tensed.

Next step
Learn more about tensegrity, and make a sample with all panels enclosed in a pocket.

Figure 32. Sample 19

26

Purpose
To experiment with Origami structures, to create clear folding lines as an instruction to the user on how to assemble the sitting object.

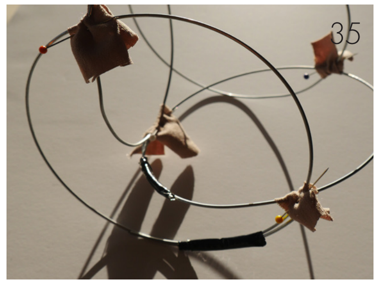
Process
Knitted on the industrial knitting machine at KNITWEAR LAB, programmed in M1Plus software. (STOLL, 2021)(KNITWEAR LAB, 2022) The 'panels' are Full Milano stitch structure, the downwards folds are single jersey on the back bed, the upwards folds are single jersey on the front bed. Combined a wool yarn and a melting yarn with unknown melting temperature, see Figure 33.

Variables
- Orientation and placement of the fold lines
- Formation of the fold lines: the number of single jersey stitches
- Stitch configuration of the 'panels'

Takeaways
The melting point of the melting yarn is too high to reach with the iron at the KNITWEAR LAB, but steaming and pressing it on the indicated fold lines resulted in an origami structure.

Next steps
Using the stitches and fold lines to fold a sitting object. Possibly another melting yarn that melts at the heat of an iron.

Figure 33. Sample 26



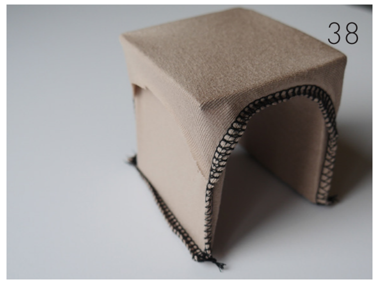


Figure 34. Sample 32

32

Purpose
Practice knitting pockets and different methods of programming them

Process
Programmed in M1Plus software, knitted in KNITWEAR LAB. (STOLL, 2021)(KNITWEAR LAB, 2022) Learned from a similar sample to program the pockets.

Variables
- Width of the pocket
- Stitch structure of the pocket, knitted on one bed

Takeaways
The single jersey around it is very thin and stretchable, see Figure 34. The pockets are so small that almost all of it curls up since single jersey will always curl.

Next step
Possibly creating a larger pocket but with a small opening, not over the full width, and an opening with an elastic yarn so it is tighter

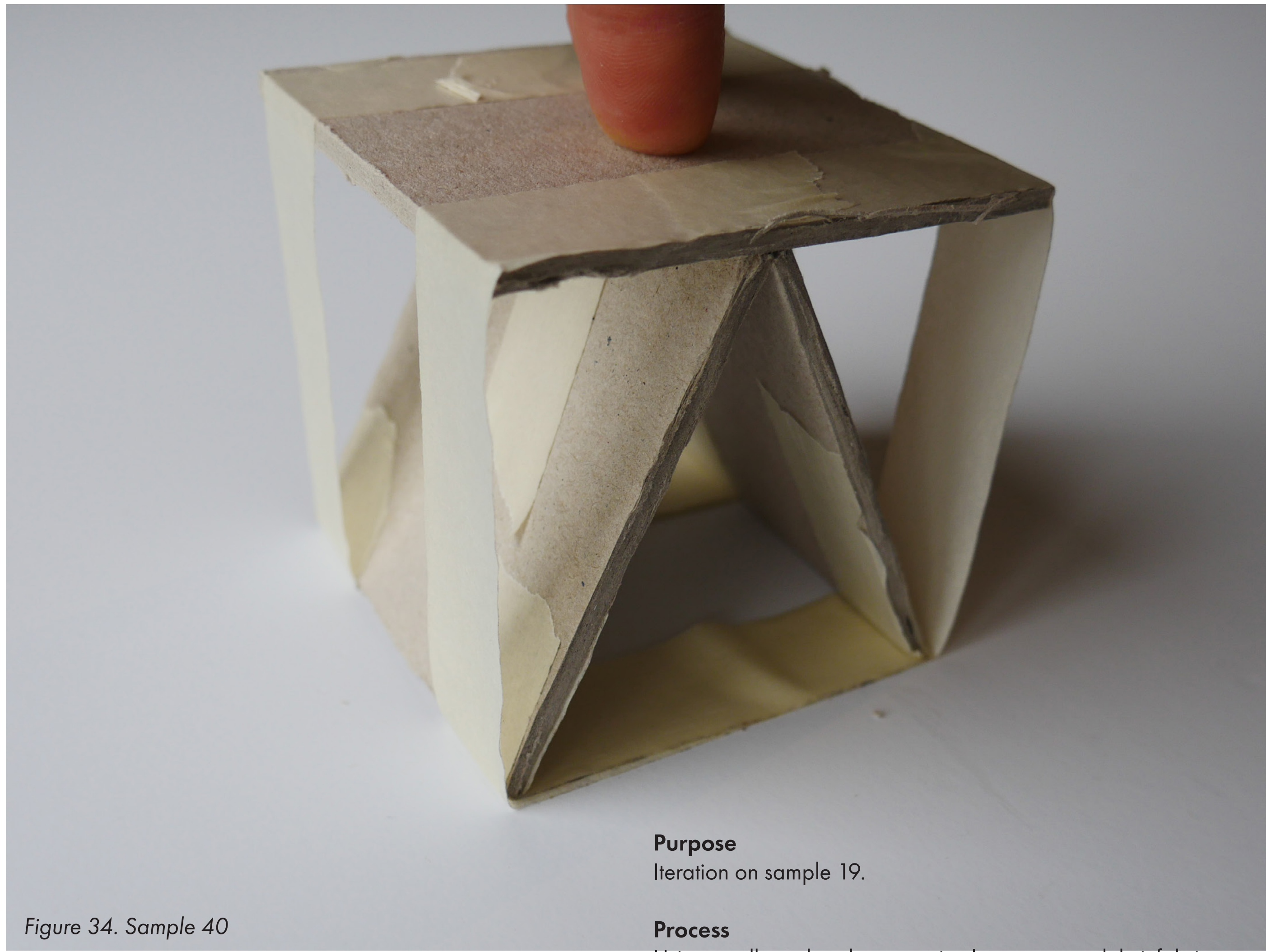


Figure 34. Sample 40

40

Purpose
Iteration on sample 19.

Process
Using cardboard and tape to simulate non-stretch knit fabric, see Figure 34.

Variables
- Stretch of the knit fabric: non-stretch knit structure functions as a cable
- Shape and material of the panels

Takeaways
The structure (only) works when: (1) the two bottom panels are connected to the center line of the panel on top, (2) the edges of the top panel are connected with a cable to the bottom panels where they touch the floor, (3) the bottom panels are connected with a cable to each other where they touch the floor. A cable connection is simulated with tape and can be created with a weave-in knit structure to minimize the stretch.

Next step
Knit it and experiment with the knitting direction and weave-in structure

44

Purpose
To create a soft hand feel and reduce stretch in the vertical direction

Process
Knitting on the domestic knitting machine, making ripples (ottomans) by holding one of the needle beds and continuing knitting with a wool yarn on the other bed, see Figure 35.

Variables
- Length of the ottoman (note that the ottoman needs to be pulled down between the beds to prevent getting stuck in the carrier
- Yarn material combination
- General knitting parameters

Takeaways
The row stitches on the back of the ripple result in less stretch than regular jersey. When stretches, the ripple feels 'soft' because the stretch is limited by the back stitches. Could be used to create a soft surface for the sitting object without the need for any filling.

Next step
Knitting it on the industrial knitting machine to experiment with the stretch reduction.

Figure 35. Sample 44

47

Purpose
Iteration on Samples 41 and 46.

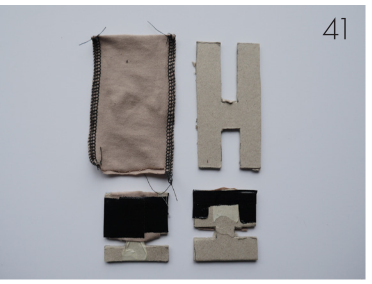
Process
Using tricot fabric, plastic rods, and a sewing machine. Cutting strips of the tricot fabric to sew tunnels on top of a rectangular piece of fabric which is later connected to make it tubular, see Figure 35.

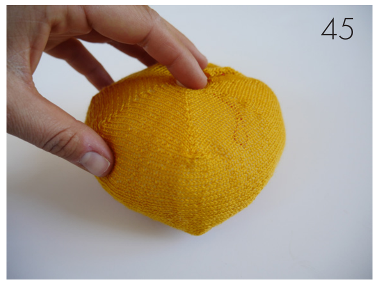
Variables
The same variables as Sample 46, and:
- Length of the rod relative to the tunnel: a longer rod inside a shorter tunnel results in a pre-stressed fabric. It is expected that when a load is applied, the fabric cannot stretch much further so the shape is more stable. However, inserting the rod is difficult.
- Shape of the 'skin': the current shape is squared with only the straight tunnels. Both could be curved to explore different geometries

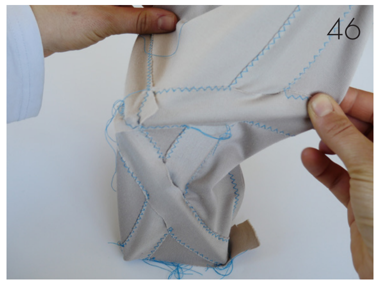
Takeaways
Sewing these tunnels requires a lot of time and material, while they could be knitted directly into the fabric, clearly highlighting the advantage of knitting this structure.

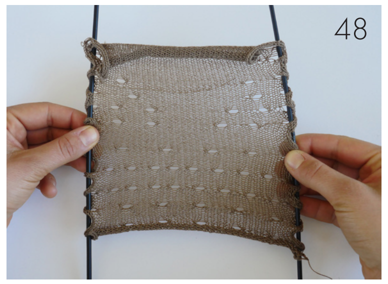
Next step
Knit it with multiple tunnels to create different possible configurations of the rods on the industrial knitting machine.

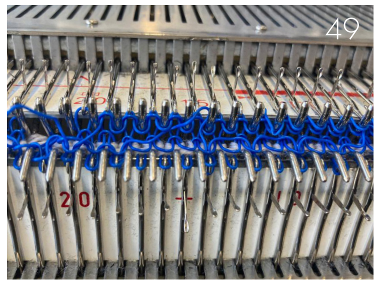
Figure 35. Sample 47











1.4 Grouping the samples

The results are processed by grouping the 49 samples to distill the parameters.

The aesthetics and behaviour of a knitted fabric depend on multiple parameters, grouped under yarn material and stitch structure. See Figure 36 for an overview of the parameters and related samples that explores the parameter.

The yarn material describes the type of fibre, the thickness (amount of plys and thickness of the individual ply), and the twist (either non, or S- or Z-twist).
The 'density' depends on all the beforementioned parameters, and the stitch length, tension on the yarn, and fabric take-down. On the domestic knitting, machine the stitch length is a value between 0 and 10. The tension on the yarn is determined by a turning knob at the top of the machine, not defined numerically. The fabric take-down, meaning the force with which the fabric is pulled down while knitting, is determined by the weights that are hanging from the machine. On an industrial knitting machine, these parameters can be defined and tuned precisely and reproducibly. The fabric take-down is determined by setting the comb take-down, belt take-down and auxiliary take-down value in the knitting software.

The stitch structure means the combination of chosen stitch types, how these stitch types are arranged, and thus also the transition between different stitch types, and possible yarn material transitions. These transitions are described as a part of the stitch structure

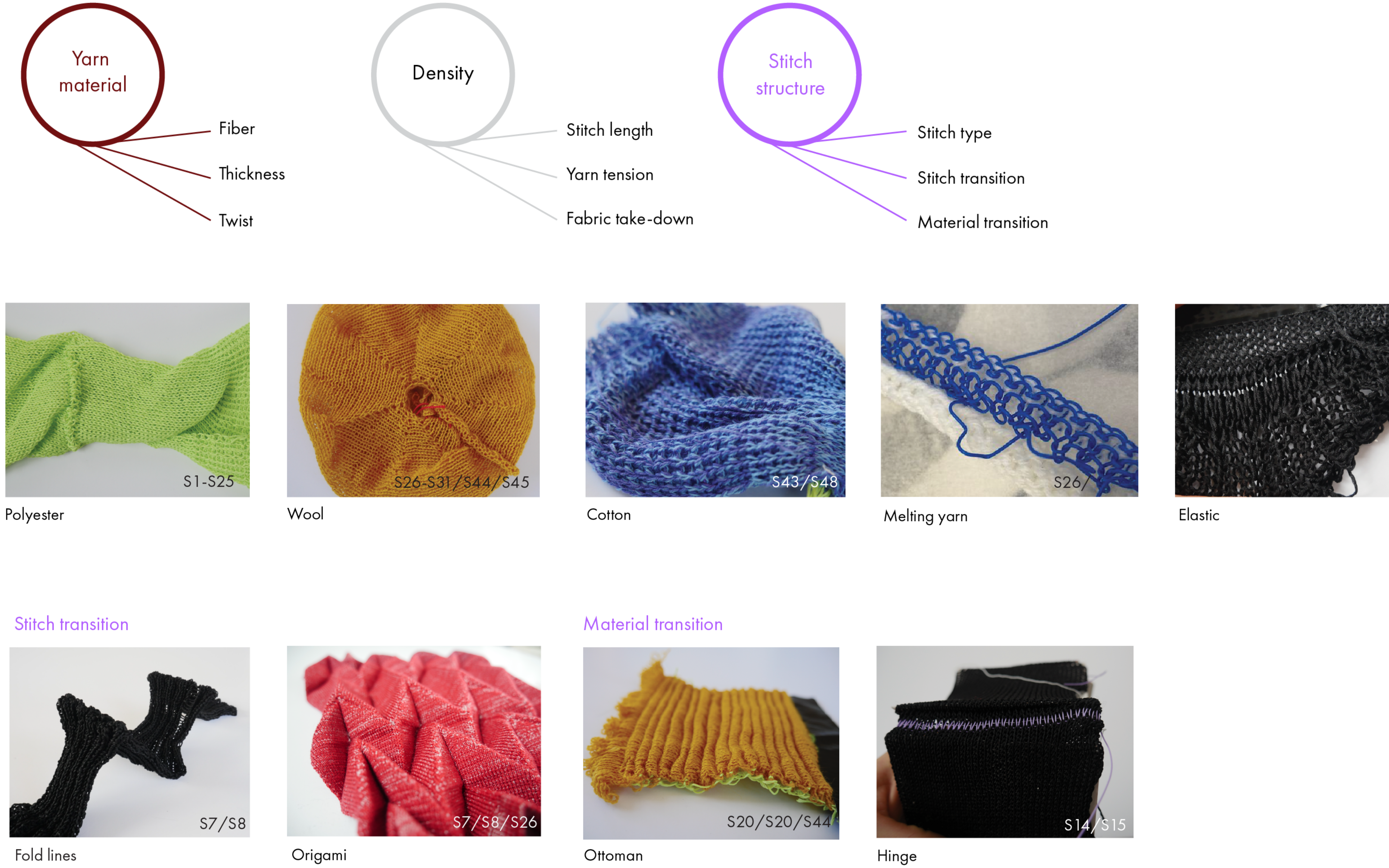


Figure 37. Knitting parameters and related samples

Figure 38 shows the interaction between a knitted fabric and an additional 'frame' material. The distinction is based on the type of frame material, and how this additional material and the knitted fabric define each other's form and behavior. The frame materials are either ultra flexible (e.g. filling), flexible (e.g. flexible tubes or plate material), or rigid (e.g. a coating). The shape or form-making can be co-dependent, where the frame material and the knit shape each other. If not, either the knit shapes the frame, or the frame shapes the knit.

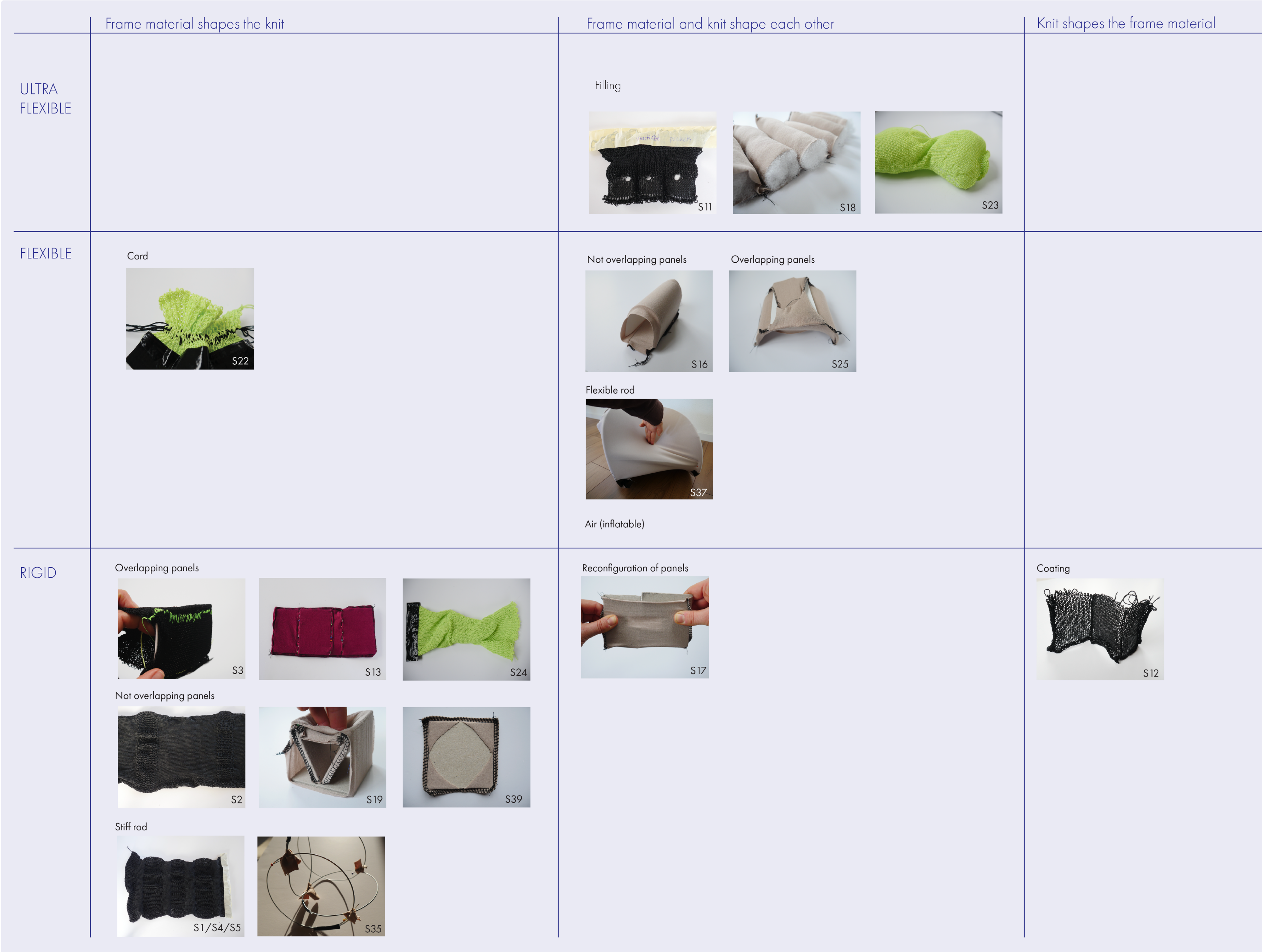


Figure 38. Interaction between additional frame material and knit

Figure 39. Methods of transformability

The samples exploring transformability are grouped based on the use of joints and/or tensioning, see Figure 39.
A rigid joint in this case is the formation of a joint-like junction where a rigid frame material functions as the joint and the knit is not involved. The knitted joint is a joint where the joint-like junction exists only because of the knitted connection between two rigid or knitted materials.
These methods are later defined in the Design Space in the section Transformability.
The distinction between the methods of transformability is relevant in this case because one of the goals of this project is that the object is transformable *through* the knitted structure. Meaning that transformability is possible because of how the object is produced, namely through knitting. As the visualisation suggests, the knit-dependence of the transformability is a scale, a combination of different methods could be used in the final design if not all transformability can be knit-dependent.

1.5 Design Space

The knowledge gained through the 'tinkering' phase is presented as Design Space in Figure 40. It describes the parameters and practical examples that can be explored to develop a 3D knitted, transformable, load-bearing object.

The Design Space is divided into three levels.

The micro level describes the material properties of both yarn and frame material. Yarns vary in their elasticity and response to heat. Frame materials vary in their flexibility and deformation -plastic, elastic, or somewhere in between.

The meso level describes the knitting of the yarn. The stitch structure is defined by its elasticity, which is caused by all knitting parameters mentioned in the previous chapter. The surface treatment is at the meso level for it alters the behaviour of the knit itself, not necessarily contributing to geometry at the macro level.
The meso level could also describe the process from frame material to frame geometry, however, the focus of this project is on knitting, not on methods of plastic bending or wood processing.

The macro level describes the geometry and transformability.

The geometry depends on the textile-frame relation, which is on a scale between knit dominant and frame dominant. A bending-active structure is for example in between the two because the final geometry relies on the interdependence of the knit and frame, where neither is dominant.

The textile 3D form making is direct or indirect, meaning the knit is given form directly through knitting (i.e. goring or increasing stitches), or indirectly after knitting (i.e. through cutting or linking) Note, the difference between the geometry and transformability, although similar example methods are given, is the reversibility. The transformability is in this case always reversible, where the geometry is not necessarily.

A 3D knitted, transformable, load-bearing object is composed of the elements of the Design Space, indicated by multiple dots within the graphs.

The transformability is described only at the macro level. On the next page, the transformability on the different levels is elaborated on.

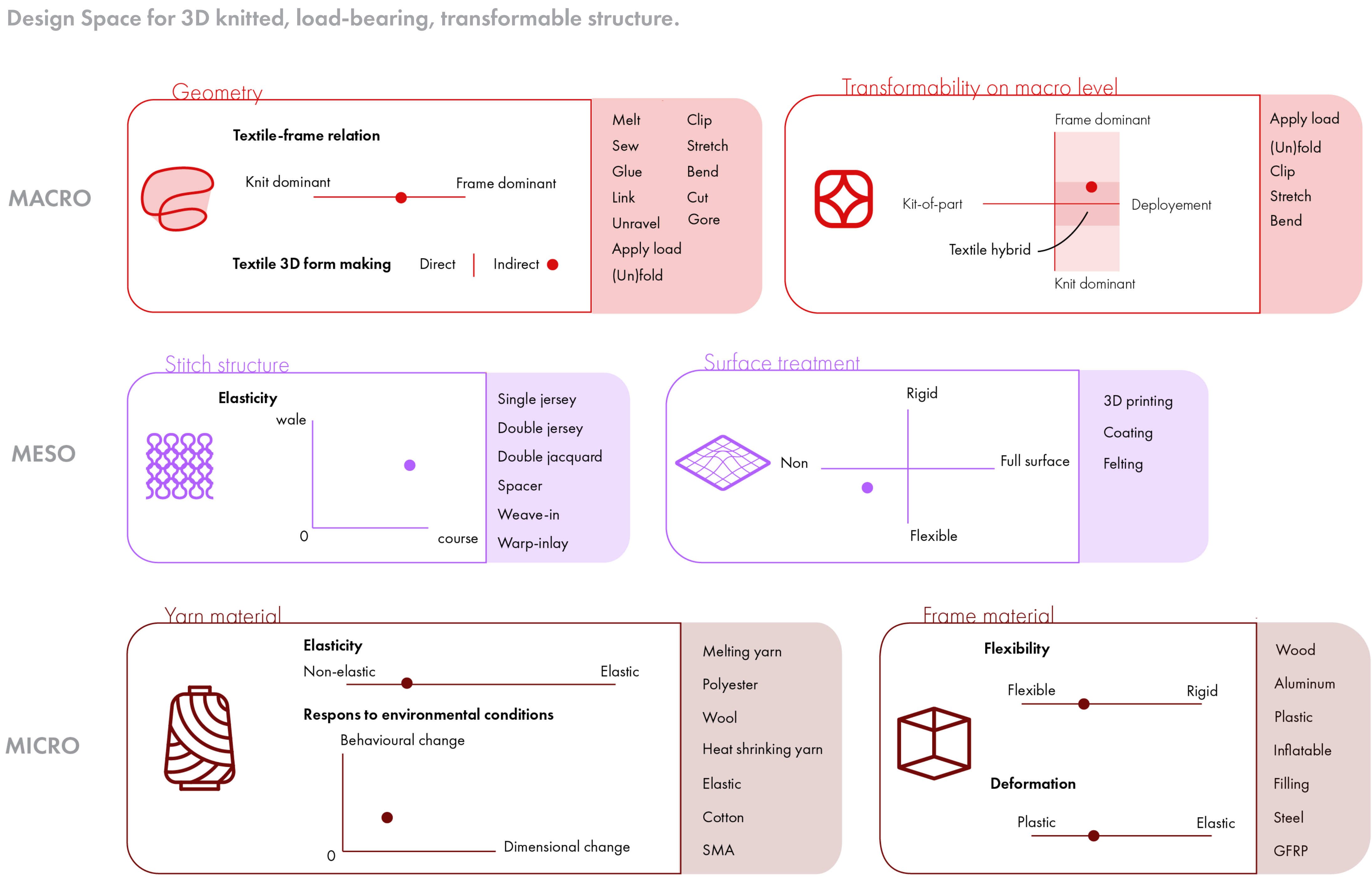


Figure 40. Design Space for 3D knitted, load-bearing, transformable structure.

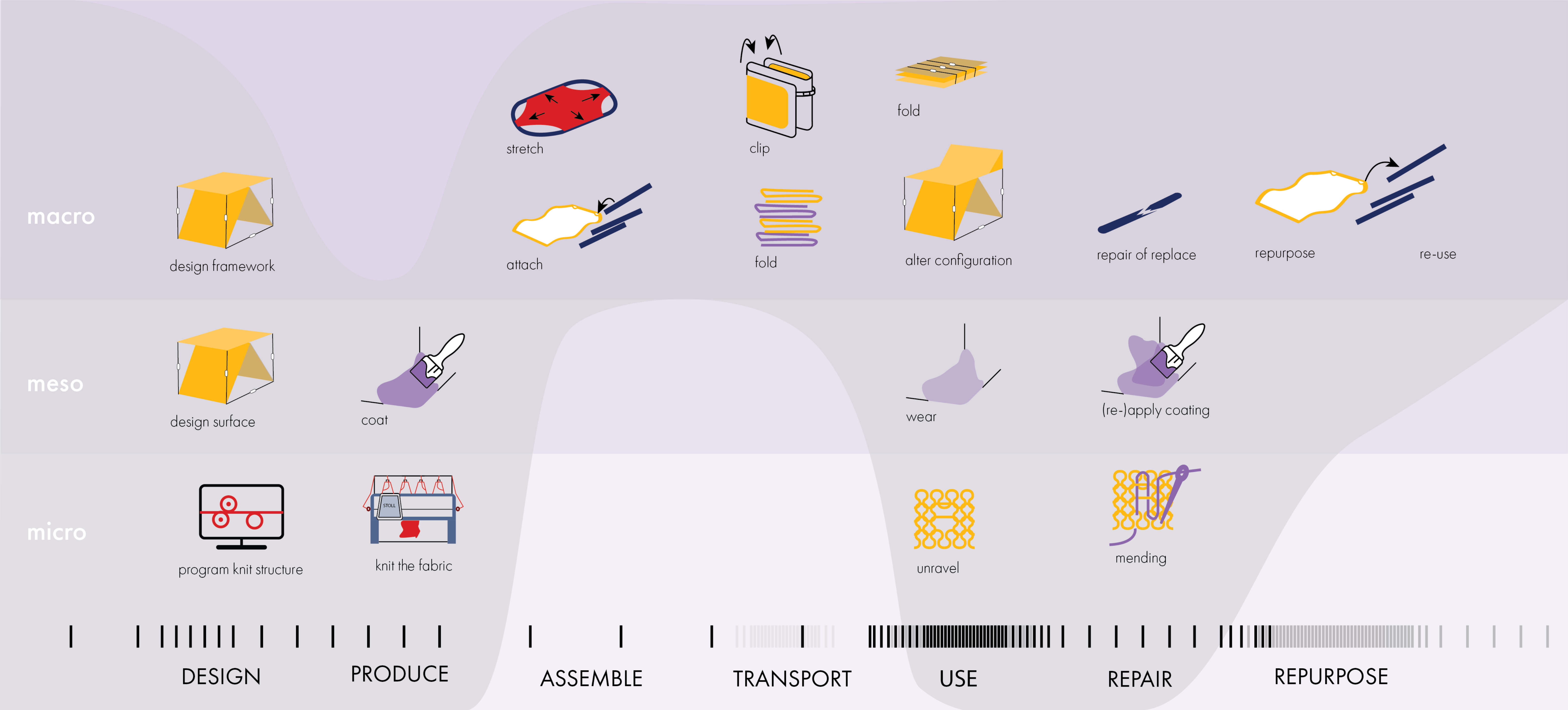


Figure 41. Transformability methods

Figure 41 shows an exploration of different ways the sitting object could be transformable during all stages of the product life cycle. First, the object is designed to be transformable through the knitted surfaces and framework. The knit is adaptable, thus transformable, by altering the stitch structure and knitting parameters in the software of the industrial knitting machine. Knitting the programmed design transforms the knit file into a physical material. During production, multiple processes can be incorporated which will transform the soft knit into a partially rigid material, or increase or decrease the stretch of the material.
Assembling the object is in this case visualized as the insertion or attachment of a framework which will tension the knit. Tensioning the knit transforms it again from a soft, stretchable material into a tensioned surface which changes the look and feel of the knit.
The object can be deployed to a planar configuration to save space while storing, possibly even separating the knit from the framework again. During use, the user could reconfigure the object for multipurpose use. The knit, framework and applied surface treatments will wear over time. Repair is executed by the user through mending the knit, repair or replacement of a frame part, or applying another rigidifying method.
Both the knit and framework could be repurposed after use.
The frequency of the lines above the phase title suggests the duration of the phases.

The level on which the transformability takes place is indicated on the side of the figure. In the Design Space only the transformability on macro level is considered a seperate parameter. The transformability that takes place on the other levels is already covered within other parameters.

1.6 Discussion

The tinkering phase gave insight into the parameters of 3D knitted, transformable, load-bearing objects. However, some limitations of the phase are worth mentioning.

The process of sample development was very iterative. Not every sample lead to another, and not all samples are the result of a predefined plan. The tinkering allows for this 'unstructured' process.
The use of the domestic knitting machine limited the speed of prototyping. Compared to the industrial knitting machine, sample-making requires time and is sensitive to human errors.

Not all knitting techniques of the domestic knitting machine can be reproduced on the industrial knitting machine. The lack of experience of the researcher with the industrial knitting machine limited the creative freedom to explore techniques on the domestic machine. For further research, it is recommended to directly use the industrial knitting machine if possible during the tinkering phase.

Some samples explore rigidifying methods to create a load-bearing structure. The material behaviour exhibited at the scale of the samples is not necessarily comparable to the behaviour of the material at a larger scale. Therefore the load-bearing properties are not evaluated in this stage. Further research into the material properties at the scale of a sitting object is required.

The Design Space indicates all parameters as a scale to demonstrate the complexity and large number of possibilities within the design space.

The examples of methods or material given for a parameter are supposed to inspire other designers and be used as a starting point. Not all possibilities within the described parameter are presented, and not all options within the parameters are explored in this research. The map is supposed to be a living document on which future research can iterate.

The Design Space is the starting point of the 'define' phase, in which the interdependence of the parameters is refined through the development of multiple concepts.

Phase 2

define

to abstract and develop concepts

2.1 Introduction

In the phase of defining, the knowledge of the previous phase is reflected upon through the development of various concepts for 3D knitted, transformable sitting objects. The object is constrained by the requirements stated below.

Requirements

Demands

1. Material
1.1 The object is for the largest part produced through knitting
1.2 Effective use of material

2. Performance
2.1 The object is transformable through the knitted material
2.2 The object is load-bearing through the knitted material
2.3 The knitted structure is adaptable: the material and stitch structure can be locally altered without compromising the performance of the object

3. Minimal (manual) production steps
3.1 Effective and efficient use of production methods, reducing manual labour where possible

Wishes

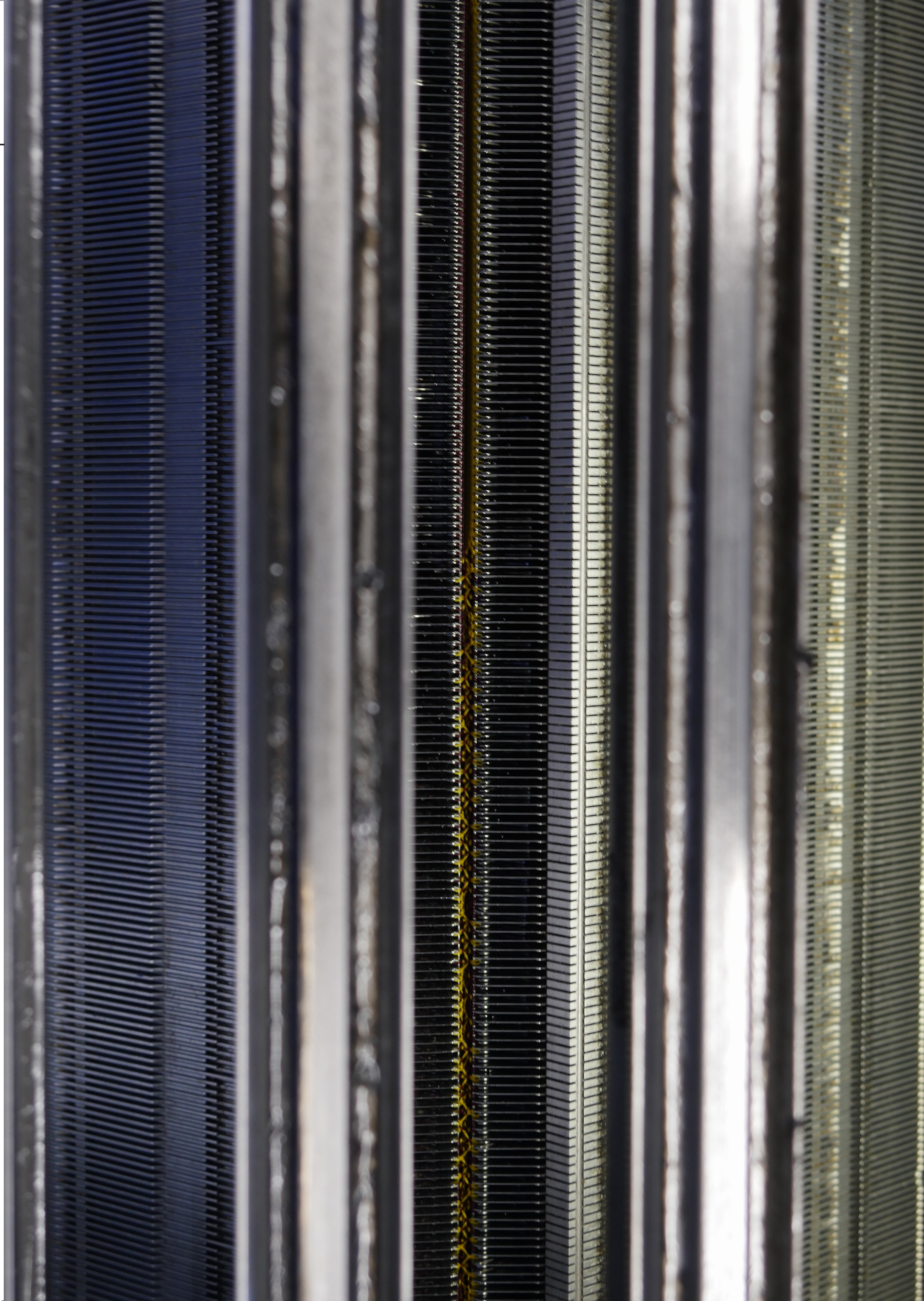
1. Material
1.3 Using knitting yarns of one pure material, no mixtures of yarns

2. Performance
2.4 The object can bear the load of a human sitting on it for at least 3 minutes.

4. Reuse & recycling
4.1 All different materials can be separated from each other to be recycled, manually or through an industrial recycling process

5. Aesthetics, meaning and emotion
5.1 The object looks “strong enough” for a user to dare to sit on it

The demands define the core elements of any 3D knitted, transformable, load-bearing object. The wishes can lead to different design directions and concepts, and help to define the final design of the demonstrator, namely the sitting object.



2.2 Preliminary concepts

Concept development of a 3D knitted, transformable sitting object can start from many perspectives.

The development is complex because of the interdependence of the parameters, and the desired interdependent relationship between the knit, framework, transformability and load-bearing capacities.

If this interdependence was not a requirement, a pile of knitted fabric would be a valid concept. Or a rigid framework with a knitted upholstery would be a valid concept. Examples of both are shown in the literature research.

All sketches of the brainstorming phase and development of the concepts are in Appendix B.

Three concepts are chosen for their different starting points. All show the interdependence of the parameters.

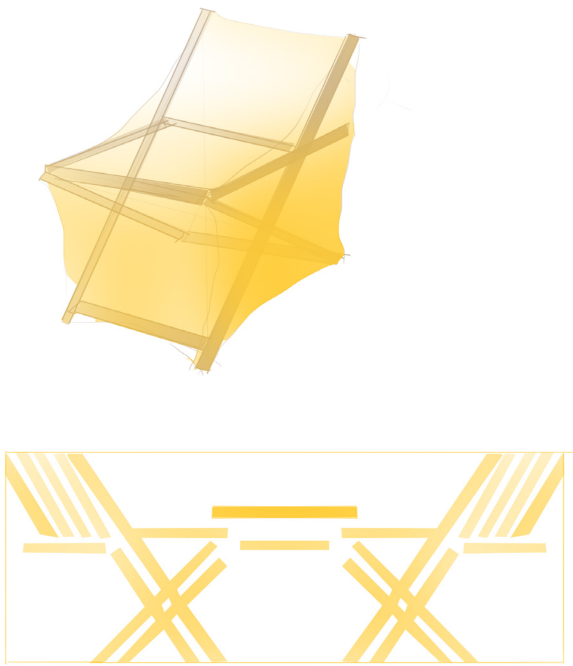


Figure 42. Concept "Klapstoel"

Concept "Klapstoel"

Starting point of development

adaptability

Concept explanation

The chair consists of a flat, double jacquard knit in which stiff rods are inserted to create the geometry of a folding chair, see Figure 42. The flat knit allows for different stitch structures and thus properties of the knit, demonstrating adaptability of knitting in general. The rods can be inserted in different configurations thus the geometry is transformable. The applied load by sitting down in the knit will tense the knit and press the rods into a load-bearing configuration.

The knit structure in this case defines the final geometry of the object and the load-bearing capacity. If a segment of knit stretches very far out under the load of a user, the structure will sag to the floor and not qualify as load-bearing. This means very specific properties of the knit are required to make of the concept load-bearing.

Although the concept started with the desire to create an object where adaptability, meaning the possibility to change the yarn material and stitch structure without compromising the performance, is exhibited, the concept turns out to barely adaptable because of the required load-bearing capacity.

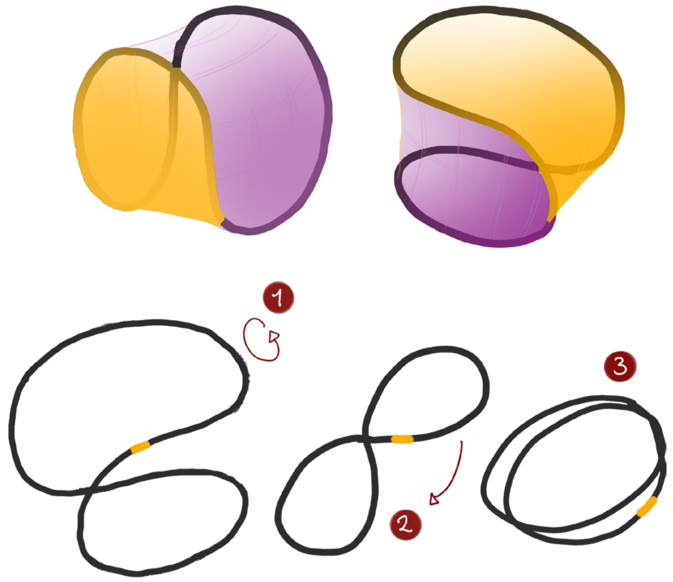


Figure 43. Concept "Pringle"

Concept "Pringle"

Starting point of development

knit-frame relation

Concept explanation

The flexible rod is tensioned onto the undeployed configuration by the stretch of the knit, which in turn functions as the sitting surface of the object, see Figure 43. Physical sampling and literature research however demonstrate the fine balance between the flexibility of the rods and the created tension in the knit, which is out of balance once a load is applied.

The flexibility of the rods which makes the transformability from flat configuration to 3D form possible, is the element that limits the load-bearing capacities.

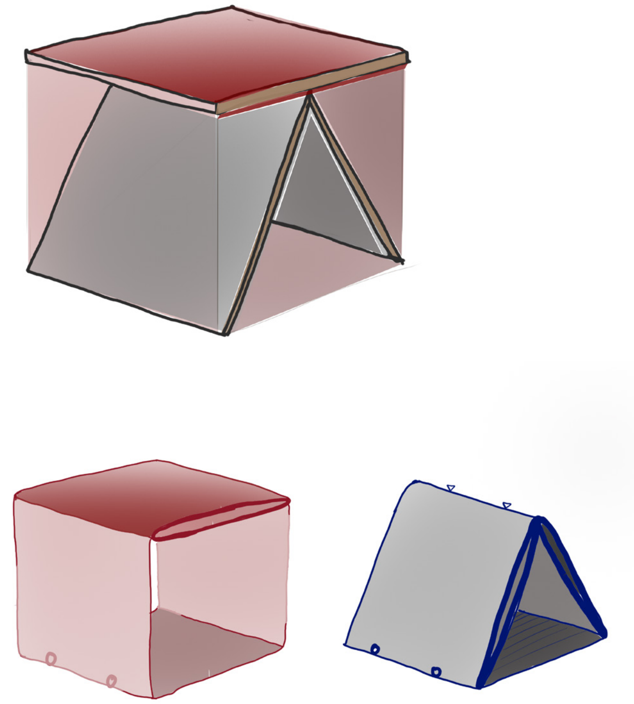


Figure 44. Concept "Balance"

Concept "Balance"

Starting point of development

knit as connection material

Concept explanation

Plate material is inserted in knitted pockets resulting in a tensegrity structure with the knit as connecting material, see Figure 44. The knit is stretched around the plates and defines the configuration of the rigid material.

The knit is utilized as a connection material through its inherent stretch, which is brought out of balance with the rigid material when a load is applied. Once the balance is off, the connection points of the rigid plate material is moved over the surface of the plate, loosing the balance of the structure, causing it to collapse to one side. Again, an interplay between knit and frame material that should not be brought out of balance.

2.3 Interdependence of the parameters

The interdependence of the main requirements -3D knitted, load-bearing, transformable-, of the to-be-design object are explained in this chapter through the practical examples of the concepts described before. See Figure 55 for an illustration of the interdependence.

Load-bearing capacity versus transformability
The use of flexible rods in a knitted structural system induce light-weight characteristics and easy transformability, but the load-bearing capacities require a delicate balance between the stiffness and flexibility of the knit and the rods. Achieving this equilibrium requires computational modeling to determine the optimal design configuration. Additional rigid elements, such as a stiff rod, may be introduced to maintain the rigidity of specific parts that would otherwise bend under load, possibly altering the method of transformability.

Streamlined production versus adaptability
Some geometries could be knitted at once using multiple layers and specific knit structures to reduce the number of production steps afterwards. However, the load-bearing properties of the knit could require specific structures of all segments. When knitting the geometry in multiple parts, separating them to be added together afterwards, the knit is more adaptable.

Streamlined production versus aesthetics
Restricting the design of a knitted structure to a seamless, one-piece construction to reduce production steps can impose constraints on the potential geometric forms that can be achieved.
Goring eliminates the need for seams later in the production process. This again impacts the aesthetics, since goring is visible in the knit as a line, see Sample 45 in Appendix A.

Load-bearing capacity versus adaptability
Integrating the knit as a fundamental load-bearing component reduces the adaptability. This is observed in the use of inlay yarns to minimize the elasticity of a particular section, which requires the use of two beds and imposes constraints on the knit's orientation, as well as its potential for shaping, and thus on the variety of stitch structures that can be used. In bending-active structures, this is especially the case, for there should be an equilibrium between the flexible rods and the tension of the knitted structure.

The complex interdependency of the parameters could be related to the domain cross-over in which this product development takes place.

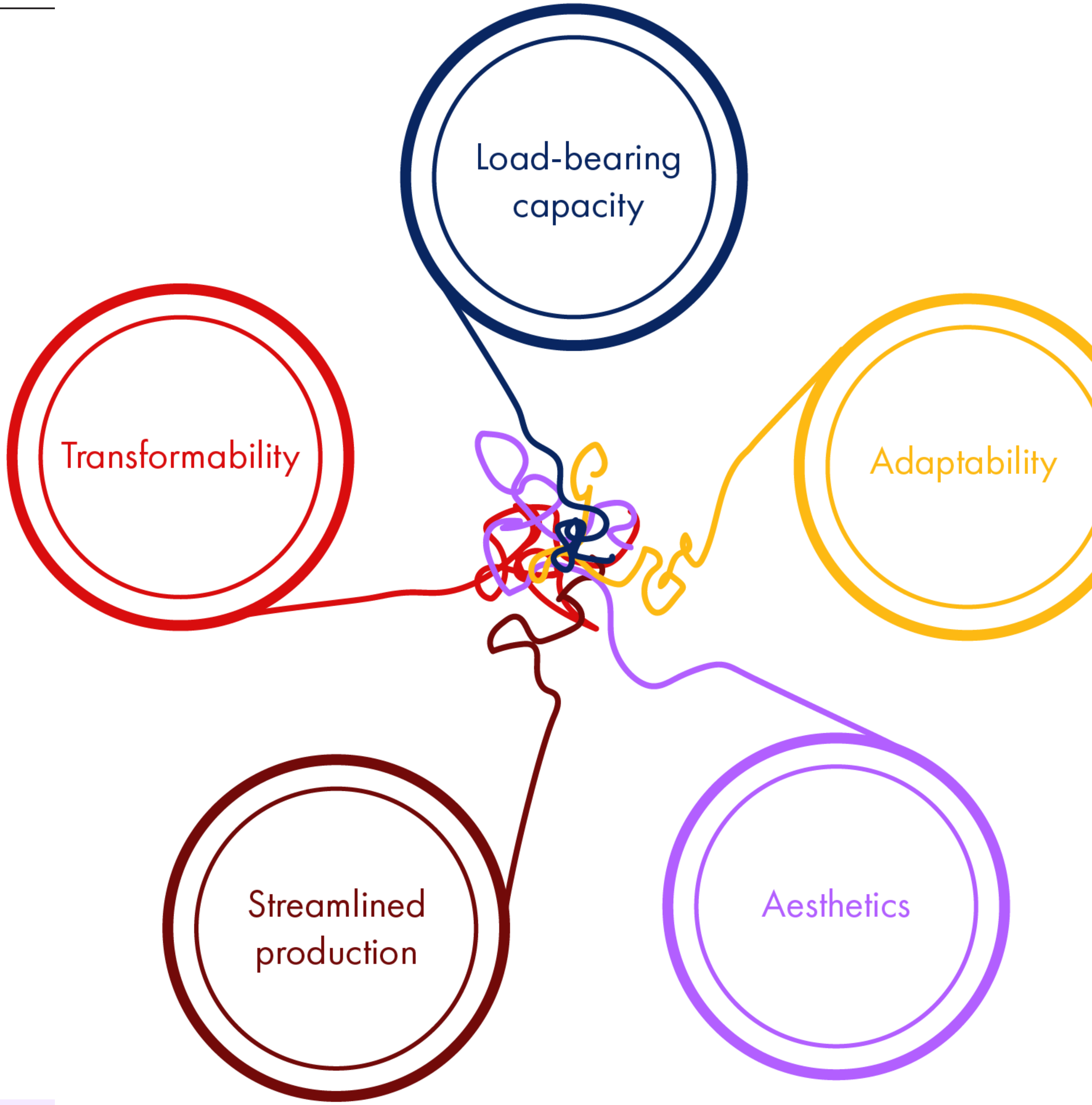


Figure 55. Interdependence of the main requirements

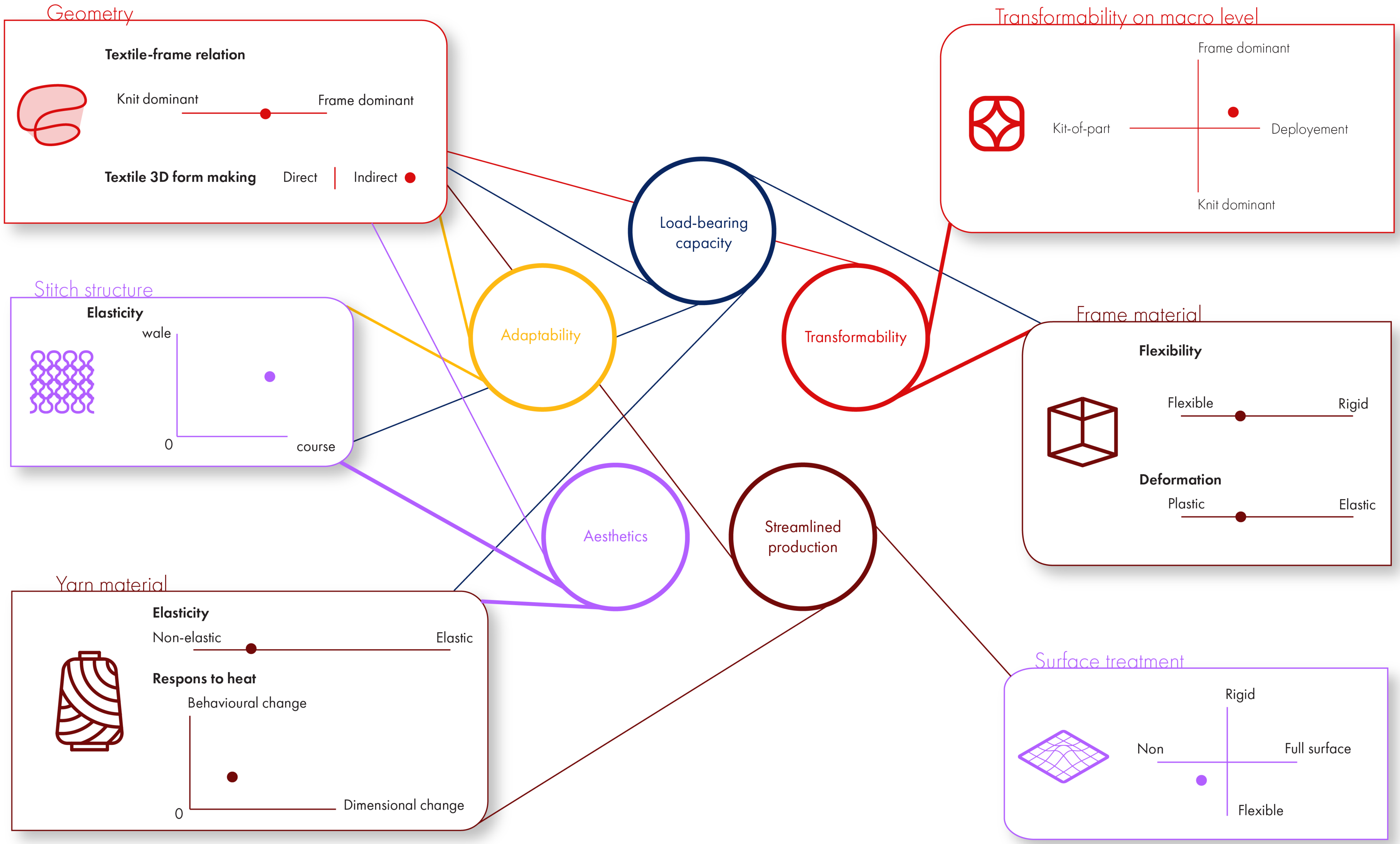


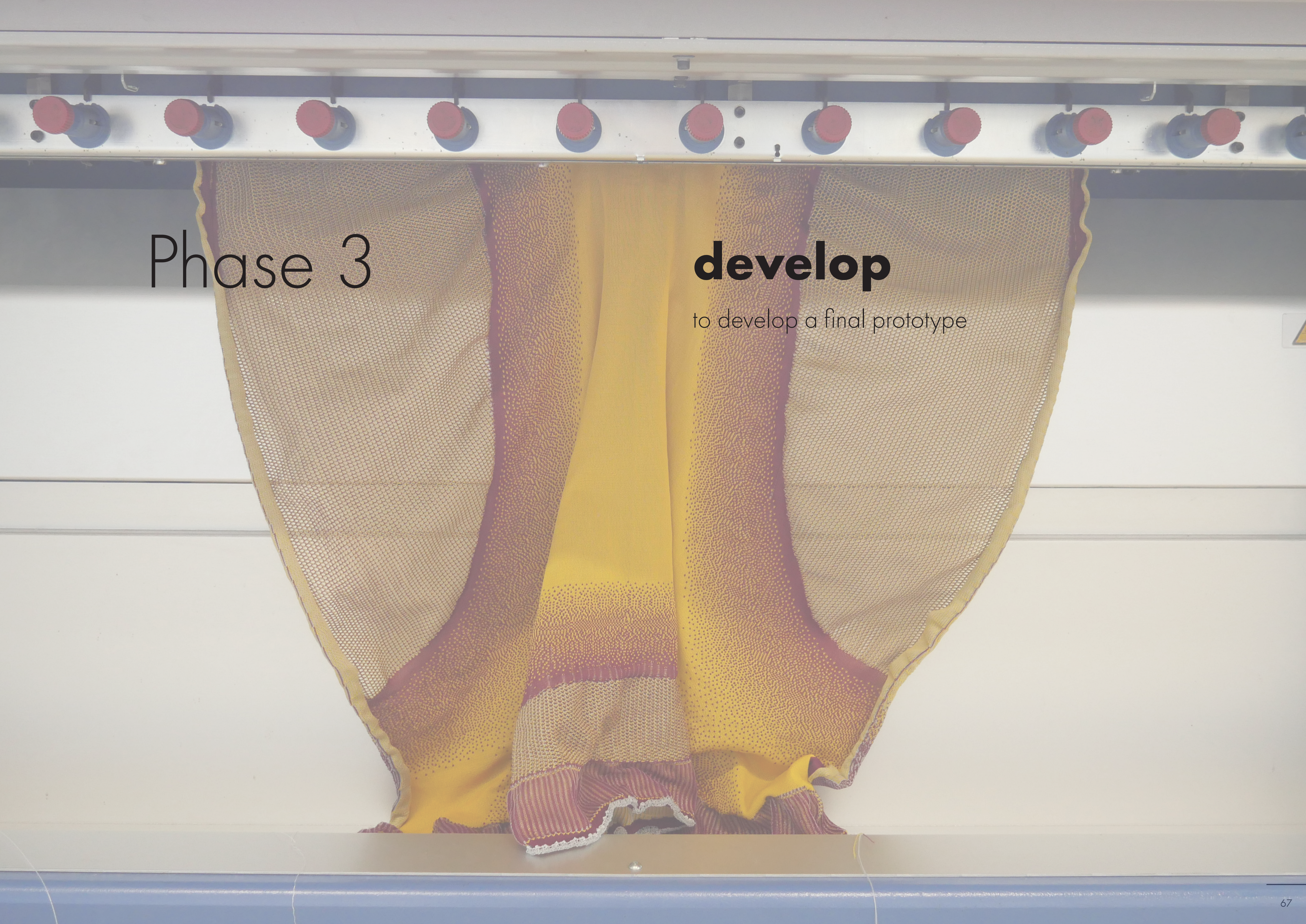
Figure 56. Interdepence within the Design Space

The concept examples show the strong relationship between the parameters. Figure 56 shows the relationship between some of them, describing the consequences. In the end, all parameters impact each other. Further research on the evaluation of practical examples can deepen the knowledge of the relationships, as will be done through the development of a final prototype in Phase 3.

The load-bearing capacity is determined by the fine balance of all elements. It is assumed that the more frame dominant the geometry, the easier it is to make the object load-bearing.
The adaptability depends largely on the geometry and stitch structure. Knit dominant geometries, meaning most of the object's form exists through the knit, and thus most of the object's load-bearing capacity results from the knit rather than the frame which makes the knit less adaptable.
The transformability at the macro level depends on the textile-frame relationship. If, for example, the relationship is frame-dominant, it is assumed the transformability will depend largely on the frame material.
The aesthetics of the object alters through the knit structure and yarn material choice, depending on the adaptability of the object. Surely the overall geometry determines the aesthetics, but the enormous range of possible aesthetics through the knit is considered to be of great importance.

Surface treatments add one or multiple extra steps to the production process, e.g. applying a coating to a part of a knitted surface. This is avoidable by reconsidering the yarn material choice, e.g. by knitting with a thermoplastic melting yarn that will harden when applying heat.

The interdependence within the Deisgn Space is taken into account during development of multiple prototypes and elaborated on for the specific design presented in the next phase, Phase 3 'develop'.



Phase 3

develop

to develop a final prototype

3.1 Introduction

The knowledge gained through the sample making and abstraction of the parameters is now demonstrated through a prototype of a 3D knitted, transformable sitting object. The object should meet the requirements stated in the Introduction of Phase 2.
The complexity of the feasibility of the presented concepts in Phase 2 made it necessary to redevelop the concepts into a new design. The brainstorming and sketching leading up to this design is shown in Appendix B.

A sketch of the design is shown in Figure 57. The working principle is shown in Figure 58. The structure is considered a textile hybrid because the geometry is achieved through a balance between the tensile, textile surfaces and the elastically bent, bending-ative, tubes. Multiple tubes are inserted in tunnels of a knitted panel, tensioning the knit and bending the tubes.
The required balance demonstrates the interdependence of the parameters of 3D knitted, load-bearing, transformable structures. See Chapter 0.2.2 for examples of textile hybrid structures. Experimentation with the flexible tubes are shown in Sample 52-54, resulting in the first prototypes of the presented final design, see Sample 56 and 64, in Appendix A.

In this third phase, the concept is developed into a final prototype.

3.2 Methodology

The process of development is iterative. Starting with the sketch and initial prototype, the considerations of the parameters are elaborated on. Thereafter multiple prototypes are made, reflected upon to articulate the possible improvement for the following iteration.

Tools
In this phase, the industrial knitting machine is used to prototype. The STOLL CMS-530 is the machine available for this project, which is programmed with the M1Plus software by STOLL. (STOLL, 2021)

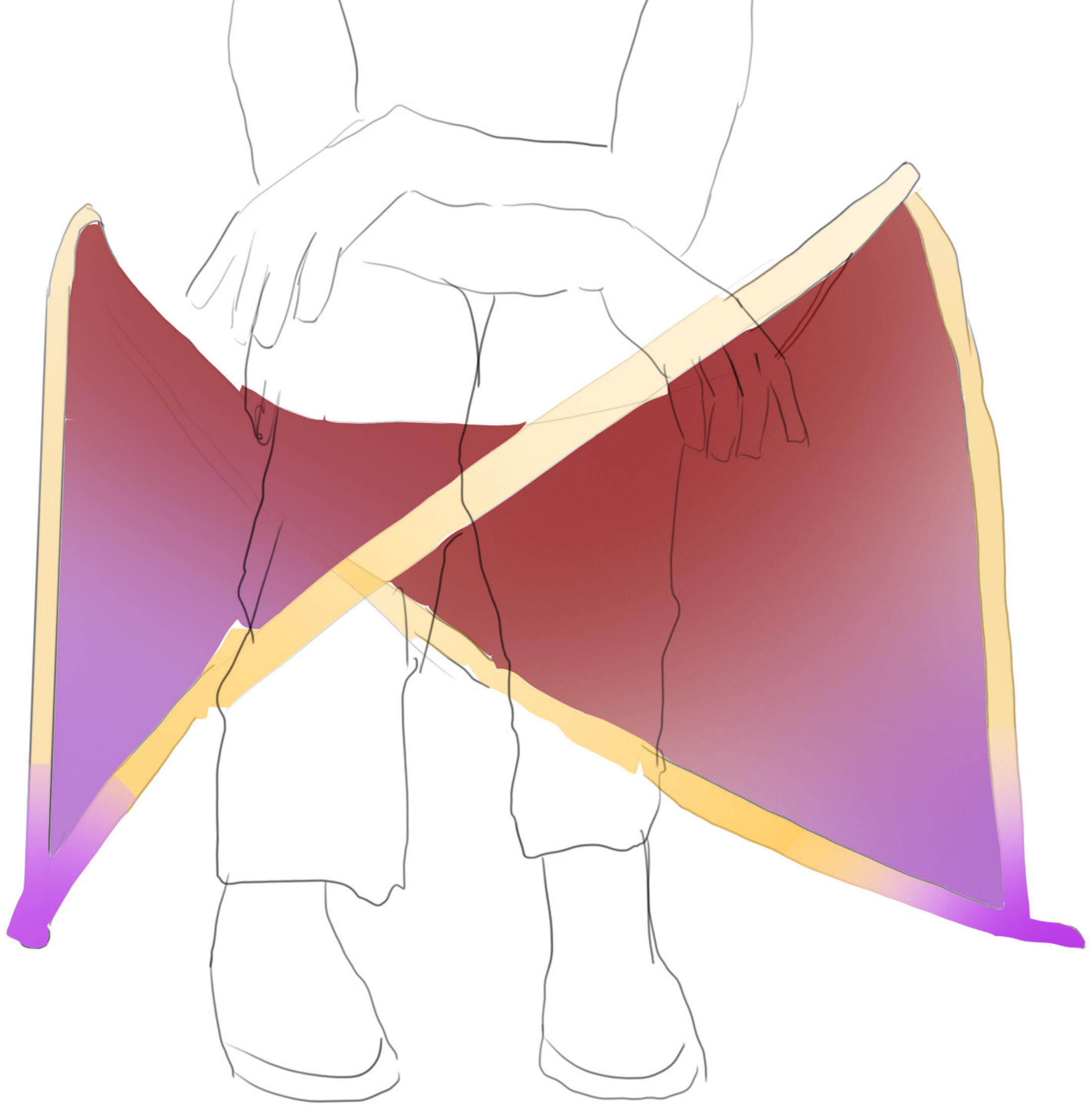


Figure 57. The final design

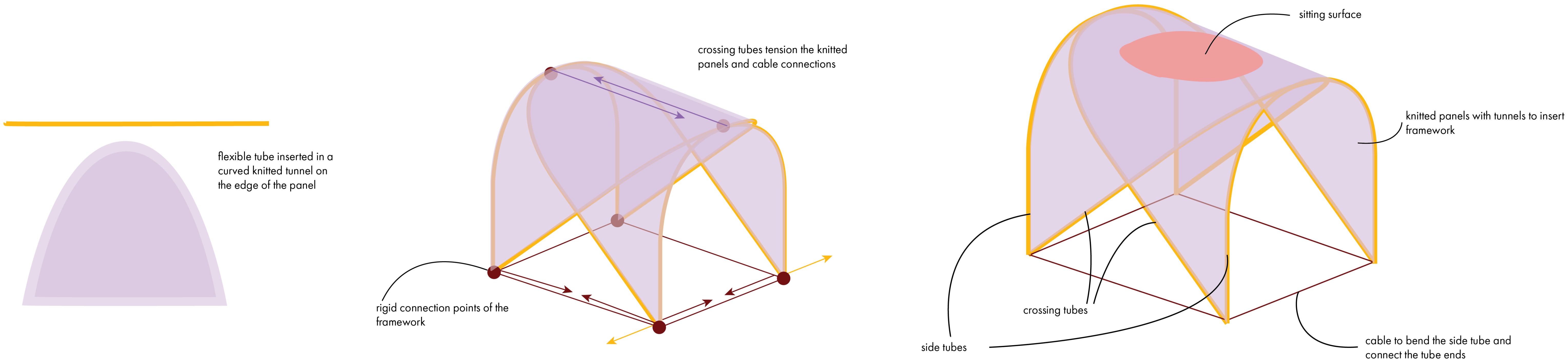


Figure 58. Working principle of the textile hybrid chair

3.3 Parameters

3.3.1 Frame geometry
The angle between the crossing tubes and the width of the object determine if the structure collapses inwards or outwards when a load is applied on the knitted top surface. The user is supposed to sit mainly on the knitted fabric, not directly on top of the tubes. The user being clamped between the tubes moving inwards is undesirable.
If the load is applied only on the knitted surface and angle beta is larger than 90 degrees, then the crossing tubes will move inwards towards the point where the load is applied, see Figure 59. If the load would be applied to the tubes themselves and the angle is larger than 90 degrees, the tubes will move outwards because the force is directly distributed over the framework.
To prevent the inwards collapse, the angle beta should be smaller than 90 degrees, see Figure 60.

3.3.2 Transformability
The transformability depends on both the framework and the knit. The fact that the tubes can be inserted and removed from the knit is independent on the exact knitted form. This kit-of-part transformability takes place either during production or by the user after buying the product as a package of straight tubes and knitted fabric.

The macro transformability does depend on the relationship between the framework and the knit, which is elaborated on in the section 'Geometry of the knit'.

3.3.3 Frame material
The initial frame prototypes are made of PVC tubes with a diameter of 16 millimeters. PVC tubes deform plastically after bending them multiple times or keeping them bent for a longer period of time. The plastic deformation is not necessarily a negative effect, as long as the tube still tensions the knitted surfaces.
As the literature study showed, glass-fibre reinforced polymers (GFRP) are mostly used in bending-active structures for their high strength and low bending stiffness.
Bending stiffness is the resistance of, in this case, a tube against bending deformation. This is a function of the modulus of elasticity, the second moment of inertia, the length of the tube and the boundary conditions. Bending strength means the amount of stress required to break a beam.
GFRP tubes are more costly, so initial prototypes are made of PVC

Form-finding tools could be used in this case to determine the dimensions and shape of the knit that would result in the bending of a tube in a certain angle. The geometry of the knit greatly depends on the stitch structure, material, and knitting machine parameters. These would have to be decided on before any modelling can take place.

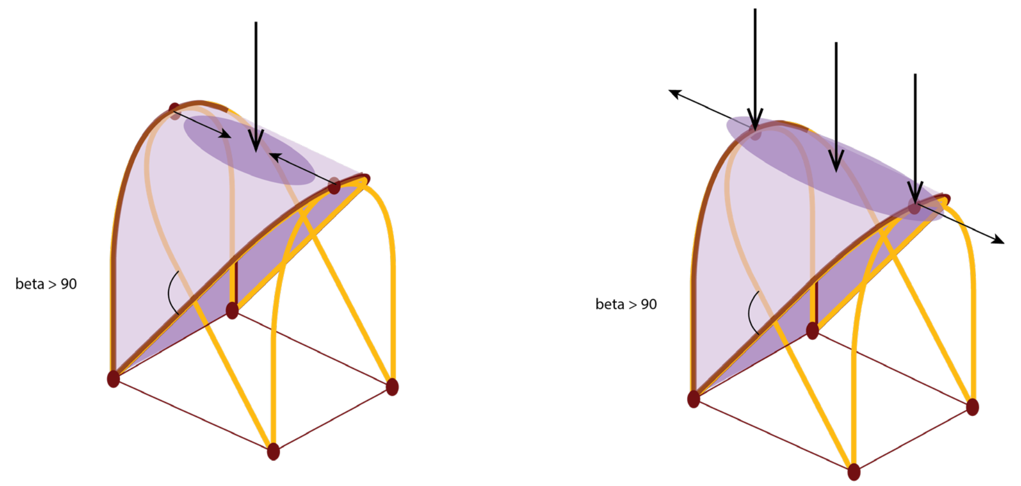


Figure 59. Crossing tube angle >90 degrees

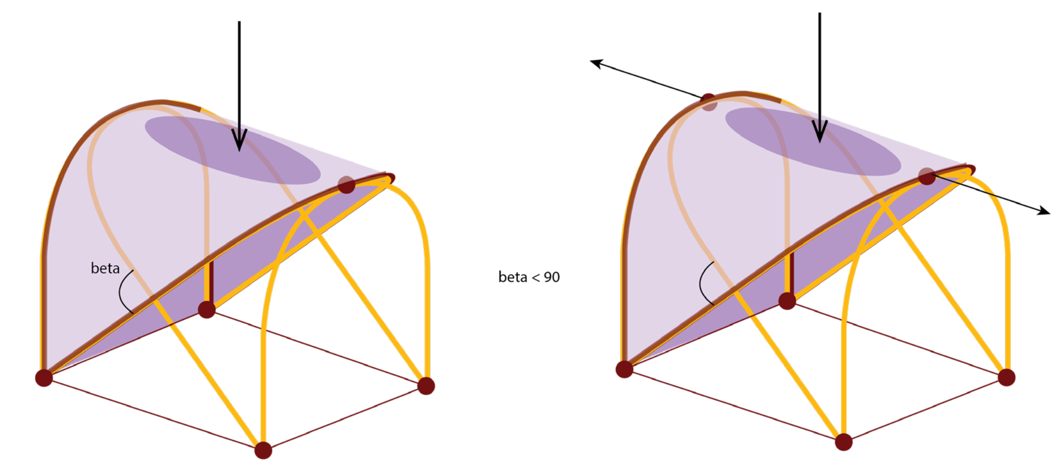


Figure 60. Crossing tube angle <90 degrees

3.3.4 Knit geometry
There are different ways the knit can shape the tubes to create the designed geometry.
The first three concept variations, see Figure 61, do not require complex direct 3D form-making of the knit, only 2D shaping. This reduces the complexity of the knit which leaves room for more complex stitch structure experimentation. This design trade-off is explained on the following page. The surfaces are knitted as separate panels. Layering the panels in the same plane, see Figure 61.1, allows one layer to be the "structural" panel on which the load-bearing capacity of the object depends, and the other panel to serve mainly ergonomic and aesthetic purposes.
The fourth and fifth concept variations require more complex form-making through goring.
The complexity of the first concept variation is in the 90-degree angle between the two planes, which requires extreme goring and widening of the shape. The inherent stretch of the knit could be utilized to create the desired geometry without the extreme goring, however, some segments of the knitted surface would not be tensioned and thus not perform as a load-bearing structural material.

The fact that out-of-plane form making is possible through knitting makes the technique stand out compared to other fabric production techniques. The limits of this direct 3D form-making are explored by making samples to realize the design presented in Figure 61.4, and explained in-depth on the following page in "Direct 3D textile form-making versus stitch structures".

Considering the limited time and experienced limits of direct 3D form-making, the prototype that will be developed is visualized in Figure 61.1, using only planar knitted shapes to allow for more possible stitch structures. Demonstrating the range of possible stitch structures shows the adaptability of knit.

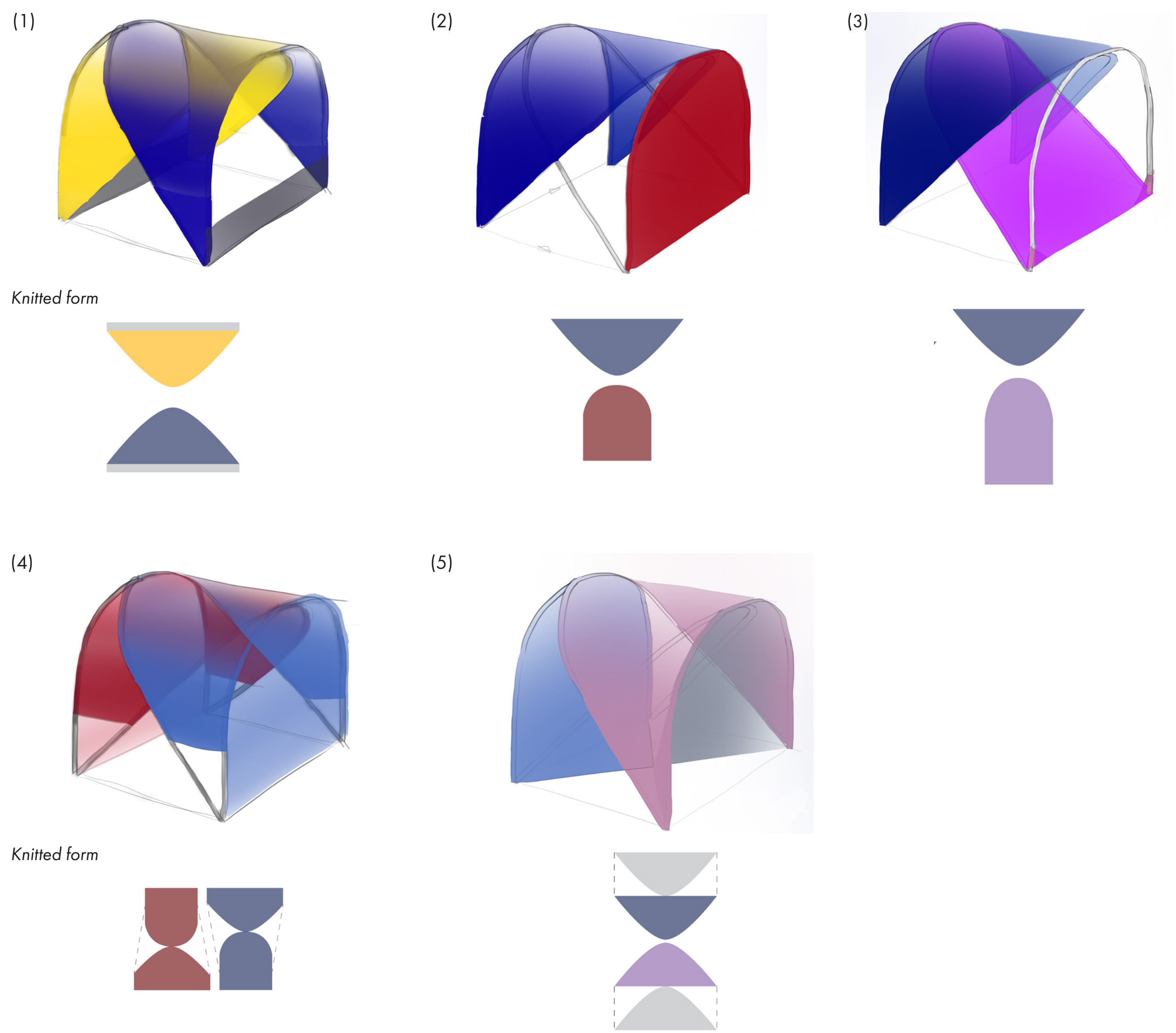


Figure 61. Designs with and withoutcomplex form making

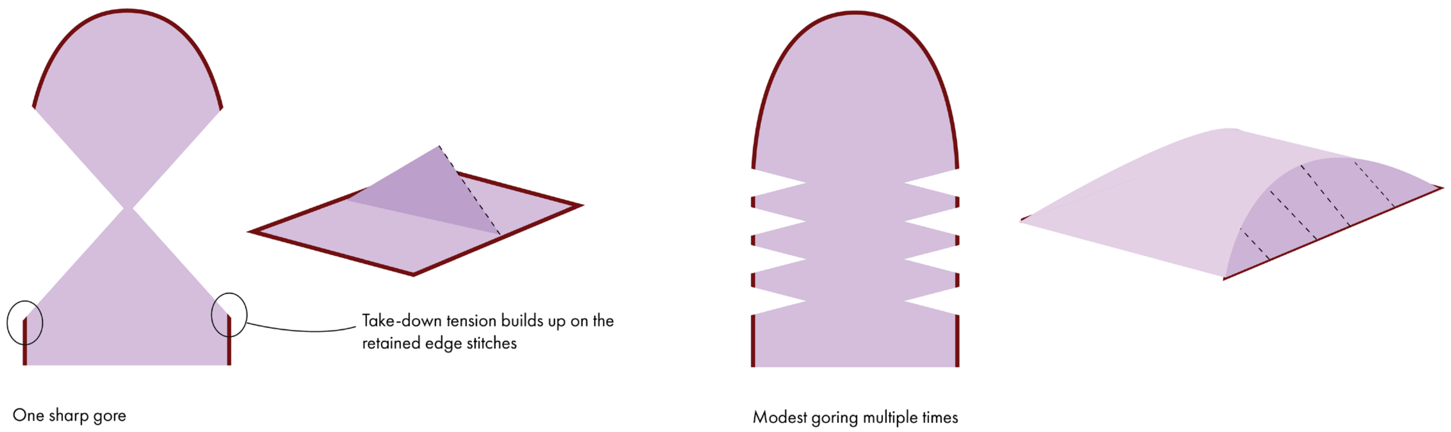


Figure 62. Goring

Direct 3D textile form-making versus stitch structure
Goring, also called short-rows, means that only a segment of the width of the course is knitted, increasing length in a specific location, see Figure 62. Direct 3D textile form-making of the knit through goring is explored through many iterations, see Figure 62-67, but has its limitations.
Goring can break the retained edge stitches easily because the take-down tension build up upon them, see Figure 63 and 64 for Sample 71. The possible steepness and amount of goring is therefore dependent on the strength of the yarn and needles. The take-down values and goring steepness can be determined through trial-and-error and can differ for each knitting machine.
A second risk of extreme goring is that the gored fabric fluffs up in between the two knitting beds, gets caught and damaged by the carrier, visible in Figure 65 showing Sample 65. Manual intervention during knitting is needed to press the knitted material down.
A third risk of goring is that the tension is not equally divided over the whole fabric, not even with the belt take-down and auxiliary take-down system. The stitch length is not well maintained when knitting with different stitch lengths horizontally next to each other. The stitch structures that require a specific stitch length are not knitted as intended, see Sample 69 in Figure 66. Again, manual intervention would be possible by pulling the knit down from either below the bed, if the comb cover can be opened while kniting.
Further research is requires to determine the exact machine parameter values for successful goring combined with complex horizontally aligned knit structures. To do so, first the desired stitch structure should be determined to have a baseline of what the stitch structure should look like, to be able to compare the results with the goring attempts.

3.3.5 Stitch structure
Two commonly used stitch structures are considered as baseline for exploration: double jacquard and spacer.
First, the double jacquard structure. Multiple yarns are knitted within one course, alternating between the front and back bed. The structure allows for a multicoloured motif on both the front and back of the knitted fabric. The transitions between the beds creates a connection between the two layers which can be utilized as pocket or tunnel. See Figure 68 for a visualization of the stitch structure. The double jacquard is used in all samples presented on the previous page.

Second, the spacer structure is a stitch structure, consisting of three yarns, as explained in Chapter 0.2.2. One yarn knits on the front bed, a second tucks between the two beds, and a third knits on the back bed. See Figure 69 for a visualization of the stitches. The fabric has limited stretch in the X direction, caused by the tucking yarn. Utilizing nylon to form the tucks creates a distance between the front and back layers, which makes the fabric feel like foam.

The stitch structure, yarn material, gauge and knitting machine parameters determine the final dimensions of a knitted swatch. When 100 needles by 100 courses are knitted with a spacer stitch structure, it results in different dimensions from when it is knitted as float jacquard. Also the stretch, in X and Y directions, will differ. Therefore it is important to decide upon the exact stitch structure, yarn type and machine parameters, before adjusting the shape of the knitted panel to come to the desired dimensions.

The demonstrator of this project is meant to show the adaptability of knitting through the wide range of structures, aesthetics, and fabric behaviours. The number of stitch structures that can be utilized in one knitted course, depends on the behaviour of the structures, meaning stretch and dimensional stability, and the dimensions of a repeat within the structure. As shown through Sample 60 and 81, aligning different stitch structures that require different take-down values can influence each other and result in both structures looking not as neat as intended. The stitchlength can be adjusted within one course for each yarn but this requires more knitting time. The take-down value can not vary within one knitting course. With this limitations in mind, the stitch structures are designed.

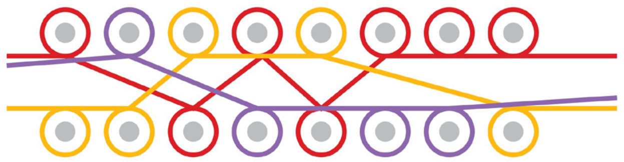


Figure 68. Double jacquard stitch structure from above

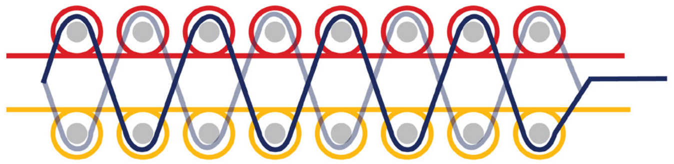


Figure 69. Spacer stitch structure from above

Figure 63. Sample 71

Figure 64. Sample 71, retained stitches that broke under tension

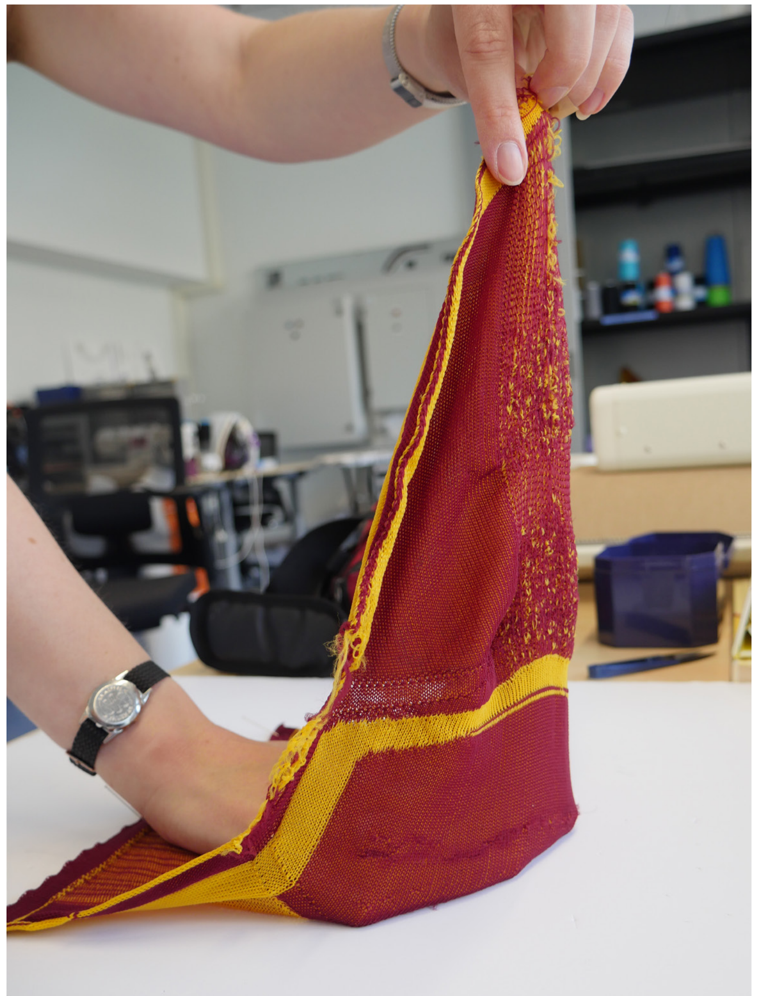


Figure 66. Sample 69

Figure 65. Sample 65

Figure 67. Sample 68

The behaviour and aesthetics of a stitch structure depend strongly on the yarn material. Thus the yarn material was decided on before experimentation with stitch structures.

Controlling textile behaviour through stitch structure

See Figure 70 for different stitch structures. In the presented design, the stretchability of the knit combined with the tubes creates the desired tension in the knitted panels. The knit should stretch to be able to insert the tubes and tension the surface. The more the geometry can tension the knitted panels, to more it prevents the user from sagging through the knit when sitting down. The level of stretch of the knit can be controlled in various ways.

Figure 70.d and Figure 70.f show both a weave-in structure designed to limit the stretch in the horizontal direction by mimicking a woven fabric, the first with two polyester yarns, the latter with two polyester yarns and nylon. This requires transfers from one bed to the other, retaining stitches on the other bed while a yarn floats in between the two beds. The necessity to use both beds for this structure makes it more complicated to knit two separate layers at the same time. If this would be needed, the stitches on both beds would have to alternate and the density of both structures would be divided in two. The weave-in structure is a known reinforcement method, it allows for the arrangement of the fiber along the load direction which increases the impact resistance. (Hasani et al., 2016)
Figure 70.e and Figure 70.h show samples designed to control the vertical stretchability.
Utilizing a stitch structure with a different maximum stretch from the surrounding stitch structures, results in maintained relaxation of the surrounding stitch structures while the other structure is stretched out to its maximum length. Segments of the knit can therefore functioning as a cable in the sitting object, whereas the other segments have an aesthetic or comfort function, by for example using decorative stitches or another yarn material for a soft hand-feel.

Figure 70.a and Figure 70.b utilize nylon yarn to increase the tensile strength of the knitted fabric by knitting it together with polyester yarns. Sample 76, see Figure 70.i showed that knitting the nylon with polyester alternating every needle, is a suitable method to increase tensile strength but maintain stretch in all directions. Alternating every needle results in a float of 1 stitch with both yarns, limiting the stretch mildly. The samples in the mentioned figures iterate on this phenomena.
Figure 70.a shows Sample 80 where the nylon is knitted on both the front and back bed, with only one cone of nylon yarn, while maintaining the seperation between the two layers and not knitting round fully. This stitch structure could be applied to reinforce only a segment of a tunnel of the panels.

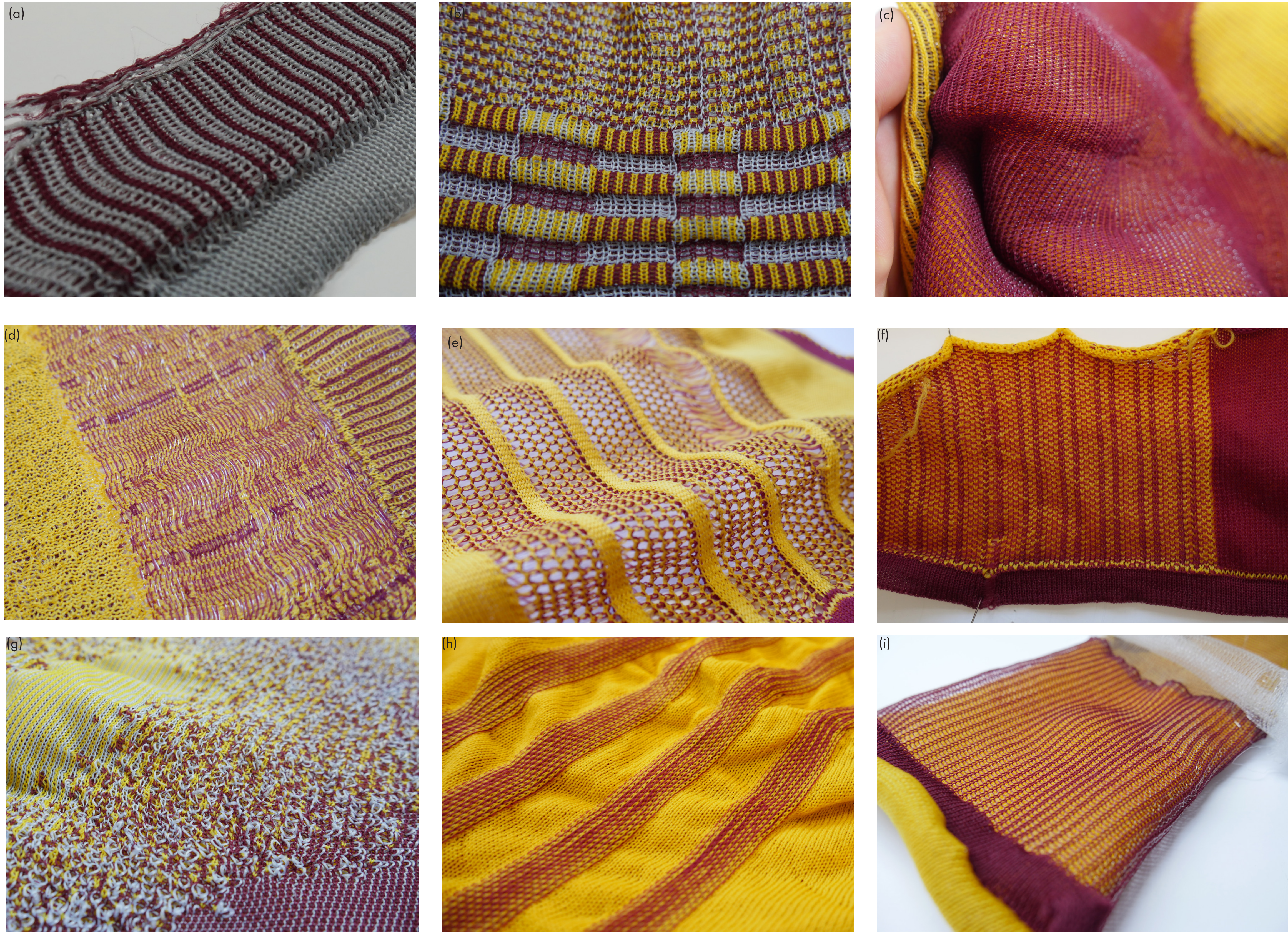


Figure 70. (a) Sample 80 (b) Sample 79 (c) Sample 59 (d) Sample 75 (e) Sample 70 (f) Sample 68 (g) Sample 74 (h) Sample 68 (i) Sample 76

3.3.6 Yarn material

The yarn material greatly impacts the tensile strength of the knitted fabric.
The fabric should not break on the load that is applied on the object, therefore yarns with high tenacity are required. The chosen yarn materials are nylon and polyester, see Figure 71.

Nylon
Nylon yarn is a synthetic thermoplastic linear polyamide. It is known for its high strength, abrasion resistance, and excellent elasticity. It has a high melting point and is resistant to chemicals, including acids and alkalis. Additionally, nylon yarn has low moisture absorption, which contributes to its dimensional stability and resistance to mildew and rotting. (Zhu et al., 2017) See Appendix C for more material properties.
There is a range of types of nylon, differing in the amount of amides in the chain. (Salud Industry, 2023) Nylon 6, in comparison to other nylon variants, is a cost-effective option that finds extensive applications in industries such as textiles, electronics, appliances, automobile manufacturing, and household products. (Guo et al., 2023)

Sustainability
Nylon a durable material because of its high strength, contributing to a long life span of a product and thus more sustainable products. However, nitrous oxide is emitted during the manufacturing of nylon which contributes to the depletion of the earth's ozone layer. (Chen & Burns, 2006) Comparing nylon to natural fibres incidates that nylon does not require finishing processes like cotton and wool do.

Polyester
Polyester yarn is another synthetic polymeric material widely used in the textile industry. It is a type of polymer belonging to the polyester family, composed mainly out of polyethylene terephthalate (PET). Polyester yarn has several distinctive properties, including high strength, great dimensional stability, and resistance to stretching and shrinkage. (Jaffe et al., 2020) It has a low moisture absorption rate, making it quick-drying and resistant to mildew and rot. Polyester yarn is also known for its resistance to most chemicals, including acids and alkalis, as well as its ease of care, as it is typically machine washable and has good wrinkle recovery properties. See Appendix C for more material properties.

Sustainability
Polyester is extensively recycled by melting the fibres, or other polyester products, and re-extruded through a spinneret. The interest in recycled polyester seems to be rising: the percentage of recycled polyester use world wide has increase from 8% in 2008 to 15% in 2021.

The polyester yarn gives a modern look and feel to the knitted fabric while maintaining its softness. The nylon can make the fabric feel smooth and tough, or soft and fluffy when knitted as a spacer.

The different yarn materials are integrated into one stitch structure to combine the material properties. Combining the nylon with the polyester yarn, the knitted fabric feels soft and has a high tenacity. The precise tensile strength of the knit depends not only on the material but also on the stitch type used within the stitch structure. Combining the two material makes the knitted fabric a composite material. (Carey, 2017) The structure possess material advantagous material properties that the individual components to not. The composite material still meets Wish 1.3, see Chapter 2.1, of using only pure material yarns, no mixtures. In theory, by unravelling the knit, the materials can be seperated, thus also complying with Wish 4.1.

Figure 71. Yarn material (from left to right): polyester (dark red), polyester (yellow), polyester (grey), nylon, melting yarn.

Figure 72. STOLL CMS 530

3.3.7 Industrial knitting machine parameters

Sample 80 brought to light the dilemma of utilizing more than three yarn feeders. If another cone of nylon yarn would be used for the sample, fewer meters of nylon yarn would be required but the knitting time would triple. The cause is that only three systems are available on the carriage of the industrial knitting machine, see Figure 72.
In Figure 73 the knitting machine is visualized from above showing the movements of the carriage needed to knit with four yarn feeders, thus four yarns.
Knitting with three yarn feeders only requires step 1. and 4. to knit two courses. Step 1. to 6. are needed two knit two courses with three yarns. In step 2. and 5. the carriage is moving without transporting any yarn feeder, called 'empty row' in M1Plus software. (STOLL, 2021)
These empty rows can be made useful if any transfers are required.
To lower production costs, the knitting time should be as short as possible, making efficient use of the movements of the carriage. Therefore, if more than three yarns are required to be knitted at the same time, the designer might as well then use all six yarns to fill up the carriage.
In Figure 70.b a sample with four yarns is shown. To prevent the increase in knitting time, only three yarns are knitted within one course, alternating the yarns every three rows. This way the nylon can be knitted in regularly to increase the tensile strength and three polyester yarns can be used to create a motif for aesthetic purposes.

The described experimentation gave insight into the parameters and limitations of the industrial knitting machine and are summarized here.

As mentioned in the section "Stitch structure", the take-down value can not vary within one course. Stitch structures that require different take-down values should not be aligned within one course.
The stitch length can be adjusted within one course and per yarn carrier.
The size of any knit shape is limited by the number of needles on the bed. In this case 699 on both the front and bed bed, so a maximum width of 699 needles. The final dimensions of the knitted panels depend on the other knitting parameters.
The carrier can pick up three yarn feeders at the same time to knit one course. When more than three yarns are required within one course, the knitting time at least doubles because the carrier has to move two times extra.

Limitations of the STOLL CMS-530 of the TU Delft
The machine has four rails over which the yarnfeeders are moved, on both the front and back side. On each side of the bed, the yarn feeders are parked, resulting in a total of 16 possible positions for yarn feeders. Only 8 yarn tension systems are available, of which two on the left side are always occupied by the draw thread and elastic comb thread.
Changing yarn feeders requires time, so for ease of production the yarn feeders are not changed. During prototyping, three yarn feeders are intarsia yarn feeders which require the whole rails. One plating yarn feeder is available.

All knowledge gained through sample making is used to produce three prototypes, the third presented as final prototype.
The assembly, technical evaluation and improvements for a next iteration are explained in the next chapter.

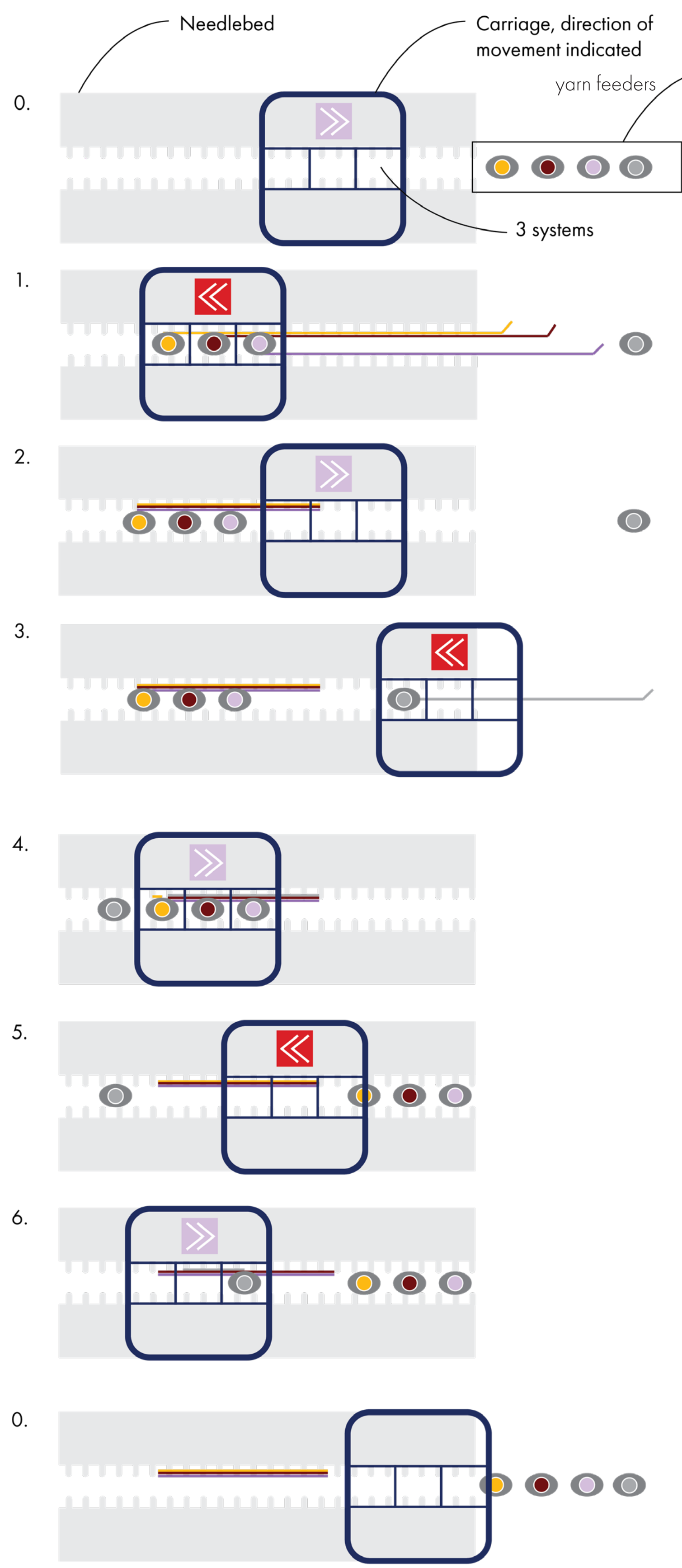


Figure 73. Carriage movement

Prototype

82

The first prototype is composed of Sample 73 and 74, two double jacquard panels. See Appendix A for details on the stitch structure. The goal of the prototye is to evaluate the production process, the load-bearing properties, and to identify possible improvements.

3.4.1 Assembly

1. The PVC tubes are inserted in the tunnels of the knit by hand. The tubes are cut to a length such that the knit is tensioned as a planar surface. The ends of the rods are covered with a rubber cap.

2. The end of the tubes are connected by cable tie through the knit around the separate tube ends, then connected to create the arch by iron wire.

3. Some ends of the tube broke through the knit, even with the rubber ends. The single jersey knit almost always breaks, the nylon combined polyester did not. A quick fix is to coat the tunnel ends.

4. The two segments are connected at the bottom using iron wire. At the top, one tie wrap through the knit on both sides are used to connected the middle of the opposite crossing rod to the side rod.

Learnings
The assembly, starting after the panels are knitted, resulted in a few learnings.

When the length of the tube is adjusted to the length of the tunnel, the tension of the surface is determined. In this case, the surface could be tensioned more but it increases the difficulty of manually inserting the tubes into the tunnel. Determining the length of the tubes after knitting can be considered an adaptability of the design. It however does add another step of manual labour to the production process.

Second, as mentioned before, the weak spots of the knit are the ends of the tunnels where the tubes ends are inserted. These segments require reinforcement, either through yarn material, stitch structure, or other rigidifying methods.

3.4.2 Preliminary technical evaluation

Load-bearing capacities
The load-bearing capacity of the prototype is evaluated by sitting on it.

Test 1
A user sits down for approximately 10 seconds without leaning fully into the chair. The attempt, see Figure 73, shows the bending of the side rods when a load is applied onto the knit. The legs of the knit tend to move outwards until the iron wire in between the legs is tensioned.

Test 2
The iron wires between the two segments are shortened to increase the tension on the crossing rods and top surface.
A user sits down for approximately 10 seconds without leaning fully into the chair.
The attempt, see Figure 74, shows the bending of the crossing rods. It seems like the user is leaning on the crossing as well as the knitted fabric.

Test 3
A user attempt to sit down, finally sitting for approximately 3 seconds before a tube poked through the knit at one of the tunnel ends, making the chair collapse partially, see Figure 75.
The user expressed feeling “anxious” while slowly leaning more into the knit.

Test 4
A user sits down in the chair sideways, despite one tube still pocking through the knit, see Figure 76 and 77. The structure does not fully collapse despite this defect. Sitting on the chair sideways requires one side tube to be lowered. It enables the user to sit only on the knit in between the crossings, and potentially lean back if the other side tube is made higher.

Figure 73. Test 1

Figure 74. Test 2

Figure 75. Test 3

Figure 76. Test 4

Figure 77. Test 4

3.4.3 Improvements

Evaluating and reflecting on the prototype resulted in some possible improvements. See Figure 78 for the improvements, explained from top to bottom below.

First, the sitting direction of the chair could improve the stability of the object. Sitting ‘sideways’ as demonstrated in Preliminary Technical Evaluation Test 4, will put more tension on the knit and frame because it is used both as sitting surface and back rest. See Figure 79 for the improved design. The back rest is heightened.

Second, the crossing tubes should be attached on top of the side tubes in other to distribute the force over the side arch.

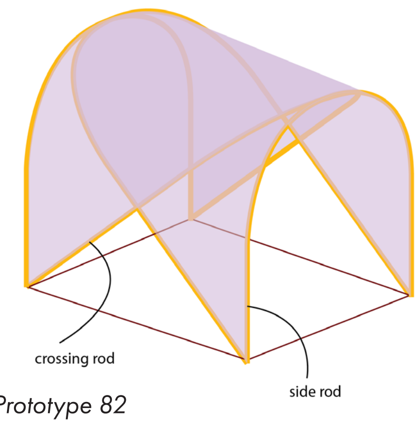
The crossing of the tubes requires a rigid connection. Inserting both crossing rods through both panels could be such a connection, however still flexible through the knit. This would change the look of the design, for the overlapping of the two panels would not be needed anymore. A more rigid solution could be to use a nut and bold through the tubes, requiring an opening in the knitted tunnel.

Additionally, a cable connection between the crossings will counter the outward movement of the crossing tubes, increasing the stability of the object.

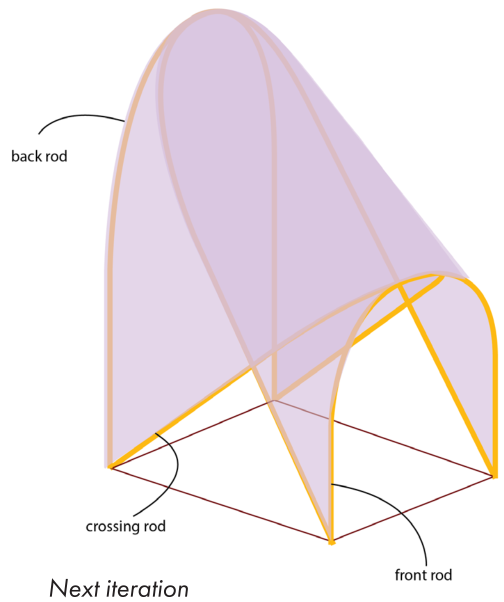
A turnbuckle between the cable connections of the side tubes can determine the height of the arch and thus the height of the sitting surface.

The tunnel ends where the tube ends meet, requires more rigidity. As Test 3 showed, these are the weakest spots where all directed forces come together. The knit can be reinforced using nylon yarn in both layers of the knit, or using a melting yarn that becomes rigid upon heating, or coating the ends of the structure.

The lesson of Prototype 82 are taken into account to develop Prototype 86.



Prototype 82



Next iteration

Figure 79. Revised sitting direction

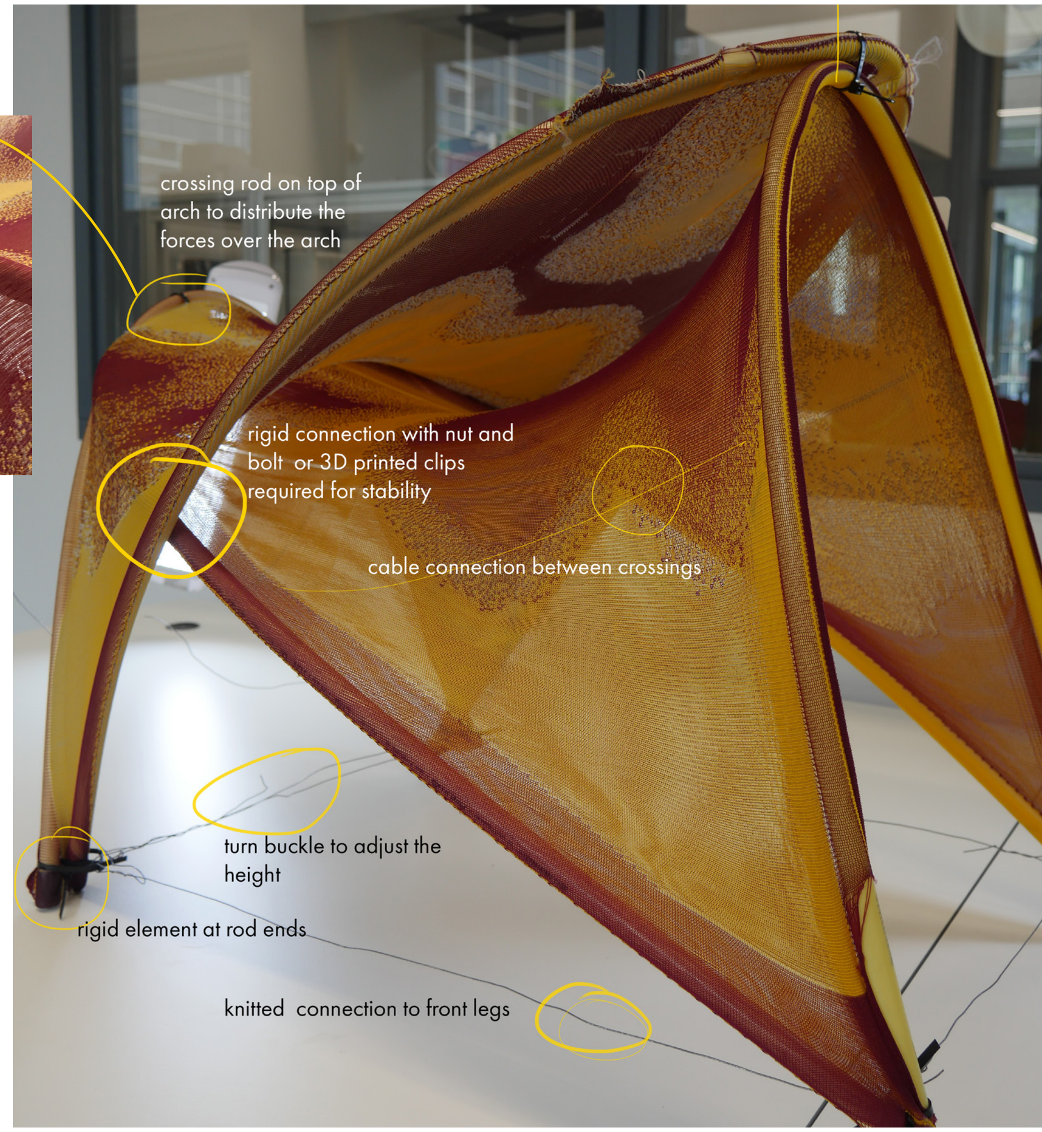


Figure 78. Improving the load-bearing capacity

Prototype 86

This second prototype is an iteration on Prototype 82, to explore the use of a spacer structure, the revised sitting direction and height difference between the front and back of the chair.

3.5.1 Assembly

The assembly is very similar to that of Prototype 82.

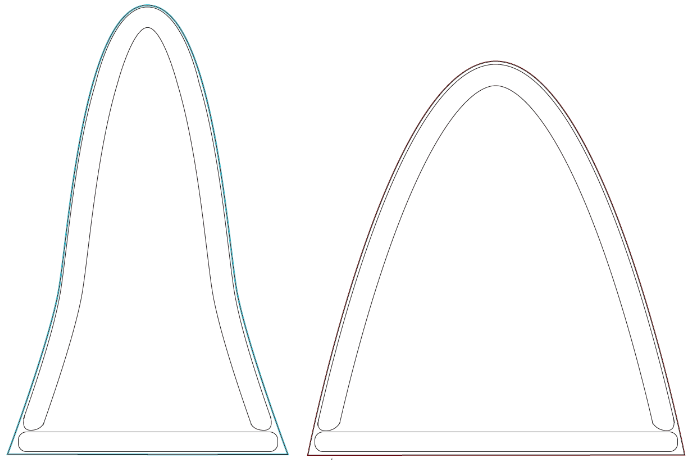


Figure 80. Sketch outline

Programming the knitted panels started with a sketch in Adobe Illustrator to be able to draw a perfectly symmetrical curvature as an outline, see Figure 80. (Adobe Systems, 2023) The drawing is imported in the M1Plus software. (STOLL, 2021) The colour arrangement of Prototype 82 is used.

Figure 81. Prototype 86

The goal of the prototype is to explore the possible height difference between the front and back of the chair, therefore the curvature and size of the panels differ. The PVC is inserted in the knitted panels. The tube ends are connecting using tie wraps and iron wire. See the final configuration in Figure 81.

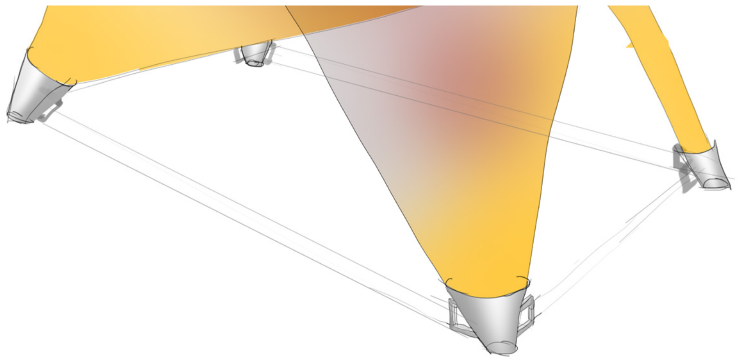


Figure 82. Sketch of ends of the legs

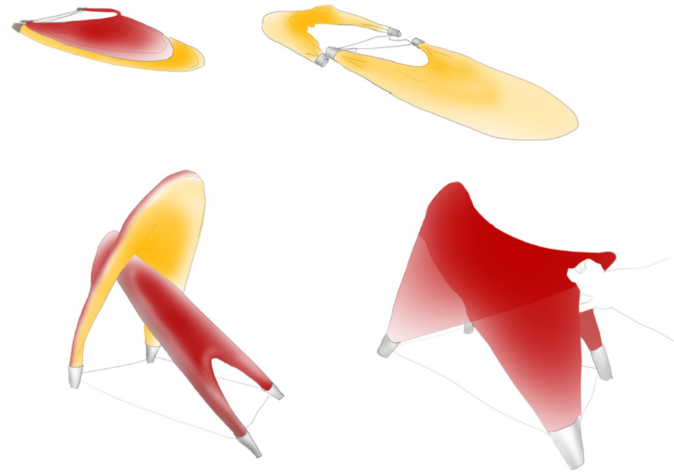


Figure 83. Transformability during use

3.5.2 Improvements

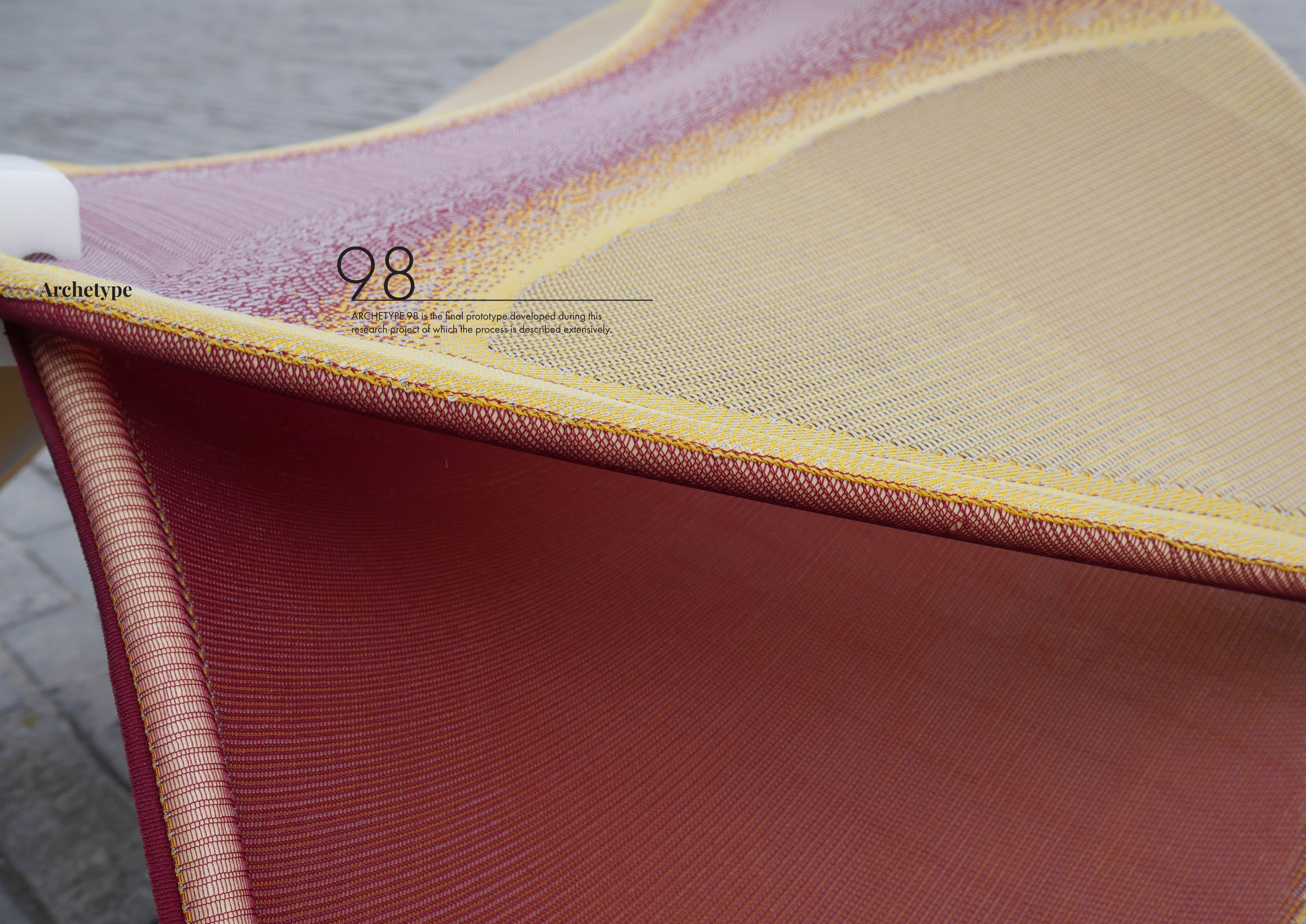
The tension caused by the length difference of the cables and crossing tube is used to create the final geometry. No further connection between the top parts is made due to limited time.
The prototype is not evaluated on the load-bearing capacity because of the small size due to the spacer stitch structure utilized in both panels.

The spacer structure has a low elasticity in the knitting direction, which makes it difficult to insert the front and back tubes into the tunnels without buckling.

The limits of the knitting machine are exposed. The widest panel is knitted at the maximum width of the knitting bed. To make the back arch even higher, the knit should stretch more, or the knitting direction should be tilted 90 degrees, which again then compromises the maximum height of the panel.

The tunnel ends did not burst under the tension of the tubes, although no load is applied. If both tube ends would poke through the knitted tunnel, the knit will slide upwards over the tube, releasing the tension in the sitting surfaces.
Sample 85, see Appendix A, is an experiment to connect the ends of the tubes with a knitted cable and reinforce the tunnel ends. The tubes however slip out of the knitted pockets.
Covering the panel ends with a 3D-printed foot can protect the tunnel ends from the friction between the tube and the floor, and can connect the cables without damaging the knitted panels. A first sketch of 3D-printed parts is shown in Figure 82.

Figure 83 shows the transformability process ‘during use’.



Archetype

98

ARCHETYPE.98 is the final prototype developed during this research project of which the process is described extensively.

3.6.1 Introduction
To show the local adaptability of the stitch structure, multiple samples of a double jacquard combined with a spacer structure are developed, see Appendix A Sample 90 to 93. The attempts led to the conclusion that this requires too many iterations for the limited time available to include it in the final prototype. Further research on this specific stitch structure combination is required.

As seen in both previous prototypes, the ends of the knitted tunnels require reinforcement to prevent the tubes from breaking through. Integrating nylon yarn in the stitch structure will increase the tensile strength but limit the elasticity of the tunnel. See Appendix C for material properties of the utilized yarn materials. Only partially knitting the nylon yarn as an intarsia structure however requires two cones of the nylon yarn, which are not available at the time. See Sample 94 in Appendix A for an example of an attempted solution.

3.6.2 Panel designs
The final prototype is an iteration of Prototype 82 and 86. The intend is to knit Panel 1 with double jacquard stitch structure and Panel 2 with spacer stitch structure.
The design process starts with a drawing in Adobe Illustrator, determining the width, height and curvature of both panels. (Adobe Systems, 2023) The maximum width of the knitting bed is used for both panels. The height of Panel 1 is 800 stitches, the height of Panel 2 is 700 stitches.
The different stitch structures and thus material properties will result in a slightly smaller second panel. The height difference creates a higher backrest and lower front part of the chair.

The exact dimensions after knitting are unknown.

The drawing of Panel 1 is opened in Adobe Photoshop to add the heatmap motif to the double jacquard. (Adobe Systems, 2023) The heatmap represents the tension in the panel, from the top of the curvature towards the ends of the rods. The drawings of Panel 1 and 2 are exported to bitmaps through Adobe Photoshop. The bitmaps are imported into the M1Plus software. (STOLL, 2021)

Manual adjustments of the drawing are required.
A mesh knit structure is added to panel 1 within the heatmap motif to show the local adjustment of the knit structures of the object.

Panel 1
The base structure of the panel is the double jacquard stitch structure. The grey forms the tunnel for the tubes: two layers are knitted separately. The knit is programmed in the symbol view of M1Plus software (STOLL, 2021), see Figure 84.

Top segment
The top segment of the panel requires a high reduction of stitches if the steepness of the tunnel is followed. Due to a lack of knowledge on how to decrease multiple stitches within one row, the reduction of stitches stops the moment the tunnel requires more than 1 stitch reduction within one row. Knitting is continued on all stitches and the switching of yarns closes off the tunnel at the top. The green line underneath the tunnel and the blue line above close off the tunnel when the line is horizontal by knitting on the front and back, and alternating knit with tuck stitches.
Before casting off, all stitches are transferred to the front bed to ensure no stitch is dropped.

Middle segment
The middle segment consists of a mesh structure, in lighter pink, and the double jacquard with dark red and yellow.
On both sides of the tunnel, the red and yellow switch to close off the tunnel on both sides. If this would not be done on the edge of the fabric, the two layers would stay separated and no tunnel is formed.

Bottom segment
As explained, it is desirable to use nylon yarn at the tunnel ends. The availability of only one cone of each needed yarn lead to the following structure at the bottom of the first panel.
The off-white and orange area utilizes three polyester yarns and a fourth nylon yarn. On the front bed, the nylon and dark red polyester are alternating knit and tuck stitches. On the back bed, the yellow and grey yarn are alternating knit and tuck stitches. The blue and light blue block at the bottom of the tunnel creates an opening in the tunnel. All stitches are transferred to the back, after which the stitches are set up again on the front bed by alternating knit and float stitches, separately from the back bed to keep the separation that creates the tunnel.
The dark grey, green and yellow above it only use the three polyester yarns. The green line is again used to close off the tunnel at the horizontal top line.

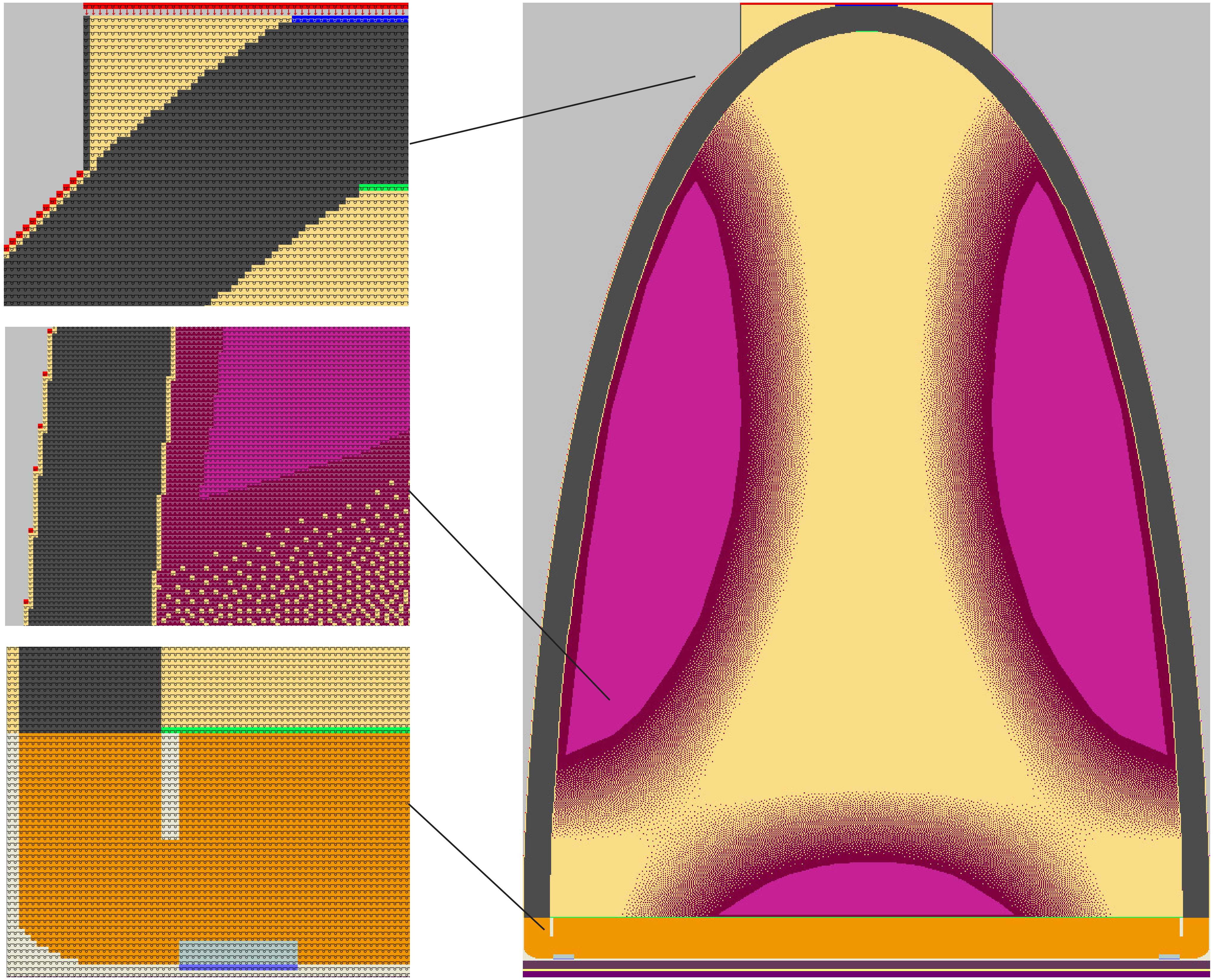


Figure 84. Symbol view of panel 1 in M1Plus software (STOLL, 2021)

Panel 2

Panel 2 is built up similarly to Panel 1 in terms of shape-making, tunnel forming (in green) and tunnel openings, see Figure 85. Here the nylon yarn is knitted throughout the whole panel. The dark grey area contains the spacer structure. The nylon yarn tucks between the two beds while the red polyester yarn knits on the front bed and the grey and yellow alternate on the back bed. The nylon alternates knit stitches with the red polyester on the front bed to form the tunnels.

The colour arrangement of both panels is shown in Figures 86 and 87.

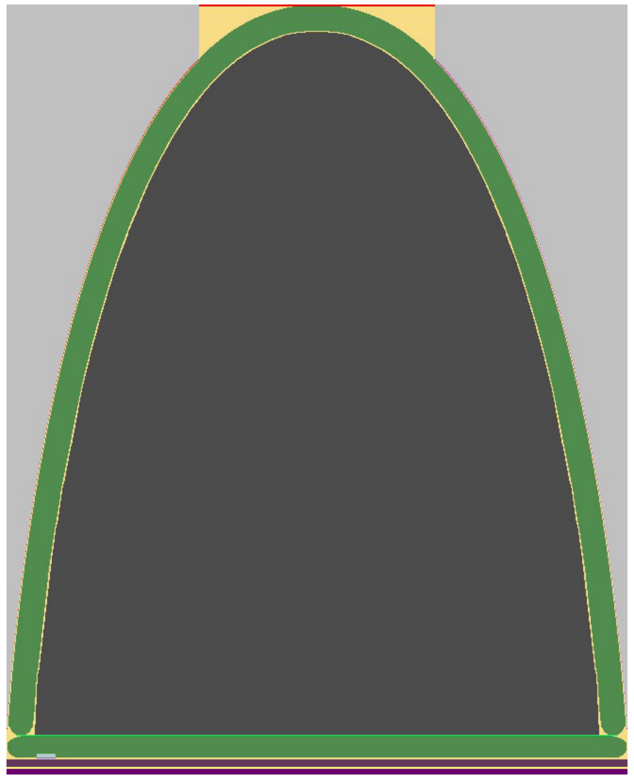


Figure 85. Symbol view of Panel 2

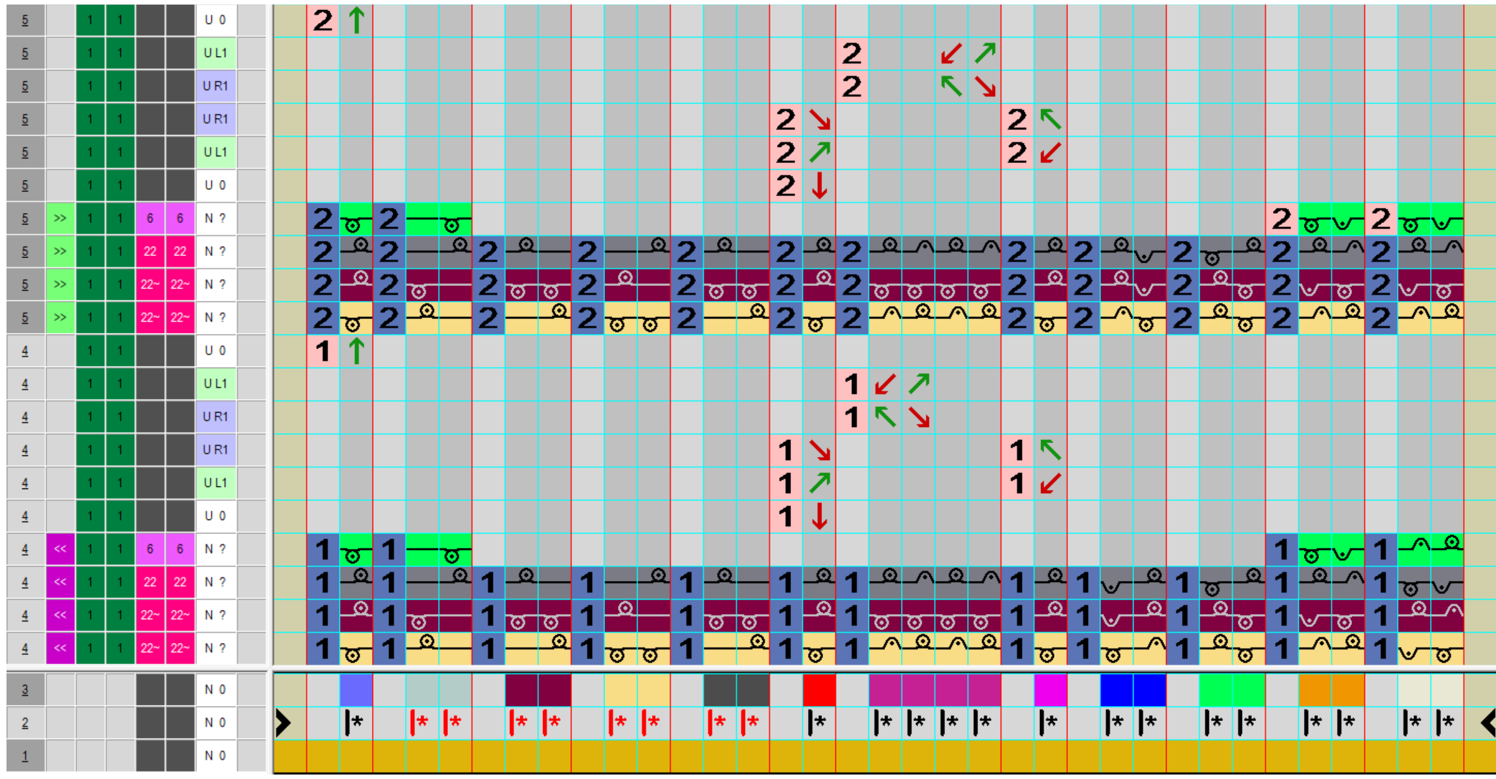


Figure 86. Colour arrangement of Panel 1

Knitting efficiency

The M1Plus software presents a 'receipt' of the knitting file when it is processed and ready to be knitted, see Figure 88 for the receipt of Panel 1 and Figure 89 for the receipt of Panel 2. (STOLL, 2021) Multiple measures are presented that can give an indication of the efficiency of the programmed knit file.
Empty rows are rows where the carrier moves over the bed without knitting or transferring any stitches.
Panel 1 has 51% transfer rows because of the segments of mesh structure. Panel 2 only has 23% transfer rows, required to create the shape of the panel. The amount of empty rows in Panel 2 is much higher than in Panel 1, resp. 14% and 3% because four yarn feeders are used, all starting at the right side, throughout the whole panel.

The knitting time of Panel 1 is 52:01 minutes and of Panel 2 71:17 minutes.

```
Program needs 1794076 Bytes.

Strokes:                2706
Empty strokes:     145     5 %

Knitting rows:    2647    47 %
Transfer rows:    2881    51 %
Split rows:          0     0 %
Empty rows:        145     3 %
WKT rows:         5673   100 %
System load:        70 %

**********************************
Simulation OK
**********************************

 Calculated knitting time:52 min  01 sec  +/- 5 % (CL-200)
```

Figure 88. Receipt of Panel 1

```
Program needs 1372164 Bytes.

Strokes:                3142
Empty strokes:     808    26 %

Knitting rows:    3536    63 %
Transfer rows:    1289    23 %
Split rows:          0     0 %
Empty rows:        808    14 %
WKT rows:         5633   100 %
System load:        60 %

**********************************
Simulation OK
**********************************

 Calculated knitting time:71 min  17 sec  +/- 5 % (CL-200)
```

Figure 89. Receipt of Panel 2

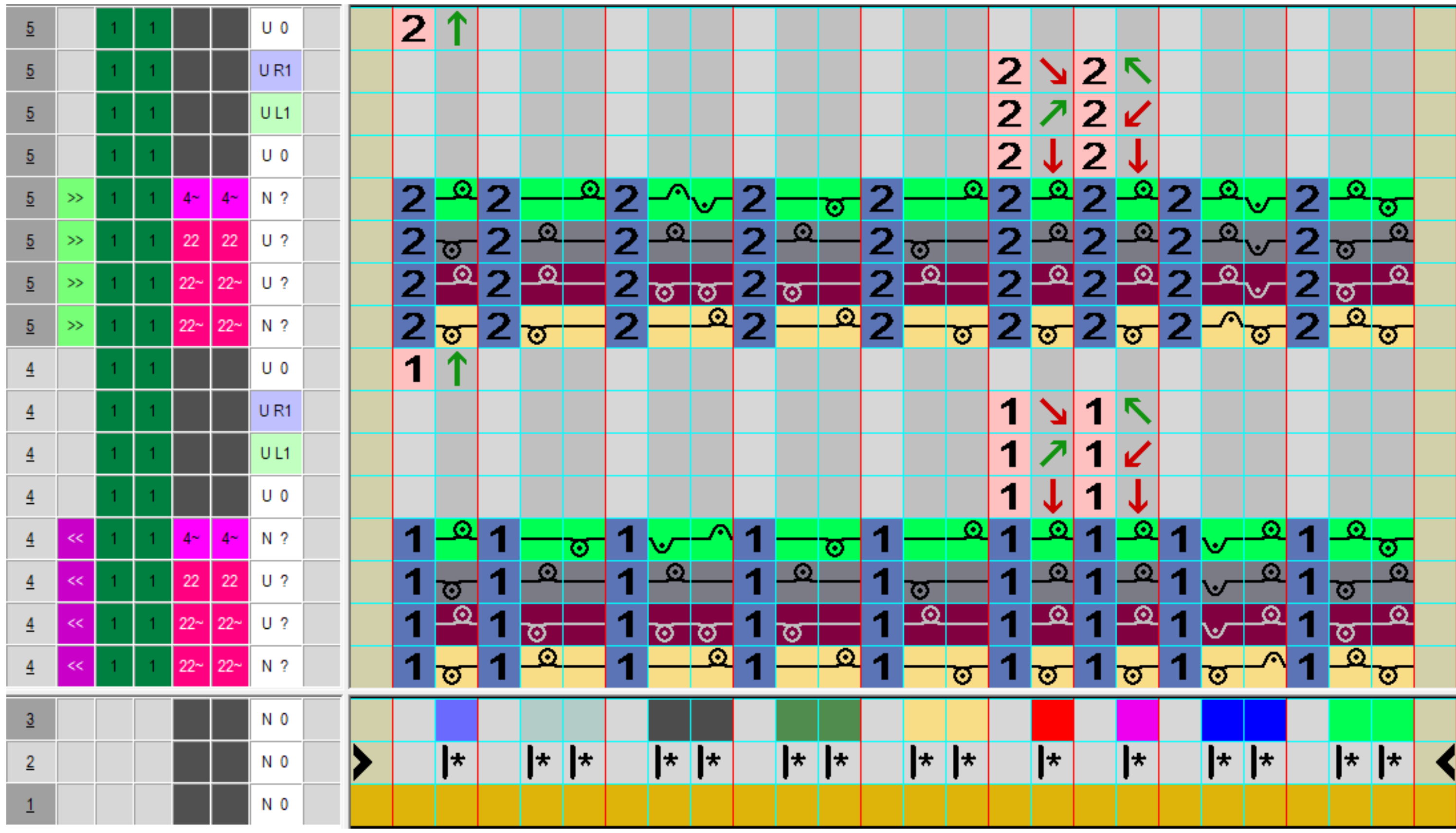


Figure 87. Colour arrangement of Panel 2

3.6.3 Geometry

The sizes of Panel 1 and 2 were expected to differ, however, the knit structures result in a size difference that is too large to create the desired geometry. As shown in Sample 96 in Appendix A, the crossing tube of Panel 1 is too long compared to the back tube of Panel 2, leading to bending outwards. It is knitted as wide to be able to create a heightened backrest. The discrepancy thus is not because the crossing tube of Panel 1 is too long, but because the back tube of Panel 2 is not long enough. This length is determined by the maximum width of the knitting bed, thus panel 2 cannot be knitted wider with this stitch structure. Therefore, Panel 1 is sized down to compensate. An attempt is made to scale the bitmap of the M1Plus (.mdv) file down using Adobe Photoshop (Adobe Systems, 2023), leading to an inaccurate new bitmap. Sizing down the knit file is done manually directly in the M1Plus software. (STOLL, 2021) A second version of the double jacquard panel is knitted, see Figure 90. Details are visible in Figure 91.

3.6.4 Frame material

To increase the bending strength and bending stiffness of the structure, GFRP tubes are used. The exact composition of the material is unknown, therefore the exact tensile and compressive strength is unknown. See Appendix C for general material properties of GFRP and PVC.
The tubes have a diameter of 8 mm and a maximum available length of 2000 mm. The GFRP tubes are inserted into the PVC tubes to maintain the tight fit of the clamps. An additional benefit of this is related to the health hazards of GFRP. To saw or sand the GFRP tubes, a mouth mask is worn and suction is applied to prevent contact with splinters. Since the object is exposed to high loads with may cause damage or buckling of the GFRP tubes, the user is shielded from any physical contact with the material by inserting the tubes into the PVC tubes. See Figure 92 for the materials.

The difference in shape of the panel is visible in Figure 93: the higher curve is created by the PVC tube, the rounder and flatter curve by the GFRP inserted in the PVC. See Figure 94 for a close-up of the stitch structure.

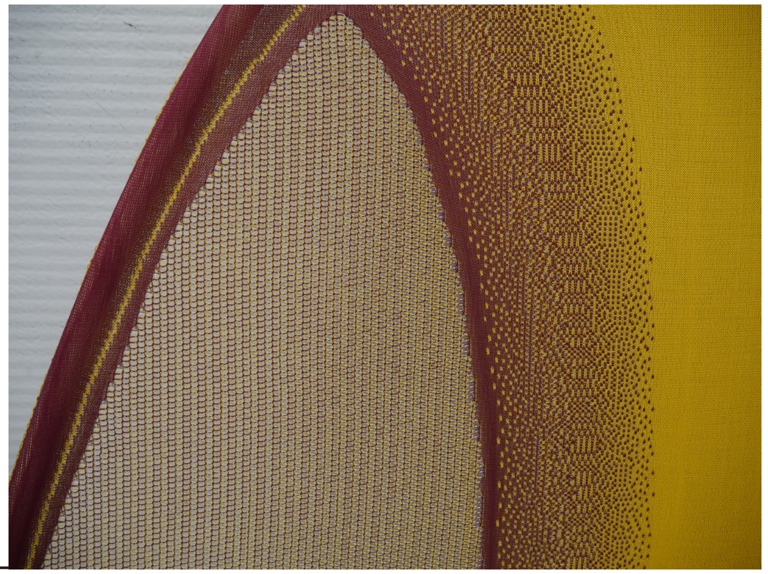


Figure 91. Panel 1 stitch structure detail

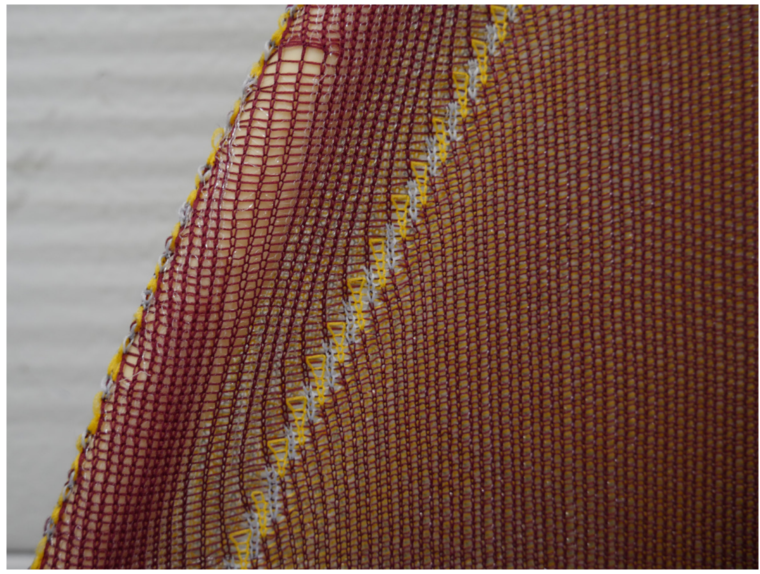


Figure 94. Panel 2 stitch structure details

Figure 90. Resized version of Panel 1

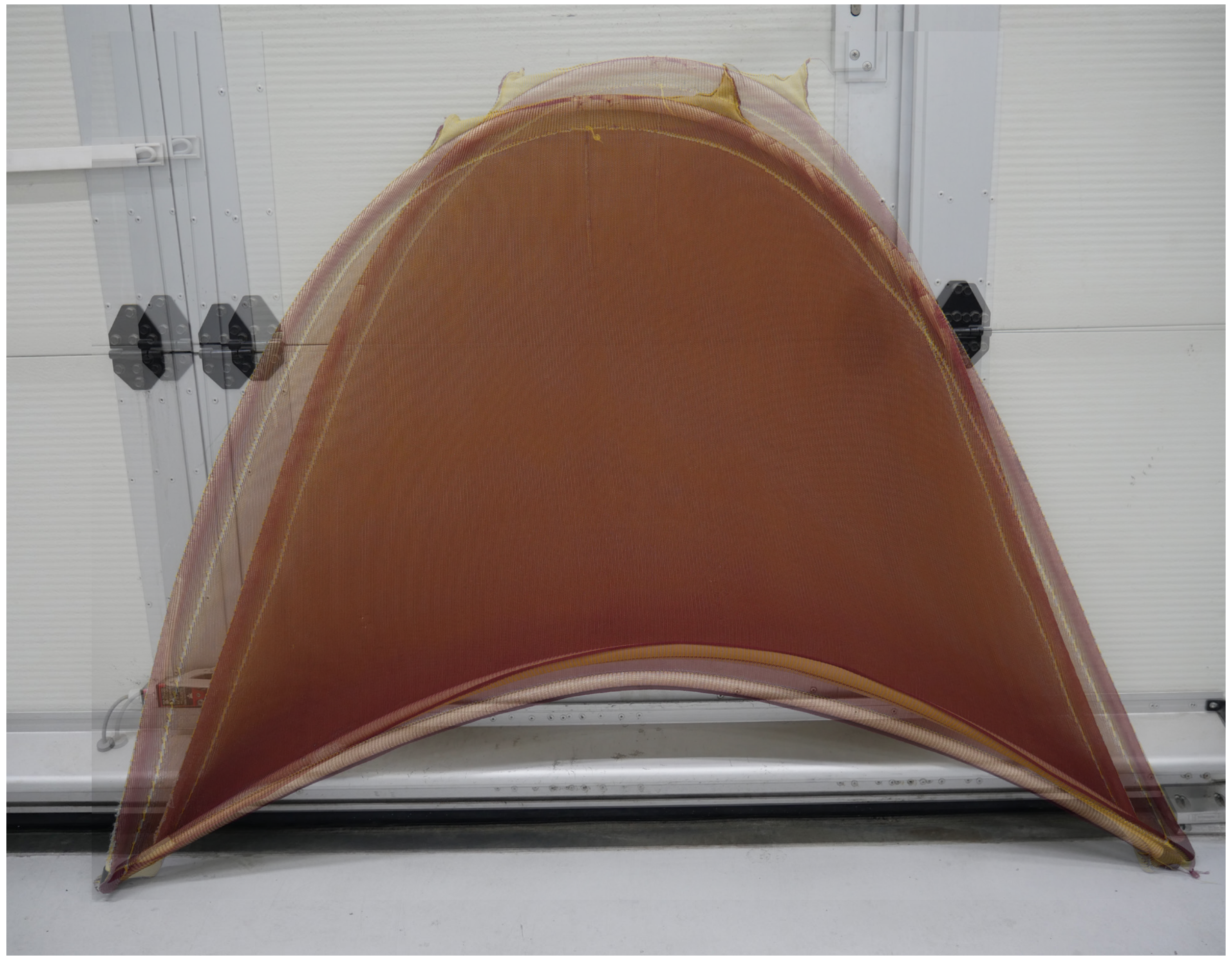


Figure 93. Curvature difference of panel when combining GFRP tube with PVC and only PVC tube

Figure 92. Solid PVC rods into the PVC tube to keep the GFRP tube in place

The two panels, each composed of the two tubes and one knitted fabric, need to be connected to create the desired geometry. Prototype 82 and 86 did not address this critical design aspect yet, so the developmment process is elaborated on in this chapter.
It is a critical part, because it greatly contributes to developing the prototype towards a product that can be evaluated on the performance and functionality.

3.6.5 Feet

The ends of the panels are connected by a 3D printed foot. The foot is designed based on the dimensions of Prototype 82, estimating the angle between the rods. The 3D model is shown in Figures 95 and 96 including the dimensions. Two holes on three sides of the foot allow for a cable to connect the feet to each other.
The feet are printed in polylactic acid (PLA), the most widely used printing material. The feet are evaluated on their fit to the panel ends. The feet are connected with steel wires and turnbuckles to make the distance between the feet adjustable, see Figure 97.

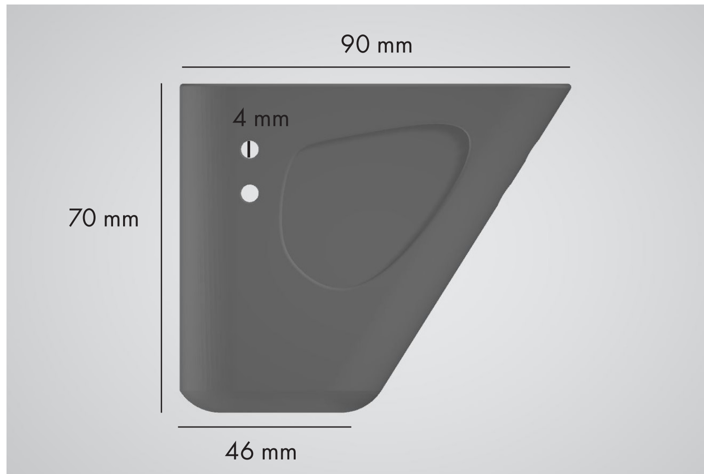


Figure 95. Foot side view

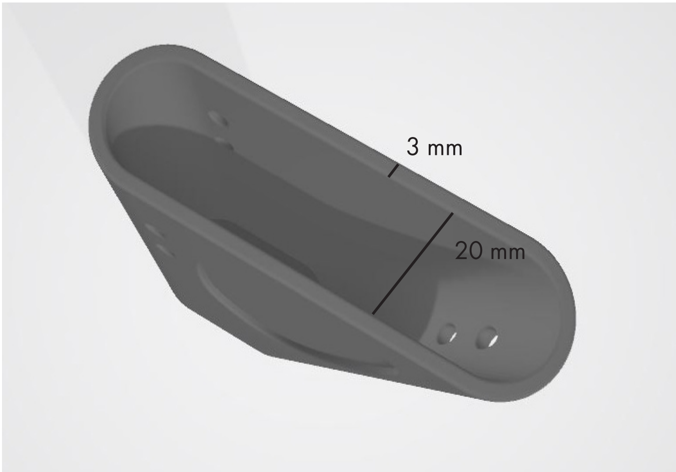
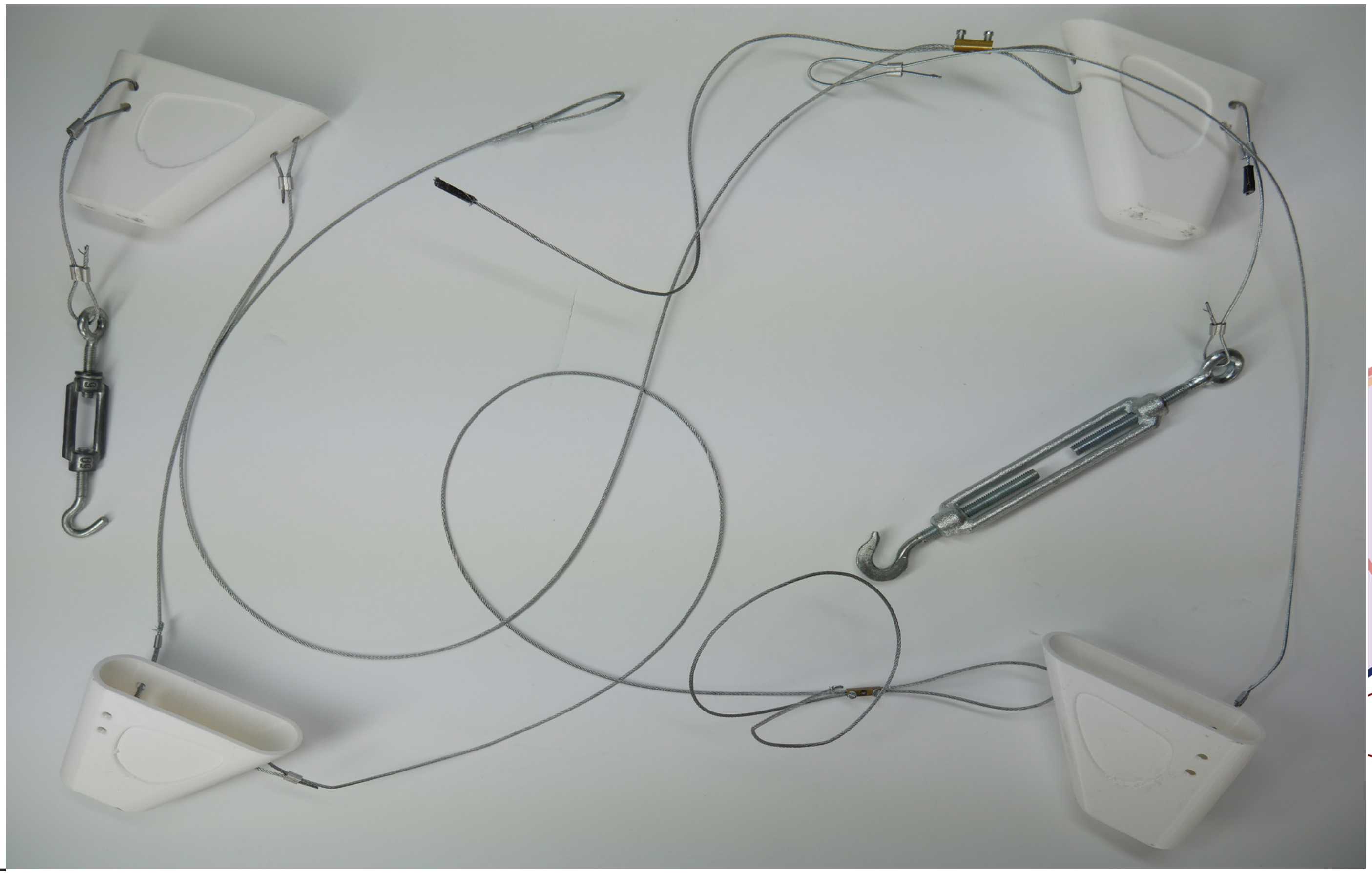


Figure 96. Foot top view: holes on three sides

Figure 97. 3D printed feet connected with cables



3.6.6 Tube fixation

As evaluated in Prototype 82, the connection of the tubes is critical.
The fixation should not allow the tubes to move out of position when the load is applied to the object, because the configuration ensures the load is directed onto the front/back tube to stabilize the structure, see Figure 98. Multiple methods of fixation are explored.

The tubes could be fixated by screwing them on top of each other. The screws would have to go through the knit which would damage the knit even if a specific hole is knitted in to create space for the screw. The knit will be pulled strongly around the fixation points when a load is applied onto the sitting surface. Creating holes in the knit in both layers of the tunnel is not considered possible without reducing the knit density of the tunnel.
Plus, the method does not allow for easy deployment.

Knitting in holes on both panels such that at deployment the holes overlap and something can be wrapped around the tubes, through the knit, is considered. The exact location of the holes would have to be predicted. Perforating the knit makes it structurally weaker, however, the connection of the rods can be strong.

Second, attachment with velcro is explored, see Figures 99 and 100. Velcro allows for easy manual deployment and fixation and is known for its strength. As hypothesized before trying, any fixation that is only attached to the knit will make the knit twist around the tubes until a position of least resistance is found. Pulling only on the knit, while not going fully around the tubes, does not fixate them in the desired position. Plus, the velcro is sewn on top, adding manual labour to the production process.

The experiment demonstrates the fixation needs to be rigid, not going through the knit but over it, and strong enough to hold the tubes in the desired configuration without displacement when load is applied.

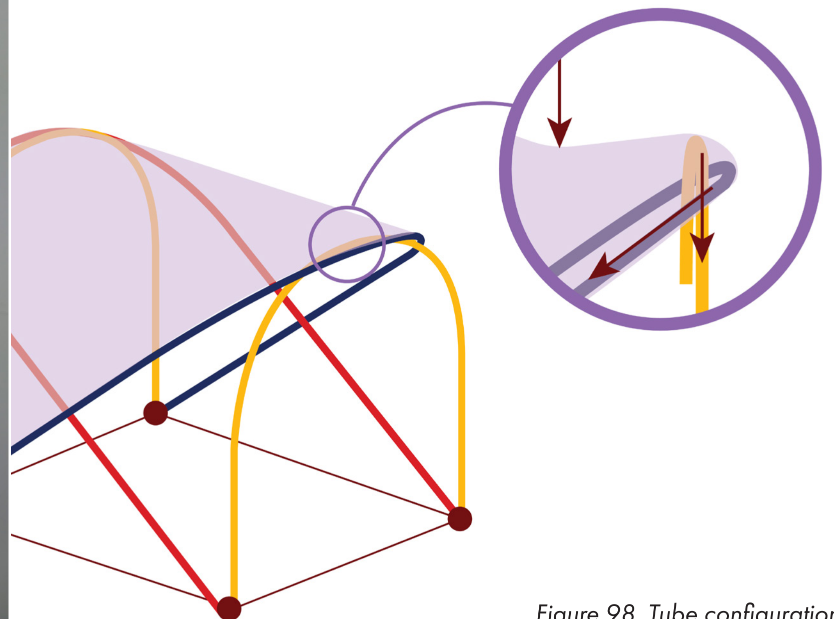


Figure 98. Tube configuration

Figure 99. Velcro attached to Prototype 82

Figure 100. Velcro attached to Prototype 82, pulling on the knit

Figure 101. Metal clamp

Clamps are designed to fixate the rods. The functionality of the clamp is explored with a strip of steel bend into a clamp, see Figure 101 (previous page). The clamp should be open on one side for the continuation of the knitted panel and fixated on the other end to clamp the tubes together. The clamp cannot consist of one part, because the flexibility it would need to open to go over the tubes would compromise the strength of the clamp. Thus the clamp needs to consist of two parts attached only on one side.
To prevent the rods from rotating around each other, two clamps are used.

The first design is made in Autodesk Fusion 360 (Autodesk, 2023), see Figure 102. The curvature of the two tubes results in a slight distance between them at the point of attachment. The distance and angle are estimated based on visual inspection of Prototype 82.

The clamps are 3D printed in PLA using the Ultimaker 2. (Ultimaker, 2013)
Two nuts and bolts are required to attach the clamp to the object. The clamps are bolted onto Prototype 82. The angle in the Y plane was not taken into account in the design. The clamp broke on the thinnest part of it when a load was applied to the tubes, see Figure 103.

The following iteration, the clamp is made thicker and printed in three different materials: PET-G, PET, and PP. PET-G is more flexible than PET and PP. PP is often used for living hinges because it is known for its excellent fatigue resistance. (Xometry, 2022) See Figure 104 for the 3D modelled adjusted design and Figure 105 for the printed clamps. The clamps are evaluated on the fixation onto the frame of Prototype 82, if the designed angle allows full encasement around the tubes, and on the possible load to be applied onto the object, see Figure 106 and 107.
A gyroid infill pattern is used because it is equally strong in X-, Y- and Z-direction, where a standard cubic infill pattern is equally strong in X- and Y- but not in Z-direction. (Dickson, 2023)

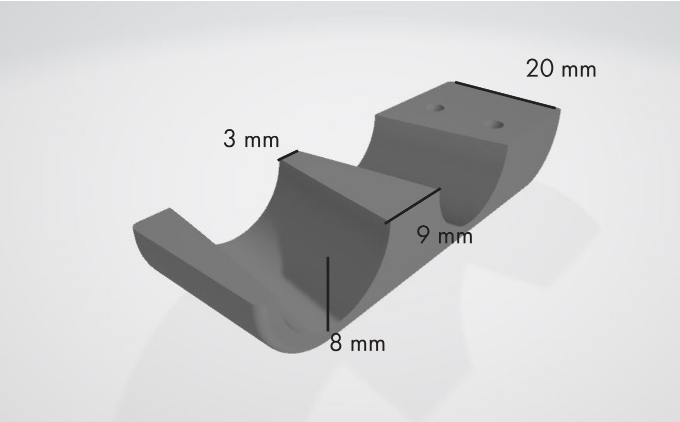


Figure 102. Clamp iteration 1

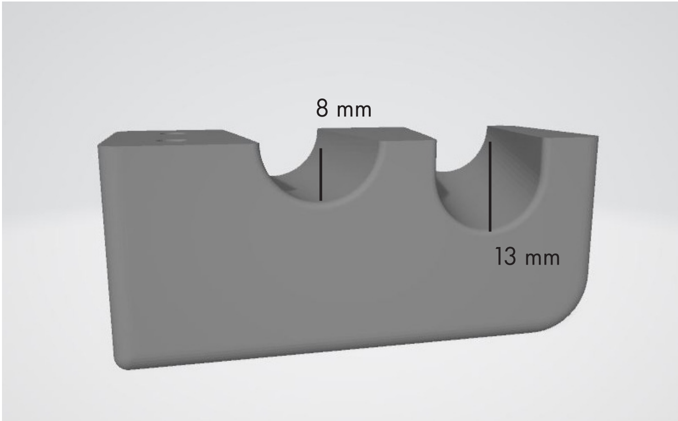


Figure 104. Clamp iteration 2

Figure 103. First PLA 3D-printed clamp

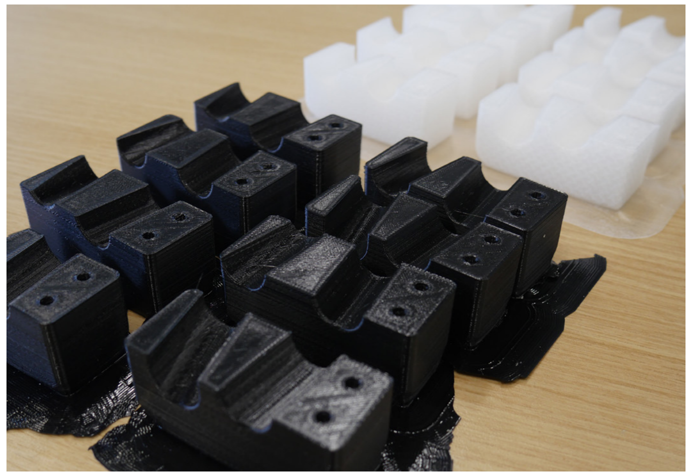


Figure 105. Printed clamps, black is PP, white it PET-G

Figure 106. Clamp attached to Prototype 82

Figure 107. Clamp attached to Prototype 82

As learned through Prototype 82, connecting the tubes at the crossings and attaching the left and right crossing with a cable could improve the stability of the object. A clamp is designed with two holes to attach the two clamps. The clamp is based on the same concept as the beforementioned clamps thus 3D printed as two parts of PLA.
The model is shown in Figure 108 and 109. The 3D printed parts are attached to Prototype 82, see Figure 110 and 111. The clamps fit tight around the PVC tubes and knit. The sharp edges of the clamp damaged the knit slightly. The clamp parts are attached with two 3 mm nuts and bolts.

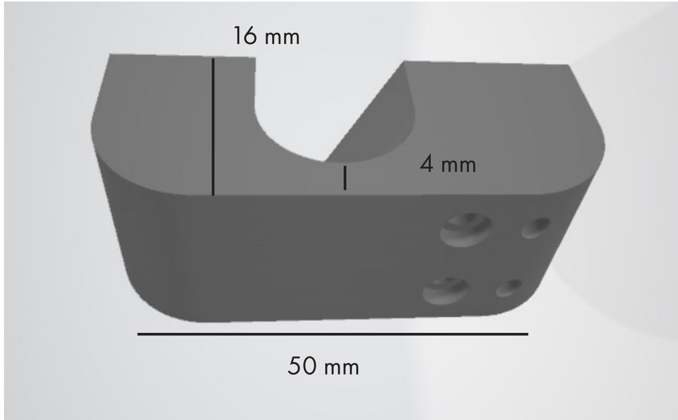


Figure 108. Side clamp front view

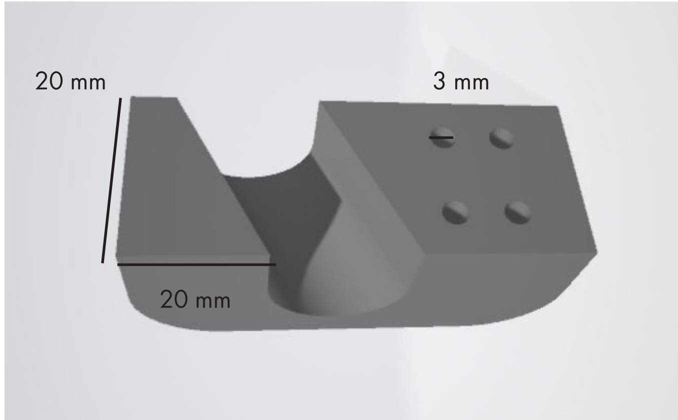


Figure 109. Side clamp back view

Figure 110. Side clamp 3D printed attached to prototype

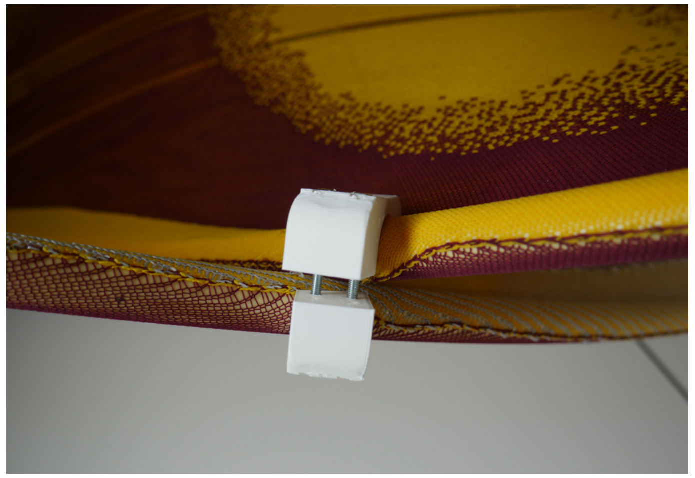
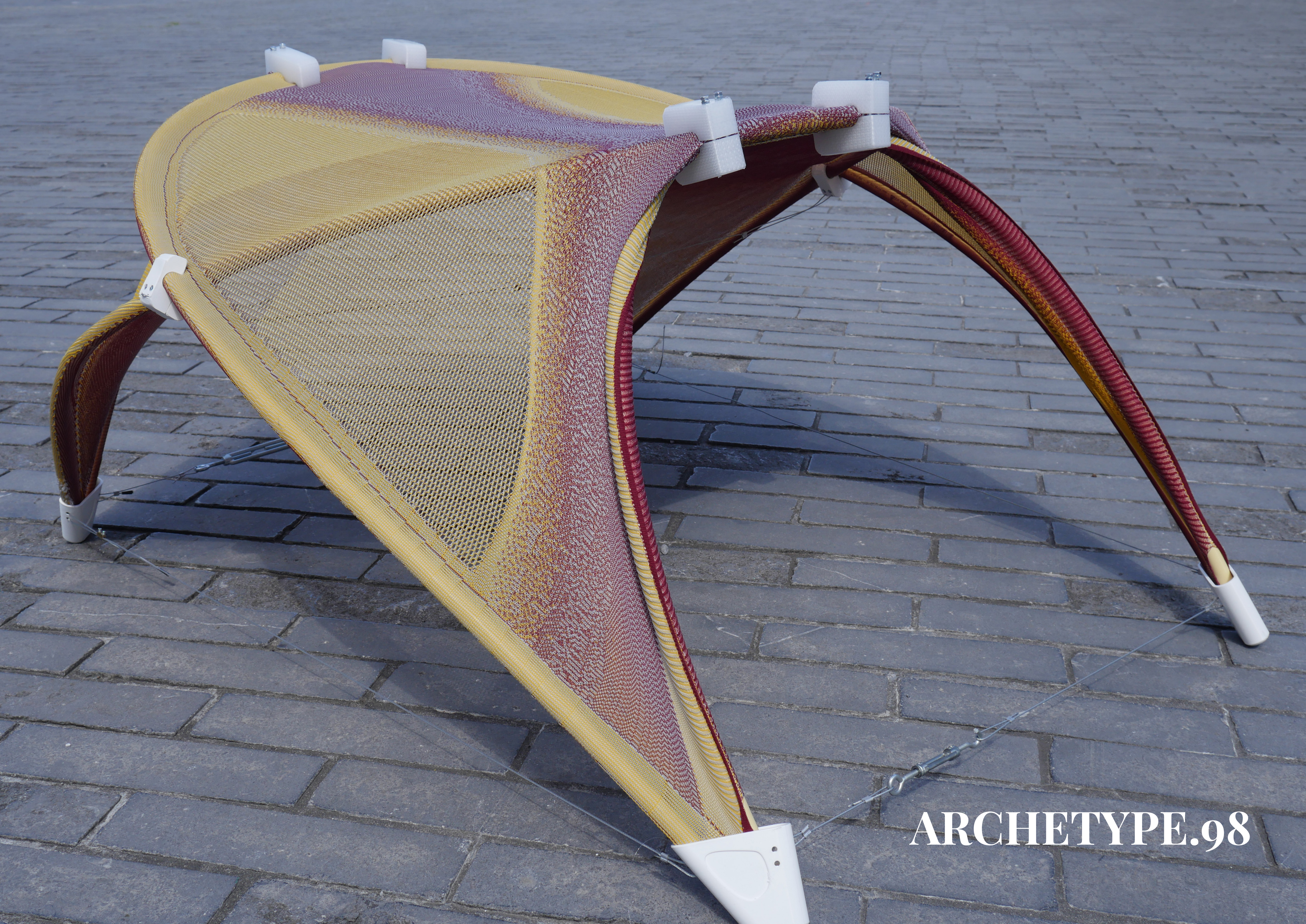
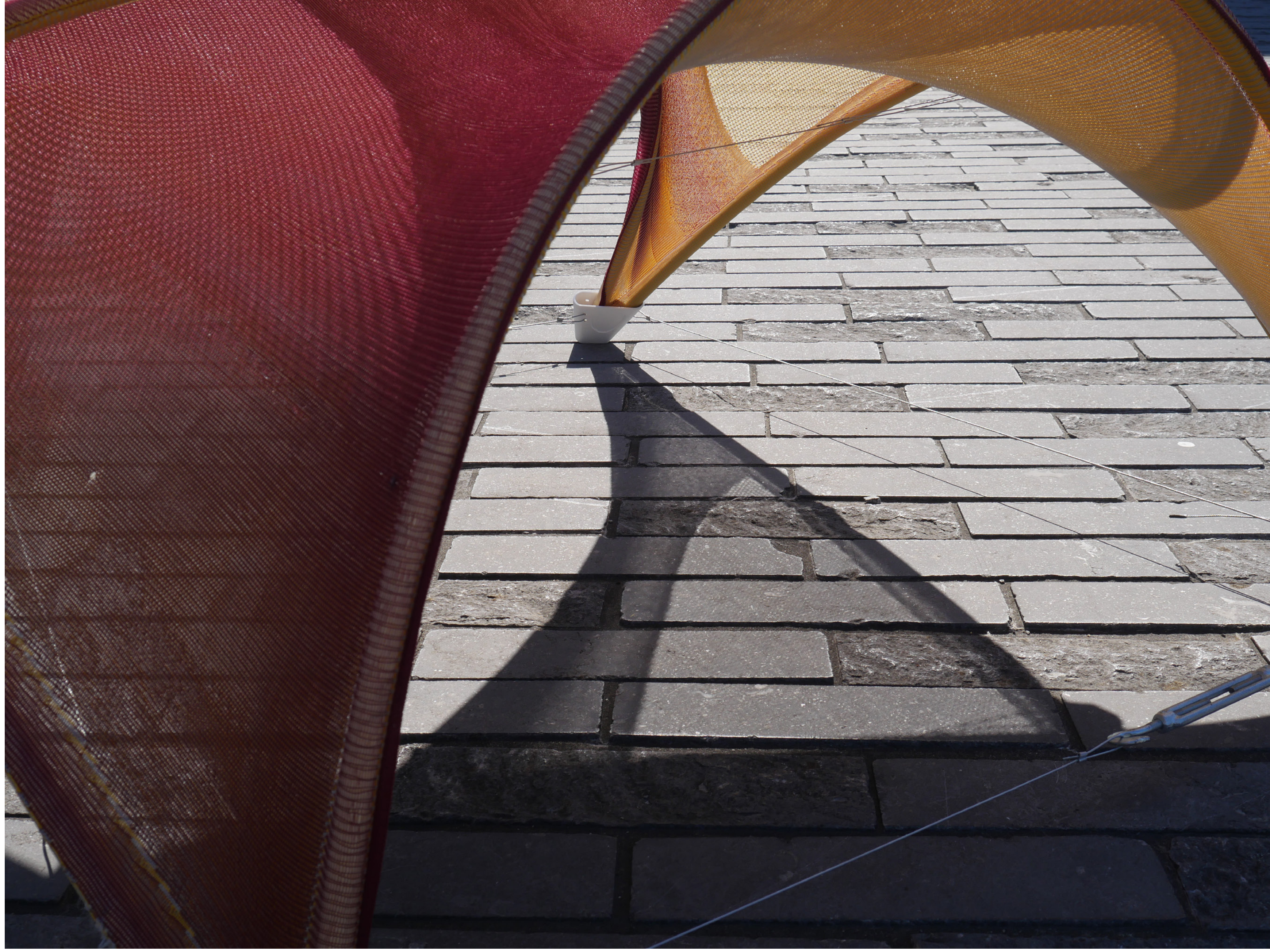
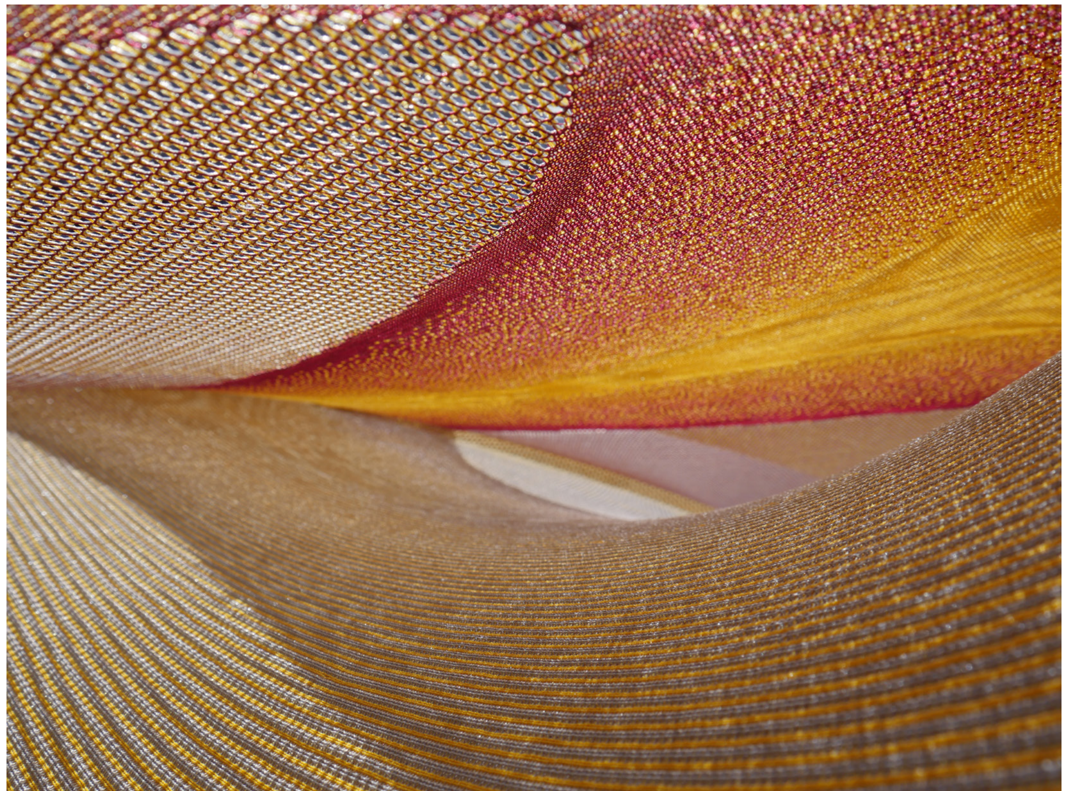


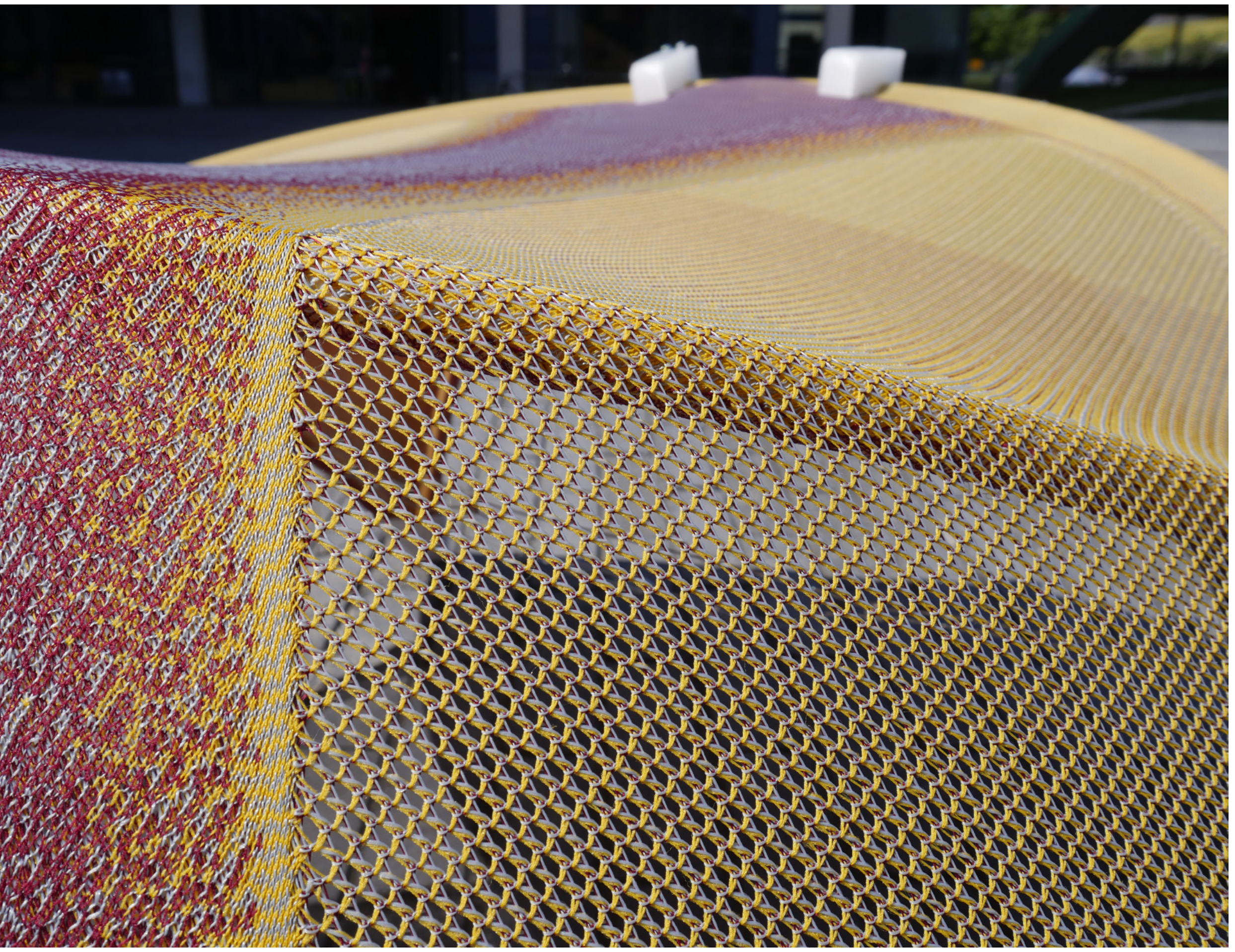
Figure 111. Side clamp 3D printed attached to prototype

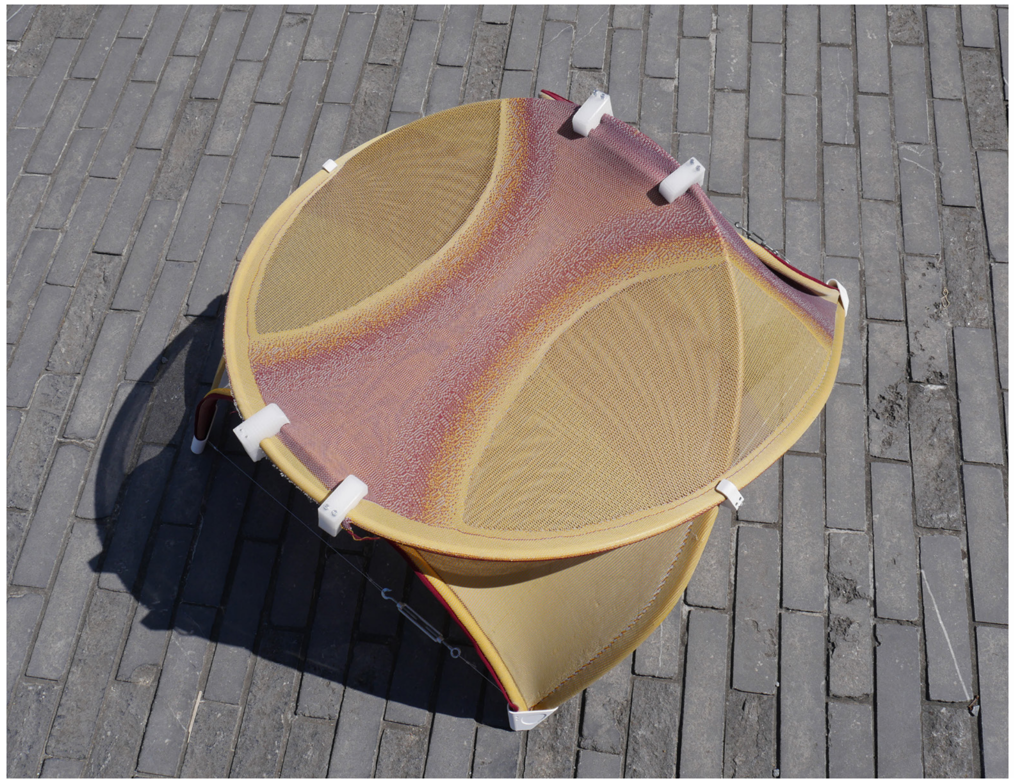
3.6.8 Final prototype
ARCHETYPE.98 is assembled in a similar manner as Prototype 82 and 86.
The result is presented on the following pages as the final prototype of this research. The prototype is evaluated in the fourth and last phase.

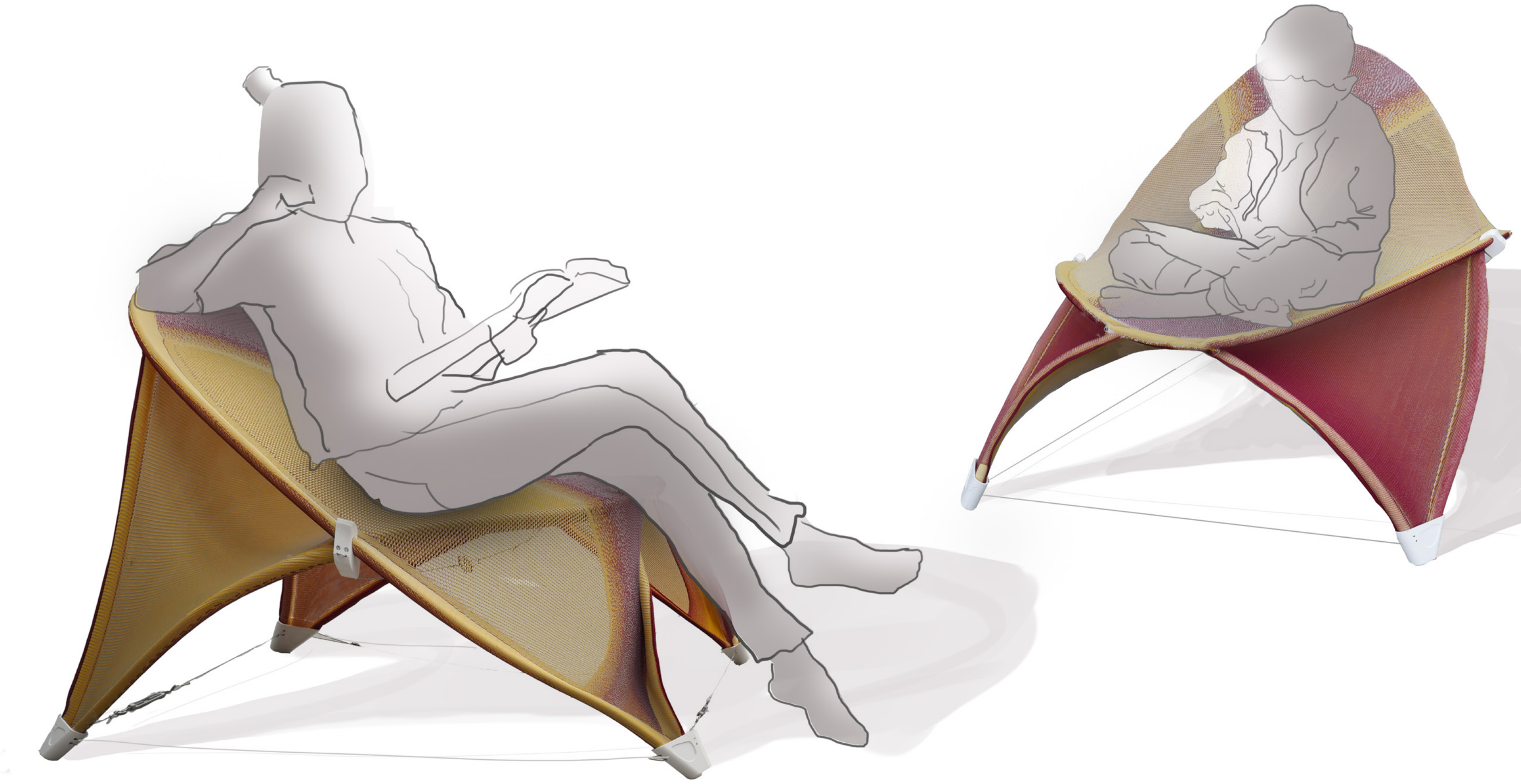

ARCHETYPE.98

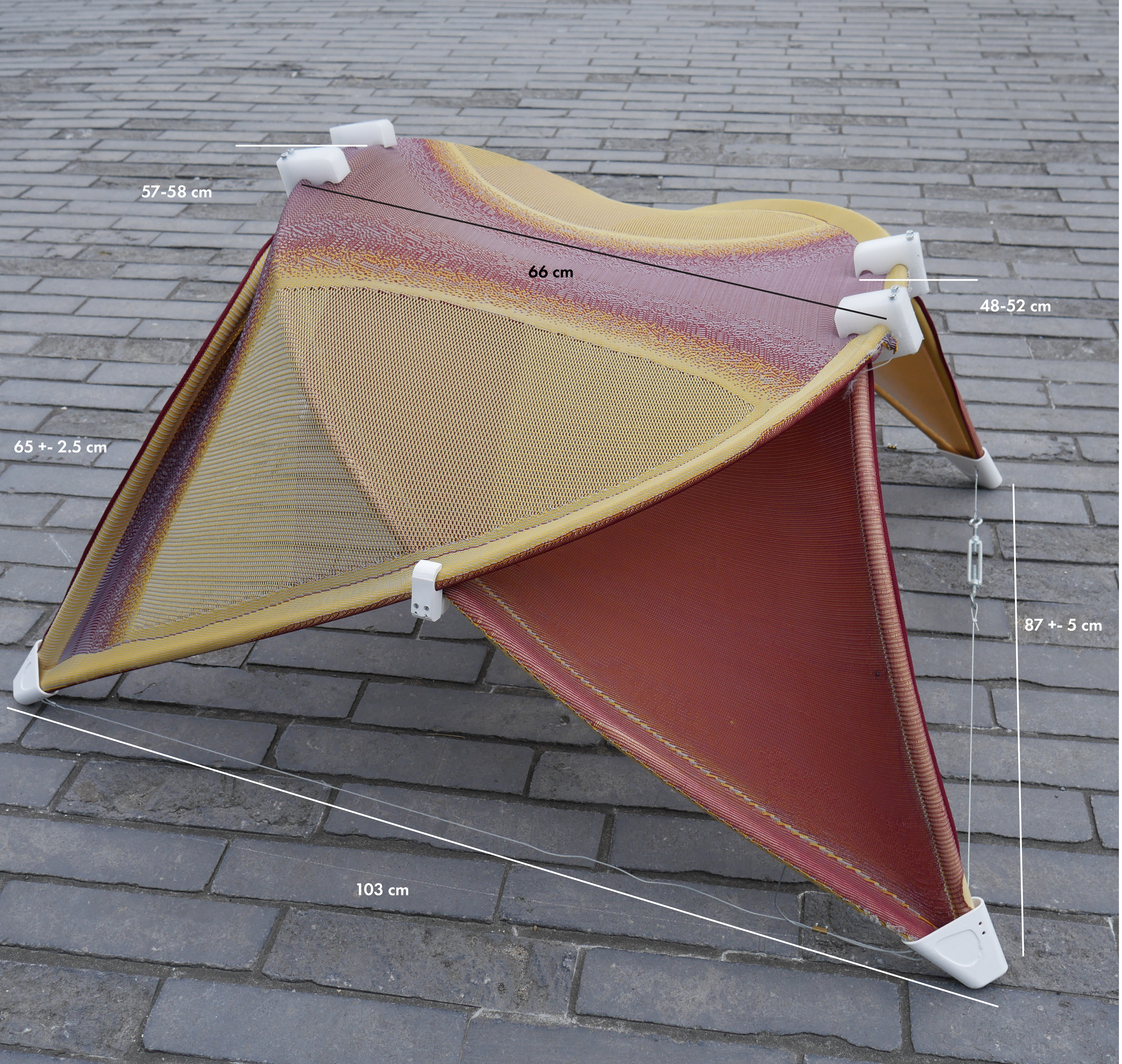












The measurements of the displayed configuration are presented in Figure 112.
A slight height difference between the front and back is visible. The height is adjustable with the turnbuckles between the front and back feet. The maximum height is determined by the length of the tubes and cables, and thus variable.

Figure 112. Final dimensions of the ARCHETYPE.98

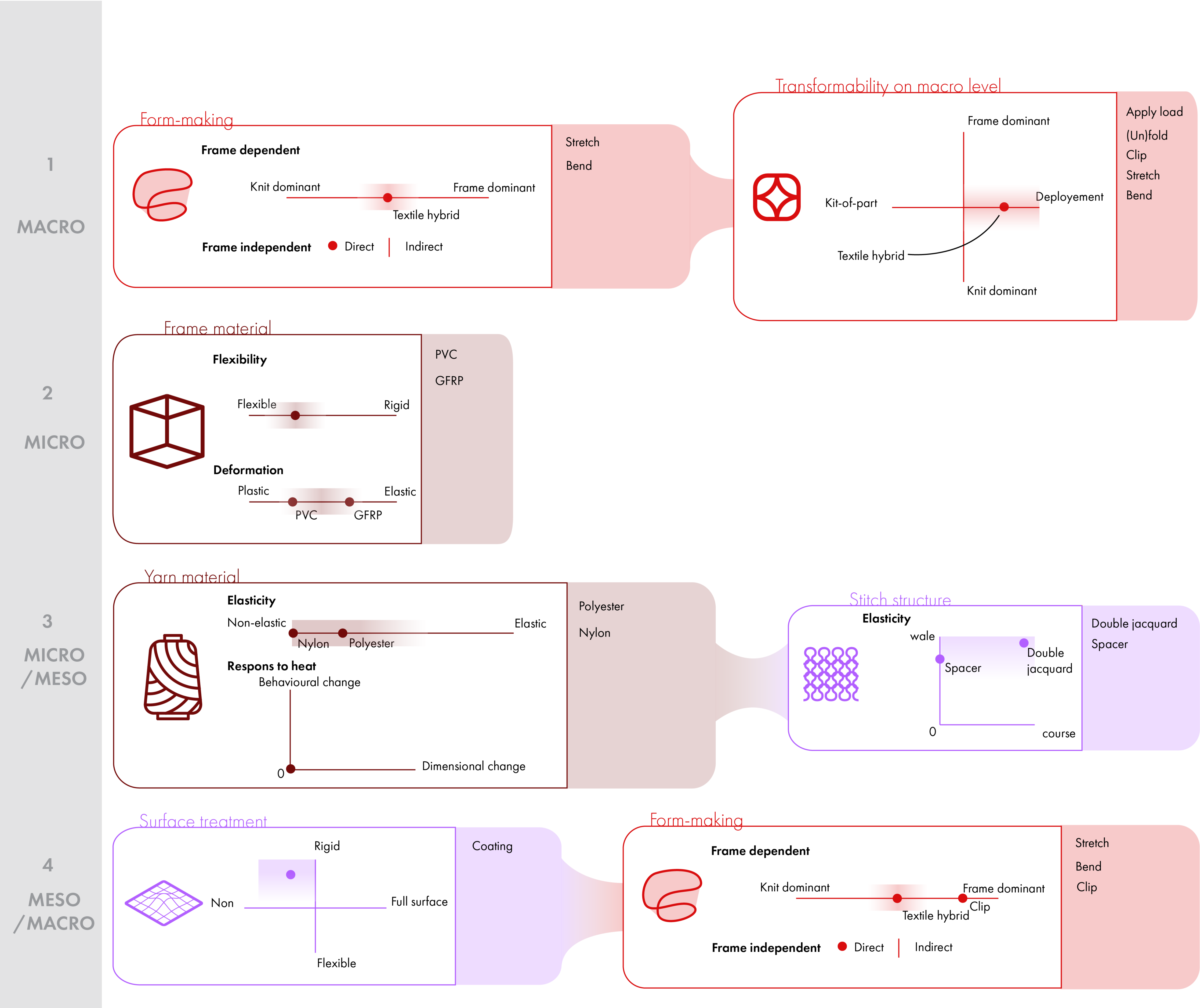


Figure 113. Development process of ARCHETYPE.98 visualized through the Design Space

Its place in Space 3.7

The development process of the ARCHETYPE.98 is visualized in the Design Space for 3D knitted, transformable, load-bearing objects, see Figure 113.
The visualization suggests a semi-linear process with interconnected parameters horizontally aligned. The form-making and Transformability at macro level are developed simultaneously through experimentation with PVC tubes to design a bending-active textile hybrid structure. The PVC tubes utilized for the prototypes gave insight into the desirable material characteristics for the final demonstrator, exploring the balance between rigid and flexible materials. When the structure was defined, the knit could be designed. The yarn material and stitch structure are very intertwined and experimented with simultaneously. The high tensile strength of the yarn is a "rigidity" that requires to be in balance with the flexibility of the stitch structure in multiple directions. Knitting allows for the partial application of this rigidity through its local adaptability. Finally, the surface treatment is utilized as a last resort, to rigidify some flexible knitted elements with coating. This necessity caused a reconsideration of the first step of the process, the overall form-making of the design.
The described route through the Design Space is applicable to Prototype 82, Prototype 86 and ARCHETYPE.98.

The broadness of this Space does not exhibit the parameter details explained in the development towards this final demonstrator. Therefore a specific Design Space for the final demonstrator is developed.

3.8 Design Space of ARCHETYPE.98

The final prototype, presented as ARCHETYPE.98, is the demonstrator of this research into 3D knitted, transformable, load-bearing structures.
The design space of the demonstrator is elaborated on to give insight into the specific parameters of this 3D-knitted, transformable, bending-active chair, see Figure 114.

The colours of the segments -yarn material, stitch structure, knit geometry and frame geometry- are related to the colours of the general Design Space, see Chapter 1.5.

The yarn materials can be chosen based on aesthetics, material properties and possible response to environmental conditions.
The material properties are strongly related to the stitch structure in which the yarn is used. The fibre type also contributes to the aesthetics of the knit.

The most important parameter of the stitch structure is the elasticity, for this is required in certain segments of the knit to allow the bending of the framework, the tensioning of the panels, and possible adaptability of the stitch structures. The elasticity can differ in the wale and course direction as the knit is an anisotropic material.
The elasticity of the structure depends on the yarn material parameters and knitting machine settings.
The knitting machine settings depend on the type of industrial machine, mainly for the possible fabric take-down systems which impact the textile 3D form-making possibilities of the knit. The stitch length can be specified for the front and back bed separately. The yarn tension systems of the STOLL CMS-530 are the yarn control unit, friction feed wheel and lateral yarn tensioner. The carriage direction is important when aligning multiple yarn materials and stitch structures horizontally.

The knit geometry is determined by the dimensions, meaning the panel height and width, either defined in pixels within the knitting software or in millimetres measured from a physical sample. The curvate steepness determines the shape of the panel and the distance between the front and back tubes of the framework.
The yarn/stitch relation means the result of the combination of yarn material and stitch structure, which can vary locally over the panel. The combination results in a certain density of the material, defined as the number of stitches in wale and course direction per square centimetre, and thus hand feel and aesthetics. The stitch structure transitions should be considered when aligning multiple stitch structures. Locally adjusting yarn material is possible, dependent on the type of industrial knitting machine available.
The maximum width of a knitting bed and the required elasticity properties in the wale and course direction determine the most suitable knitting direction.
The tube-knit connection is either by inserting the tubes into knitted tunnels or by threading a tube through knitted holes. Anything requiring additional material is not considered relevant to this design.
The frame geometry is defined by the flexibility of the tube material -the bending strength and stiffness-, the length of the tubes and the length of the cables connecting the feet. The length of the tubes is determined by the length of the knitted tunnel and the elasticity of the knit, thus by the stitch structure and yarn material. The length of the cable connecting the front and back tubes is balanced with the crossing tube, determining the depth of the chair. Together they determine the tension of the knitted surface and thus the sagging of the chair when a load is applied. The length of the cable between the feet of the front tube and back tube determines the bending of the tubes and thus the height of the chair.
The number of tubes and the height difference between the front and back can be increased to vary the overall geometry of the ARCHETYPE.98.

The tube material properties, meaning the flexibility (bending stiffness and bending strength) and deformation, are determined by the chosen material and its diameter and length.
The tube configuration determines the structural performance of the chair. Partially rigid tubes could improve the load-bearing capacity of the structure, or reduce possible undesirable bending of the structure when a user sits down in the chair. Combinations of configurations can be explored, varying the placement and thus local flexibility. To make the tube insertion into the knitted tunnel easier, the tube can be split into parts with different bending stiffnesses. This does potentially compromise the streamlined production process.

The tube-tube connection determines the transformability: a connection using a clamp can be utilized by a user to transform the object from flat to deployed configuration. Screwing the frame together compromises the ease of transformability but possibly improves the structural performance.
The production process -for example, 3D printing, CNC-milling or injection moulding-, material and dimensions determine the performance of the clamp.

The parameters for the feet are the material, height, angle, wall thickness and manufacturing process. Topology optimization can be performed to reduce material usage.
The feet are connected using a cable, either steel or knitted. Only steel is evaluated through the demonstrator. Expressing the desire to knit as many elements of the chair as possible requires tensile testing of a knitted cable. The transformability is possible by connecting the feet with a clip or hook and adjusting the length with a turnbuckle or other tensioning system.

The design balances the flexibility of the frame and the elasticity of the knit.

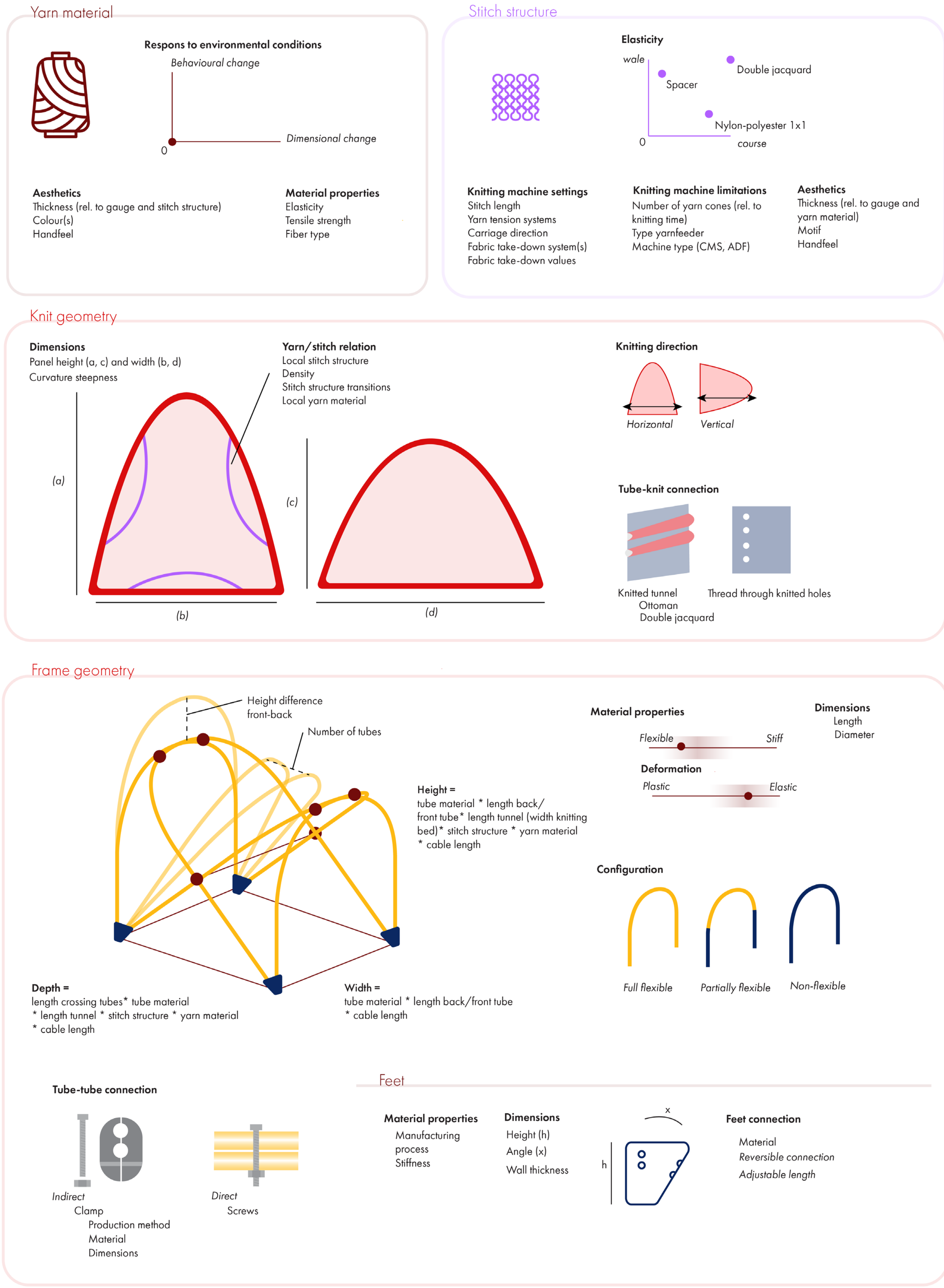


Figure 114. Design Space of the ARCHETYPE.98

Phase 4

evaluate

to evaluate the final prototype
and results of the project

4.1 Introduction

The ARCHETYPE.98 is evaluated on the main requirements defined at the second phase of the research: load-bearing capacity, transformability, adaptability, streamlined production process and the aesthetics. The technical opportunities, constraints and key technical qualities are summarized in Figure 115 and further elaborated on through the separate evaluations of the requirements in this chapter.

4.2 Methodology

The load-bearing capacity is evaluated through a technical evaluation.
The aesthetics are evaluated through user research.
The transformability is discussed shortly during the user research, and evaluated through a demonstration of the transformability to address points of improvement.
The production process of the final prototype is visualized and reflected upon.
The adaptability is elaborated on in Phase 3 of the research, which inspired a short brainstorm for other applications for 3D knitted, transformable, load-bearing objects.
The results are summarized and further elaborated on in the final discussion of this research.

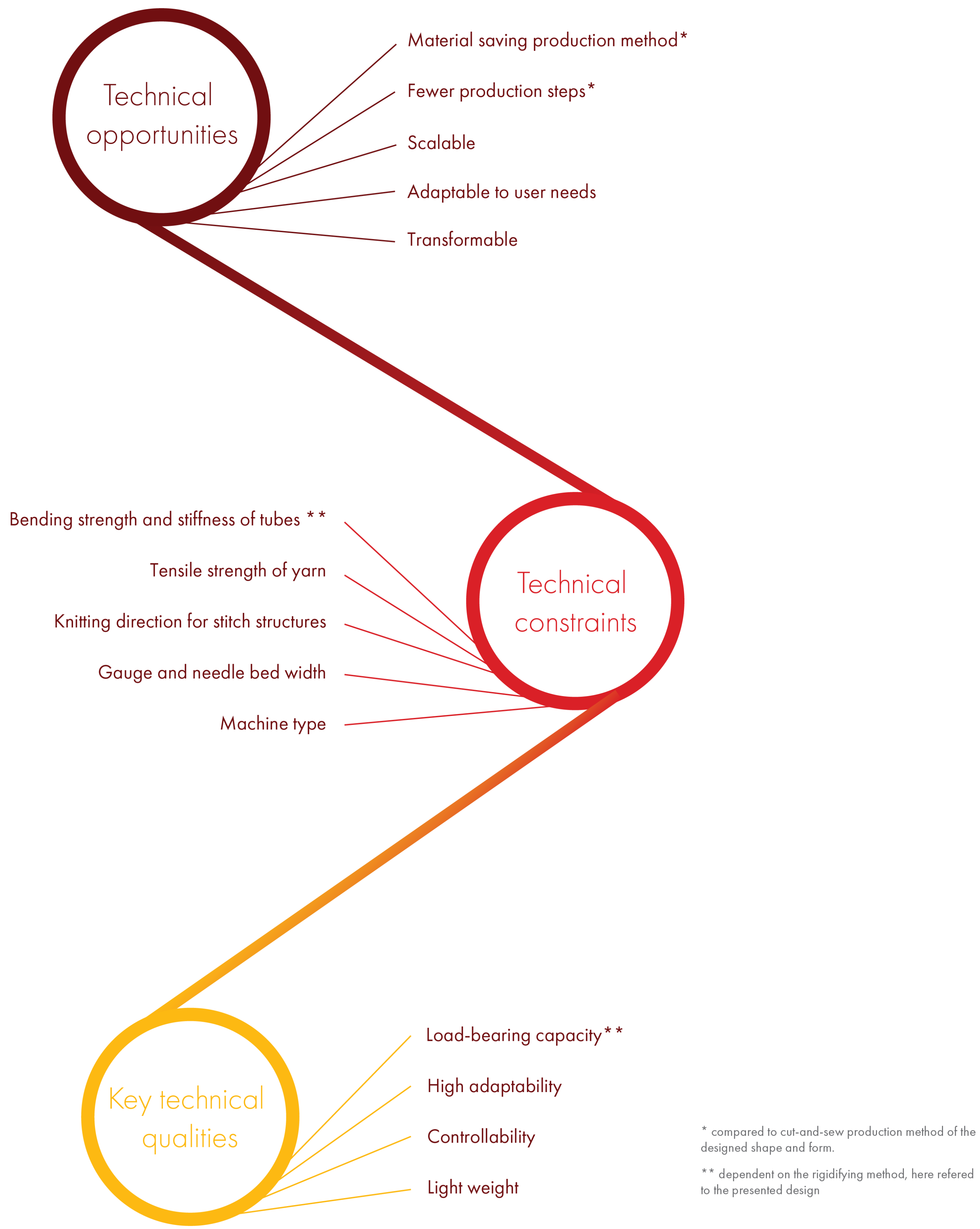


Figure 115. Technical opportunities, technical constraints and key technical qualities of the ARCHETYPE.98

4.3 Technical evaluation

4.3.1 Introduction
The goal of the technical evaluation is to evaluate the behaviour of the textile hybrid structure when a load is applied on top of the sitting surface. The design of the ARCHETYPE.98 however looks and it is expected to behave like a tent when the load is applied, with a soft membrane of which the shape depends on the internal stresses. (Chesnokov, 2023) A widely used method for finding the shape of a soft membrane is the Force Density Method. Pre-stressing a membrane behaves similarly to pre-stressing a cable and is therefore discretised by a cable mesh. Chesnokov et al. performed a Finite Element Analysis for non-linear structural analysis on a fragment of a tent roof using EASY software, see Figure 116. Using this method, specific membrane properties can be assigned to the membrane which in this case are the characteristics of the different stitch structures. The methods are developed to predict the relationship between membrane properties and form under tension.
Due to the limited time available and the complexity of the design, this type of analysis is not conducted but recommended for further research.

A great difficulty in chair design results from the fact that the act of sitting is often studied through a static activity while during actual use it is a dynamic act. (Paoliello & Carrasco, 2008) Therefore is the use of a chair commonly evaluated by cyclic loading, defined as a load being applied, removed and reapplied, mimicking a user sitting down, standing up, and sitting down over and over again, see Figure 117. Cyclic loading causes material failure because a crack can initiate and propagate even when the local stresses are far below the yield limit of the material if enough cycles are applied. (Albinmousa & Topper, 2022)
The European Committee for Standardization (CEN) specified the minimum requirements for the strength, safety and durability of domestic seatings for adults. The tests are based on a person who weighs up to 110 kilograms. A total force of 1300 N should be applied to the seat on a circular surface of 200 millimetres in diameter according to the EN 12520. (Suarez et al., 2021)

The goal of the technical evaluation is primarily to evaluate the load that can be applied onto the knitted sitting surface of the chair without damaging the object permanently. Second, the evaluation should point out what the weak spots of the design are that need to be improved in the next iterations. Therefore, the deflection of the object under static load is visually inspected. A non-contact method is suitable to observe deformation in a membrane structure. (Huang et al., 2022)

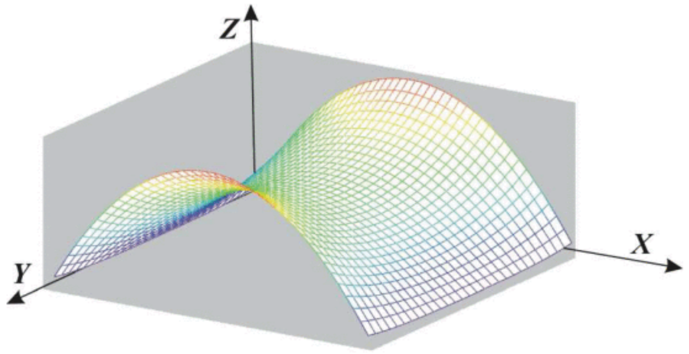


Figure 116. FEA on fragment of tent roof using EASY-software (Chesnokov, 2023)


Figure 117. Strength evaluation of chair, photograph by Julien Lanoo (Quality Controller, n.d.)

Hypothesis
During the development, multiple weak spots came to light.
As discussed in Prototypes 82 and 86, the tunnel ends are the weak spots of the knit.
The clamps are at risk of breaking, bending, and twisting around the frame. If a clamp fails, the other clamp on the same side is expected to fail shortly after. The stress on the knit is increased around the clamps, potentially leading to damage to the knit.
It is hypothesized, that the top clamps are the first to burst open or break when the load is increased.

4.3.2 Methodology
Loads are applied onto the knitted sitting surface, distributed over an estimated surface of 1600 square centimetres. The load is explicitly applied only onto the knit, for the object should be load-bearing through the knitted material, see Chapter 2.1 for the requirements.
Three cameras are positioned around the object to record the deformation of the object when the load is applied and to trace back the first moments of failure of the object. One camera films the top, one the side view, and one the front. The setup is illustrated in Figure 118 and pictured in Figure 119.
Loads are laid down in the middle of the sitting surface. The load is increased until a first indication of damage is observed, either through visual or auditive inspection by the researcher. The film footage from the three viewpoints is analysed to visualize the deformation of the chair under load.
If the hypothesis is true, the tubes are connected at the top by threading them together with iron wire on the locations of the clamps. The test is continued to evaluate the second point of failure.

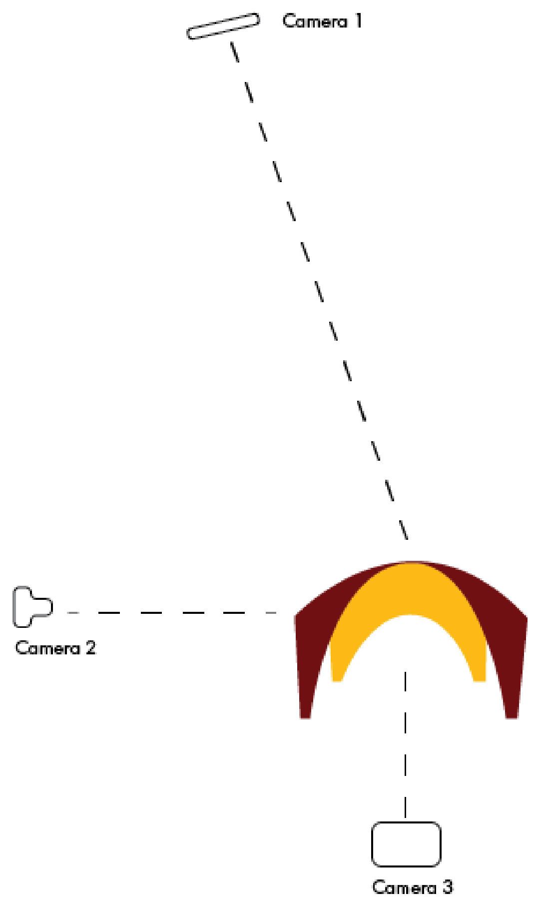


Figure 118. Technical evaluation test setup schematic

Load	Mass (kg)
Load 1	7.75
Load 2	8.66
Load 3	2.68
Load 4	3.89
Load 5	10.45
Load 6	2.46
Load 7	1.29
Load 8	1.33
Load 9-31	1.50

Table 1. Mass of the loads applied during technical evaluation

4.3.3 Results
The test is conducted twice, see Figure 120.

Test 1
The maximum load applied onto the centre of the sitting surface of the chair is 50.30 kg, equivalent to ~493 N.
The load is not increased further because the crossing tube of Panel 2 is exhibiting the first signs of buckling at the point where the solid PVC rod ends inside the PVC tube. Without a load, Panel 1 and Panel 2 do not touch each other at the sitting surface area. At 12 kilograms, both panels carry the weight. The cable between the crossing tubes touches the face of the panels. The deformation of the crossing tube of Panel 1 is larger than that of Panel 2, towards a double curve around the crossing. The clamps did not break open, bent under the load, or twisted around the frame.


Figure 119. Technical evaluation test setup

Test 1

0 kg

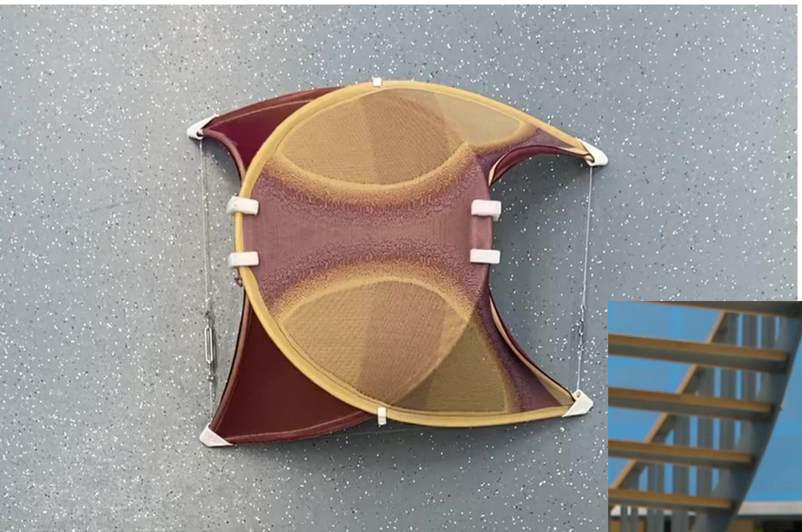
12.0 kg

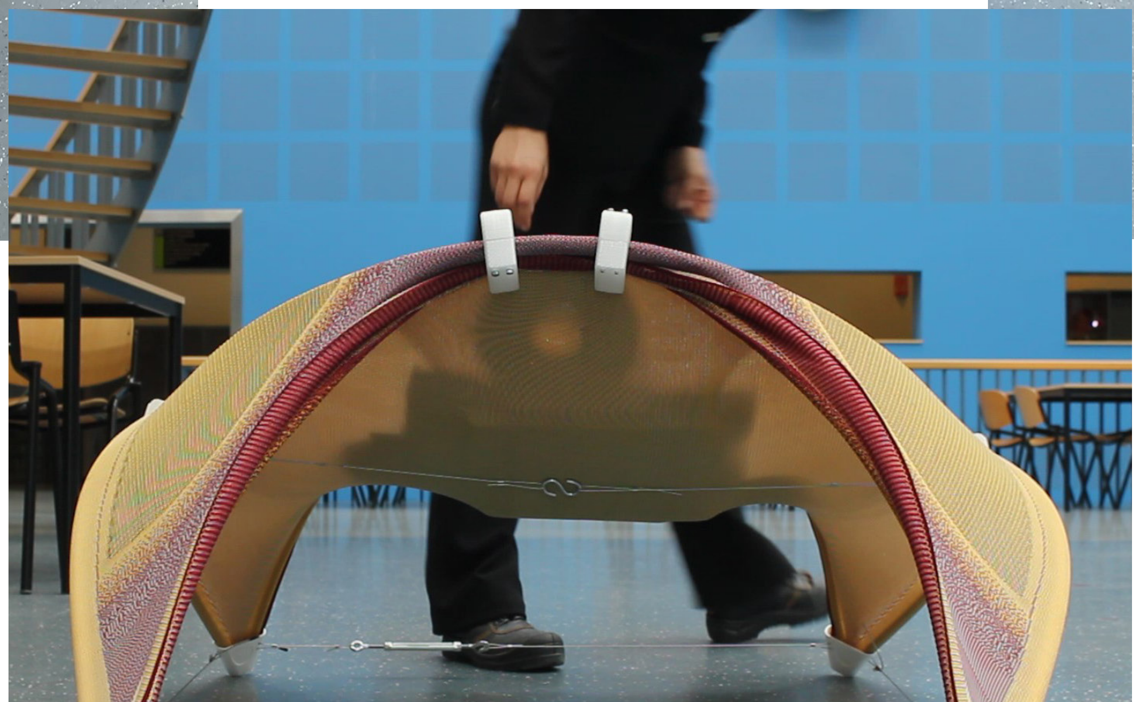
35.4 kg

50.3 kg

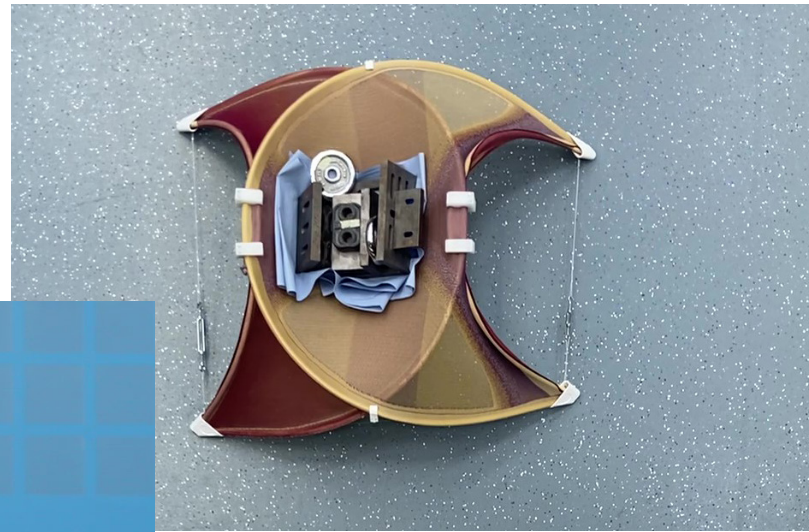
Test 2

0 kg





38.7 kg



58.2 kg

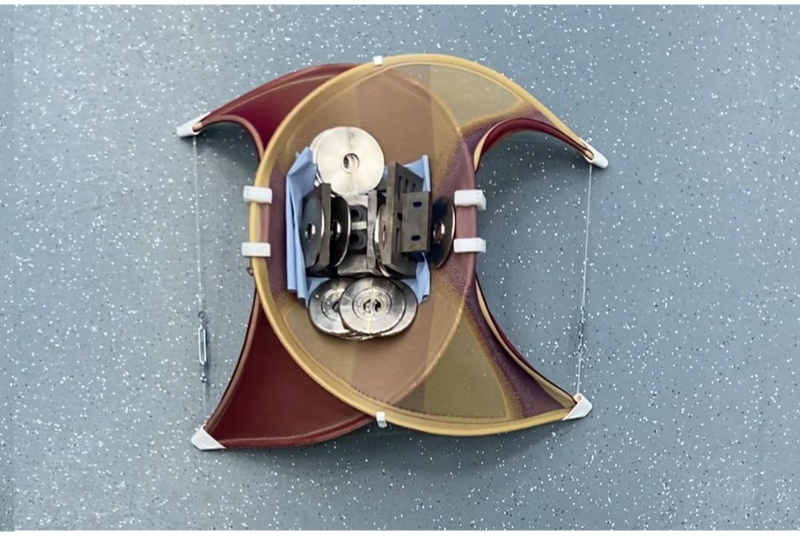


Figure 120. Collage of photos of Test 1 and 2

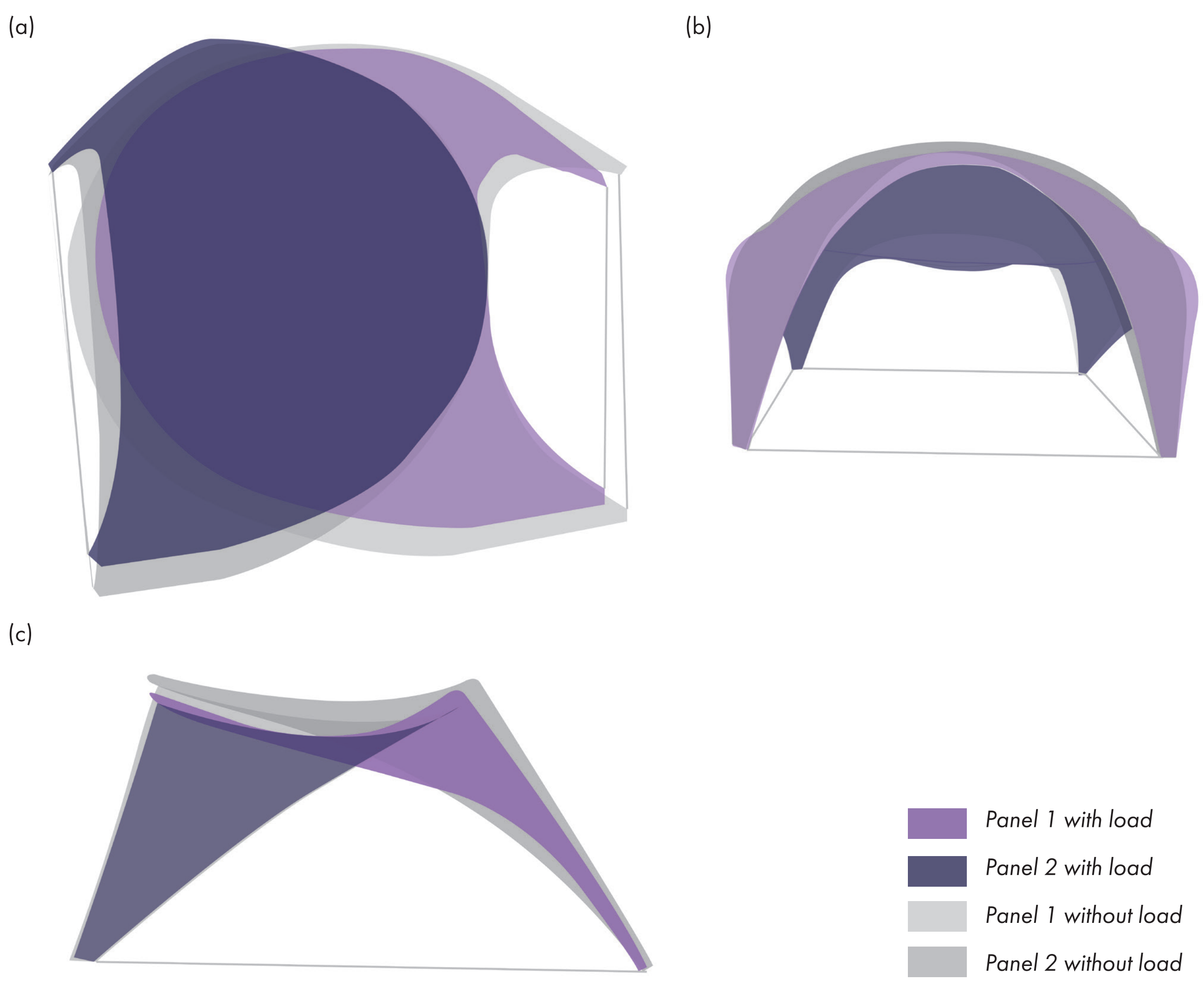


Figure 121. Deflection of the object when 50.3 kg is applied on the sitting surface. a = top view, b = front view, c = side view

The knit is not damaged at the tunnel ends. Slight damage to panel 2 is observed underneath the clamps. See Figure 121 for the deflection of the object.

Preparation for test 2
The PVC rods are removed from the panels and the GFRP is elongated to the same length as the PVC tube. All PVC tubes thus contain a GFRP tube over the whole length. The damage to Panel 2 is repaired by hand. See Appendix D Technical Evaluation for details.

Test 2
The maximum load applied onto the centre of the sitting surface of the chair is 58.19 kg, equivalent to ~571 N. The load is not increased further because damage to the front GFRP tube was audible by the researcher.
The clamps did not break open, bent under the load, or twisted around the frame. No further damage to the knit is perceived.
The knit is not damaged at the tunnel ends after the second test. See Figure 122 for the deflection of the object. See Appendix D Technical Evaluation for details. Figure 123 on the following page illustrates the technical performance of the ARCHETYPE.98 .

4.3.4 Discussion
Test 1 showed that the difference in bending stiffness of the PVC rod inside the PVC tube and the GFRP tube inside the PVC tube caused the near buckling of the crossing tube of Panel 2, which is expected to break under an increased load. Before conducting test 2, the GFRP tube is extended over the full length of the tunnel to prevent this, allowing it to increase the load. The sound of the GFRP tube indicated plastic deformation, meaning damage to the object.
Therefore the load is not increased over 58.19 kg (~570.9 N) at which point no damage to the knit or clamps is observed. The applied force of 570.9 N is distributed over a larger surface than recommended by the CEN. The object does not meet the standards of the CEN.

Some limitations to this evaluation are noted.
The test is conducted twice with the same prototype. The first test might have caused unobserved damage which lead to the failure during the second evaluation. To be able to draw any conclusions on the load-bearing capacity of the object, the test should be conducted multiple times, including cyclic loading, and utilizing accurate measuring equipment.

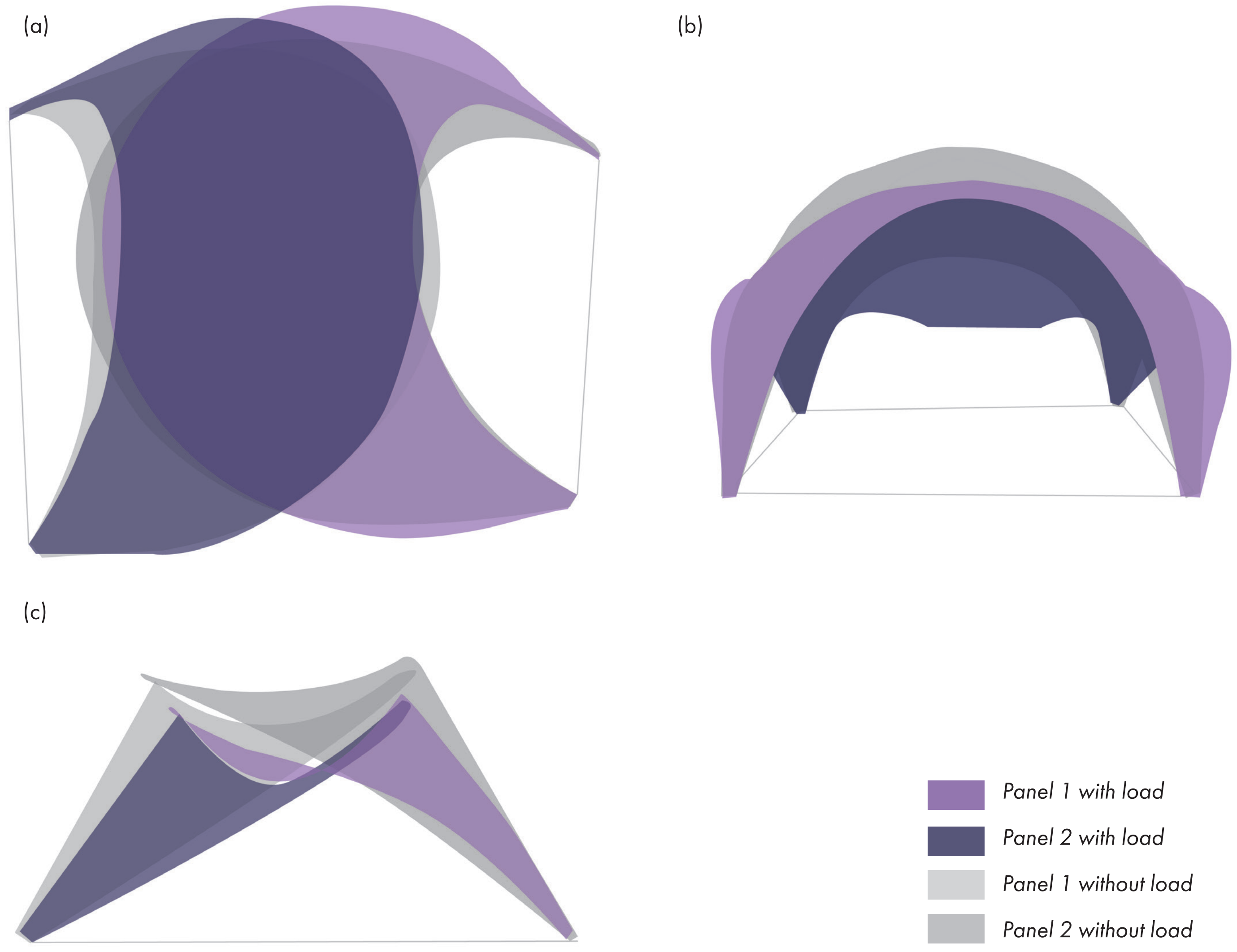


Figure 122. Deflection of the object when 58.2 kg is applied on the sitting surface. a = top view, b = front view, c = side view

After the second test, it is observed that the cable between the crossings had failed. It is unknown whether this occurred during the first or second test. It is expected to have happened during the second test because the sitting surface was shortened with an increasing load. This inwards movement is partially prevented by the cable between the crossings.

The cable between the crossings contributes directly to the load-bearing capacity of the surface because the knit sags onto the cable when the load is applied. A future user would sit directly onto the cable, feeling this hard line which could be experienced as unpleasant.
This unintended function of the cable explains the increased sagging of the knit where the load is applied in the second test.

The deformation of the membrane surface could be quantified accurately by using laser sensors to measure the response of the structure at multiple locations simultaneously. This method is expensive, thus in this study, multiple cameras are utilised for visual inspection of the deformation. The deformation should be quantified in further research to evaluate the structural performance of the object.

The bursting strength is a commonly used measure to evaluate the performance of knitted fabrics and would be a suitable addition to the conducted technical evaluation. (ISO 13938-2:2019, n.d.)
The expected weakest spots could have been evaluated in advance. However, the object is composed of two panels with multiple stitch structures and yarn materials. The bursting strength of one stitch structure would not give insight into the behaviour of the total structure, since the exact force distributions within the membrane are unknown. This elaborate evaluation is not possible within the timeframe.

Additionally, the connection between the knitted membrane and the bending-active framework is of importance to the total performance of the object. Only evaluating the framework and the knitted textile separately would eliminate the effect of the tunnel connections and clamps which contribute to the overall performance of the object.

4.3.5 Conclusion
The tubes are identified as the first element of the object to exhibit damage when load is applied onto the sitting surface. Improvement of the framework is required to improve the strength of the chair.

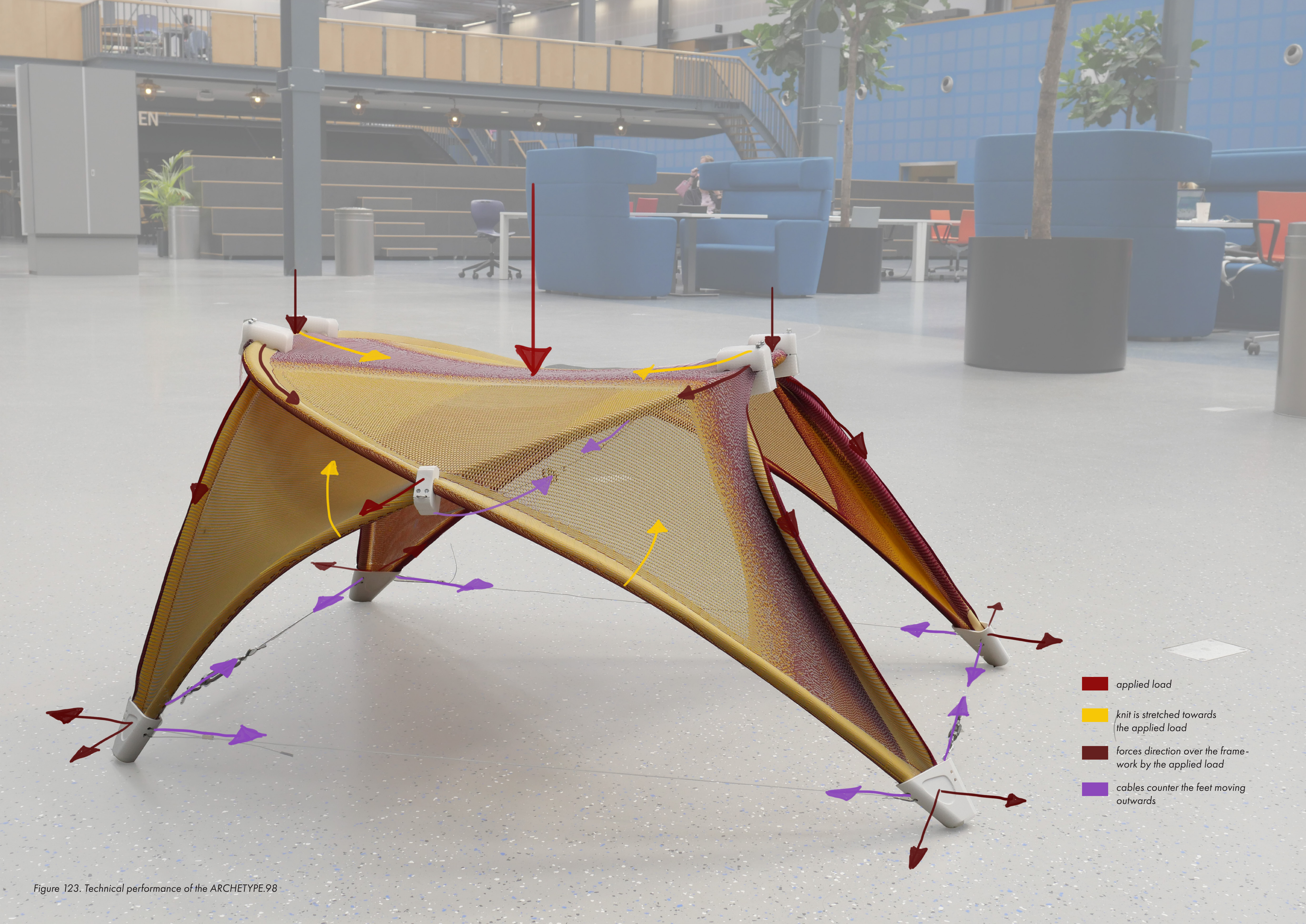


Figure 123. Technical performance of the ARCHETYPE.98

4.4 User evaluation

4.4.1 Introduction
The user evaluation is conducted to evaluate the final prototype on material experience. The characterisation of the object through user evaluation articulates the material experience and possible improvements to balance the novelty of the designed chair and the application of 3D knitting to create a design that is most advanced, yet acceptable. (Loewy, 1950)
Not allowing the participants to sit on the prototype, due to the limited load-bearing capacity, limits the goal of the study to the material experience when looking at and touching the object.

4.4.2 Method
Participants are recruited from the faculty of Industrial Design Engineering. The participant is invited to answer multiple questions regarding the material experience -aesthetics, meaning and emotions- while first observing the prototype, and thereafter touching the prototype. Initial questions are asked regarding demographics and knowledge of knitting, and permission to take photographs. The photos are anonymized.

The questions are inspired by the research of Karana et al. (2015). While the participant observes the prototype, the following questions are asked:
- What is your first impression of the object?
- How would you describe the object?
- What are associations with the object due to its aesthetics?

While the participant touches the prototype, the following questions are asked:
- What do you feel when touching the material?
- What are your associations with the material when touching it?
- What are the most and the least pleasing sensorial qualities of the material?

During the interview, the researcher writes down the answers to the questions. Additional observations considering particular viewpoints of the participant or contact with the object are noted. The answers are grouped based on similarity, to evaluate the overall aesthetics of the chair.

4.4.3 Results
Participants
Three participants are interviewed, see Appendix E for the demographics and notes. "P1" means Participant 1, etc.
Comments by people passing by while assembling the final prototype are also taken into account as 'first impression' descriptions and taken together under the name "Passengers". The "Passengers" did not know the function of the object. The chair is shown to an employee of the design furniture store "DEJA VU" to ask for a first impression. The comments are named "DEJA VU".

The results are described below, grouped on four themes: first impression, functionality and performance, hand feel of the knit, and overall look of the chair.

First impression
A first comment on the chair is often the word "interesting". Some mentioned it looks like a "tent", or a "scale model of something very large". One participant even attempted to experience it as a larger structure by laying down beneath it, see Figure 124.
The object is described as "dynamic, like it can jump" and "lively, slender and agile". The "roundness" is considered "fun" by one participant.

Functionality and performance
The overall shape does not look like a chair according to the third participant, making him doubt whether he could sit on it at all. All participants mentioned, while looking it and afterwards touching the chair, they think the chair would not be able to hold them, because of the bending, sagging, and "fragility" of the framework and knit. All were surprised when the researcher mentioned the object could bear a load of 58 kilograms.
The first participant would want to "lounge" in it, wanting to "be able to lay down" in the chair. The second participant mentioned he would sit on the middle segment because that "looks solid, the rest is transparent thus not stable". He would sit "cross-legged" because he would not know where to place his legs. The third participant mentioned the bending of the frame made him doubt the performance of the chair. The employee of the furniture story commented the chair looked very "interesting", but that "when a chair sags, elder people should still be able to get out of the chair."

Handfeel of the knit
When asked to touch and interact with the chair, all participants touched only the top surface of the object, not the second panel below, see Figure 125. The mesh structure is described as "fish skin texture" and "fishnet" texture. Two mentioned it to feel "coarse" after which one participant mentioned to feel "like touching it while lounging in the chair", and "relaxing". The bottom panel felt "nice but less interesting, just smooth" according to the first participant. The second participant expressed the double jacquard segment feels "soft like stockings, like lingerie, quite sensual". One participant addressed the fact that the chair is knitted by himself. "I know it is knitted. It is strange, it is very thin and I know knitting from my mom who makes sweaters, so I would assume this is woven"

The overall look of the chair
The chair is described in various ways, mainly addressing the novelty of the design of the object. "In a museum, this would not look out-of-place, but in a lounge corner it would be very novel". As said, the object is not immediately recognized as a chair, which demonstrates the novelty. Terms mentioned when describing the chair are "calm", "serene", "peaceful", and "floating". The chair is considered to look and feel lightweight by all participants, see Figure 126.

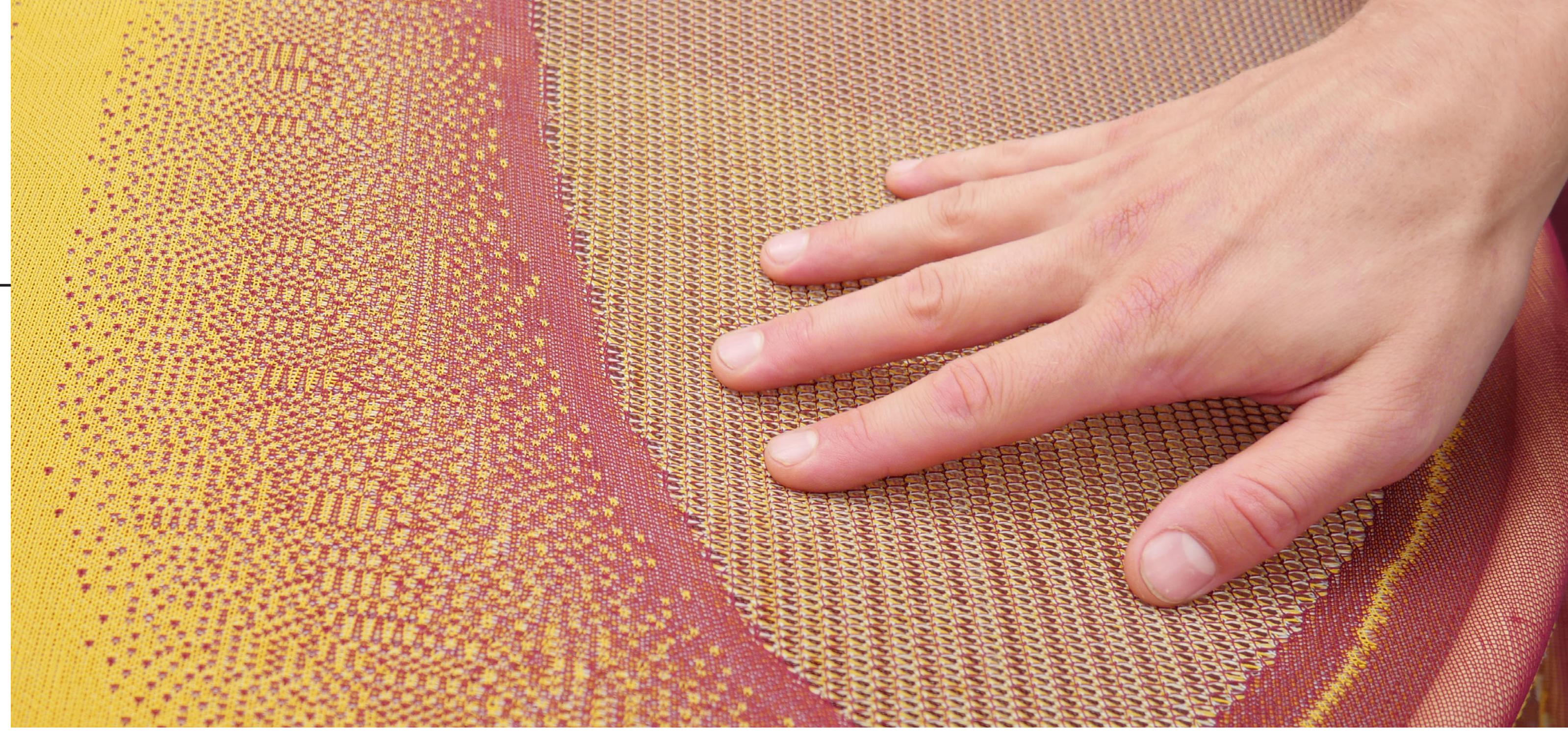


Figure 125. Participants feels the surface of the knit

"It is so beautiful, just like I would not take my persian carpet with me when I go camping, I could not take this chair with me anywhere"

4.4.4 Discussion
To conclude, all participants were doubtful about the functionality and performance, which is valid considering the results of the technical evaluation and the object's preliminary stage of development.
The design looks novel and is often misinterpreted to be a scale model of a larger structure, or a tent. The novelty is concluded from the descriptions of "interesting" and suitable for a museum. This can mean the design is too advanced to be accepted by a larger public.
The physical light weightiness is mentioned, as well as the visual airiness of the design. This could contribute to the fact that no participant considered it to look (or feel) strong enough to hold them while sitting.
The enthusiasm of the participants about the "interesting" design suggests the desirability of the object, however much needs to be improved in future iterations on the performance to give future users the idea they can actually sit on the knit.

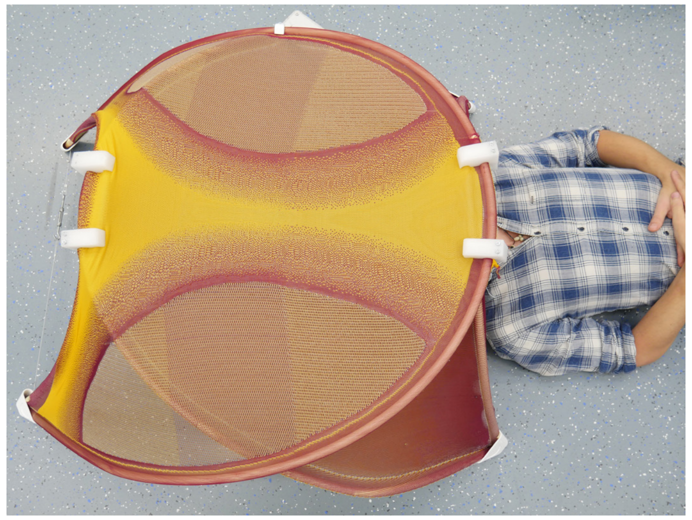


Figure 124. Participant laying down underneath the prototype

The limited number of participants makes the validity of the study doubtful. All interviewees are males around the age of 25, and students of the Industrial Engineering Faculty of the TU Delft, implying selection bias.
The transformability is not evaluated because the clamps are merely a first prototype. The ease of use should be evaluated by a more developed clamping system, together with the overall deployment of the chair.
The sitting experience is not assessed because the technical evaluation showed there is no guarantee the prototype won't damage under the load of a human. The sitting experience is expected to greatly impact the overall material experience of the object because of the expressed "fragility" of the look and feel of it. The fragility can be explored further in the following iterations, to find a balance between the "lightweight" and "fragile" look, and "dynamic" and "lounge" experience.

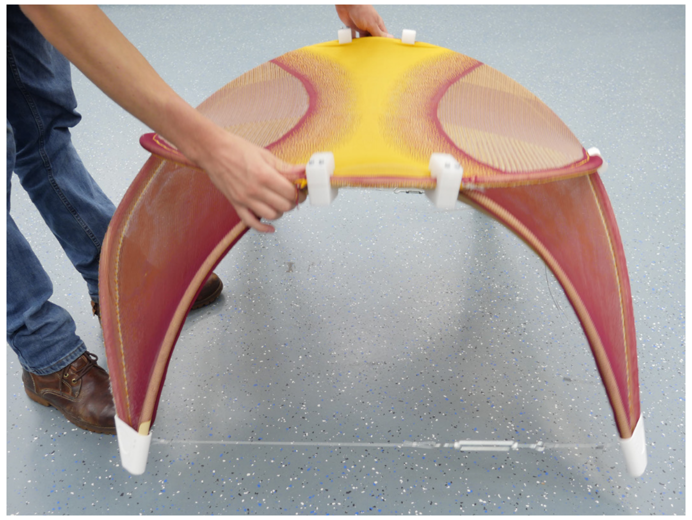
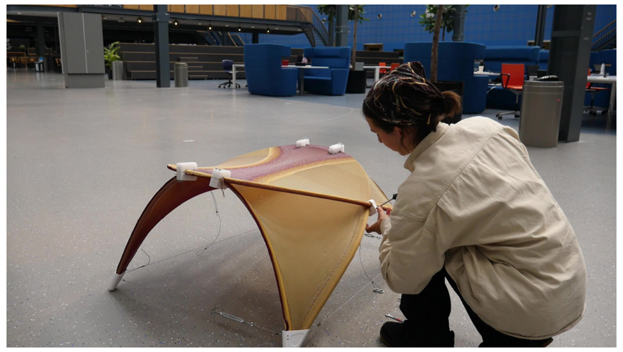


Figure 126. Participants feeling the weight of the chair

4.5 Transformability

The transformability at the macro level is demonstrated step by step in Figure 127. The clamps now require a wrench and screw-driver to mount and demount. In future iterations, the clamps will be developed such that they can be released and reattached with a simple hand movement to ease the transformability for the user. The transformability alters the ARCHETYPE.98 from a sitting object to a flat configuration which allows for transportation as a smaller object. The feet can be removed during transport to avoid the tension being released unexpectedly, which could cause harm or damage to the object or surroundings.

Unclip the center cable.



Demount the side clamps with screwdriver.

Demount the clamps with wrench

on both sides.

This releases the tension on the panels.

Unclip the cable between the feet.

Remove the feet from the panels.

Rearrange the panel to the desired configuration.

Reinsert the panels in the feet.

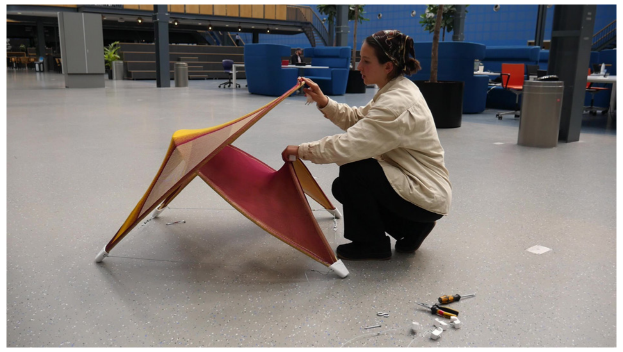
Connect the cable between the feet with the turn buckles.

Evaluate the cable lengths.

Lift the panels, determine which panel goes on top.

Place crossing tube of bottom panel underneath top panel.

Push the top panel downwards.



Tension the object by attaching the top and bottom panel.

Mount the clamps with a wrench.

on both sides.

Mount the side clamps and clip the cable in between.

Figure 127. Transformability at macro level

Figure 128. Configuration with the yellow side up

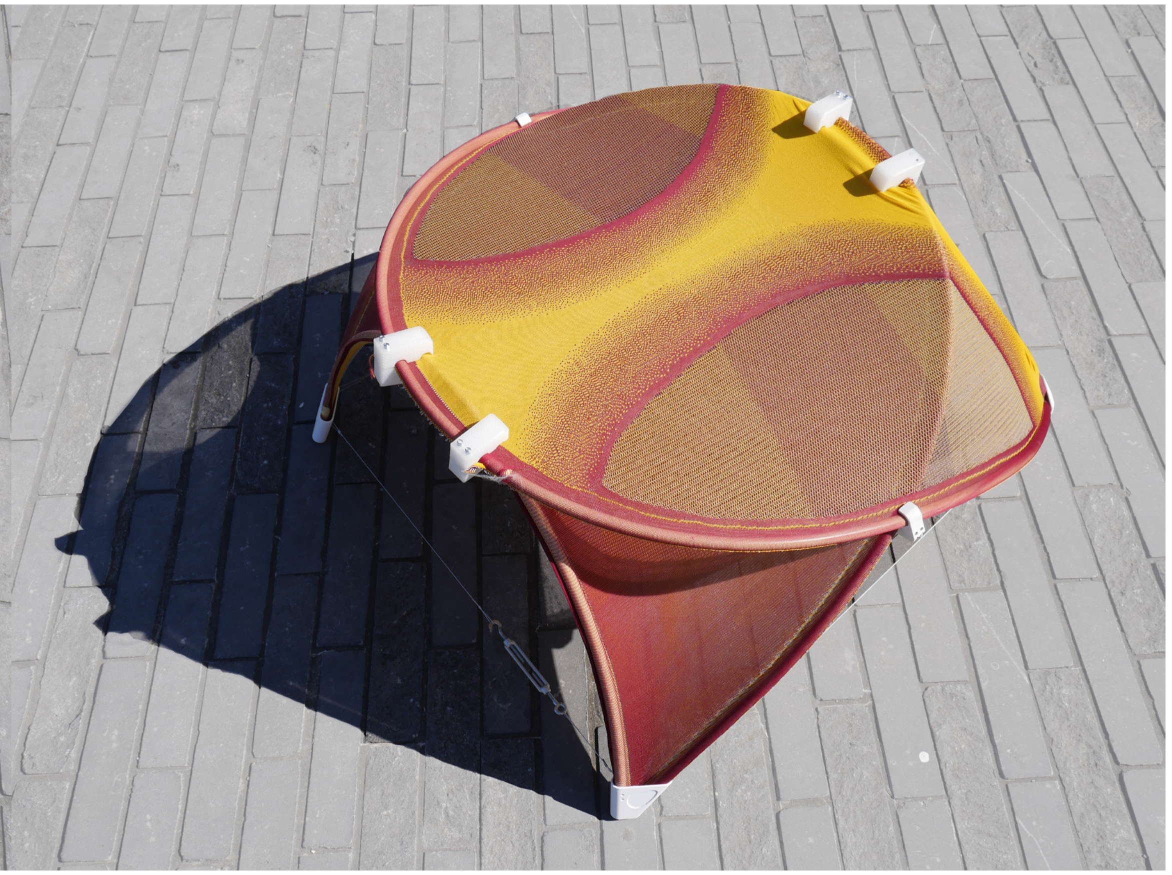


Figure 129. Configuration with the red side up

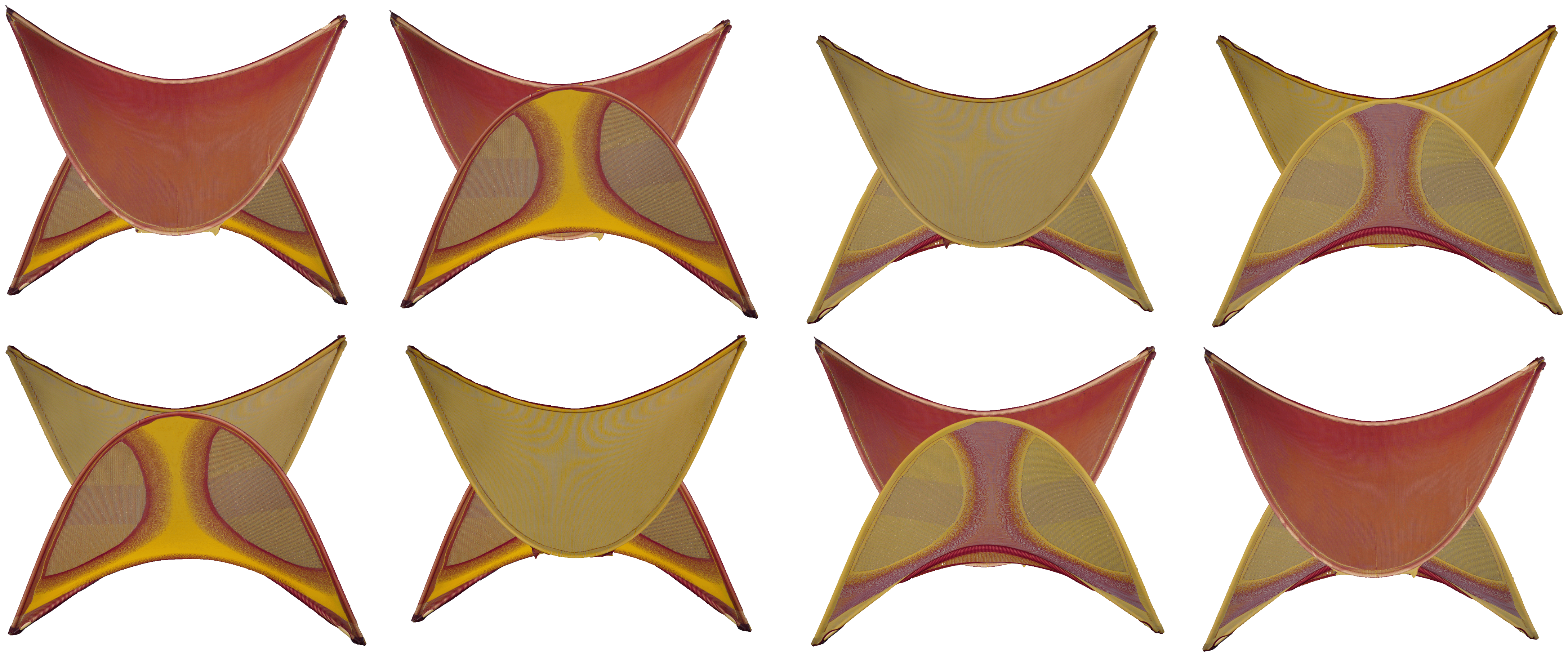


Figure 130. All possible aesthetics that can be created with ARCHETYPE.98

Adaptability 4.6

The adaptability of the design is defined as being able to locally adapt the stitch structure and yarn material to vary the properties of the knit. The three prototypes developed in the third phase all have a different material expression, only varying the stitch structure. The number of samples produced in the short time span of this project exhibits the enormous amount of possible material expression that can be created with 3D knitting. ARCHETYPE.98 is composed of two panels with similar function and performance, however with varying stitch structures and materials, even combining multiple structures within one panel. Therefore the design is considered highly adaptable.

Two panels allow for eight different aesthetics.

The transformability allows for 8 different aesthetics of the ARCHETYPE.98 by reconfiguration the two panels. Both sides of the panel have a different colour composition and various stitch structures, see Figure 128 and 129. Altering which panel is on top, and which side of the panel is shown above, creates the opportunity to have 8 different aesthetic configurations, see Figure 130.

4.7 Production process

The production process of the ARCHETYPE.98 is visualized in Figure 131. A requirement of the ARCHETYPE.98 is the effective and efficient use of the production methods, reducing manual labour where possible. Multiple design choices are based on this requirement, such as the choice to not use goring to directly 3D shape the knitted panels.

Evaluation of the Prototype 82 and 86 brought to light that multiple rigidifying methods, meaning a frame, clamps and feet, are required to create the desired geometry and to be able to evaluate its performance. Consequently, multiple steps and manufacturing techniques are added to the production process.
The production process of the ARCHETYPE.98 is considered on-demand, for the materials used are widely available -PVC, GFRP, polyester yarn, nylon yarn, PET-G and PLA- and the whole production process is conducted by the researcher.

The total production time greatly depends on the available machinery. Scaling up production of the ARCHETYPE.98 would require different production methods, such as injection moulding the currently 3D printed parts, which could reduce manual labour. Changing the production methods and processes will impact the production price.

The production of a regular lounge chair or sofa includes producing a wooden framework, attaching multiple layers of foam, and thereafter stapling the upholstery fabric over it. (De Bruijn, 2023) The adaptability of the knit and possible softness of the knitted structures replace the foam. The knit then provides the desirable comfort. This greatly reduces the amount of material and manual labour needed. The production process of the ARCHETYPE.98 also eliminates the need for upholstery cutting and sewing.

The adjustments of the knitting machine parameters and panel dimensions can require sampling which takes time and requires materials.

Material choices
The material choices greatly impact the production process. The material requirements were that the largest part should be produced through knitting and effective use of material. The 'largest part' is not specified but merely a guideline to steer the development process. Knitting the panel is not the most time-consuming part of the production, nor is it the largest contribution to the total mass of the object.
The ARCHETYPE.98 weighs 1798 grams. Panel 1 weighs 124 grams. Panel 2, weighs 164 grams. The feet and cables weigh 374 grams. The top clamps weigh 170 grams. The frame weighs 966 grams.
To compare, an explicitly lightweight camping chair weighs 500 to 1000 grams but is considerably smaller in size.
The weight of the separate elements is not a measure used to evaluate the materials during development, thus not taken as a measure to evaluate the final design.
The effective use of material can be improved in future iterations by utilizing topology optimization to reduce the material needed for the feet and clamps, possibly even the knitted surface.
The described production process results in little waste. The only waste produced to knit the panels is the programmed waste yarn that is required to properly set up the stitches on the knitting machine, see Figure 132. Only the adhesion material of the 3D printed clamps and feet are wasted, no supported is needed for the prints.
The custom sized PVC and GFRP tubes can result in some waste material, depending on the initial length of the material. This waste is eliminated during the production of multiple similar objects.
If the same geometry would be produced with regular cut-and-sew techniques, the production process would require more machinery, time, manual labour, and result in fabric waste material, see Figure 133.

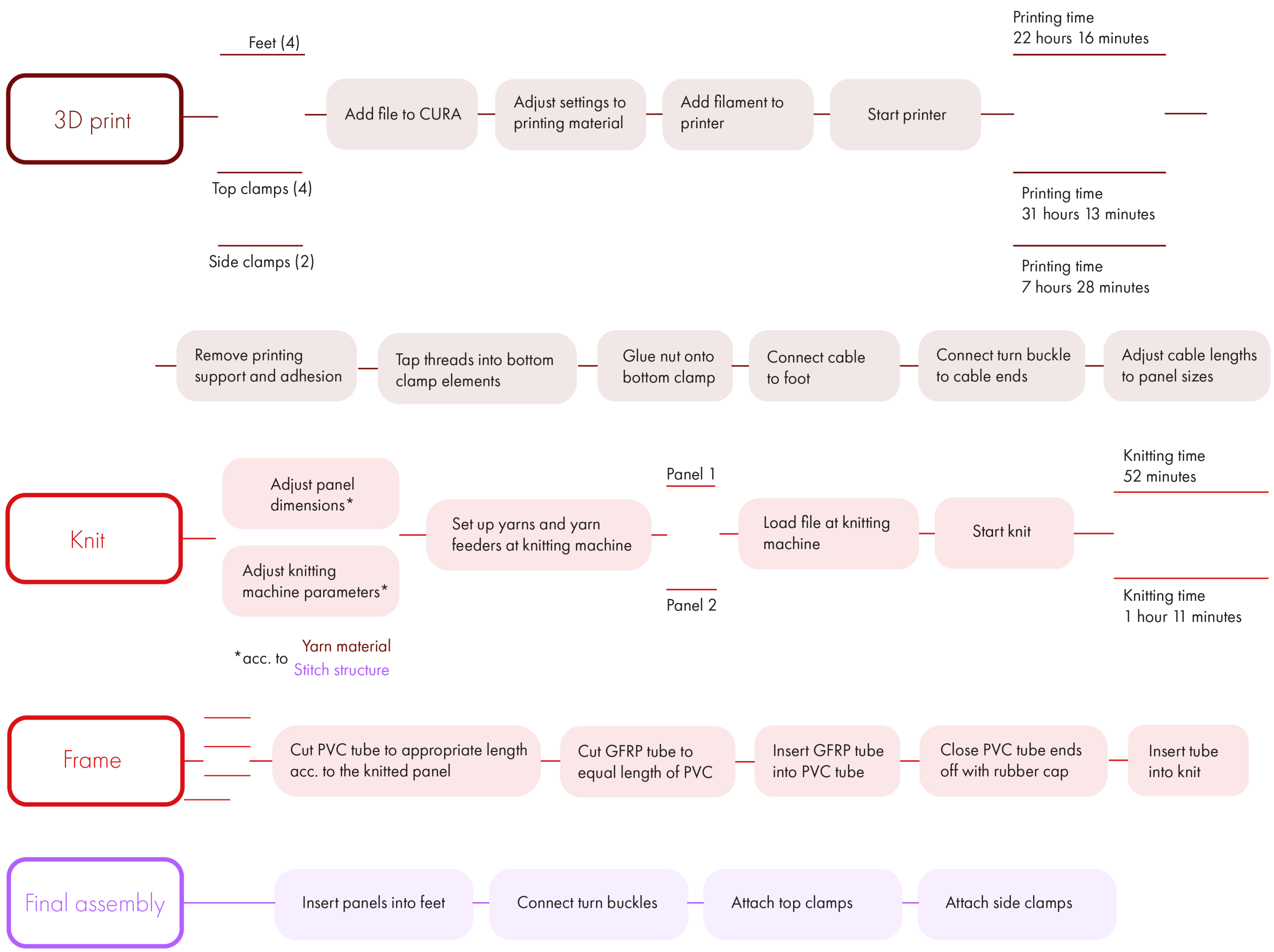


Figure 131. Production process of ARCHETYPE.98

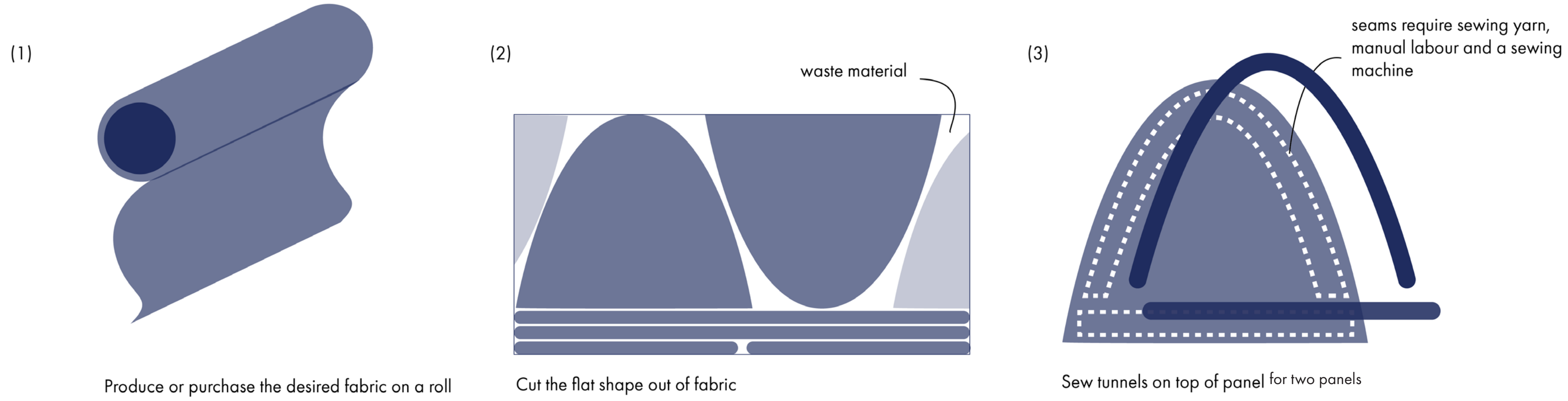


Figure 133. Production process of cut-and-sew panel

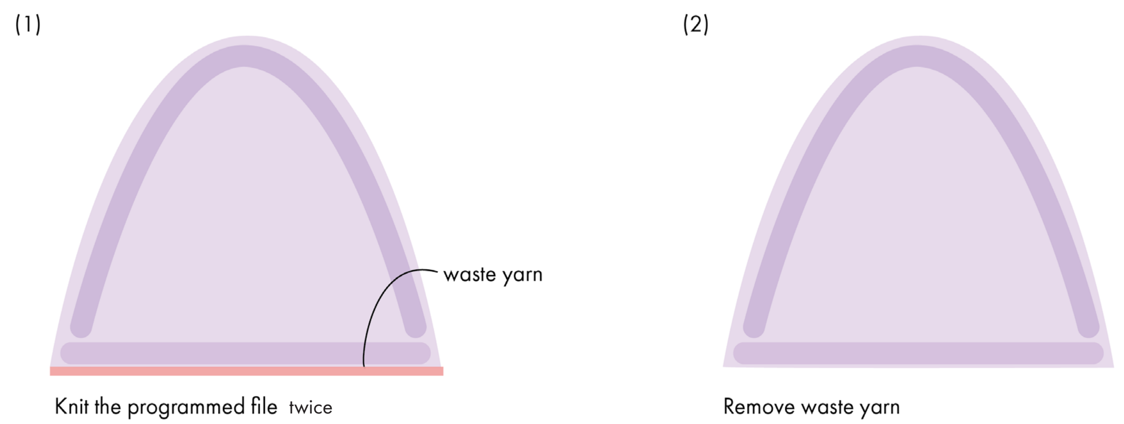


Figure 132. Production process of knitted panel

4.8 Results

The results of the evaluation phase are summarized in this section.

Load-bearing

The technical evaluation showed that this prototype can bear a load of 58.2 kilograms after which the first signs of permanent damage showed.
It exhibited that the load-bearing capacity is not limited by the knit but by the framework material. This highlights the great potential of the knit to be able to bear even larger loads since the load is directly applied onto the knitted sitting surface. Since it does not meet the requirements for official testing of sitting objects, it is still considered a valuable outcome. The sitting object is merely a demonstrator to be able to search for the opportunities and limits of knitting for load-bearing structures, into which the evaluation does give insight.

Adaptable

The knit structure of the designed object is to a certain extent adaptable in terms of yarn material and stitch structure.
As shown through prototyping, the stitch structure can be locally adjusted in the main sitting surface without compromising the performance of the object. The stitch structure and yarn material of the tunnels in which the frame are inserted, are the least adaptable for two reasons. First, knitting a tunnel requires knitting on both beds separately, which limits the stitch structure possibilities. Second, the tunnel ends are prone to damage when a load is applied onto the object thus this area requires specific yarns and stitch structures.

The material 'knitting' is considered highly adaptable overall for the great number of parameters that can be adjusted, and the wide range of applications shown in the literature study, through the development of the demonstrator and the short brainstorm of other applications, see Appendix G.

Transformable

The transformability of the final design takes place in multiple stages of the chair's life cycle.

During production, the aesthetics transform by changing the motif, yarn material or stitch structure, which is shows the adaptability of the design.
Second, transformability occurs through the insertion of the framework into the knitted panels. The flexible tubes are bent into a curve defined by the shape of the knitted material, thus transforming *through* the knitted material.
The user can transform the object by deploying it and reconfiguration the panels for various aesthetics. The desirable final geometry of the ARCHETYPE.89 is shown in Figure 134. The exact height of the chair can be altered with the turnbuckles.
After use, the beforementioned processes can be reversed. The object is deployed and the different components are separated. Therefore is the object transformable through the knitted material.

Streamlined production process

The effective and efficient use of the materials is kept in mind during the final prototype's development. At this stage, manual labour is very dependent on the budget and available production methods. In a later stage, 3D printing of parts can be injection moulded, eliminating any post-processing steps of the clamps and feet. The production process results in a minimal amount of waste which could be eliminated when production is scaled up. Compared to common cut-and-sew production methods of textile-based objects, the production process is highly streamlined.

Aesthetics

The aesthetics of the object is not considered elaborately during the development and detailing of the design. It however did impact the design choices inexplicitely.
The aesthetics are only evaluated after the development of the object through the user evaluation. This short study can be used to develop a Material Experience Vision and redesign the object according to this vision.
The aesthetics of the ARCHETYPE.98 is highly adaptive by altering the motif, yarn colours and stitch structures of the panels. The eight possible configurations of the chair result in different aesthetics.

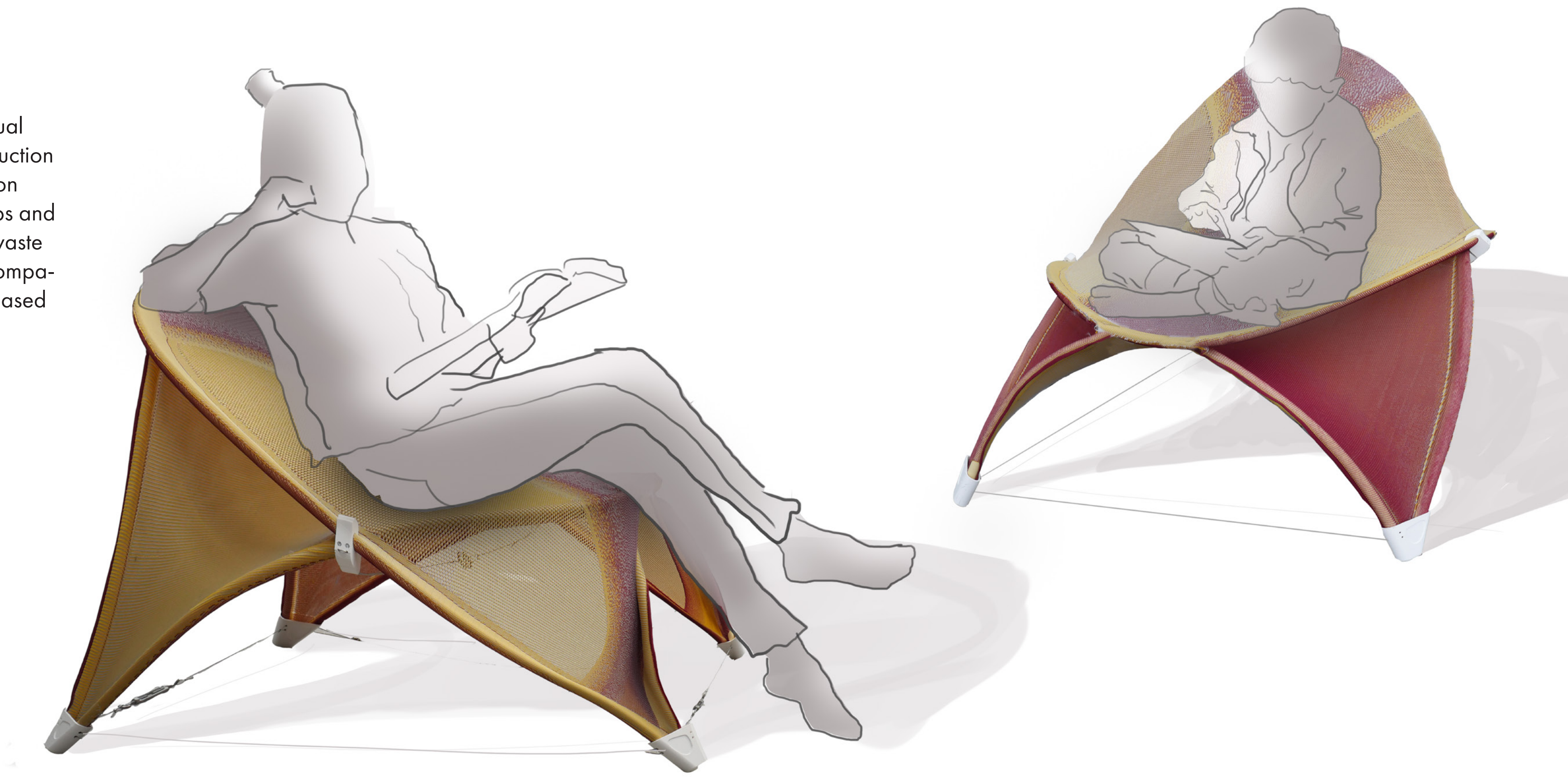


Figure 134. Illustration of the desired final geometry and use scenario of the ARCHETYPE.98

5.1 Discussion

The limitations, opportunities and recommendations of the research are discussed in this chapter, elaborating on the applied methodology, developed design space and demonstrator.

Methodology

The method of Material Driven Design (MDD) is usually applied to a material, such as coffee grounds, and not to a material production process like knitting. It is however considered to be very suitable in this case. The application of the 'material' knitting to create a load-bearing, transformable object is novel and requires an explorative and open approach to find creative solutions to posssible problems. The parameters of the 'material' are processes, ways of making, not environmental conditions or merely material combination. The MDD method allows for this tinkering and critical reflection.

The familiarity with the 'material' however might also have limited the creativity of the presented solutions. The designer should use all knowledge about knitting to further develop the production technique, and at the same time let go of all knowledge and abstract the technique to find novel applications and practices.

The MDD approach has not been applied to the extent presented by Karana et al. (2015). The Material Experience Vision is attempted to address during the concept development but is not utilized to direct any design decisions. See Appendix F for the preliminary Material Experience Vision. The related interview questions presented in the article are merely used to identify possible aesthetics, meanings and emotions that users associate with the final prototype. The aesthetics are described as a consequence of the structural development of the object. It is however impossible that the aesthetics have been disregarded completely in the process: sketches and prototypes always convey a certain aesthetics on which decisions might have been based inexplicitly.
However, applying the method to the extent considered suitable by the researcher, did allow for the wide exploration of the 'material'. Through this process, a well-known textile production method could be applied for a novel purpose. It is highly recommended to re-invent existing production methods through this explorative process, to come to novel applications, aesthetics and production processes that can make our products more sustainable.

Design Space

The design of the ARCHETYPE.98 is based on the presented general Design Space which contains the possible materials and methods that were inspired by a short literature study and material tinkering phase. It makes the parameters explicit to an extent not described in the studied literature yet. The Design Space allows other researchers and designers to develop other objects with this low-waste method of producing 3D knitted, transformable, load-bearing objects. The design space could be refined by experimenting systematically to evaluate all parameter combinations. The defined relationship between the parameters might differ according to the choices made within the Design Space, the applied domain and the requirements of the application.
The refined Design Space for ARCHETYPE.98 gives insight into the parameters of a bending-active 3D knitted object. The parameters show the wide range of possibilities to adjust the design to specific user needs or use scenarios. This makes the design process reproducible for future designers or researchers in order to continue the development of these types of objects.

Tools

For this project, the use of the STOLL CMS-530 knitting machine is based on availability. An industrial knitting machine of Steiger was less available but would have been suitable for this application since the needles are thicker and less easily broken. (Steiger Participations SA, 2022) As explained in Chapter 3.3.7, the machine has its limitations which were to be worked with during this project. The designed knitted panels have two functions, first structural -to bend the tubes into the desired curvature and to bear the load of a user-, and then aesthetic. The aesthetic elements, such as the fineness of the knit, are possible because of the fine gauge of the STOLL, which is usually used for apparel production. The Steiger has proven to be suitable for knitting for architectural scale, see Chapter 0.2.2. The designed object has characteristics of both domains so the choice between the STOLL and Steiger is based foremost on availability.

The design and production of the ARCHETYPE.98 is limited by the available resources. The knitting parameters are tuned as much as possible, limited by the knowledge and experience of the designer with the industrial knitting machine. Reproducing the object with another machine requires reconsideration of these parameters.

The ARCHETYPE.98

The development of the ARCHETYPE.98 has brought to light some limitations and opportunities of the design and production methods.

The design of the ARCHETYPE.98 is based on experimentation with PVC tubes. The first prototype is developed using both stretch and non-stretch fabrics. This is only a representation of the behaviour of knitted textiles, so the final design is limited by these prototyping material possibilities.

There are several aspects in which the object can be enhanced.

Panel connections

The feet are a solution to the problem of the tube not staying in the desired configuration within the knit, see Chapter 3.4.1. Further research could be conducted into possible yarn materials and stitch structures to reinforce the knitted area to give it the desired rigidity. The reinforcement of the tube ends using polyester yarn combined with nylon did improve the bursting strength compared to only polyester yarn, concluded from the fact that the tubes did not burst through the knitted tunnel ends. Research into the bursting strength of stitch structures is required to further reinforce the segments, specifically the stich structure knitted on a single bed without any transfers. Reinforcement of the tunnel ends will increase the product's lifetime.
The clamps to attach the two panels are designed from a structural perspective, with little consideration of the aesthetics or ease of use. Similarly, the side clamps can be improved in terms of aesthetics, ease of use, functionality and material usage. The clamps allow for the desired transformability of the object, which is not evaluated with future users in this study.

Frame material

GFRP tubes are utilized in the final prototype. The tubes are more expensive and have a higher bending stiffness than PVC tubes. The stiffness results in more tension in the knitted surfaces, which also makes it harder to insert them into the knitted panels and thus to tense the knit. Only one diameter of the PVC and GFRP tubes is evaluated in this research. The material choice is based on the availability of resources, further material research is required. To improve the load-bearing capacity it could be considered to use a stiff framework: an aluminum frame bend to the desired curvature, for example of DAC aluminium. (DAC, n.d.) This eliminates the unique selling point of the ARCHETYPE.98, namely the fact that the knit determines the geometry by curving the flexible frame. The knit would however still determine the geometry for it determines the depth of the chair through its stretch. The chair would also still be deployable.

Stitch structures

Many stitch structures have been developed throughout the research, see Appendix A. The structures are not iterated on elaborately but merely show the realm of possibilities. The partial spacer structure, and the double jacquard pockets with filling (see Appendix A Sample 11 and 90-93) show great potential for further exploration of the ergonomics of the ARCHETYPE.98. Possible local application of these structures can increase the user's comfort and reduces the need for a more elaborate production process, e.g. adding padding to a sitting surface, or additional seams required to create pockets for filling.

Yarn material

The yarn materials used on the industrial knitting machine are limited to polyester and nylon due to the limited resources available. In the earlier stage of the research, it is shown that different materials can be combined to create a soft hand feel and desirable technical characteristics, i.e. tensile strength and bursting strength. In future development, this should be explored to improve the aesthetics, usability and performance of the sitting object.

Geometry

The shape of the knitted panels has undergone numerous iterations and testing to achieve the geometry for the intended design. However, the uniqueness of the ARCHETYPE.98 lies in the adaptability of the design, allowing it to remain functional even if the knitted geometry deviates slightly. The adaptability is enabled by adjusting the number of tubes and the tubes' length, which allows for a variation in the resulting tension of the panel surfaces.
This flexibility in the production process is possible because of the manual labour during assembly. When scaling up the production process, the suitable length of the tubes can be measured and reproduced.
It should be acknowledged that altering the length of the tubes, and thus the tension in the knitted surfaces, may influence the load-bearing capacity of the object. This modification potentially affects the weight the structure can support, requiring careful consideration during the design process.

The implications of this innovative production process can be profound. Firstly, the adaptability of the product to the knitwork introduces a level of unpredictability in the final outcome. While this uncertainty may present challenges in maintaining strict uniformity, it also opens doors to the creation of unique and organic designs. Embracing the variation introduced by the knitwork's influence can result in unique products.

On the other hand, the reliance on knit introduces the need for a thorough understanding of material properties and behaviour. Designers and manufacturers must grasp the intricacies of the designed stitch structures and yarn material choices to manage the uncertainties that may arise. This necessitates a deeper exploration of the material's technical characteristics and its interactions during the shaping process. This is further elaborated on in Chapter 5.2.

Chair?

The technical evaluation in this study is limited. The limitations of the study are discussed in Chapter 4.3.4. Given the limited load-bearing capacity of the ARCHETYPE.98, the conclusion on it being a chair could be questioned. However the sitting object is merely a demonstrator of the researcher, to bring to light the limitations and opportunities of 3D knitted, load-bearing, transformable structures. Therefore the ergonomics is not taken into account in this research. Further research could elaborate on the possible stitch structure to improve the user's comfort when sitting on the chair.
The demonstrator proves that creating highly adaptable, transformable, light-weight structures produced with low-waste production methods can be load-bearing, and hopefully inspire other designers to adopt this novel method of producing textile-form.

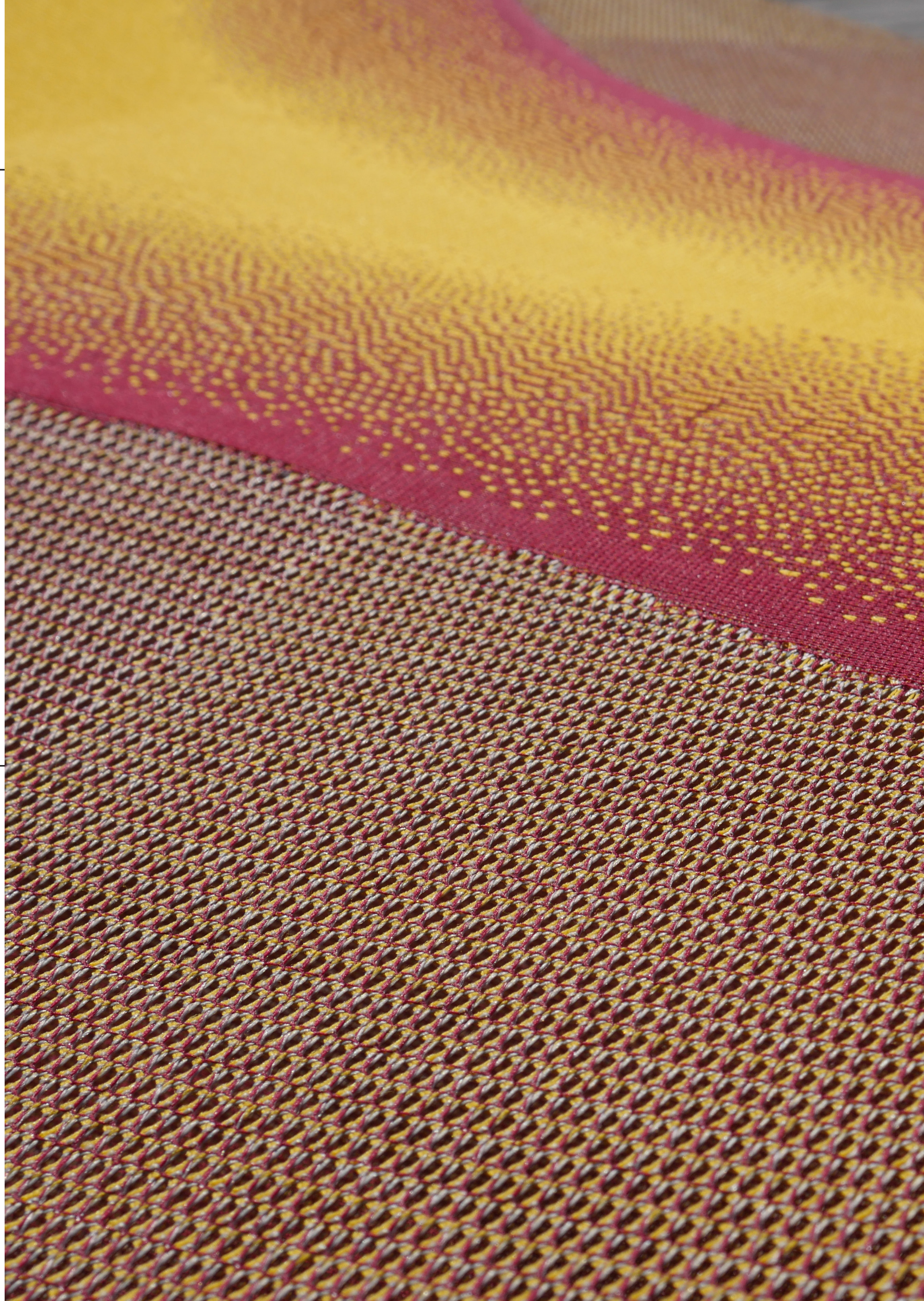
5.2 Recommendations

In addition to already mentioned the future research required to improve the ARCHETYPE.98, there are some recommendations beyond the scope of this research.

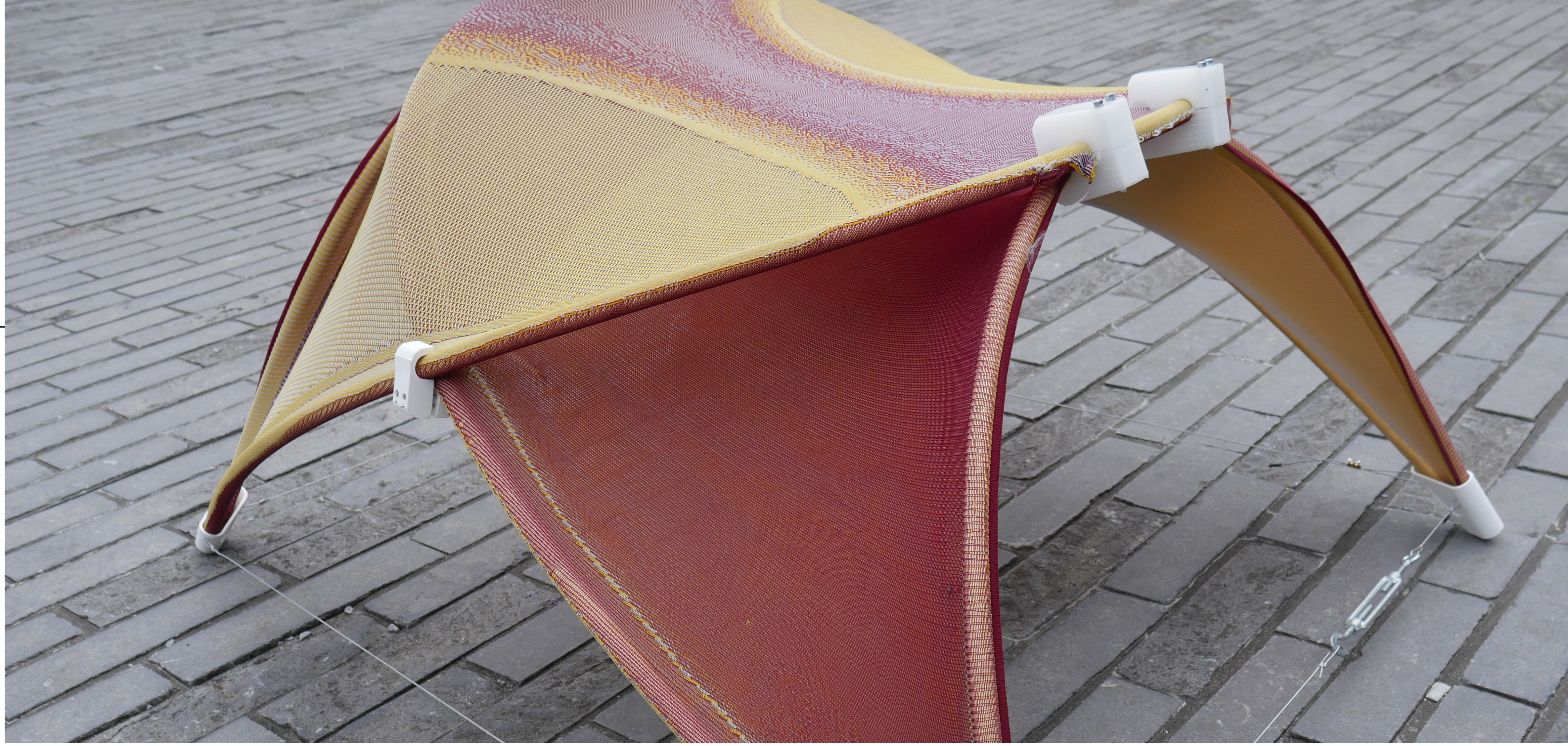
Modelling and predicting the knitted material behaviour
First, the development of software to model and predict knitted material behaviour could greatly improve the process of development of any 3D knitted object.
The elasticity, elasticity directions and dimensions of knitted fabric depend on the yarn material, stitch length, knitting machine parameters, stitch structure, stitch structure layout within the shape, and the programmed dimensions. The M1Plus software of STOLL only visualizes what the knitted fabric will look like in terms of knit structure and yarn colours, not taking into account any other properties. The iterative process of adjusting the parameters in the software to come to the desired look and feel of a knit structure requires time and material. This increases the difficulty of designing and prototyping such objects. The research thus also exhibits the limits of the STOLL CMS-530 knitting machine to some extent. The large number of parameters however also exhibits the great extent of control over knitted textiles.
The software developed by STOLL utilized in this project is M1Plus. The latest version is CreatePlus. (STOLL, 2021) A major drawback in the development of the ARCHETYPE.98 is the inability to scale the design within the software, as explained in Chapter 3.6.3. Manually scaling down the panel takes time, and is an inaccurate method. The adaptability of the design would improve greatly if this is made possible within the M1Plus software directly.

Modelling and predicting the textile hybrid behaviour
The development of software to model and predict the textile hybrid behaviour could immensely improve the process of development of 3D knitted load-bearing structures.
Modelling the behaviour of the flexible tubes and knitted panels potentially gives insight into the forces resulting from the tensioning of the knit and the application of a load on the object. Additionally, it could save time and reduce material usage. To be able to evaluate the currently developed final prototype, the object should be produced in the desired final materials. When testing the load-bearing capacity, possible unrepairable damage can be caused to the knit or other parts of the object. This process can become costly if the material is expensive. Therefore, the development of accurate modelling and prediction tools for textile hybrid structural behaviour is required.
Research in this line of field is being conducted at the moment, for example by David-Sikora et al. (2020). According to his research, the actual material performance data of a textile structure should be identified and used as input for a textile hybrid structure digital model. The data includes the modulus of elasticity, tensile strength and the stress-strain curve for non-linear analysis. The study formulates the principles of hybrid structures to employ a physical and computational model of the BeTa Pavilion. An iterative process is described in which the knitted fabric's mechanical properties are used to update the computational model and perform linear and non-linear analyses. The described iterations are comparable to the development process of the ARCHETYPE.98: alternating between adjustments in the knit, and the dimensions and material of the framework. The digital model of Davis-Sikora et al. (2020) however did not represent the geometry of the physical model accurately. The knitted textile pockets are the weakest points of the structure and further exploration of yarn choice, 3D printing materials and GFRP rod flexibility is advised. The long-term deformation and textile creep are addressed as future research topics in order to withstand installation.
The recommendation of Davis-Sikora et al. is similar to the conclusions of this research. It also exhibits great difficulty to model and predict textile hybrid structures. Especially considering the different yarn materials and stitch structures utilized within one knitted panel. The beforementioned mechanical properties of each segment should be determined and updated in the computational model. This indicates the complexity of textile hybrid structures such as the ARCHETYPE.98. Further research in this domain is recommended to expand the range of applications of this low-waste, adaptive textile-form method.

To conclude, further development of 3D knitted, load-bearing, transformable objects can be brought forward by the introduction of modelling software in which the knit structure and textile hybrid structure can be evaluated before production.



5.3 Conclusions



The research demonstrated how traditional textile production methods can be transformed by taking inspiration from architecture, fashion design, and industrial design. Rigid and flexible knitted elements are explored for a load-bearing, transformable structure, to further develop our understanding of the benefits of adapting textile hybrid structural behaviour via material, process and geometry. The ARCHETYPE.98 -a transformable, bending-active, lightweight, sitting object- shows the approach is beneficial for the environment for its low waste, adaptable design and on-demand production possibilities.

The research is concluded by discussing the results in terms of feasibility, viability and desirability.

Feasible.

3D knitted, transformable, load-bearing objects have been shown to be feasible through the demonstrator of this project, the sitting object. The ARCHETYPE.98 exemplifies how knitting can be used as structural material on which the load-bearing properties and transformability depend.
The final prototype exhibits multiple rigidifying methods combined into one object to obtain the load-bearing capacities. Combining several methods greatly expands the realm of possibilities on how to make a 3D knitted, transformable, load-bearing object.
Mapping the Design Space of both the general topic and the demonstrator made the process explicit and reproducible for other designers and researchers, bringing this interdisciplinary approach forward.

Viable.

The demonstrator is developed with widely available materials, e.g. PVC tubes and polyester yarns, showing the accessibility of the method. The Design Space exhibits a wide range of materials and methods, resulting in a pool of possibilities ranging from more inexpensive to expensive. Developing knitted textiles on the industrial knitting machine is highly iterative due to the software, making the process time- and cost-effective. The adaptable textile surfaces allow for personalization, eliminating the need for additional production processes. The transformability and minimal weight make the ARCHETYPE.98 easy to transport.

Desirable.

Knitwear is growing in popularity for its adaptability, personalization possibilities and low waste during production. The novel application developed in this project incorporates the desirable adaptability into a functional object.
The knitting software enables an iterative design process. The material properties and aesthetics can be adjusted locally in different parts of the object. A user can customize sitting surfaces, colors, and motifs to create a personal object for extended use. (Mugge et al., 2005) The production method is also desirable for its low waste due to its shape- and form-making possibilities. If the same prototypes would be produced with cut-and-sew methods, the amount of waste would drastically increase.
The final prototype will be exhibited at the Dutch Design Week 2023. The interest in the object shows desirability.

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Appendix A: Samples

1

Purpose
To create tunnels to insert a bone structure to tension the knit. Experimenting with round knitting.

Process
Domestic knitting machine.
Selecting 30 needles on main and ribber bed, in H (alternating position). Knitting approx. 10 rows plain knit.
Round knitting: carriage on right, select left Part and right N to PR.
Knit approx 10 rows. Repeat

Variables
- Tunnel length and width, and thus determining the shape of what is inserted in it, using the knit as tensioner.
- General knitting parameters: tension, yarn material, stitch type

Take-aways
The round knit parts stretch less than the parts in between, resp. a single jersey and full needle rib. When tensioning this, the tunnels can stretch less than the rest of the material, so not effectively tentioning it all over.

Next step
Try to knit the tunnels as here, but the structure in between as a plain knit on one bed to eliminate the rib structure.

2

Purpose
To try to make pockets

Process
Similar to Sample 1, elongating the round knitted part and shortening the rib structure.

Variables
- Pocket size, and thus determining the shape of what is inserted in it, using the knit as tensioner.
- General knitting parameters: tension, yarn material, stitch type

Take-aways
Regular tubular knitting results in closed pockets without opening to insert anything into the pocket. Again the round knitted parts are less stretchy than the rib.

Next step
Finding ways to create pockets with openings so something can be inserted but cannot fall out of the pocket by itself.

4

Purpose
To make tunnels by elongating the knit on one bed.

Process
When both buttons go from N to PR, only the main bed will be knitted. Knitting all needles on rib (on H) for a few courses. Then knitting only the main bed, untill the stitches are not formed well anymore. Knitting the rib again.

Variables
- Tunnel length and width, and thus determining the shape of what is inserted in it, using the knit as tensioner.
- General knitting parameters: tension, yarn material, stitch type

Take-aways
The tunnels are open from both sides. On the back side of the tunnel there is only one course of stitches which are very elongated, resulting in vertical floats.

Next step
Knitting the back of the tunnel with elastic yarn to create a hinge?

3

Purpose
As first thought on how to use hard plate material inside the pockets of a knitted structure where the knit functions as a hinge and creates a tension to keep the plates in place.

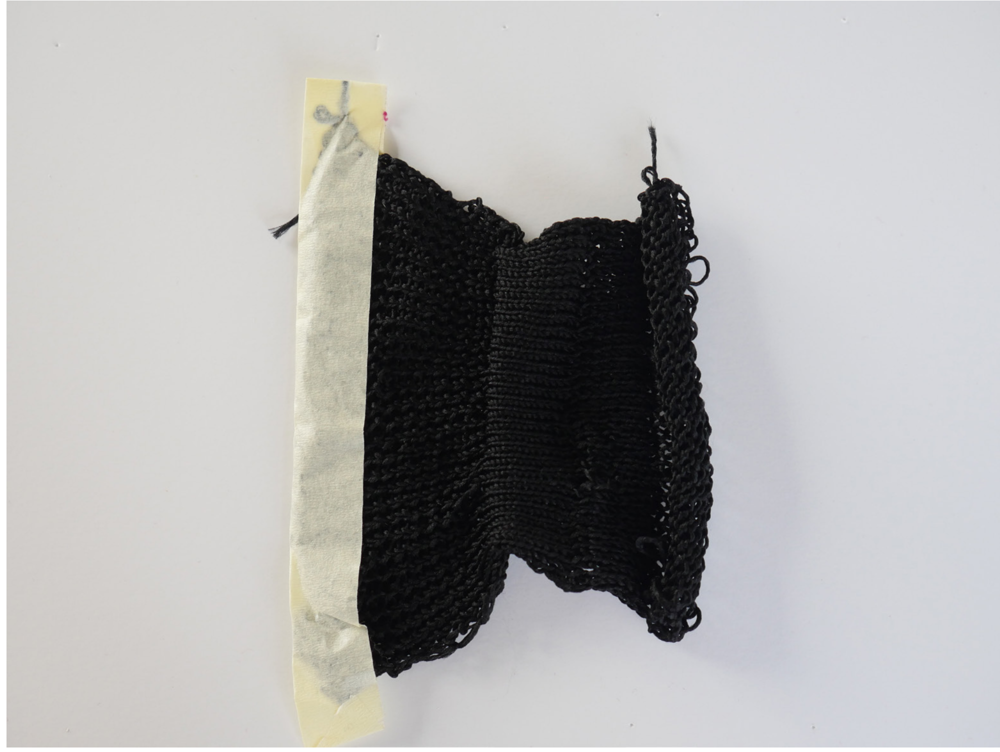
Process
Using the lock machine to connect squared pieces of tricot fabric. Using pins to enclose cardboard inside the pockets. The pockets and thus panels overlap approx. 2 centimeters

Variables
- Size of both the pocket and the inserted plate material will determine the pre-stretch of the knit and thus the stretch and stress when the configuration is altered
- Placement of the pockets and panels in a larger knit structure
- General knitting parameters: tension, yarn material, stitch type

Take-aways
The stretch of the fabric works well to keep the panels at a 90 degrees angle when placed as such. This works both ways, when left is over right or right over left.

Next step
To knit this. Three layers need to be knitted.

5



Why did I make it?
Continuation on Sample 4, trying to create a tunnel that is elongated on one side.

How was it made?
Knitting rib for approx. 20 rows. Knit half round: carriage on right, set left Part and right N to PR, knit two rows, carriage on the right again, set right Part and left N to PR. Repeat. Knit half round for approx. 10 rows. Knit only main bed for 5 rows. Close tunnel by knitting rib again.

What is the result?
An elongated front part of the tunnel, which is open on one side. The back of not stretched as much as in Sample 4. Gives a direction to which the fabric should bent.

6

Purpose
See if the re-entrant auxetic structures behaves actually auxetic when made of knitted stretch fabric.

Process
Shape cut from warp knitted stretch fabric, attached with lock machine.

Variables
- Type of auxetic structure
- The ratio between the widest and smallest distance of the repeating shape

Take-aways
The results should be measured to determine if the structure is actually auxetic

Next step
Knit the structure on the domestic knitting machine on a single bed and double bed rib structure?
Try another auxetic structure.

7

Purpose
Inspired by Victoria Salmon, looked like a hinge function or a directed fold line.

Process
Knitting rib structure 2x2 for approx. 20 rows. Changing all needles to the other bed, creating the opposite rib pattern, again knit 20 rows. Repeat.

Variables
- width of rib
- using a stiffer yarn might make angle stay in shape more
- General knitting parameters

Take-aways
Where the rib is changed, a wider 'fold' is created. When the knit is stretched out horizontally on these spots, the ribs fold into each other, creating an angle in the fabric. It does not undo by itself, one can more the 'hinge' between 0 to approx. 90 degrees?
Potential hinge or guided fold line to assemble a product.
Not a stiff hinge yet.

Next step
1. Creating this 'hinge' only on a fold line, pockets to be filled with plate material to test if the fold then still holds (because of the weight of the plates)

2. Knit a horizontal hinge with this rib strucure

3. Experiment with wider or smaller rib structures and the effect on the hinge function.

8

Purpose
As iteration on Sample 7, creating a horizontal rib hinge.

Process
Knitting approx. 10 needles on main bed, 10 needles on ribber bed for 10 courses. Switch all stitches to opposite bed, repeat.

Variables
Same variables as Sample 7

Take-aways
Where the rib is changed, a wider 'fold' is created. The rib is wider than in Sample 7 but works similar so far.

Next step
See Sample 7.

9

Purpose
To experiment with the ‘hold’ functi-on on the domestic knitting machine

Process
Using the ‘hold’ function on both beds, similar to working with this function on a single bed knitting machine. Creating short rows.

Take-aways
Not very nice sample, many stitches fell.

Next step
Practice the short rows.

10

Purpose
To experiment with the ‘hold’ func-tion on the domestic knitting ma-chine, to create an angle between different planes, tunnels or pockets.

Process
Using the ‘hold’ function on both beds, similar to working with this function on a single bed knitting machine. Creating short rows (without counting, no regular struc-ture). Afterwards making a closed tunnel.

Variables
- the steepness of the slope, vari-eing the direction of the tunnel
- the amount of tunnels: possibly overlapping

Take-aways
The curved structure does not stretch equally, because the distance (and thus amount of stitches/course) between the tunnels is different.

Next step
Using the short rows on other structures than a rib. Possibly cre-ating pockets in shapes other than squares, or even hinges in different directions.

11

Purpose
To experiment how to make multiple pockets next to each other horizontally.

Process
Knitting round, but skipping two stitches on the ribber bed where the seam between two pockets would be. After every two rows, the created floats on the ribber bed are manually transport to the main bed, knitting the stitch on those needles again. Before closing by creating a rib structure on all needles, above each pockets one stitch is transfered to the left/right, to create a hole to be able to fill the pocket.

Variables
- size and shape of the pockets
- volume of stuffing inside
- material stuffing

Take-aways
Three pockets next to each other. Although it required manual actions, these might be doable on the industrial machine. The float just need to be transfered, not necessarily knitted directly after-wards.

Next step
Scaling this up, possibly creating different sizes of pockets next to each other, or making tunnels instead of pockets.
Finding a different method to get to a similar result?

12



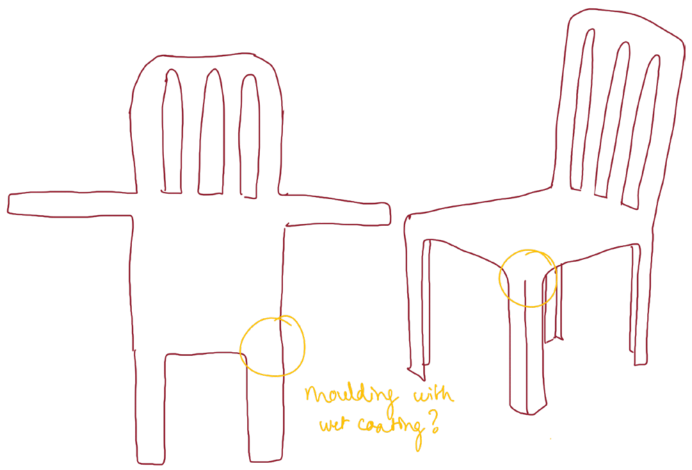
Purpose
To experiment with a coating, to harden a whole segment

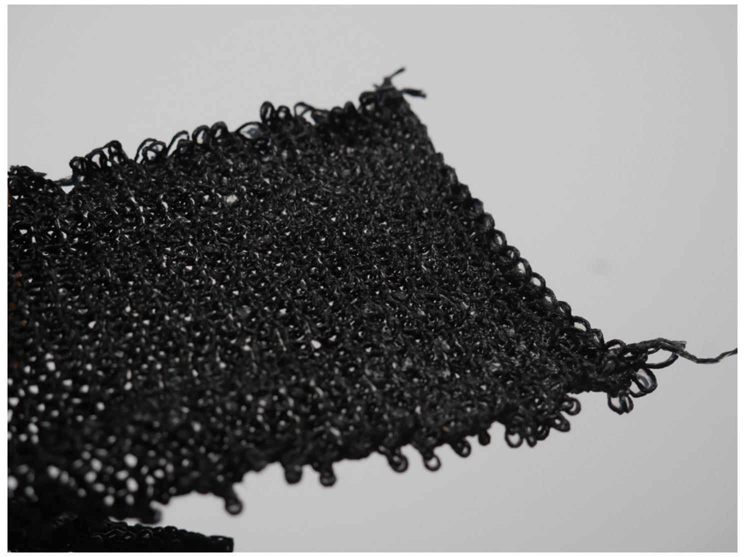
Process
Using Paverpol, a textile hardener that works well with natural materials. Applied onto knitted fabric (plain and a rib) and regular tricot fabric. Tried to pour it over, dip it in, brush it onto the surface.

Variables
- Size and shape of the coated part on a knitted part, only coating a strip or the whole segment, or even a corner or tunnel shape
- amount of coating: using a thin layer leaves the material flexible
- type of coating: possibly dissolvable with heat or water, stronger coating that makes it even more rigid
- knitted structure: a porous knit structure becomes more rigid, because the holes can be filled with coating

Take-aways
The rib structure that was soaked into the Paverpol is very stiff, still flexible and not brittle at all. It is stronger than the plain knit, logical since the rib creates a thicker material so containing more of the hardener.

Next step
Apply it onto a 3D sample of a box, to be knitted on the Steiger.





13

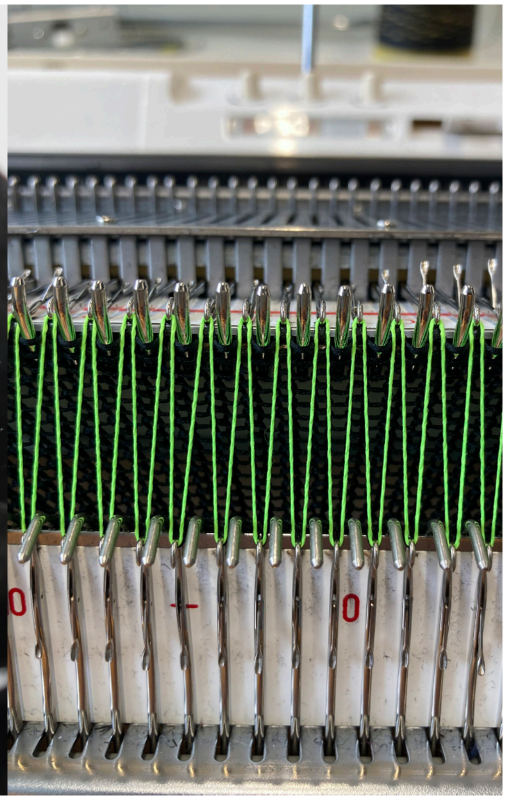
Purpose
Try the overlapping pockets

Process
Knitting round, openings the beds, wrapping the green yarn between the stitches to create the length difference between back and front.

Variables
- Length of the wrapped elongated stitches
- Seperating the two pockets fully or partially to just keep elements in place but still connected

Take-aways
Openings the beds is not possible on industrial machine. The cardboard inside will stay in the middle of the wrapped yarn, so half the length is used to elongate. Not enough.

Next step
Improve to be able to make overlapping pockets on the Steiger. See Sample 24 for iteration.



14

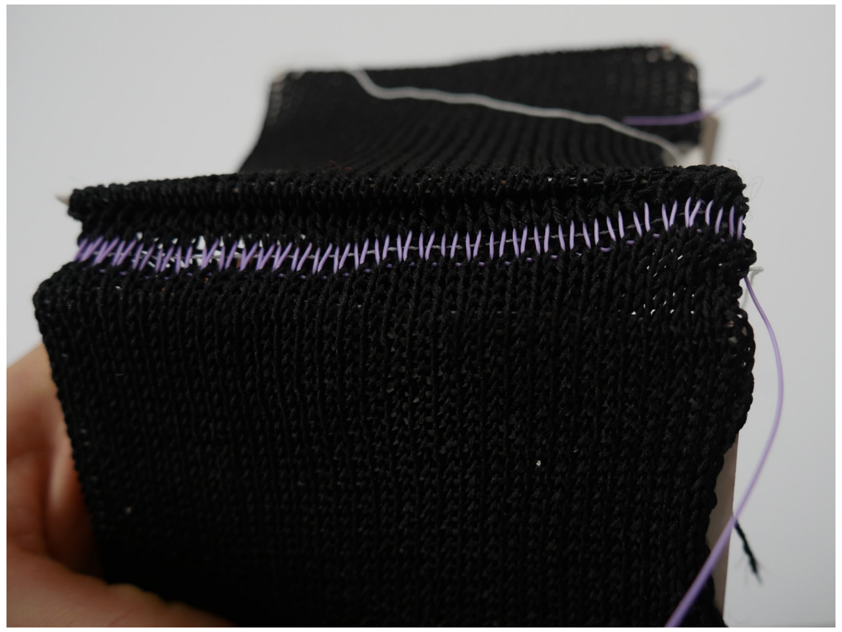
Purpose
To create a forces angle, a hinge that returns to its original position

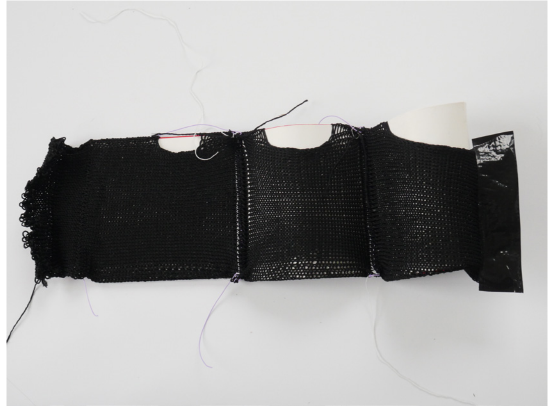
Process
Knitting a pocket, knitting one course with elastic yarn on the back bed, knitting one course of electric wire on the front bed. Repeat

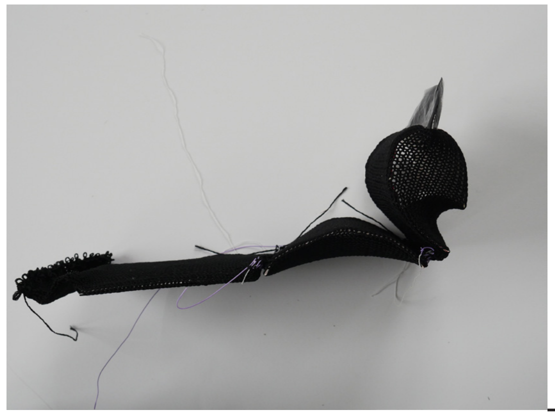
Variables
- Stiffness of the yarn, however dependent on the gauge and needle selection whether it can still be knitted
- Stitch length with the stiff yarn

Take-aways
The electric yarn is stiff in the vertical direction, can stretch out horizotally but will not return to original shape. Does not work as expected, the elastic does not pull enough?

Next step
Using only the elastic to create a corner.







15

Purpose
Try a forced corner with elastic

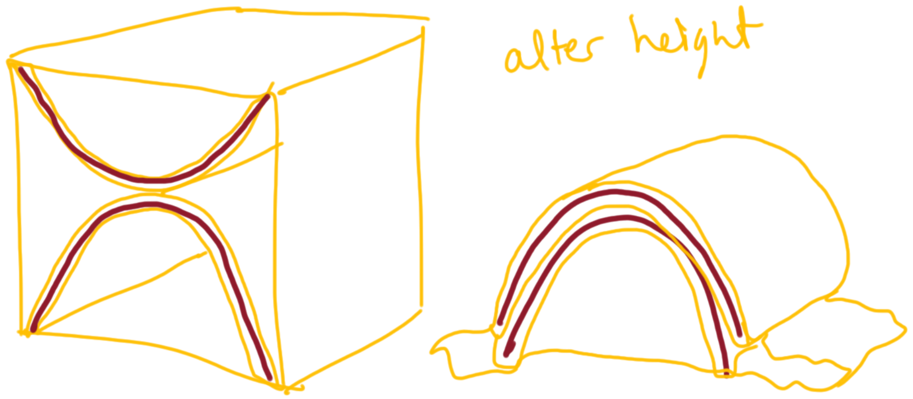
Process
Knit plain, knit few rows only on back bed, knit elastic yarn on front bed, knit together.

Variables
- elasticity of the elastic yarn
- amount of rows knitted on the opposite bed

Take-aways
Sample to small to see clearly, so knit bigger. The angle is obvious.

Next step
Recreate on the Steiger on larger piece, create a box.

16



Purpose
Experiment with cardboard and the tension of the fabric.

Process
All made of tricot fabric and lock machine. The first is a sample with a plastic sheet inside.
The second and third photo are of the same sample: inspired by a pillowcase to ensure the cardboard is completely closed off.

Variables
- The length or stretch of the top and bottom fabric layer, this determines the bending angle of the plate material inside
- The plate material characteristics; the stiffer, the more the fabric will stretch out instead of making the plate bend; and vise versa

Take-aways
To insert hard material the opening should be large enough, and the stretch of the material the material and thus the final shape are hard to control.

Next step
Researching through literature what material combinations are possible to create a balance between the tensioning element and the plate.

17

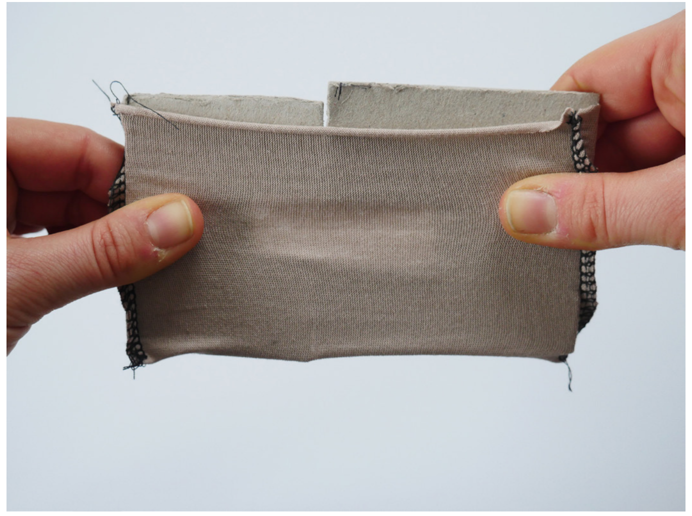
Purpose
To create a reversible but stable material connection

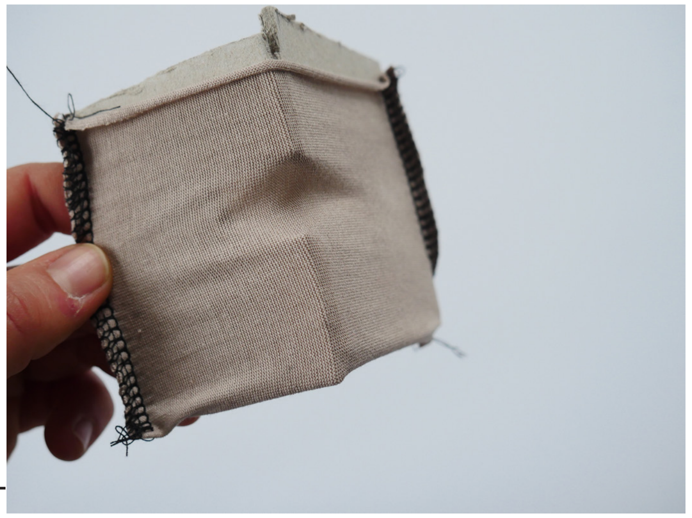
Process
Using bought tricot fabric and lock machine, and coardboard.

Variables
- The width of the panels relative to the fabric pocket
- the stretchability of the fabric pocket

Take-aways
The size of the hinge depends on the stretch and flexibility of the knit.

Next step
Knit the shape of the cardboard and cover them both.





18

Purpose
To explore the possibility of small soft pockets

Process
Made of tricot fabric and lock machine, creating pockets that are stuffed with polyester filling material.

Variables
- the size of the pocket relative to the amount of filling material
- the distance between the adjacent pockets

Take-aways
The pillows can hold each other, enabling different positions. The filling is too soft to create a rigid shape.

Next step
Knit on Steiger, try another filling, specify the distance between the pillows and the size, to make them ‘grab each other’

19

Purpose
To try to create a sitting object using the stretch of the fabric as tensioner and contruction.

Process
Made using tricot fabric and lock machine, and three cardboard panels, cut to a size to fit inside the pocket while tensing it.

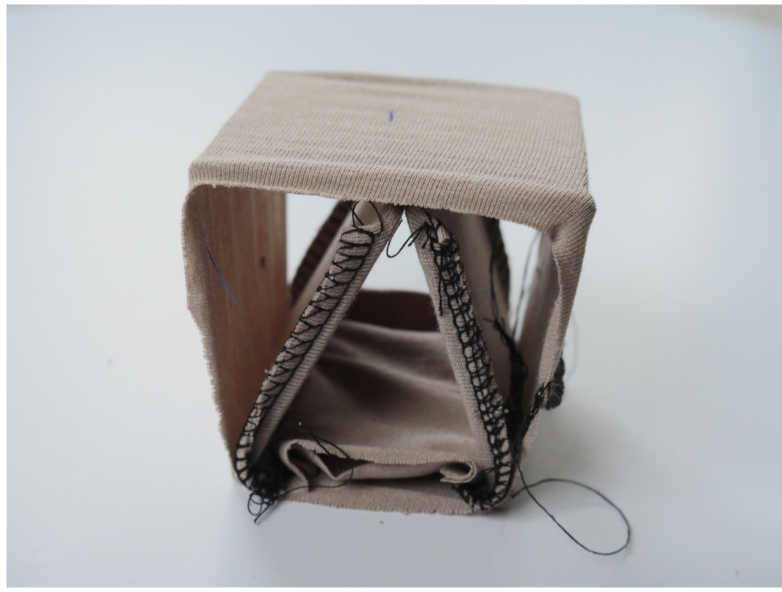
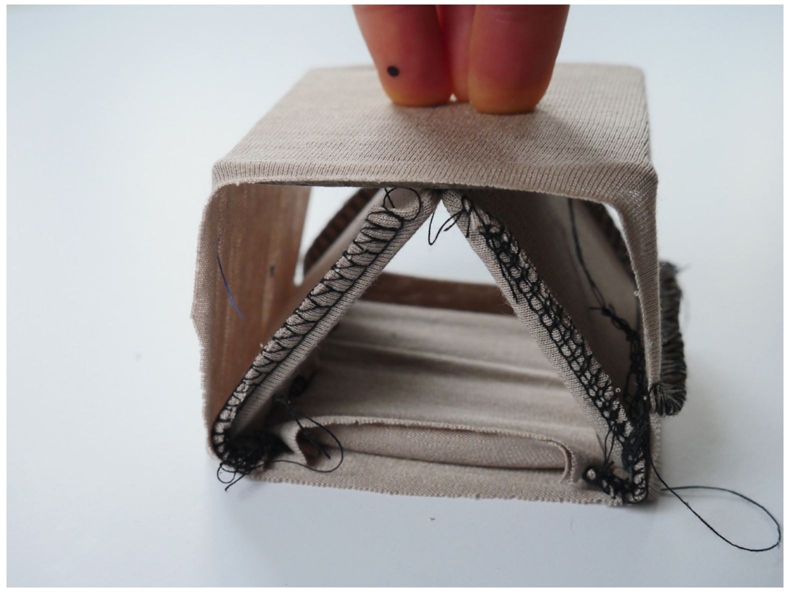
Variables
- The stretch of the knitted structure: hold the panels in place and determines how much the panels can move when a force down-wards is applied
- The size of the panels relative to each other and to the fabric structure around it
- The connection points of the fabric to each other and possibly to the panels

Take-aways
The downward force from 'sitting' on top results in the side fabric being relaxed, where I hoped it would tense because the inner panels are further apart because of the pressure, stretching the fabric around it. But it only stretches the bottom part of it, while the sides are relaxed.
Upside down works better: by sitting down, the cardboard is pushed outwards and the fabric is tensed.

Next step
Learn more about tensegrity, and make a sample in which the top panel is also enclosed in a pocket.






20

Purpose
To create 'soft' handfeel with the polyester and not too much stretch

Process
Making ripples by holding one of the needle beds, on both sides alternating.
One of the ripples has elastic held stitches, resulting in more stretch but a more pulled ripple.

Variables
- The length of the ripple
- General knitting parameters

Take-aways
The stitch that are held on the back of the ripple result in less stretch than regular jersey. When stretches, the fabric still feels 'soft' because the ripples are not stretches so the fabric is still in a relaxed state partly. Could be used to create a soft surface for the sitting object without the need of any filling.

Next step
Experiment with different materials. See Sample 21 and 44 for interation.

21

Purpose
To create 'soft' handfeel with the polyester and not too much stretch. Iteration on Sample 20.

Process
Making partial ripples by holding a few adjacent stitches.

Variables
- The width of the ripples

Take-aways
The stitch that are held on the back of the ripple result in less stretch than regular jersey. When stretches, the fabric still feels 'soft' because the ripples are not stretches so the fabric is still in a relaxed state partly. Could be used to create a soft surface for the sitting object without the need of any filling. The difference with Sample 20 is that the soft surface is only on one side.

Next step
Experiment with different materials.

22

Purpose
To create a cord or pull thread

Process
Laying in yarn between the two beds while knitting full needle stitches

Variables
- Material: seems very important for the 'cord' yarn needs to slide between the knitted structure
- Stitch length: leaving more or less room for the cord to lay between the rows, thus making it easier or harder to pull the cord through

Take-aways
Multiple threads together can be pulled to create a ripple in the fabric. Could be used to tighten a fabric structure, to knod the fabric to another material or to close a pocket structure.

Next step
Try different materials for the knit and cord, and make it on the industrial machine on the side/ at the end of a pocket. See Sample 43 for iteration.

23

Purpose
To explore 3D shape making on the domestic machine.

Process
Knitted with 100% polyester yarn on the domestic knitting machine. Holding the back stitches to knit more rows on the front, approximately 3 front rows for each back row, to create a larger panel on the front. The width is altered by increasing and decreasing on the sides. After knitting the pocket is stuffed with polyester filling.

Take-aways
Using filling to stuff the shape does not necessarily result in a flat back panel, because the side seams are not 'rigid'. The knit is still round so the volume of the filling is still divided over the full round, not necessarily more to the front where there is a wider panel. The shape is a little twisted, probably because of the polyester yarn twisting while knitting.

What is a next step?
Use 3D form making to create a box or chair-like shape.

24

Why did I make it?
To knit two overlapping pockets in a way that would be replicable on the industrial knitting machine.

How was it made?
Knitting round, holding alternating stitches of the front bed, knitting 6 rows, then transfering this 'ripple' to the back bed. Continue knitting round to create the second pocket.

What is the result?
The bridge stitches stick a little to the front bed, the overlap is smaller than expected. The length of the bridge and thus the overlap is limited because the amount of extra ripple rows is limited.
The polyester yarn makes the pockets twist, which is not very desirable.

What is a next step?
Replicating it on the industrial machine, with possibly a more stable yarn such as wool.

25

Purpose
To experiment is two curved panels could create a 'snap system' that could stretch or relax another structure.

Process
Two pockets are created attached to each other on two sides. The panels inside the pockets are larger than the pocket, resulting in a tensed and curved panel. One panel curved but could be relaxed when the panel on the back is curved in the other direction.

Variables
- the size of the pocket in relation to the size of the plate
- the stretch of the knitted fabric in relation to the flexibility/rigidity of the plate material

Take-aways
The material and stiffness of the panel very much determines the effect and thus require thorough material research.

Next step
Finding the stiffness of the knitted structure that I want to use for this 'clicking' system

26

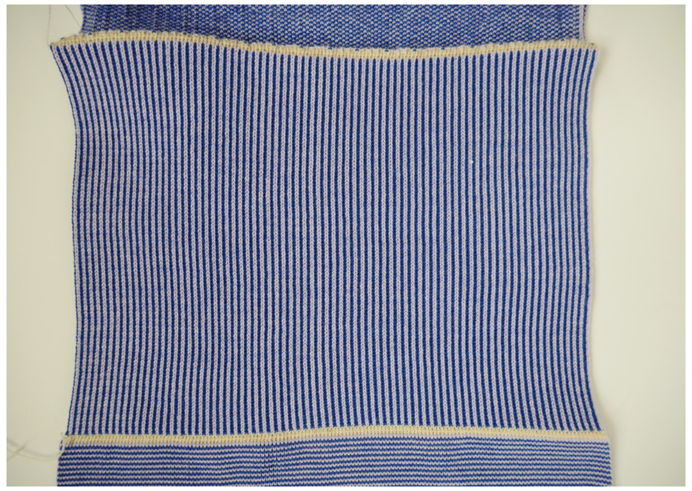
Purpose
To experiment with Origami structures, because it could be used to indicate clear folding lines as instruction for the user how to build the stting object (use cues)

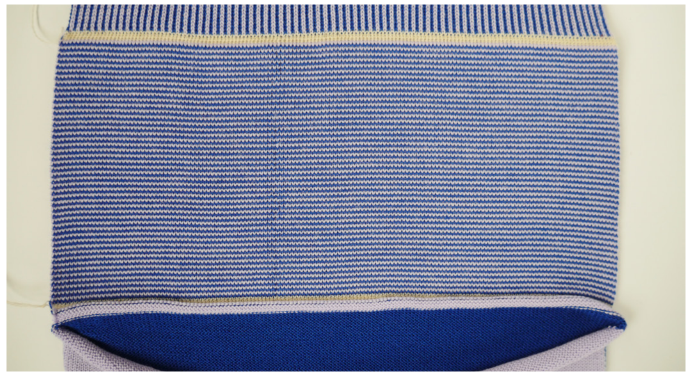
Process
On the industrial knitting machin, using M1Plus (STOLL, 2021). The 'panels' are full milano, the downwards folds are single jersey on the back bed, the upwards folds are single jersey on the front bed. Combined a wool yarn with a melting yarn.

Variables
- the orientation and placement of the fold lines
- the formation of the fold lines: the amount of single jersey stitches
- the stitch configuration of the 'panels'

Take-aways
The melting point of the melting yarn is too high to reach with the iron at the KNITWEAR LAB, but steaming and pressing it on the indicated foldlines resulted in an origami structure.

Next steps
Using the stitches and holdlines to fold a sitting object. Possibly another melting yarn that melts at the heat of an iron.





27-31

Purpose
To experiment with different knit structures of the same yarn to feel the different characteristics of the structure.

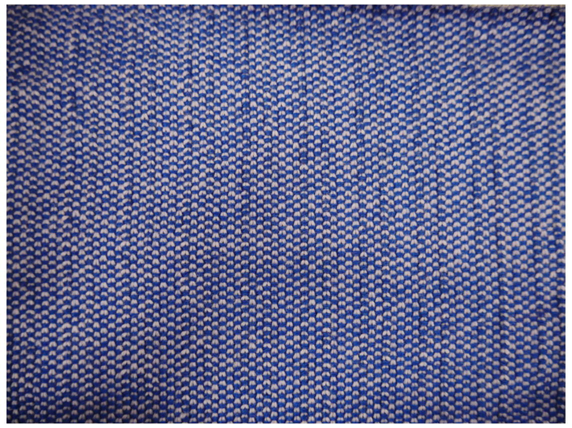
Process
On the Stoll, using M1Plus. From top to bottom: weave-in, a tubular with tuck in between holding the layers together, full milano, pocket, mesh.

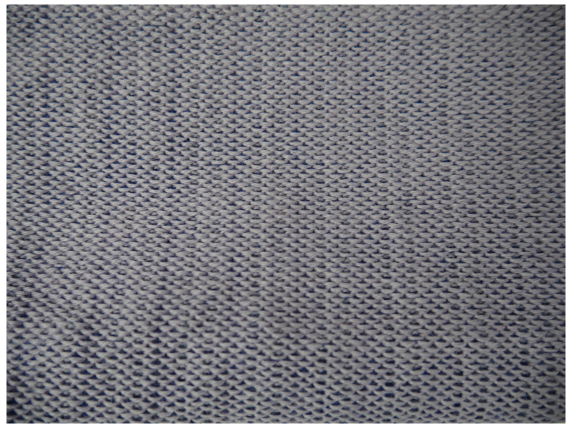
Variables
- the stitch structures

Take-aways
The final dimensions are determined by the stitch structures, since all samples are programmed for the same amount of needles and rows and the dimensions are different.
The weave-in does not stretch in the weave direction. The tubular-with-tuck is thick and dense. The full milano is very stable in the vertical direction. The mesh is extra stretchable because of its structure.

Next steps
Replicating the structures with different yarn on the Steiger.

27

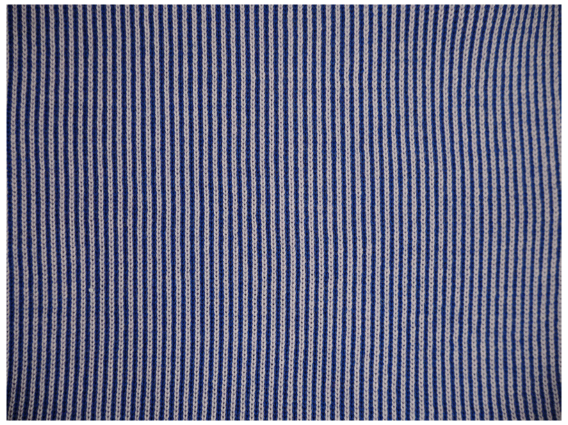


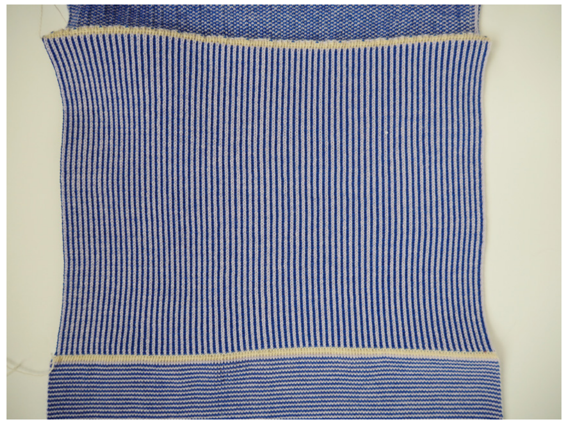


Why did I make it?
To replicate a weave-in structure to create a non-stretch fabric in the weft direction

How was it made?
Transfering stitches from front to back or vise versa to let the float be tucked between the stitches.

What is the result?
Almost no stretch in the weft direction. Very flat and light structure.

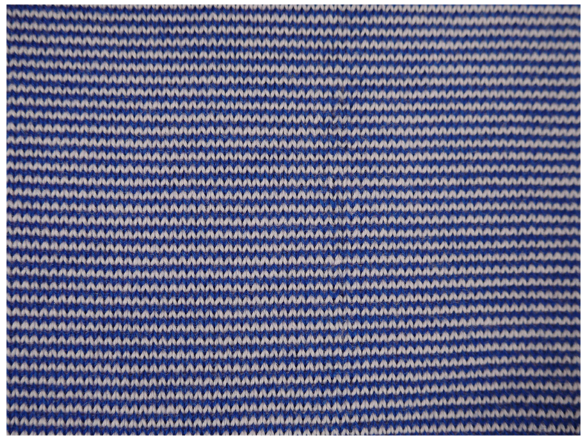


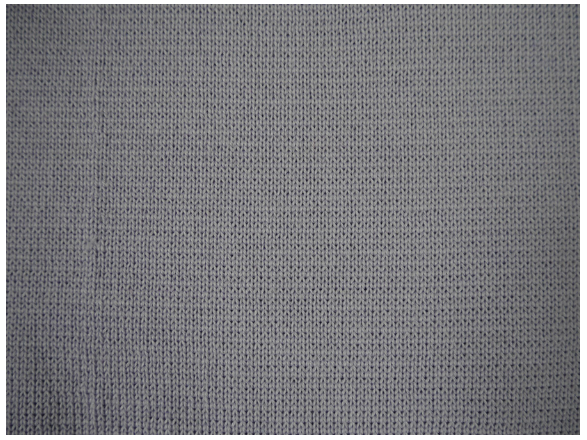


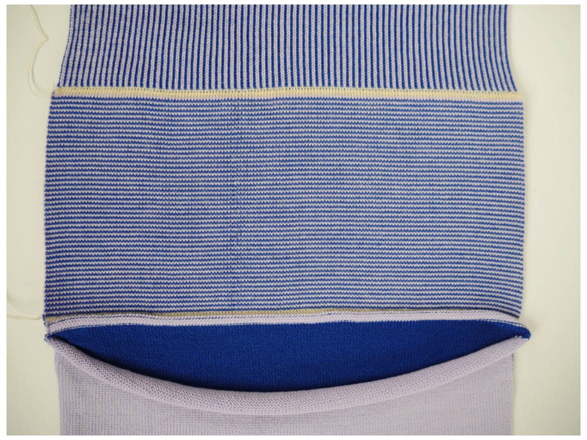
Why did I make it?
To make a dense fabric

What is the result?
Dense and very stretchable fabric.

28







Why did I make it?
Half milano is supposed to be stable in the warp direction

How was it made?
Half milano with two wool yarns

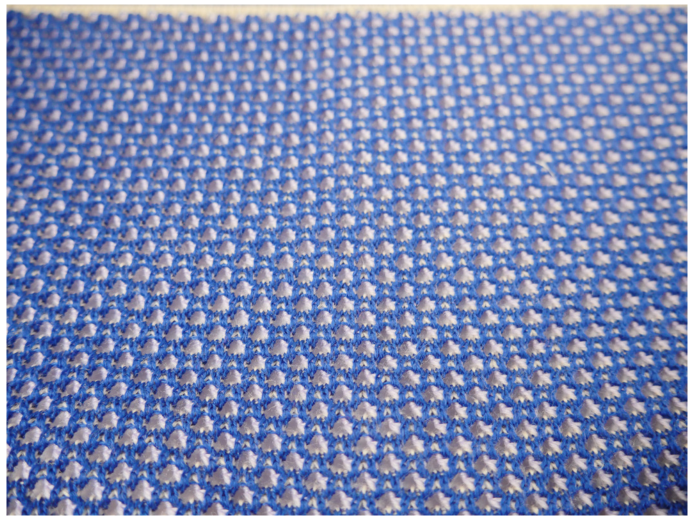
What is the result?
Stable in the warp direction, stretchable in the weft direction.

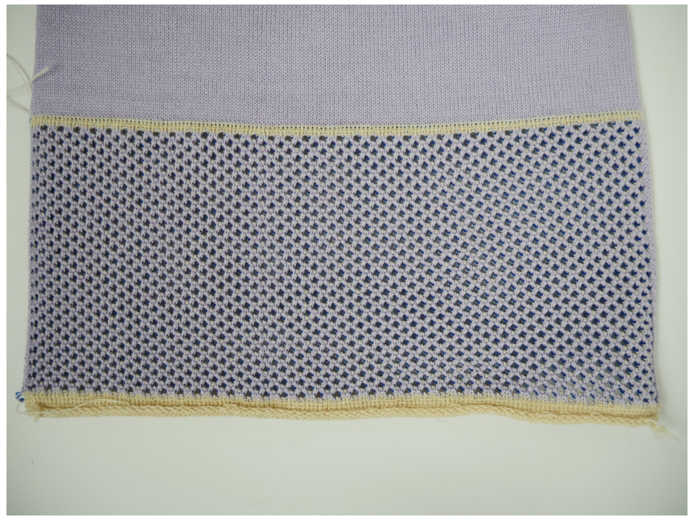
29

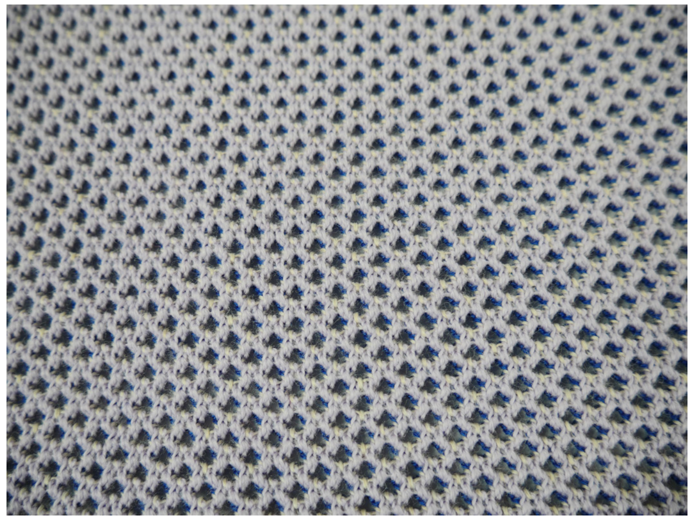
Why did I make it?
To make a large pocket

What is the result?
Single jersey is of course very stretchy. The pocket is large, the end curls up.

30





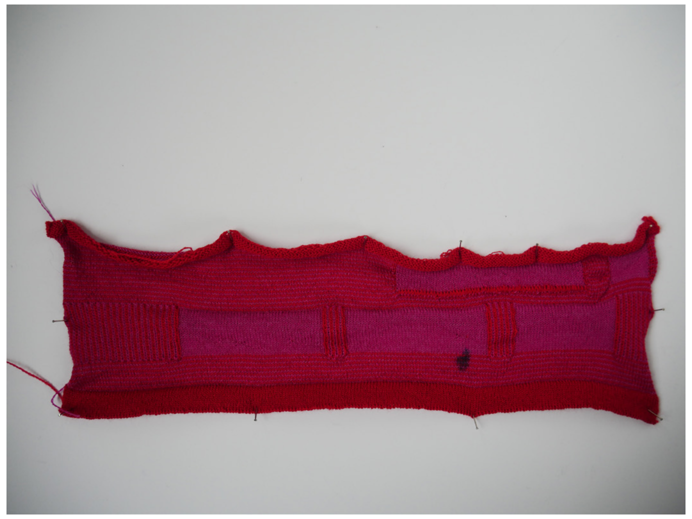


Why did I make it?
Structure to create a semi transparant but strong knit

How was it made?
Pointelle repeat structure in a jacquard

What is the result?
Mesh like structure that is still strong possibly to hold a load.

31

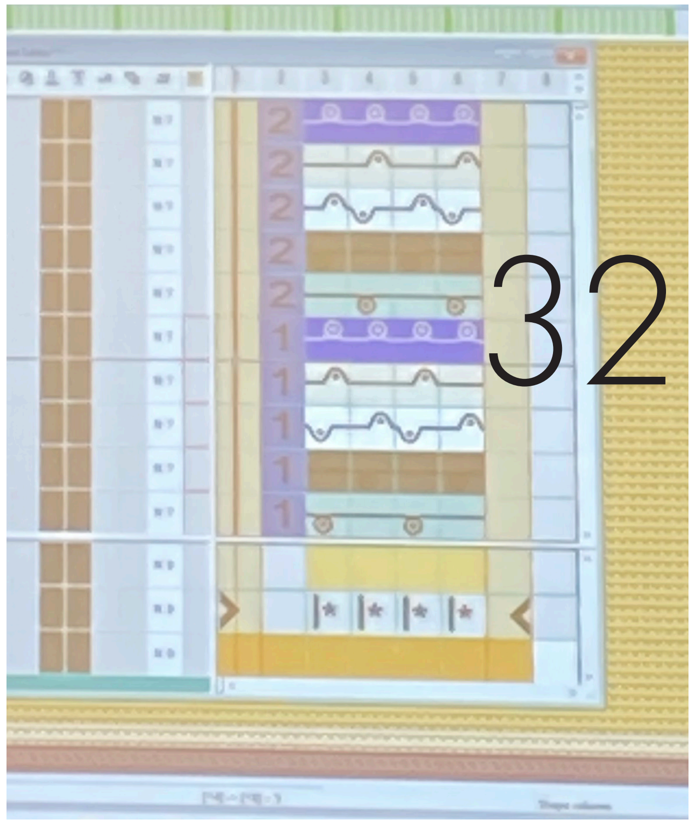


Why did I make it?
Practice pockets and different methods of programming them

What is the result?
The single jersey around it is very thin and stretchable. The pockets are so small that almost all of it curls up.

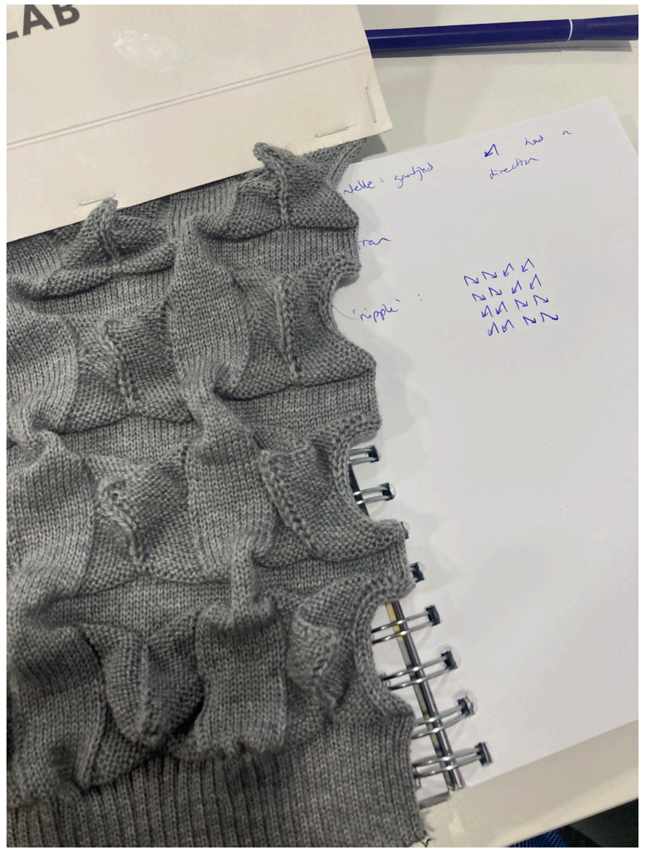
Next step
Possibly creating a larger pocket but with a small opening, not over the full width, and a opening with an elastic yarn so it is tighter

32



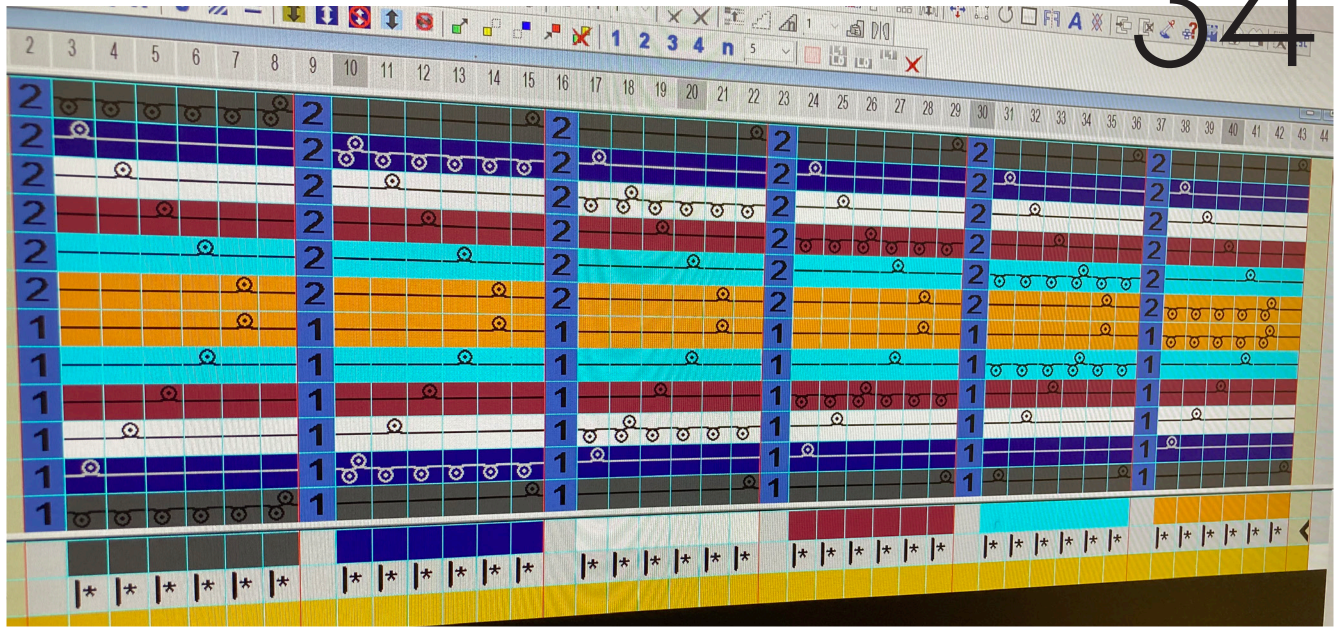
Very dense, non stretchable, strong fabric.

33

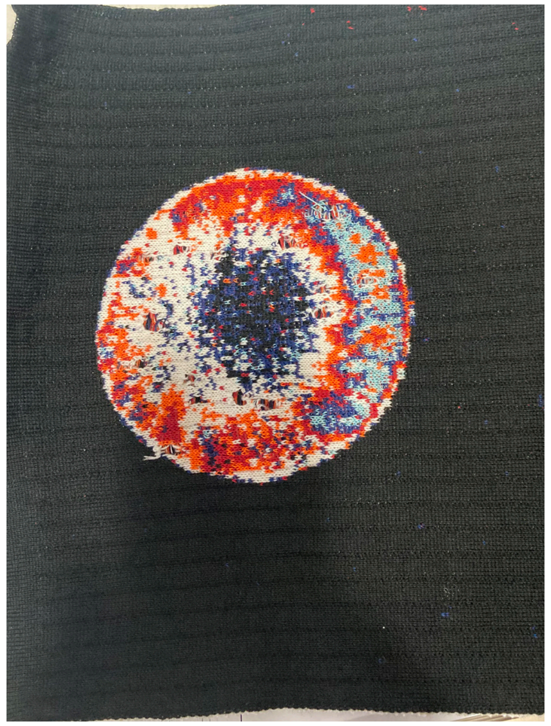


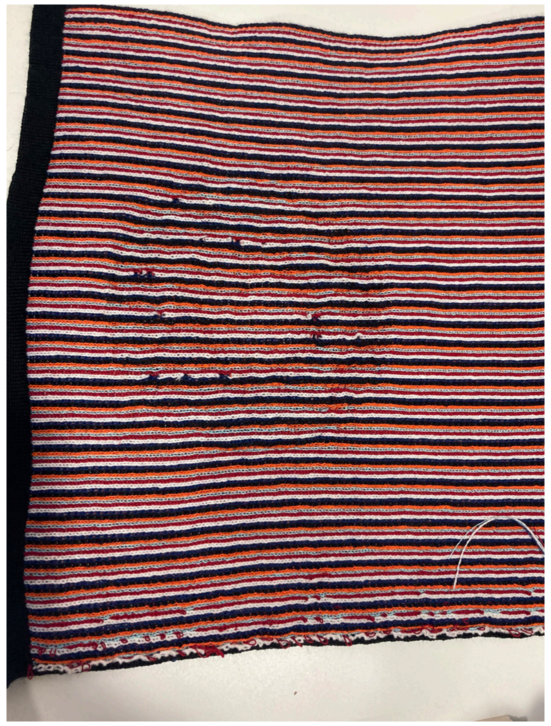
“nipple”, using pointelle structures to create 3D shape

34



6 colour jacquard structure.





35

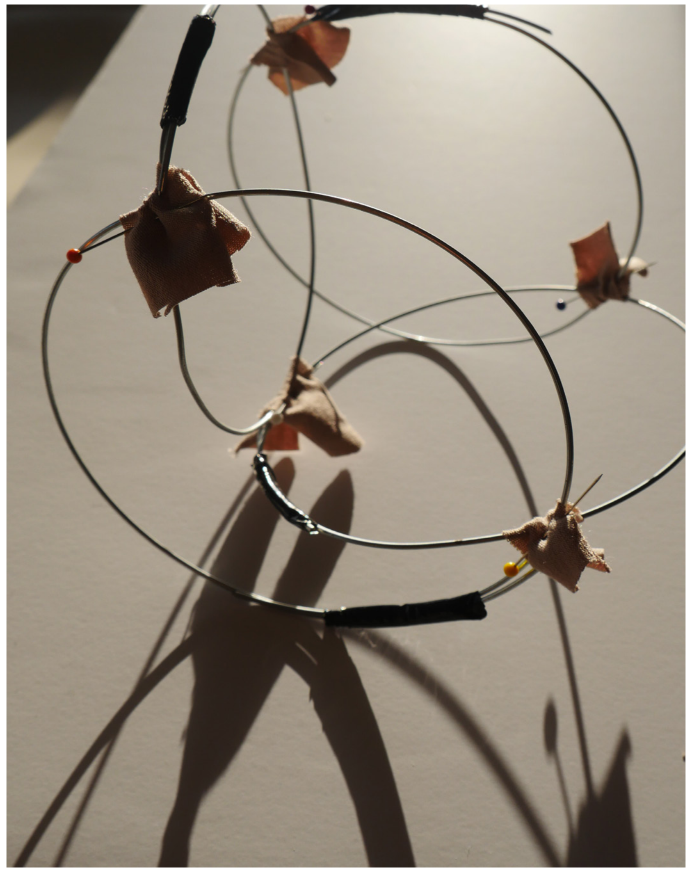
Purpose
Inspired by the chair of Verner Panton. The assumption was that the joints could be knitted and thus flexible.

Process
Using iron wire and small tricot fabric pieces to create 'knitted joints'.

Variables
- The tightness of the knitted joints
- The degree of freedom with which the joints can more over the iron wire
- Knitted surface to fill the iron wire circles so it is an actual sitting object

Take-aways
These joints do allow different configurations of the loops, and thus also a flat folded configuration for transport. The structure was very unstable because the flexible joints could move over the hoops. If the joints would be set on a certain part of the hoops, the different configurations can not be made. It is a trade of between rigidity, stability and deployement.

Next step
Finding a way to use the 'knitted joints' but keeping them in a certain spot on the iron wire.



Verner Panton

36

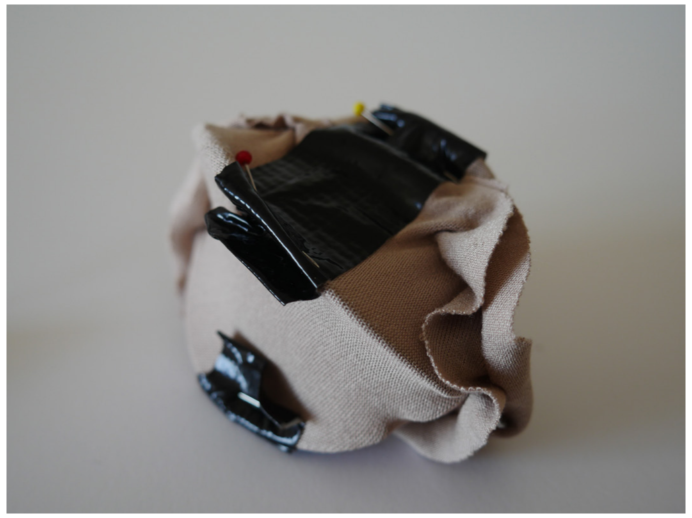
Purpose
Iteration of sample 35, try to create a hinge with the iron wire.

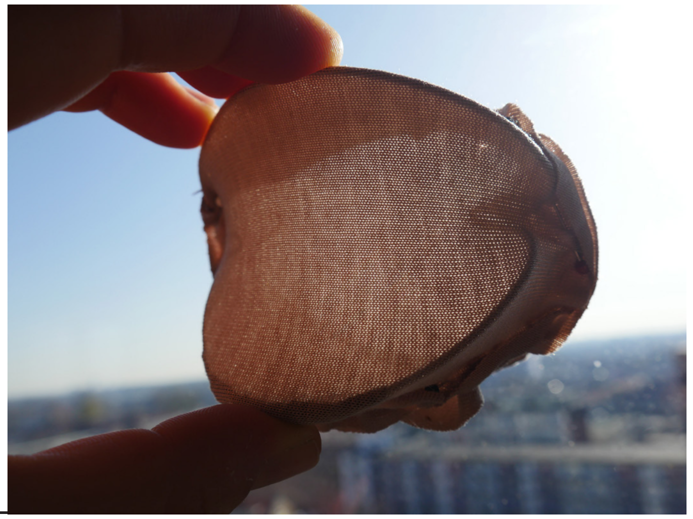
Process
Using iron wire, tricot fabric and duct-tape to mimic a non-stret-chable fabric segment.

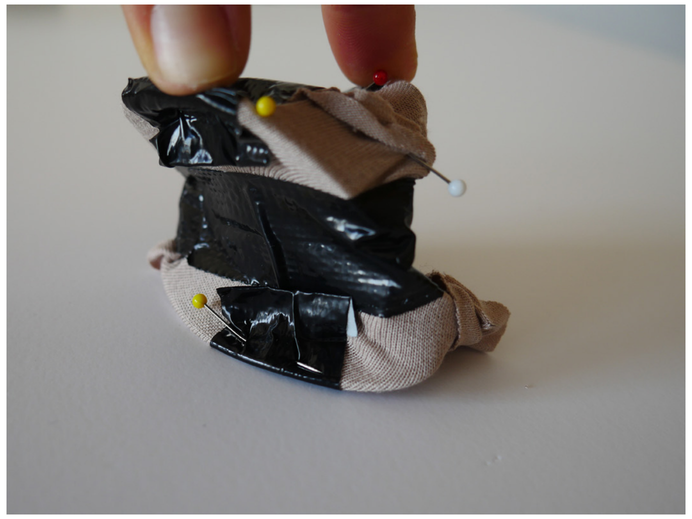
Variables
- The tightness of the knitted ‘skin’ around the frame
- The hinge of the iron wire

Take-aways
The two corners in the frame are to hook into each other to create a cross. The cross was supposed to be supported by the fabric. The structure can hold a load when the top and bottom of the two frames are not able to seperate more than a certain distance. Additionally, the fabric should not stretch and be very tight on the area where the two frames interlock, to hold them together when pressure is applied. These three non-stretch areas still leave en-ough stretch so the two frames can be seperated inside the cover and thus allow for deployability.

Next step
Find a way to knit this, including the non-stretchable segments.







37

Purpose
Inspired by the pop-up tents of Queshua, try to make a sitting object using tent rods.

Process
Using tent rods, tricot fabric and duct-tape to mimic non-stretcha-ble fabric segments.

Variables
- The tightness of the knitted ‘skin’ around the frame
- The strength of the tent rods.
- The placement of the non-stretchable fabric segments

Take-aways
The pringle alllows for different sitting structures on different sides. The frame can both be flexible (foldable) or rigid. A rigid frame would allow for more difference in the stretch of the fabrics, and then it could be 6 different structures. The flexible frame however requires more in-depth material research.

Next step
Develop this sample into a concept.

38

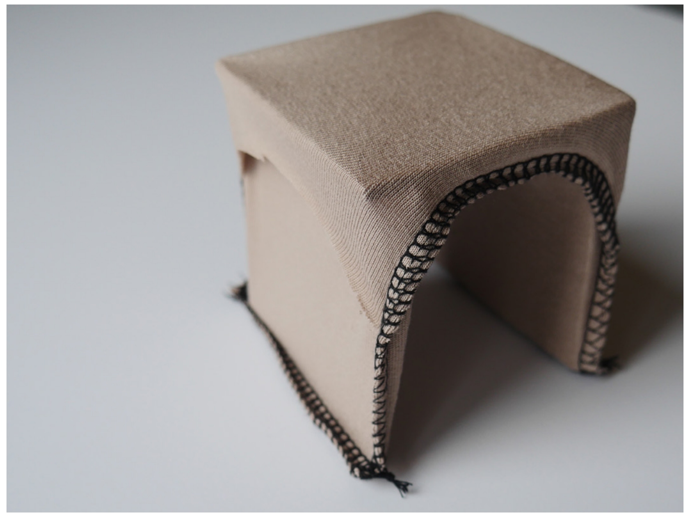
Purpose
Iteration on sample 3. The difference is the amount of panels, the configuration and the closure of the pockets.

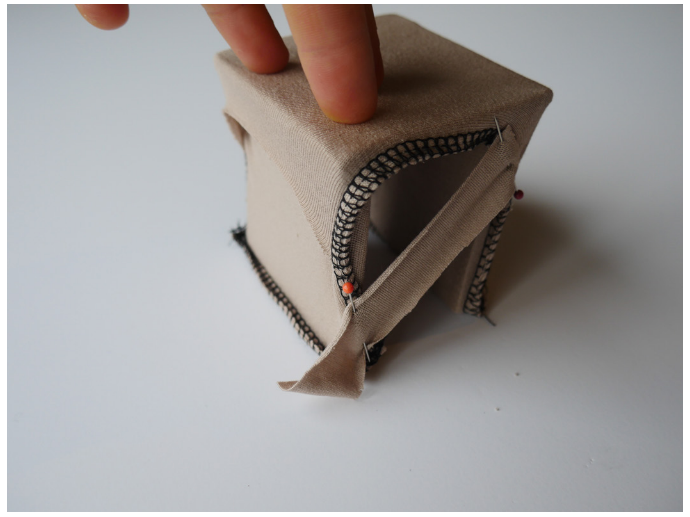
Process
Using tricot fabric, overlock machine and cardboard.

Variables
- The size of the pockets and cardboard panels relative to each other
- The overlap of the panels: the more overlap, the more the fabric is pulled when creating a angle smaller than 180 degrees

Take-aways
The top 'pocket' is not closed, because this is not needed to create the desired shape and it allows for full seperation of the panels and fabric. The side panels can be inserted in the pockets that are closed on three sides, the top panel is enclosed by a large channel, open on two sides. Similar to sample 3, the stretch in the fabric and the overlap in the panels creates a tension when the configuration is altered from flat to 3D.
The shape is still instable. An attempt to stabilize with two cables pulling to opposite sides did not succeed. When pressure is applied on the top panel, the construction fall to either sides.
This could be solved by adding two pockets on the sides, creating four side panels that stabilize each other.

Next step
Develop this sample into a concept.





39

By making openings in the knit in which the panels can be inserted, there is no need for another pockets to keep a panel in place. Can be used when three layers of panels need to be connected.

Connecting with corner pockets can be used together with a cord.

40

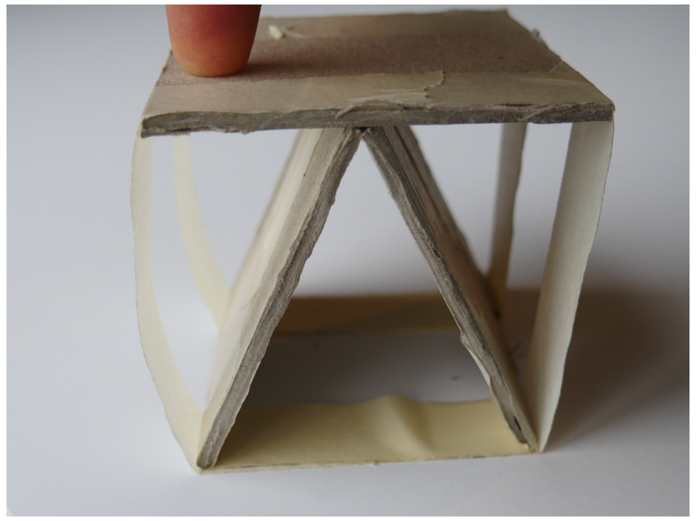
Purpose
Iteration on sample 19.

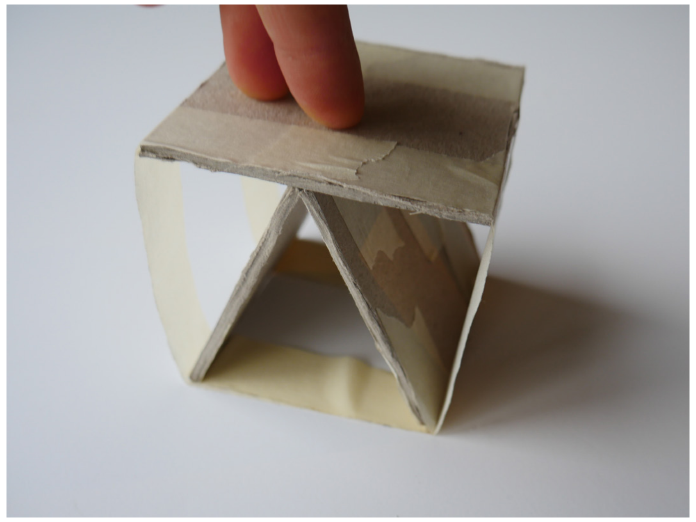
Process
Using cardboard and tape to simulate non-stretch knit fabric.

Variables
- The shape and material of the panels

Take-aways
The structure works (only) when: (1) the two bottom panels are attached to the center line of the panel on top, (2) the end of the flat panel are attached to where the bottom panels touch the floor with a cable connection (3) the bottom panels are attached to each other where they touch the floor with a cable connection. A cable connection is simulated with the table and can be created with a weave-in knit structure: no stretch in the weave-in direction. This can be made with the knitting machine by knitting two tunnels for the three panels. The direction of the knit is considered to make this possibly without the need of more than 2 layers of fabric. Important that the two bottom panels do not move away from each other more, so a strong connection of the panels to the floor fabric is required.

Next step
Develop this sample into a concept.





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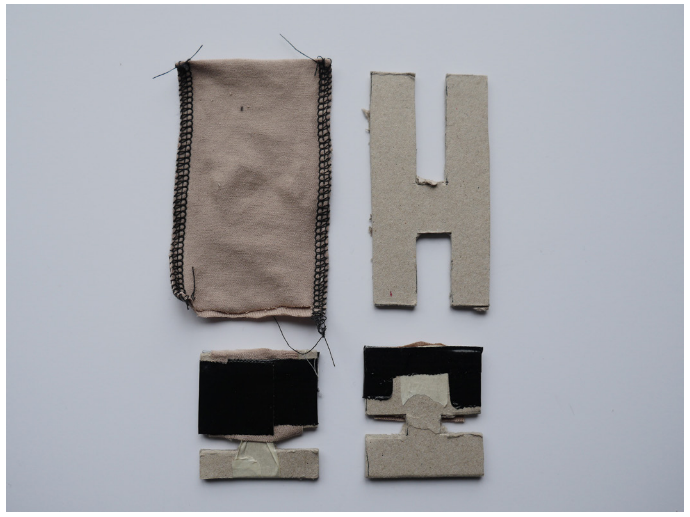
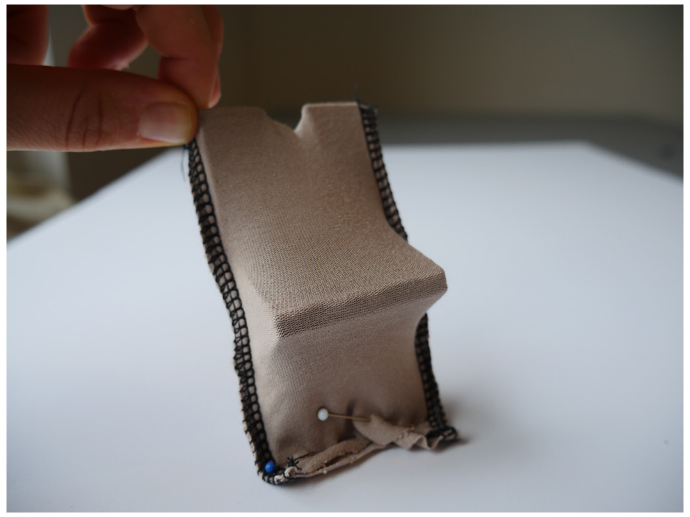




Purpose
Inspired by wood connections and the wish to create a sample where the fabric is the connection material.

Process
Using cardboard and tricot fabric.

Variables
- The shape and material of the panels
- The connection between the panels: the cut outs hold the panels in a certain configuration and allow for deployement.

Take-aways
The seat and the front foot of the chair need to be connected at the edges of the panels such that their are stable on top of each other. Thus these need to be connected: using two rigid pockets that are connected.
Questionniable whether this is a desirable concept, what makes that this knitted connection is 'better' (minimizes production steps, more adaptable, easier to recycle) than a regular folding chair.

Next step
Iterate on the principle of 'knit as connection material' for a fol-ding chair, see sample 42, 46, 47.

42

Using the stretch of the skin around the panels to reach a stable configuration. Stretch all around works well to keep the panels in place. The fact that the corners of the top panel are in line with the sides/diagonal is probably contributing to the stability. Succesful sample, to be continued.

43

Purpose
To create a cord or pull thread

Process
Laying in polyester yarn between the two beds while knitting full needle stitches with two plys of cotton.

Variables
- Material: seems very important for the 'cord' yarn needs to slide between the knitted structure
- Stitch length: leaving more or less room for the cord to lay between the rows, thus making it easier or harder to pull the cord through

Take-aways
Multiple threads together can be pulled to create a ripple in the fabric. Could be used to tighten a fabric structure, to knod the fabric to another material or to close a pocket structure. The two different materials don't have much friction so the cord can slide through easily.

Next step
See Sample 20 for earlier iterations.

44

Purpose
To create 'soft' handfeel with the polyester and not too much stretch

Process
Making ripples by holding one of the needle beds, on both sides alternating.
One of the ripples has elastic held stitches, resulting in more stretch but a more pulled ripple.

Variables
- The length of the ripple
- The combination fo the two materials, or possibly another material for each ripple
- General knitting parameters

Take-aways
The stitch that are held on the back of the ripple result in less stretch than regular jersey. When stretches, the fabric still feels 'soft' because the ripples are not stretches so the fabric is still in a relaxed state partly. Could be used to create a soft surface for the sitting object without the need of any stuffing.

Next step
See Sample 21 and 22 for earlier iterations.

45

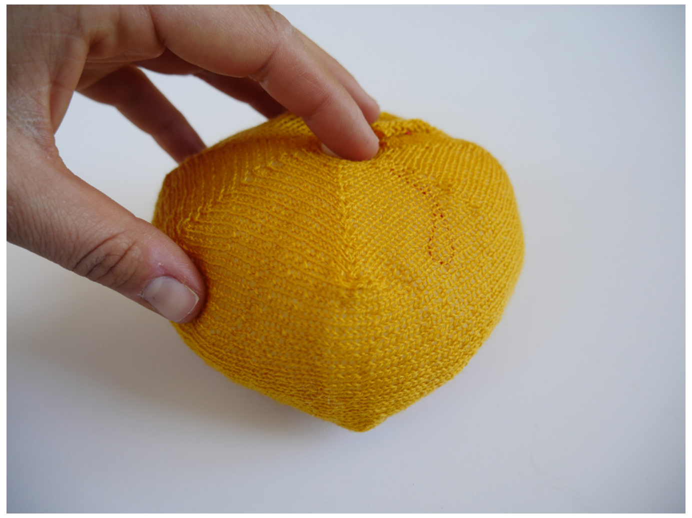
Purpose
Iteration on Sample 9 and 10.

Process
Goring on both sides of a squared shaped to create a ball. Woolen yarn, stuffed with polyester stuffing.

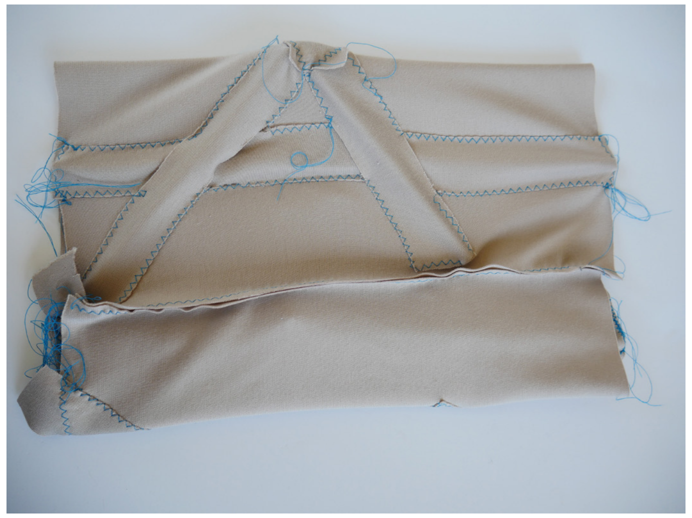
Variables
- The slope of the goring, which defines the roundness of the final shape
- General knitting parameters
- The suffing material: stiffer, softer, more, less

Take-aways
The ball does not fully close at the top and bottom (which is the sides of the knit when on the machine) on purpose, to not put too much pressure on the outer stitches while goring this much.

Next step
In essence, this is already a sitting object. By replacing the stuffing with a stiffer material it could be a regular poof or beanbag. Goring can be applied on any sample to create 3D shapes.



46



Why?
Trying to make a folding chair through a 'skin' knit. Testing if a circular knit with tunnels knitted as a jacquard can be used to inert rods that will result in a folding chair 3D shape.

How?
Using stretch fabric to speed up the process (compared to knitting this immediately). Sewing the tunnels on top from strips of the same fabric, cut in straight direction. The rods are 4mm diameter polyester

What?
It was expected that the stretch between the rods between the bottom two legs would stretch enough to make the two feet stand stable and not too much to keep the shape. The fabric does not stretch enough to create the desired effect.

Variables?
(1) width of the tunnels: to leave some room for the rods to set, and to insert the rod
(2) place to insert rod: when the opening is in the middle, it is very hard to insert the rods. Somewhere at 3/5 is best to insert with ease and to keep the rod in place when force is applied.
(3) stretch of the fabric: when knitting, each segment can have a different amount of stretch, thus the shape can be determined quite precisely.

What's next?
Try the same principle again with a different layout of the rods.

47

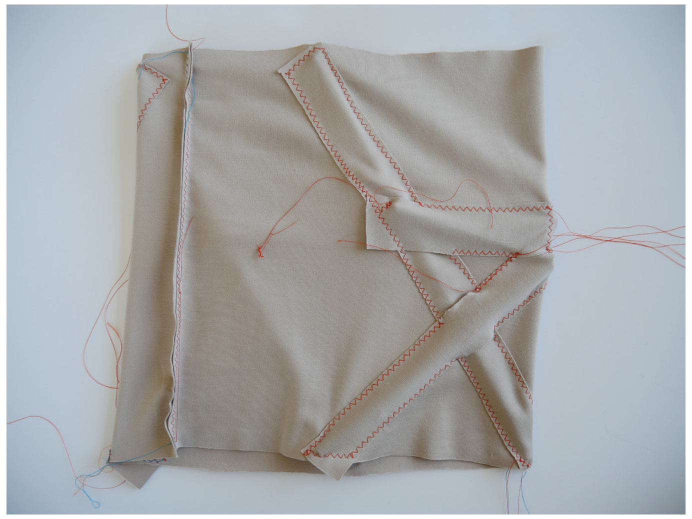
Purpose
Iteration on sample 41 and 46.

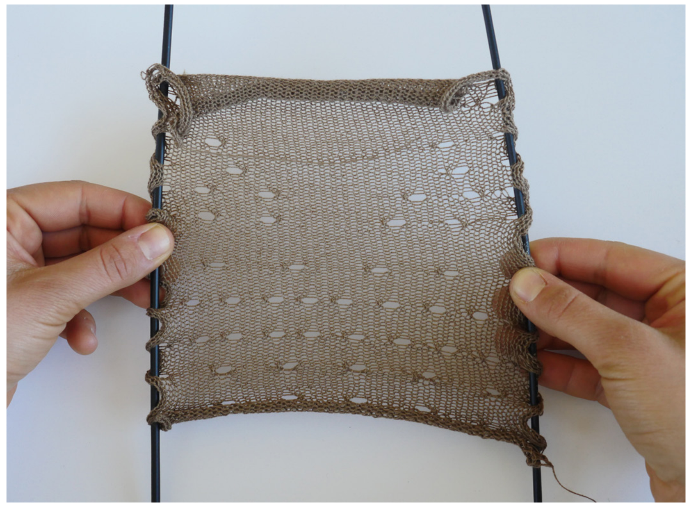
Process
Using tricot fabric, plastic rods and a sewing machine. Cutting strips of the tricot fabric to sew tunnels on top of a rectangular piece of fabric which is later connected to make it tubular.

Variables
The same variables as Sample 45 with some additions:
- The length of the rod compared to the tunnel: a longer rod inside a shorter tunnel results in a pre-stressed fabric. It is expected that when a load is applied, the fabric cannot stretch much further so the shape is more stable. However, inserting the rod can become more difficult.
- The shape of the 'skin': current shape is squared with only the tunnels added in straight lines. Both the shape of the 'skin' and the tunnels could be curved to result in different geometries.

Take-aways
Placing the tunnels such that it already looked like a set-up folding chair resulted in a folding share shape when the rods were inserted. The 'sitting surface' should be closed tightly to make it possible to apply a load on it.

Next step
Knit this with multiple tunnels to create different possible configurations of the rods, on the industrial machine. Develop it into a concept or benchmark it to a regular folding chair.





48

Purpose
To experiment with the behavior of a knit with different possible configurations of insertion of the rods.

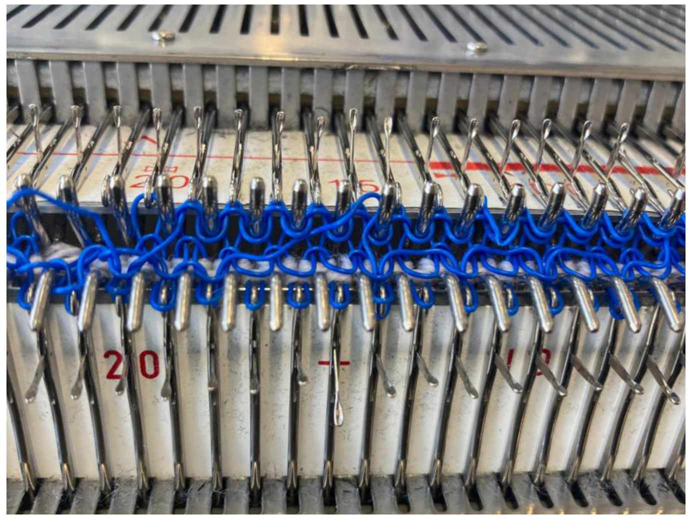
Process
Single jersey knit with cotton on the single bed domestic machine, with multiple pointelles in different courses. Placement not based on a pattern.

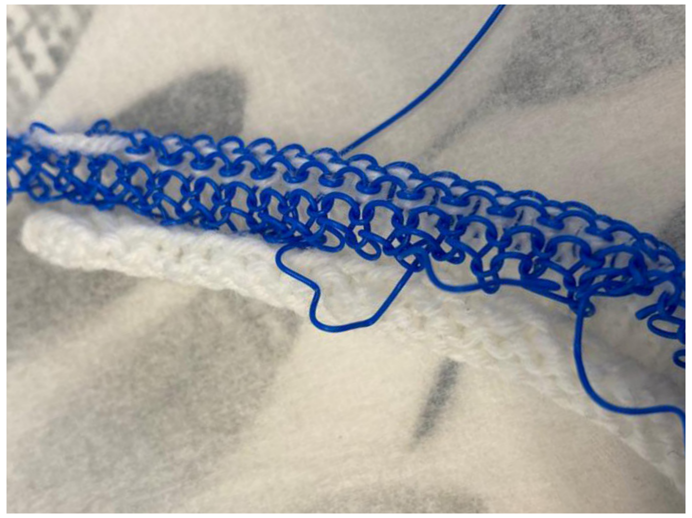
Variables
- The size of the pointelles and rod
- The stitch type and thus the stretch

Take-aways
As expected did the tension in the fabric on different spots change when the width of the fabric between the rods is altered. The amount of pointelles might alter the stretch of the fabric, causing the spots with mor pointelles to stretch less (?) because the pointelles already pre-stress the stitches which it is created from.

Next step
Try this with segements with different stitch structures in between to create a surface with different tensions when tensioned on the sides.

49





Purpose
To experiment with melting yarn

Process
Directly knitting the melting yarn, first trial on the double bed (top image), second on the single bed of the domestic knitting machine (second and third image)

Variables
- The type of melting yarn: thickness, material, melting point
- General knitting parameters

Take-aways
This specifc melting yarn was to thick for the domestic knitting machine. The yarn was ironed, which melted the outer blue layer of the yarn, leaving the core of the yarn unmelted and rigid. When pulling on the structure, the melted connections between the yarn broke easily.

Next step
Try to weave the yarn into a knitted structure with a wool or cotton yarn, so the thickness of the yarn is less of a problem.

50

Second attempt on the knitting machine with my own file, knitting all by myself.

Improvements for next iteration:
- the weave structure now shows the curve of the tunnels, which it should not (change from red to black star in program)
- the transition between the weave-in and the half-milano-variation is too wide, it is very stretchy, not desired.
- the openings in the tunnels are not open. Change them to the sides, then it also has less effect on the stability of the tunnel

During knitting, the take-down was increased with 5%.

The actual first attempt broke four needles, because it the weave-in yarn pulled too much on the tunnel structure that was not set up properly for the rounded parts. After, the transitions between all structures was considered.

The weave-in curls up very much, because it is basically a single-jersey structure. Could be useful to rigidity with coating?

The transitions between the knit structures. The tunnels are knitted with more rows, and thus longer.

The back of the weave-in looks very different. Consider this for aesthetics.

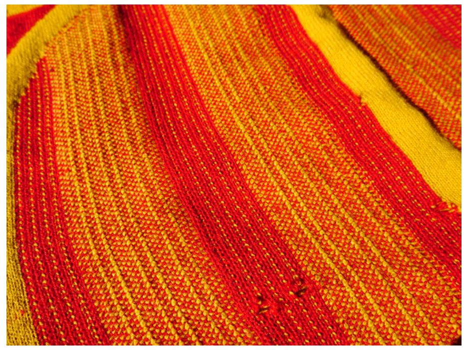
51

Attempt to combine the horizontal and vertical stable stitch structures. Horizontally stable is the weave-in mimic. Vertically stable is the half milano variation, different from a full milano because of the surrounding stitch structures.

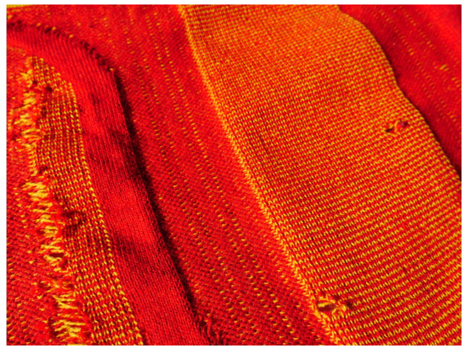
The horizontal structure indeed takes out the stretch in the x-direction. The vertically stable structure is also very stable in its dimensions: it will not curl up and will lay flat by itself.

The tunnels are popping up because the density is not equal in the different structures.

Alternating the horizonal and vertical stable stitch pattern did not result in the sum of their properties.



The small holes in the knit are the result of flaws in the knitting machine, the large ladder of the programming.



52

Next steps
- the end need a lot more strength, possibly double the fabric, some reversion that can strengthen it.
- cross in the middle necessary, helps a lot with the stability
- the angle

53

The rod ends are used as the legs of the object to create more stability, instead of letting it lean only on the curved edges.
To stabilize the structure a cross is still required, and a top surface that will push outwards to keep the legs from collapsing inwards.

54

Adding a bending-active element that is transformed into the sitting surface by the user.

The sitting surface is created, which should keep the legs outwards and prevent them from collapsing inwards when the user sits down. This however does not happend for th user will only sit on the fabric, and not on the rods itself.

The bottom end of the elipse needs to be connected to the other legs very strongly, to create a bending in the rods.

55

The final concept consist of two units, together forming a sitting object. The transformability is simple: a unfolding and kit-of-part when connecting the two units. The knit can be used inside-out for different aesthetics, and elements can be added for more comfort or additional functions: more rods for armrests or a backrest, pockets on the sides.

The concept is simple but does pushes the limits of possible knittable extreme geometries with this machine, meant for fashion. As learning more about the limits of the current machinery, this is an interesting case to work out.

The structure could be compared to a regular folding seating, in terms of production process, material use, weight and aesthetics. The production process could be shorter, for this product only requires the knitting of the two units, after which the rods can be inserted by the user. Nothing but four rods and the knit is needed.

The concept demonstrates the different structures of a knit, the different functions.

The layering of the two panels allows for more strength, different functionalities, differen aesthetics,

Present three versions?

- material saving one: reducing the knit as much as possible

- additional functionalities: armrests etc

- aesthetics and comfort

Challenges

- make the crossing of the rods strong enough.

- extreme shaping

-

56

Attempt to recreate a simple folding chair, inspired by camping furniture.

In principle, only the two crossing bows in the middle are required to make the sitting object. The side bown however are added for potential arm rests, and to create a wider range of knitting possibilities.

The most important learning from this prototype is the fact that the scicor construction works when either the rods angle between the top and bottom rods are below 90 degrees, only then a load applied on the fabric between them will lead to a downwards movement of the rods, instead of upwards/inwards. If the angle is less than 90 degrees, as in most of these camping chairs, the force of the user is applied directly onto the rods, and not only onto the fabric that is in between. When only sitting on the fabric, the construction will collapse inwards.

While making this prototype, it was discovered that there are many ways to create this construction. The amount of ways this object therefore is large, which leads to the opportunity to find a way to knit the object and showing the different types of knitted structures possible.

57

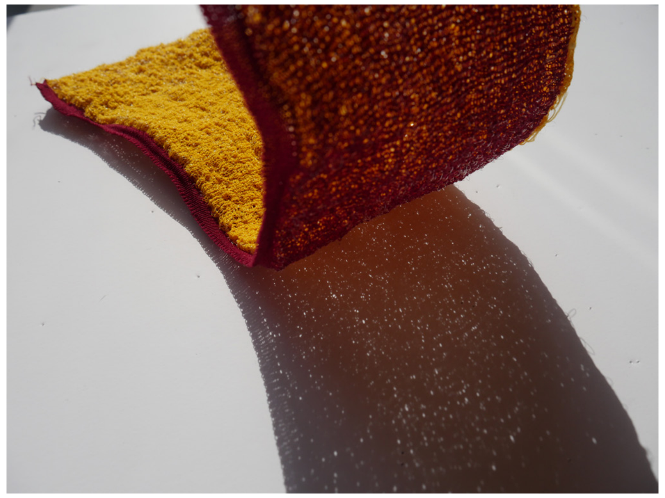
Experiment with 100% polyester yarn, with goring and decre-asing using the Pointelle modules in M1Plus.

The goring is not very visible, possibly because the stitches are very small and the same steepness of goring of Sample 7.1 was used. The shaping at the top is not as steep as expected, other methods of shaping need to be explored.

58

Experiment with nylon yarn to create a spacer fabric.
The nylon it tucking between front and back every row, while the front and back are knitted on every needle with the red and yellow polyester. The stitch length in this sample was 11.5 for all three yarns.

The result is a spung like fabric, where the nylon is sticking out of the outer layers, creating a very irregular red and yellow surfa-ce. The fabric is not very dense. It does not stretch much in the horizontal direction, probably of the interlock stitch created with the nylon.



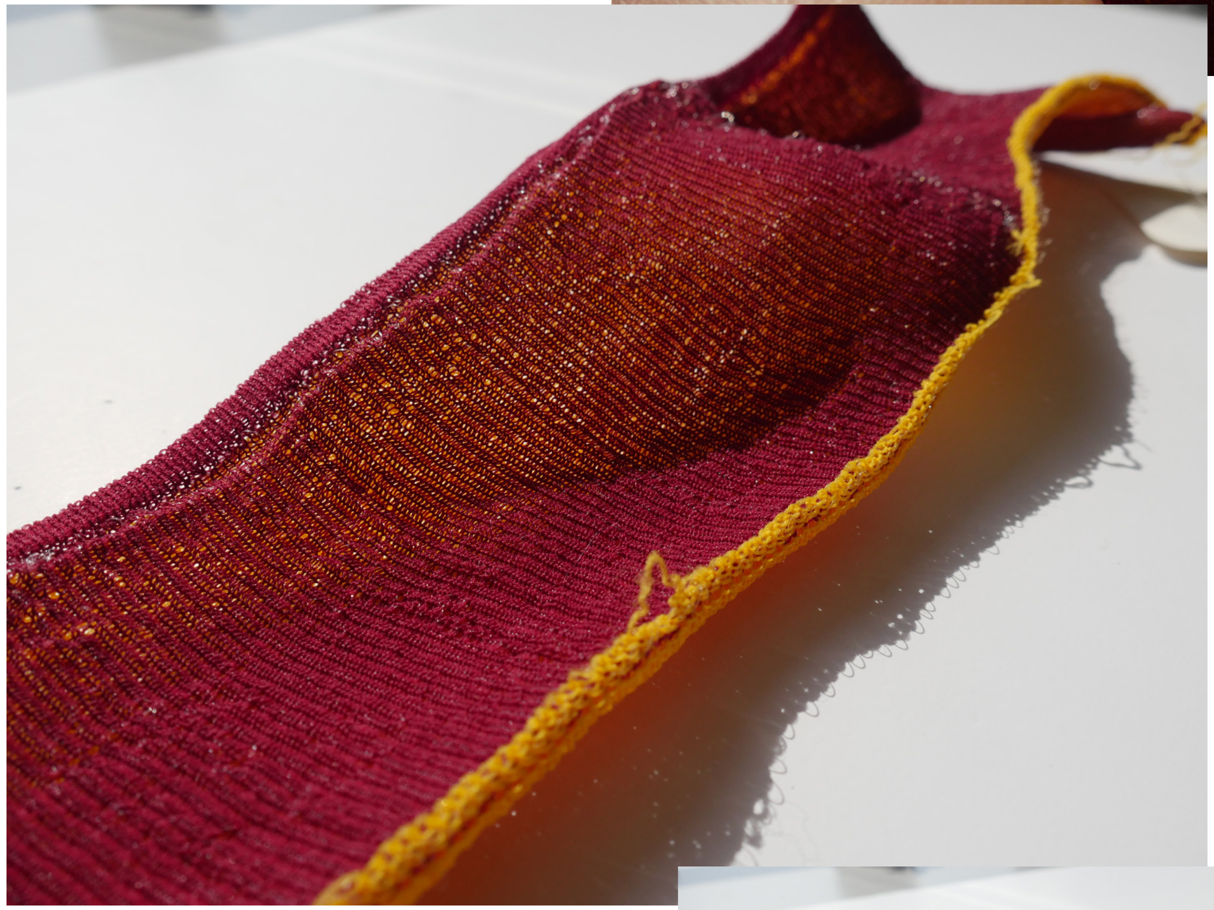
59

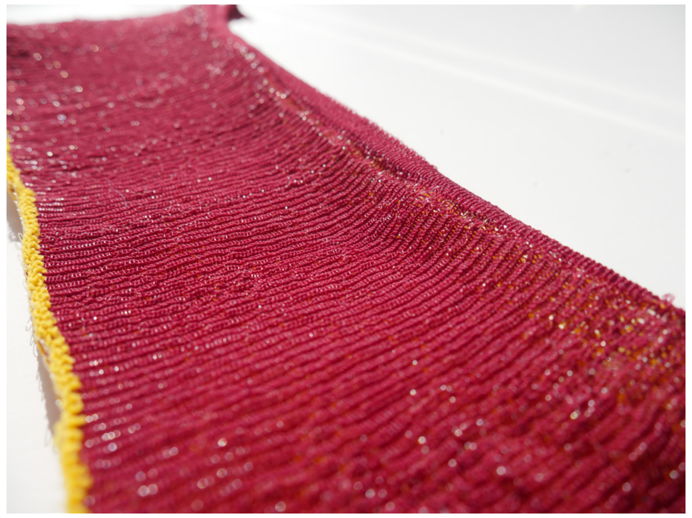
Iteration on sample 9, decreasing the stitchlength.

The result is a much cleaner look, the nylon sticks out less, and the red and yellow are more even. In the horizontal direction again much less stretch compared to the vertical direction.

The fabric is dimensionally stable, and feels stiff. When pulled, the fabric stays in that position a little.

Because of the transparancy of the nylon, the red and yellow seem to be floating on top of each other.





60

Ajour with Adam.

- Do not place different ajour structure horizontally next to each other if they require different stitch lengths, or adjust the stitch length for each structure
- Knitted at stitch length 13.5



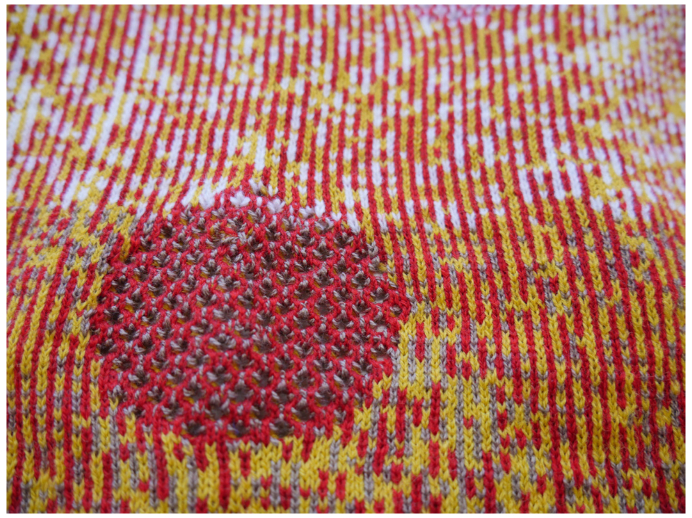

61

Jacquard with Adam

- White acrylic is too thick (for this structure)

- Auxilery take-down should be closed: extra take-down right underneath the bed, for goring and small samples.





62

Intarsia with Adam

- The intarsia yarn feeders need to be on the whole row, and the stoppers need to be the other way around then with normal yarn feeders.

63

Plating with Adam

- Programming plating does not require any special actions apart from assignint the plating yarn feeder to the right yarn feeder in the Yarn Fields.
- The two yarns come from two sides.

64

Main learnings:

- the visibility of both top and bottom of the fabric can be used in the aesthetics
- The crossing rods can best be in between the side rods.
- No attachment of the crossing rods necessary.

First full scale prototype with PVC rods, tricot fabric for the tunnels, cotton fabric for the surfaces.

Transformation through deployement, by releasing one connection after which the construction folds downwards to flat configuration. Full transformation by removing the rods from the tunnels.

65

Floating jacquard with tunnels, extreme goring and shaping.

Learnings
- the belt takedown starts after approx. 300 rows
- horizontal tunnels need to be closed with full needle, colour changing does not make a tunnel.
- Shaping worked
- Take-down did not work, at the end it was still ‘casting off’ on all needles that were originally there

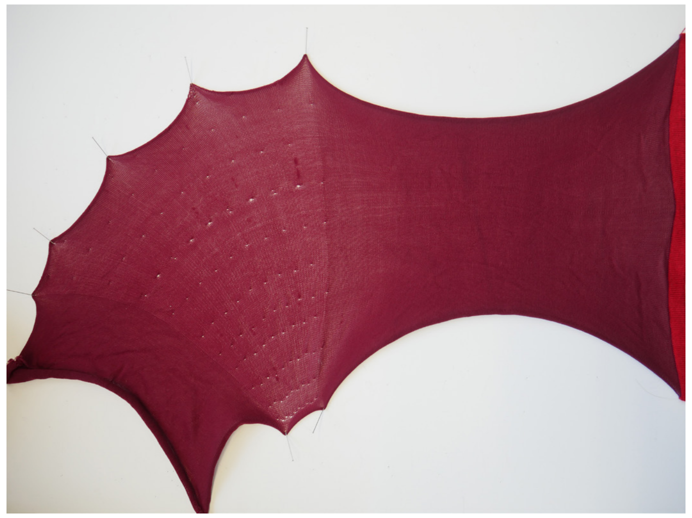
Decide: do I knit simple geometries to have more room for texture exploration, or do I want to focus on complex geometries and not have much time left probably for the surfaces?

66

Extreme goring.

First two attempts with acrylic the yarn breaks.

Third with 100% polyester and the same settings, the yarn does not break. The polyester is stronger and more appropriate for shaping.



67

Three iterations are done to test the goring limits of the knitting machine.

The parameters that can be adjusted are
- the steepness of the goring
- the amount of goring rows: the more goring, the more knit that will be created in one place, without the machine pulling as hard on it, so the material potentially fluffs up between the beds, making it hard or impossible to continue knitting. Additionally, the stitches that are retained at both sides of the goring, will need to withstand the pulling of the comb and belt, without material being added to it.
- the yarn material: the strength of the yarn material determines how long the end stitches can withstand the take-down
- the take-down: increasing the belt take-down value helps the increase of material to be takes down, but also increases the tension on the end stitches.

Sample 1

Sample 2

The first samples does not show much shaping, for the goring was limited, see Figure XX.

The second sample shows multiple low-steepness gorings after each other, creating a rounder goring. The first gore did rupture at the end stitches.

The third samples shows two extreme gorings, which create a tip in the fabric. The going was too much for the end stitches to hold. The first tip has holes also on the stitches within the gore, possibly because the material was fluffing up and got stuck in between the systems while being retained. The belts are at a certain distance below the beds, so at the second gore the belt probably grabbed the fabric so the fabric could not fluff up as much, it did however break the end stitches.

All samples are made with an older cotton-acrylic mixed yarn. Possibly using a stronger, polyester-blend yarn can lead to less rupture with the more extreme goring.

Sample 3

68

Attempt one to knit the 1:1 panel.

- Did not include a transition row between the weave-in and the tubular jacquard, which results in setting up the back bed in thin air which is not possible.

Tucking stripes to reduce the vertical stretch.

Attempt two to knitting 1:1.

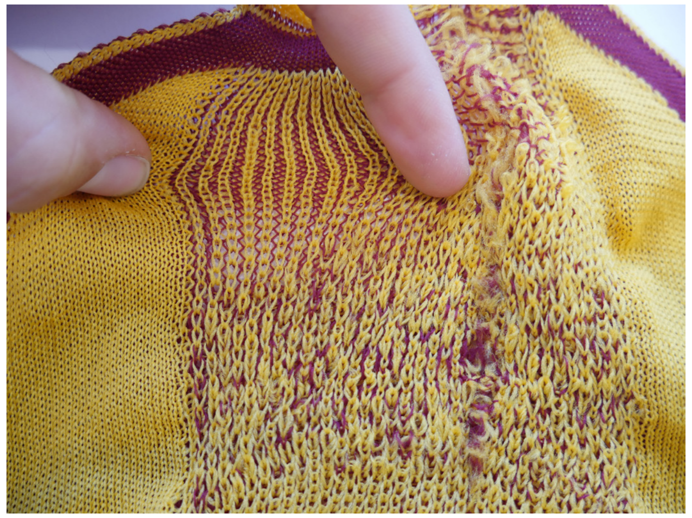
The top tunnel was not closed.
The goring did break the end of the fabric. Test if this much gorin gis necessary because the fabric stretches this much.

Side openings for both tunnels. The tunnels stretch a lot because it is a single jersey.

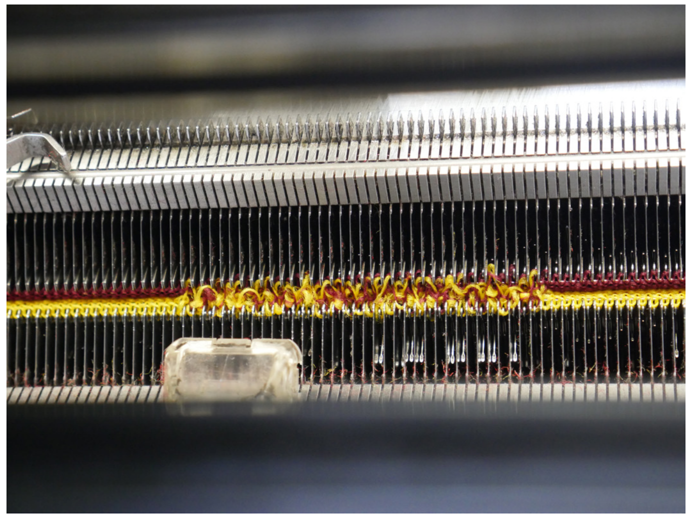
69

Too much goring, the end stitches broke.

Transition stitch between the weave-in and tubular is very stretchy and large.

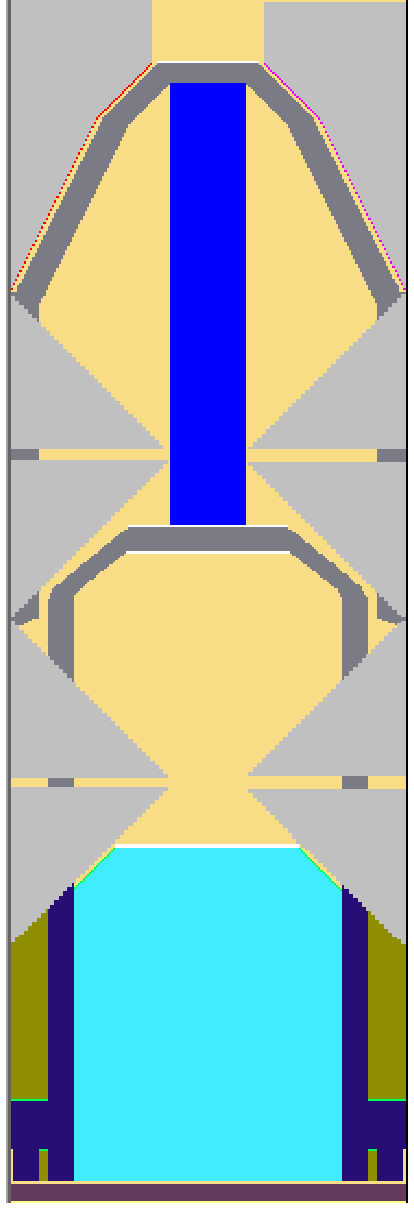


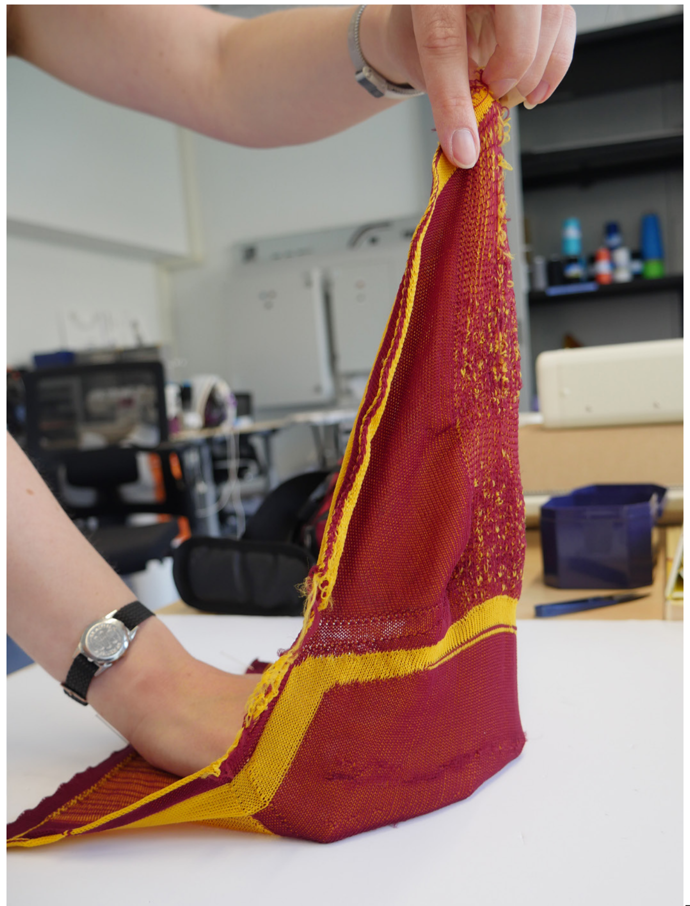
The structure in the middle did not work well, probably because the loops are too loose for the amount of stitches next to it.

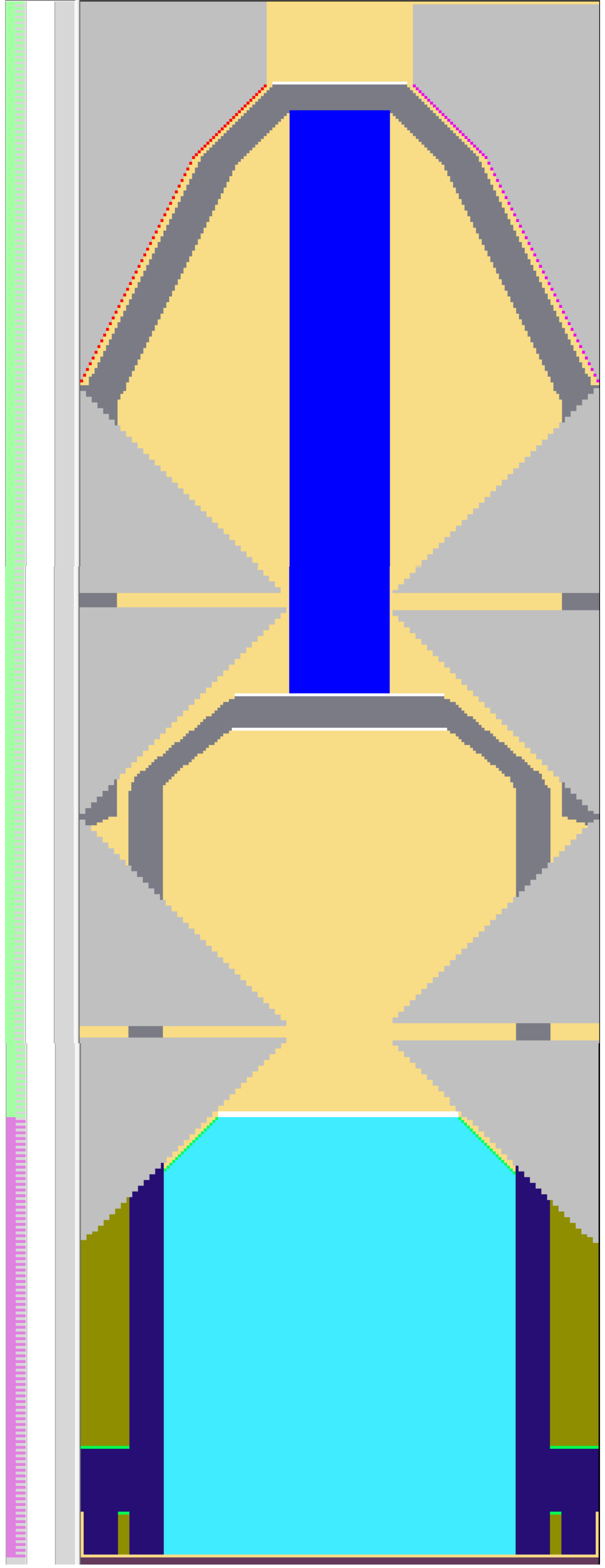


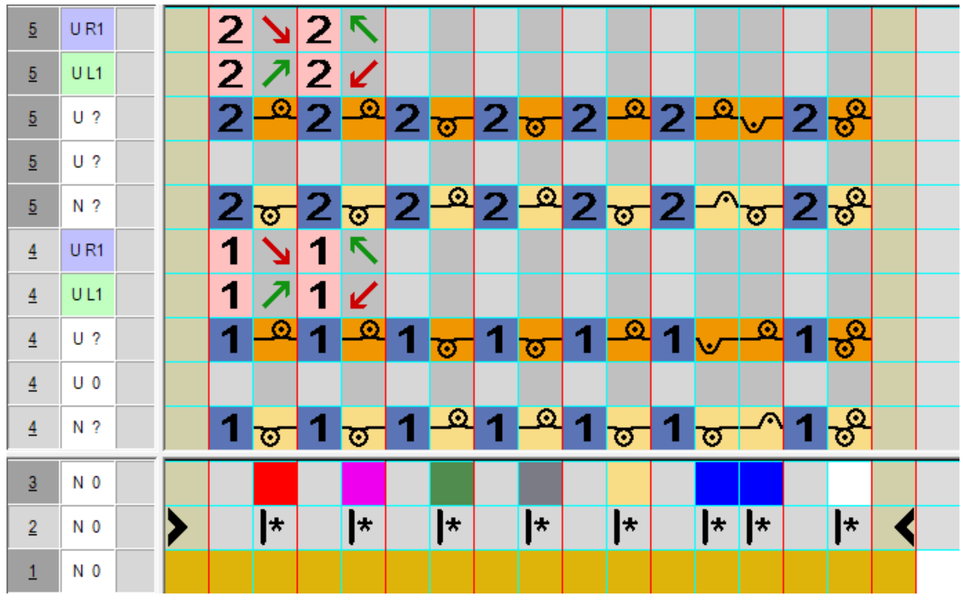
Already visible in the machine; the tucks were fluffing up and not held down properly.

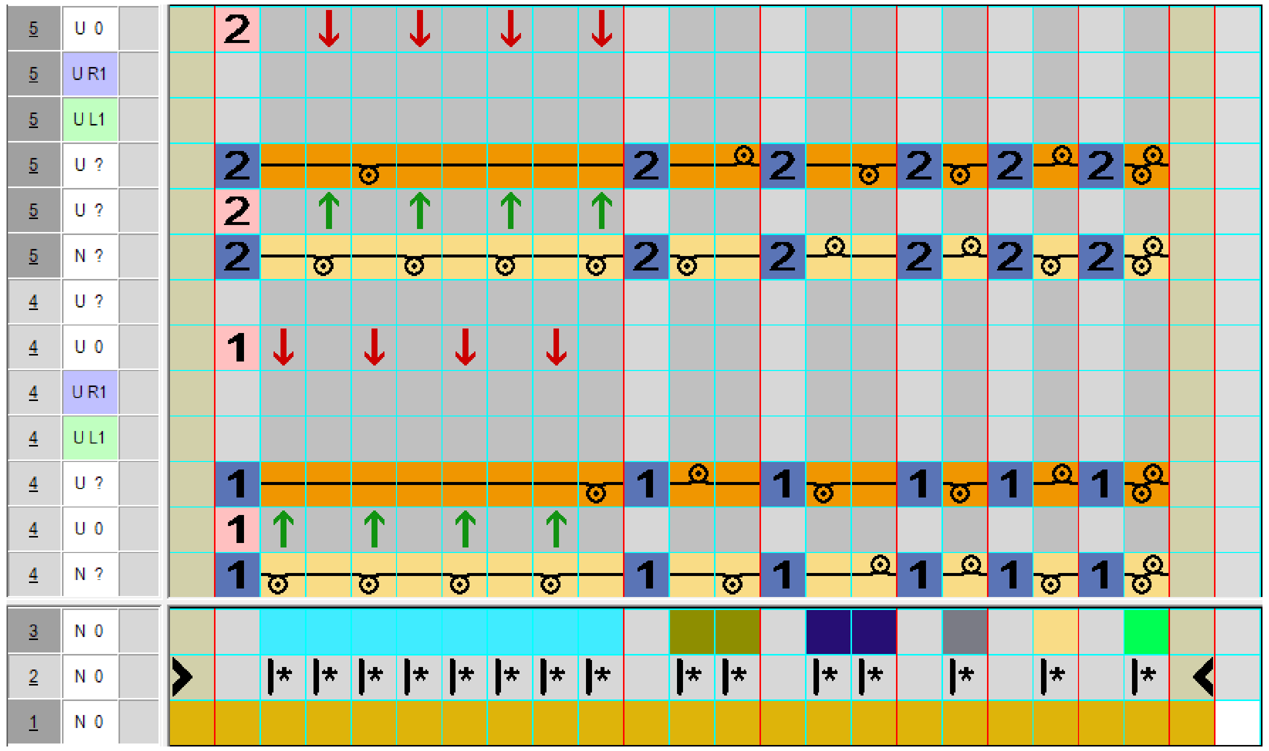
The shaping did work out as desired: the top part is at a 90 degree angle with the bottom part.








5 U R1
5 U L1
5 U ?
5 U ?
5 N ?
4 U R1
4 U L1
4 U ?
4 U 0
4 N ?
3 N 0
2 N 0
1 N 0


5 U 0
5 U R1
5 U L1
5 U ?
5 U ?
5 N ?
4 U ?
4 U 0
4 U R1
4 U L1
4 U ?
4 U 0
4 N ?
3 N 0
2 N 0
1 N 0

70

In this iteration the goring is placed right above the first tunnel, for the side rods. The goring is as extreme as Sample 19.

The crossing rod can be inserted at the bottom next to the side rod through the opening on the side. The end of the side rod tunnel is angled to create more tention on the knit at the bottom where the rods need to be pulled together and the forces are highest.

The goring stilll broke the end stitches.
Iterations are necessary to determine the right take-down value and stitch length, which requires trial and error.

A net structure is knitted in between the middle segments of the tunnels to controll the stretch, functioning as cables. The structure do not stretch as much as the tubular jacquard next to it. The The structure does increase the knitting time however, because of the amount of transfers necessary to make the pointelles.

71

The goring is placed right above the tunnel, divided over two spots to decrease the steepness of the goring.The end stitches did still break, but the damadge was already less than in Sample 20.

Shortrows right below the middle of the tunnel to create space to cut an opening. This opening can be knitted in and opened by unravelling, further research is required.

Cut the shortrows and prevented unravelling by using the lockma-chine.

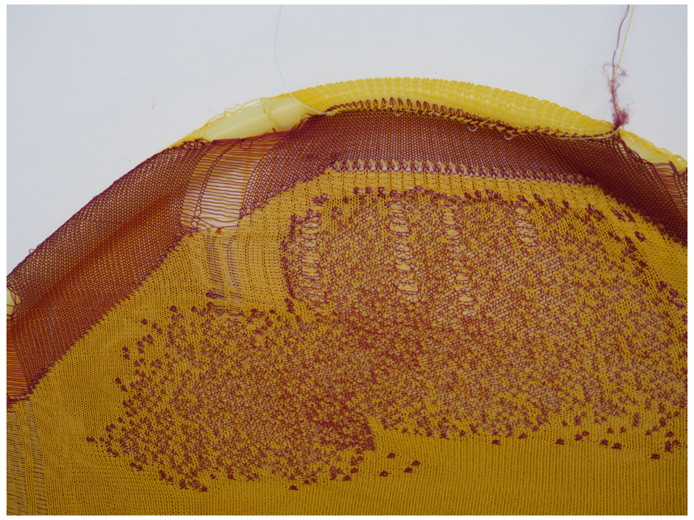
The opening can be stretched open further, increasing the length of the tunnel without the need for more knitting.

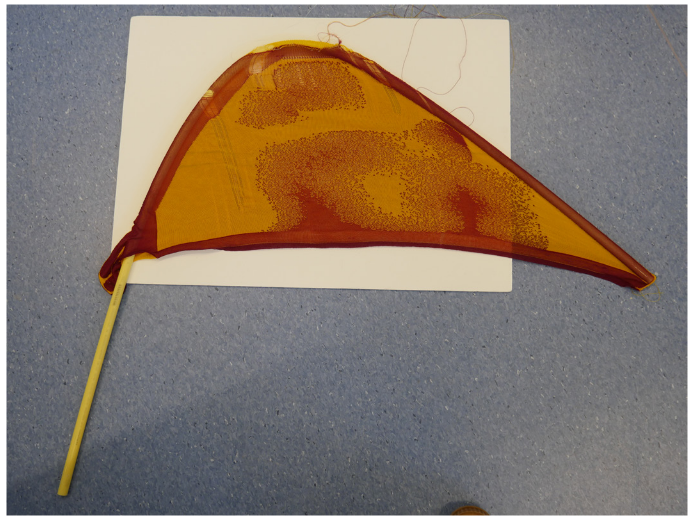
72

Attempt to knit the sitting panel through which both the side rod and crossing rod are inserted in a tunnel.
The size of the panel is estimated based on previous samples, depending on the knit structure.

The result contains some flaws. The shape making to create the triangular silhouette

To improve in this file
- bind off: more all back stitches to front first, bind-off is on one bed
- with the side rod in, the crossing rod does not fit in and needs more space.
- close off your tunnels......

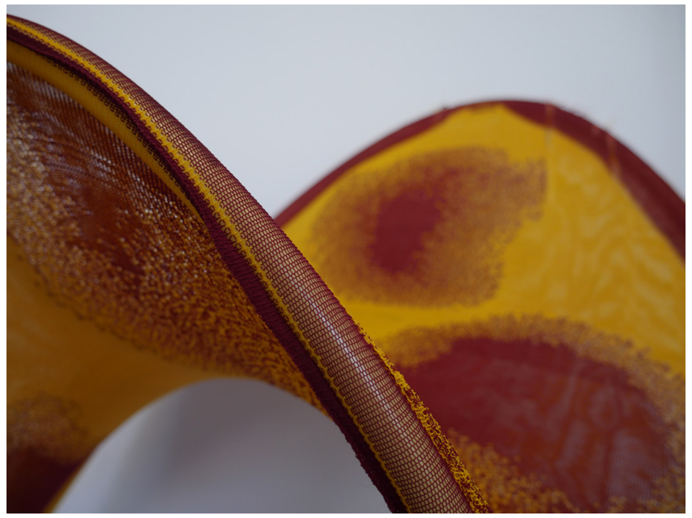




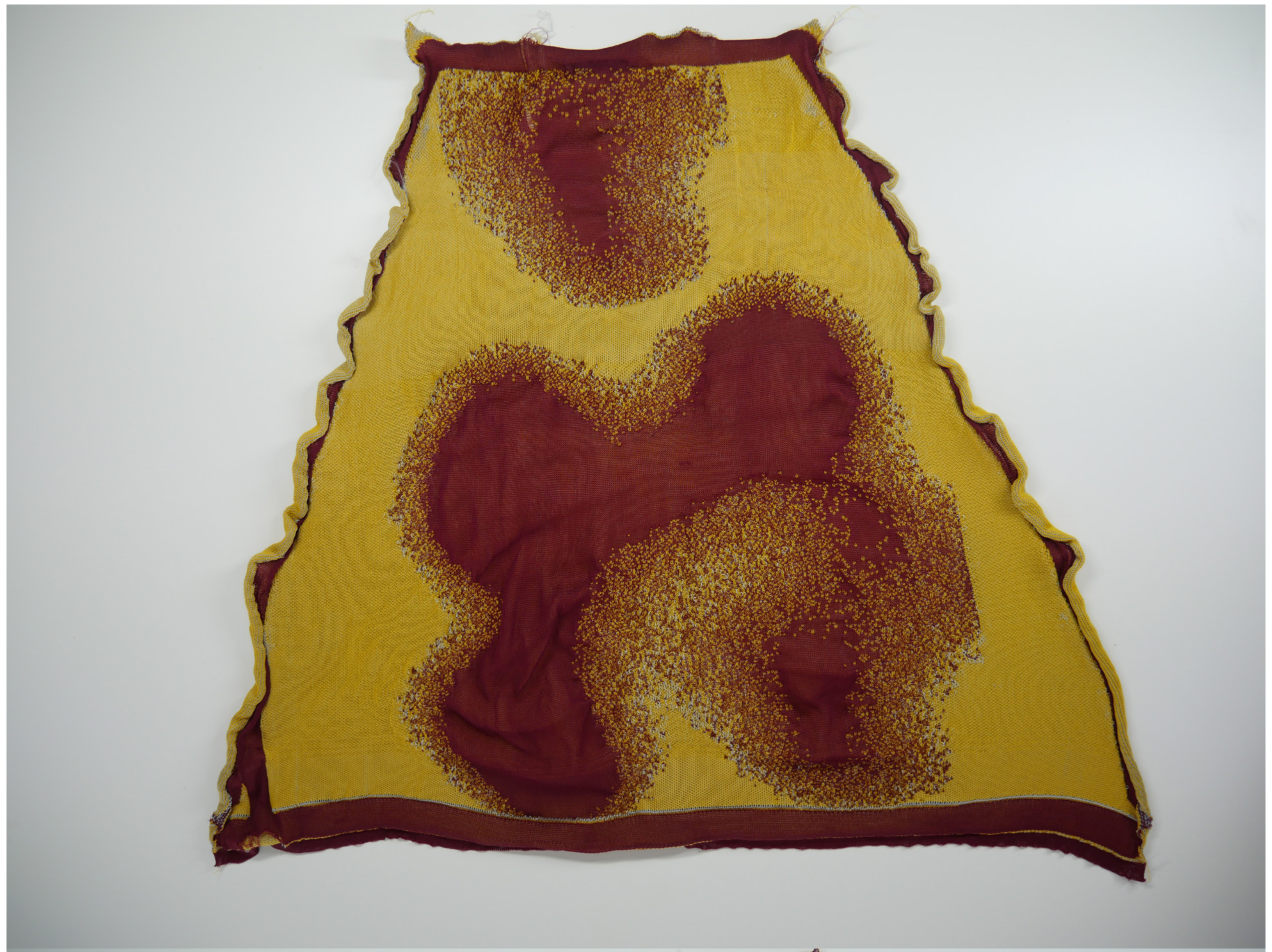
73

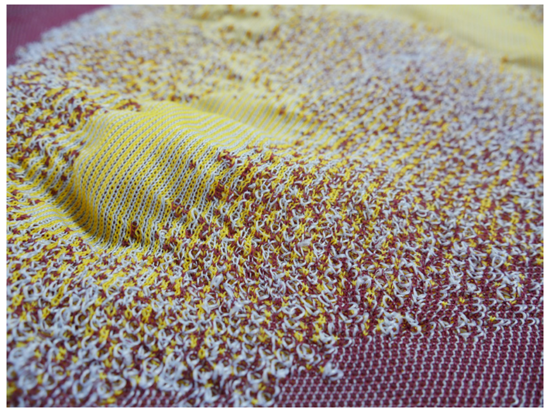
To improve
- bind off: more all back stitches to front first, bind-off is on one bed
- a little shorter surface
- try to find a way to keep the crossing rod between the other rod, or a way to connect the
- make stronger, use nylon

Other methods to reinforce the ends:
using stronger yarn (nylon)
denser knit structure

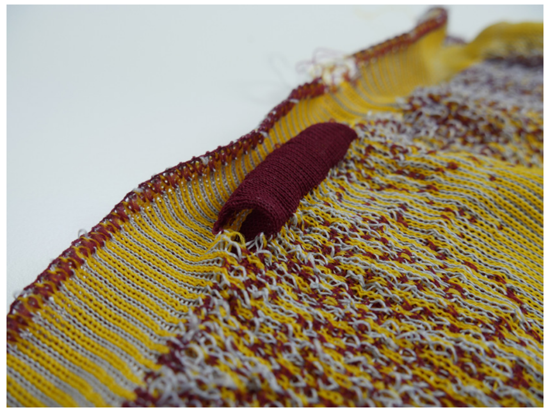


74

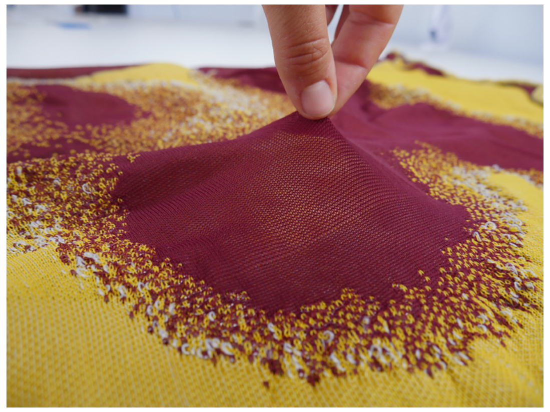




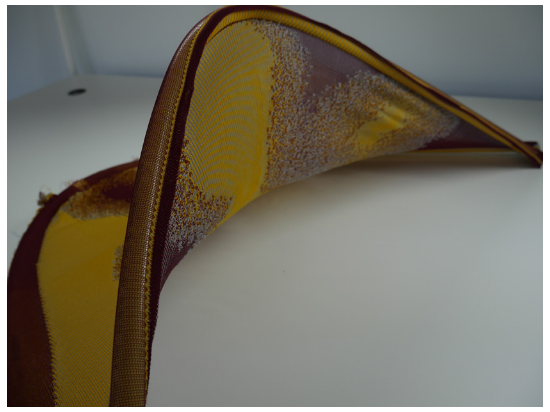
The grey yarn requires a lower stitch length, it is sticking out compared to the yellow and red.

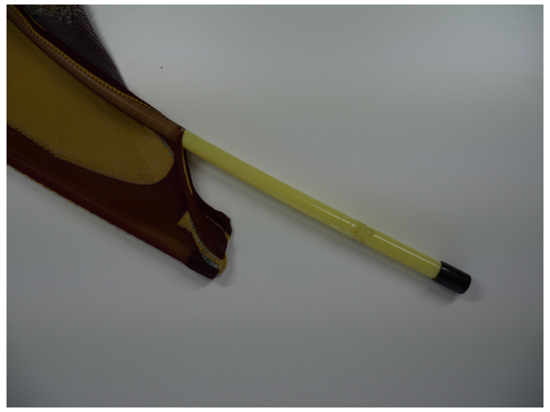


Knitting the large ottoman required manual intervention because the yarn was fluffing up. It was not caught yet by the auxilery take-down. The holes on the sides are still too small for the PVC rod to fit through.



The float jacquard in the red spots allows for filling to be used, or even inflatables inserted in these areas, requireing a small holes.



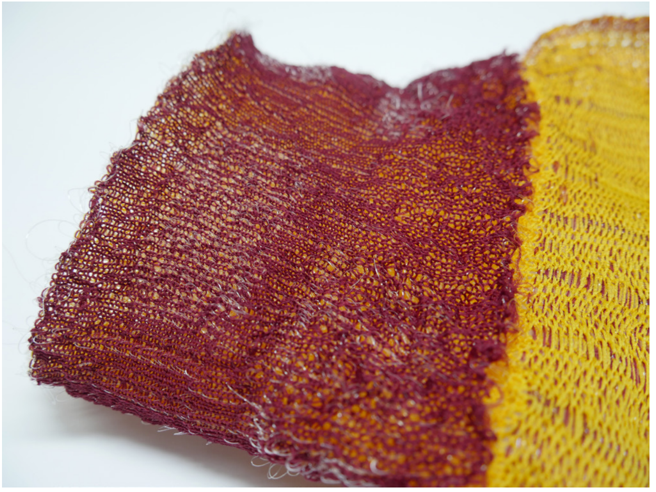


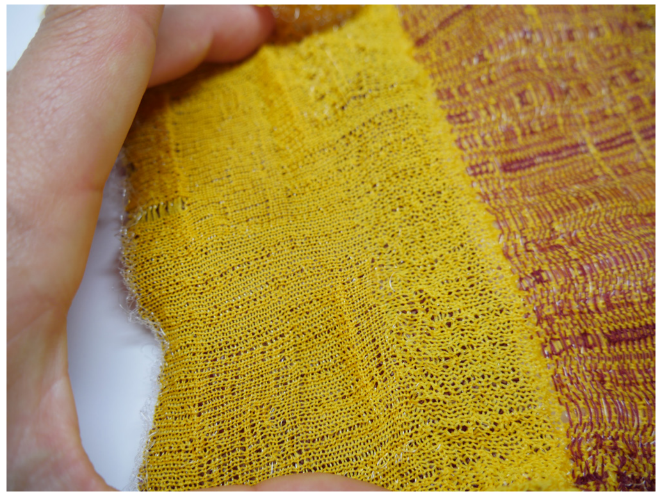
Dimensions were altered relative to Sample 23. Simultaniously changing the knit structures makes it impossiblle to say what contributed to what change in dimension, the overall knit shape or the knit structures.

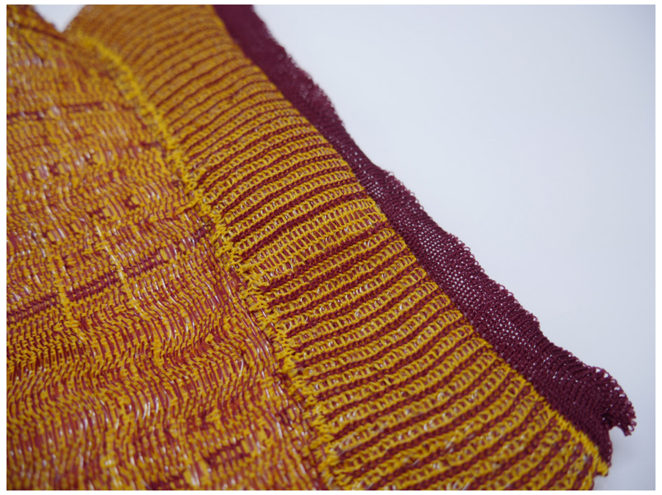
Learning: first determine the exact knit structures to be used, then start to alter the shape.

75

The stitchlength is too long, the nylon is sticking out of the outer layers.

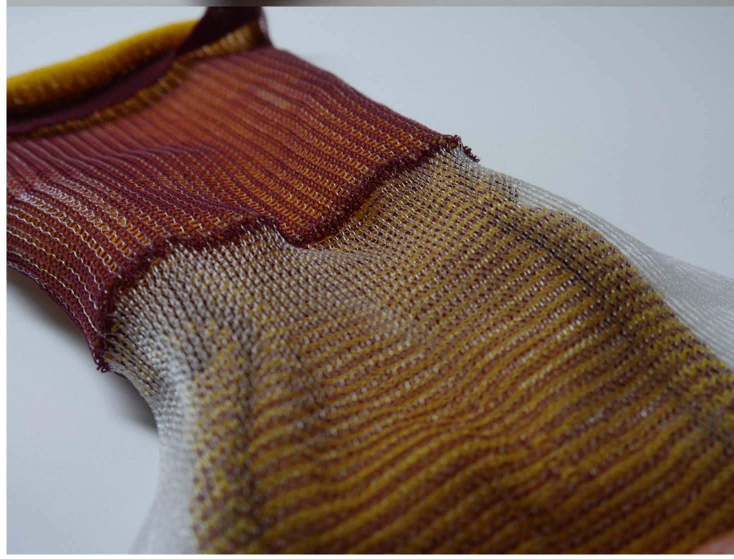


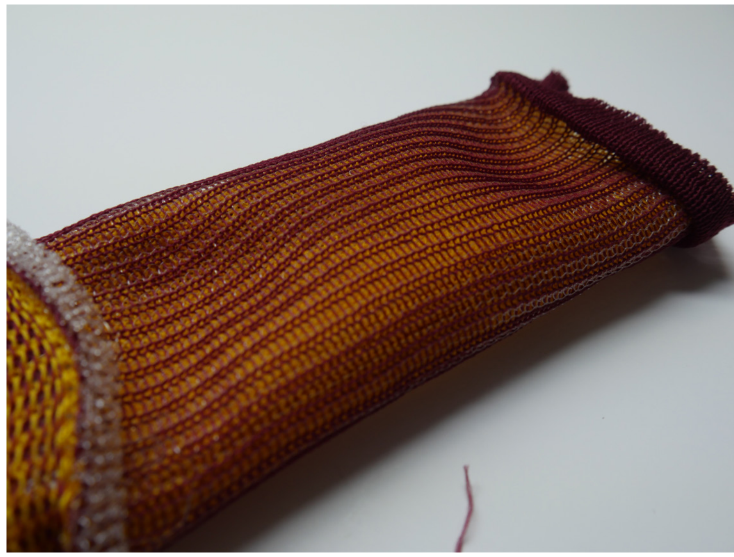




76

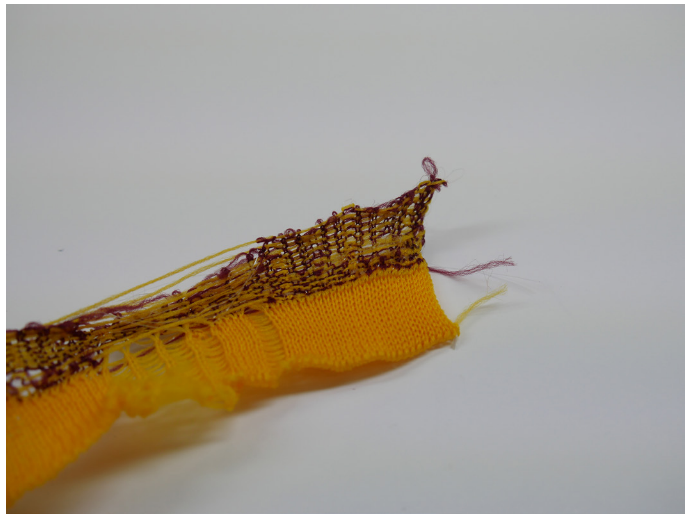
Knitting only nylon breaks easily if the take-down is not set correctly.
The nylon 1x1 with polyester on one bed and full polyester on the other bed knits well, resulting in a strong fabric with soft handfeel on one side





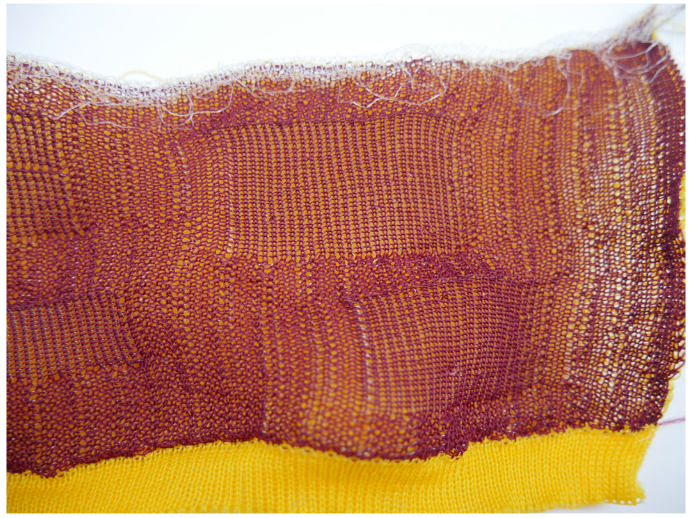
77

Attempt to make the weave-in structure with weaving in both polyester and nylon. Did not work, very irregular although the file is the same as previous successful weave-in samples.



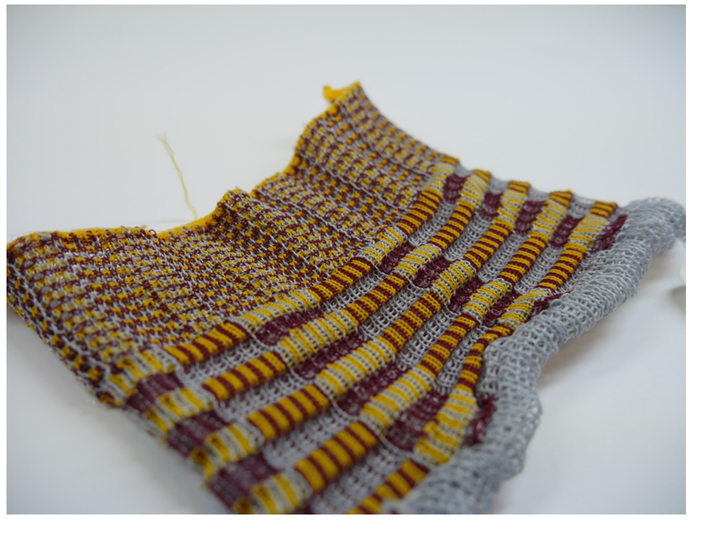
78

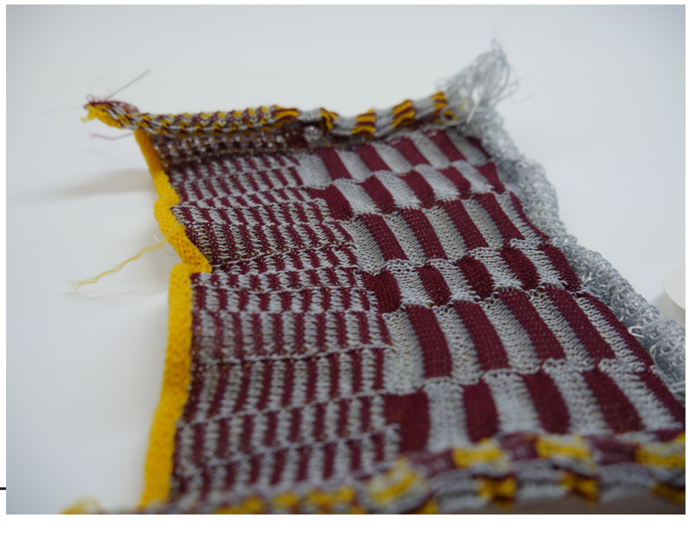
Second attempt to knit the spacer structure, see Sample 25 top part. Changed the stitch length from 12 to 11 for the outer layers and 9 for the nylon tucking in between.
The segments with the most dense nylon tucking are the most regular. The nylon does not stick out of the outer layers, even after extreme stretching.



79

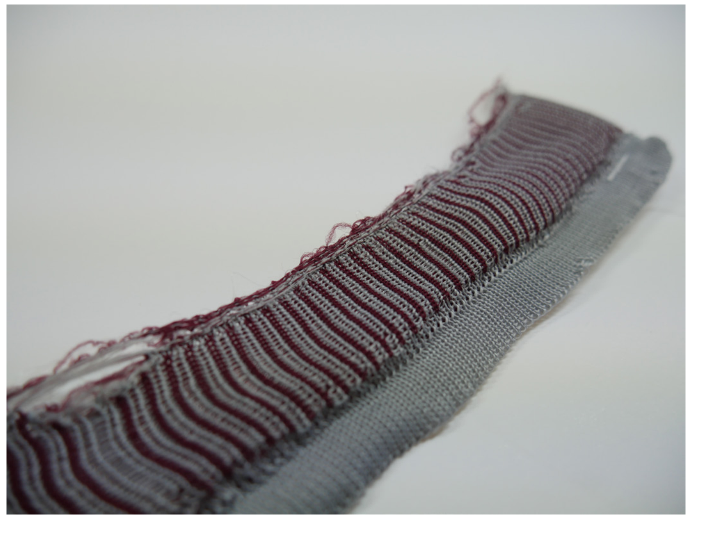
Knitting the nylon with two polyester yarns, every 6 and 2 rows, alternating with knitting with 3 polyester yarns. Attempt to use the nylon in only segments of the knit to experiment whether this still results in strong knit (tensile strength) as expected from nylon yarn, however using 3 polyester yarns instead of 2 for aesthetics. The yarns are alternating because then still 3 systems are used instead of 4, which would double the knitting time.

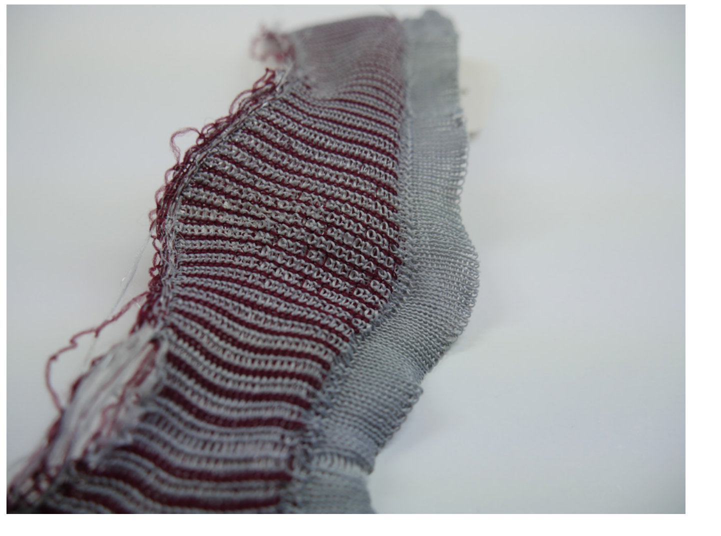




80

Expected to have a high tensile strength, for the nylon is floating between front and back layer, only knitting every 4th needle. Attempt to knit with one cone of nylon, using it on both beds without connecting front and back, and leaving one end open so it could be used only in a segment of the knit.





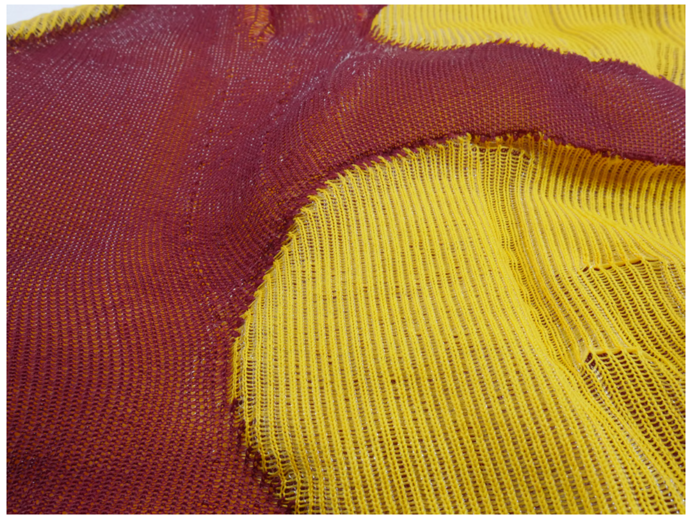
81

Knitted with two polyester yarns and nylon. The first attempt damadged the knitting bed because the nylon was tensioned too high, at stitchlength 9. In this case the stitchlength of the nylon is 10 and of both polyester yarns 11.

The spacer parts look and feel as intended: no nylon sticking out, feeling thick and fluffy, almost no stretch in the horizontal directi-on.

The circles are knitted as seperate layers, the yellow alternating every stitch with nylon, the red a single jersey. The stitch structure results in different dimensions than the spacer, resulting in a non-flat knit.

Again there are some flaws, not only at the top but also in the middle of the circles.



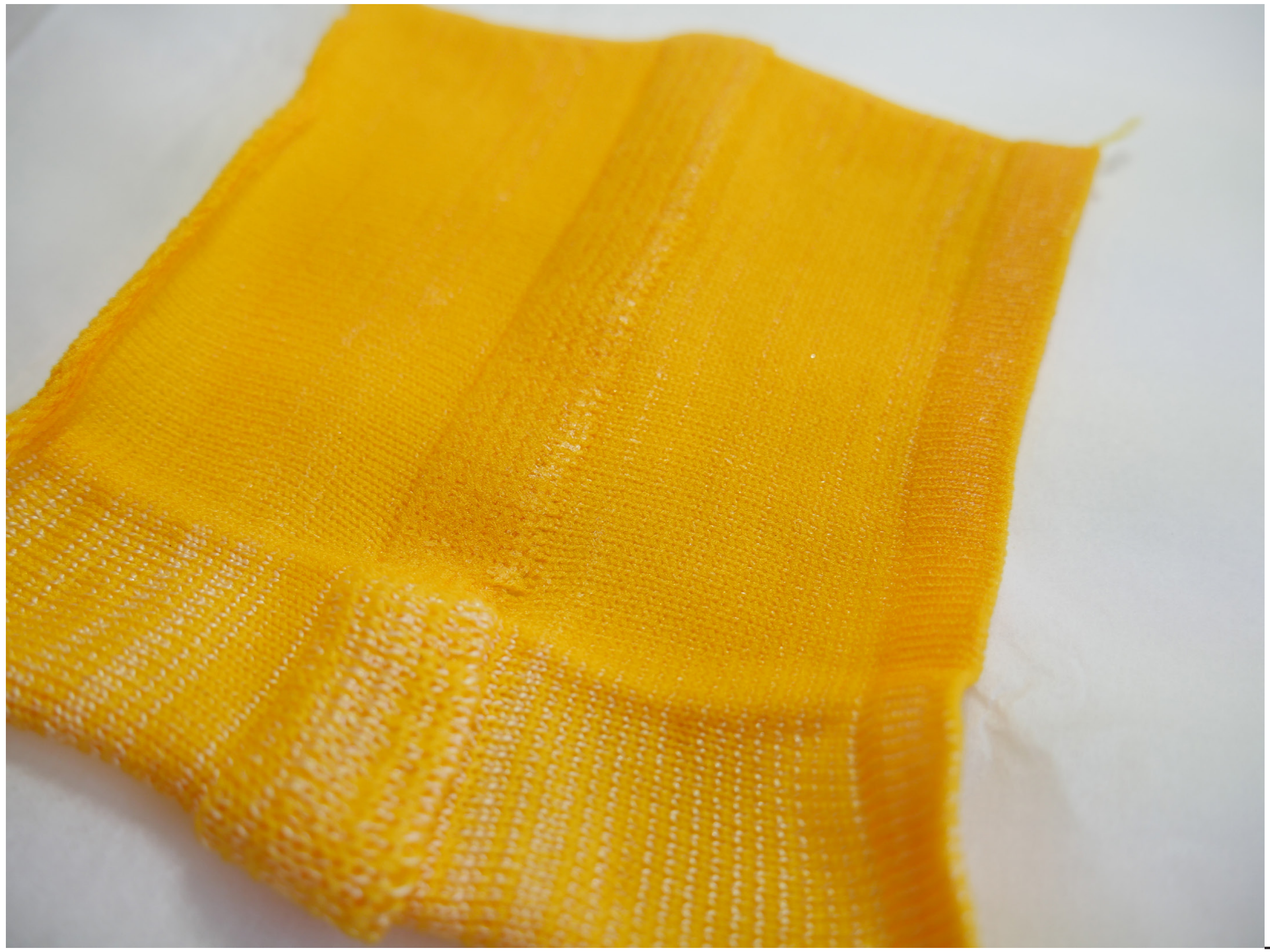
83

Experiment with melting yarn, plating the melting yarn with po-lyester.

A single jersey and a full needle structure.

The sample is heated using an iron. Ironing makes the yarn melt and give a rubber like handfeel. The stretch is reduced in all directions.

Possibly suitable for the ends of the panels as reinforcement.



84

Attempt to cast off using a rib thread in the middle of a sample after which knitting is continued.
Two layers of single jersey.

The yellow threat was cut/clamped after casting off, which caused the segment on the bottom left to unravel.

The cast-off and setting up however are succesful and could be used to knit a strip directly to the panels that could function as a cable.

85

'cable_band'

Meant as cable to attach the ends of the legs of the chair to each other by inserting them in small pockets. A nylon and polyester yarn combined on the back (red) and a melting yarn with polyester combined on the front (yellow).

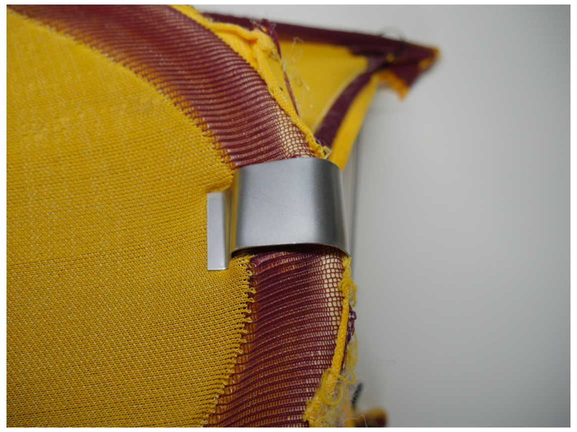
The openings are wide enough for one pipe, as all the fabric around it should also fit in which was not calculated in advance. The yellow yarns were set up to create the pocket opening but would get stuck easily to the back layer during knitting. Hand manipulation required to solve this while knitting. Making the pocket openings smaller would decrease the chance of the yarns getting stuck, but would make it impossible to use the pocket effectively.

A cable with openings, holes, in it would be more effectice and easier to make.

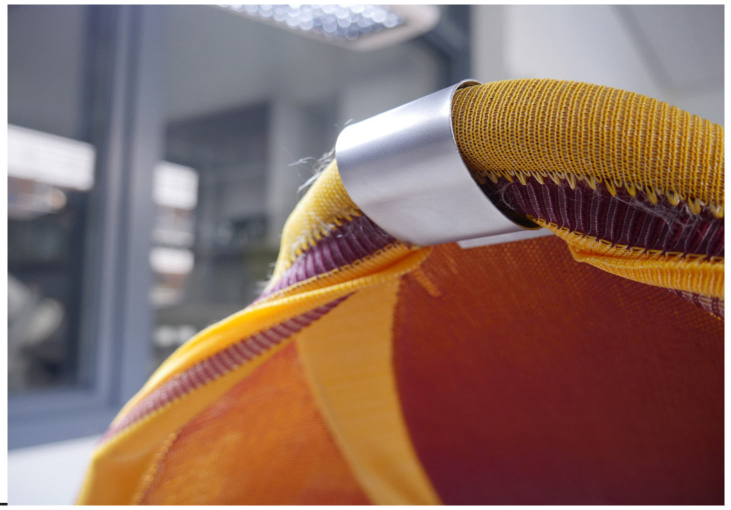
87

To make an attachement between the two rods that is reversible by the user, the clip should either go over the knit or be partially covered by the knit. Making a clip that partially sticks out of the knit requires a knitted hole, which requires both beds to be available to make the transfers to the sides to create the hole. Since the rods are inside a tunnel, created by two seperate layers requiring the two beds, making a hole in the tunnel results in a lower knit density. THis is undesirable given the location on the structure: right at the top of the rod where the tension is very high when a person sits down in the chair.
A non-knitted hole could be created with an eye-lid or cutting and coating. This requires post-processing in addition to making the clip and attaching this to the rods.
Therefore a clip over the knit is designed, to leave the knit at full density and in tact. The aesthetics of the clip are important because it is highly visible.

Metal plate material bent into a clip to hold the two rods horizontally aligned.
The structures stays in shape. A 3D printed clip consisting of 2 parts that can be tightened with a bolt can increase the pressure on the two rods. The clips can be evaluated on eaes-of-use in a later development phase.

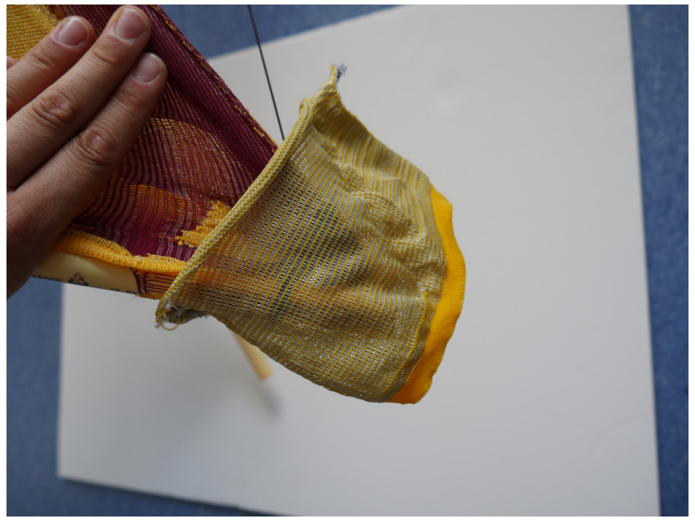


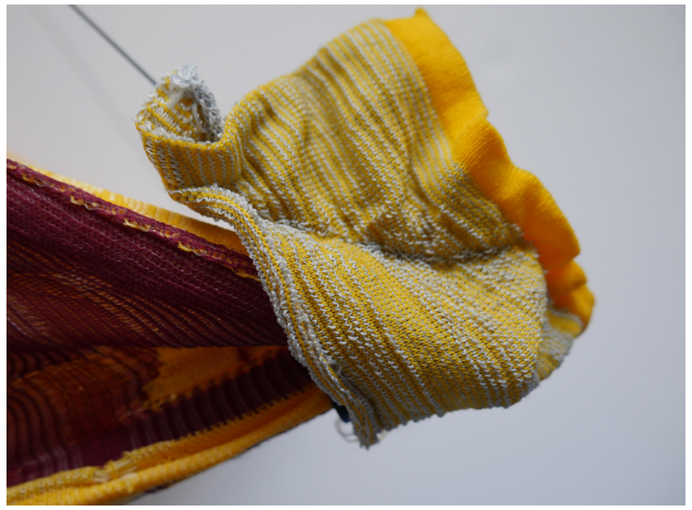
This image shows the clip that connects the backrest of the chair. The top knit goes over the bottom/back knit, to ensure the front crossing rod leans onto the back rod, dividing the load over the back legs of the chair.



88

Using thermoplastic heatshrinking yarn in an attempt to knit a 'sock' like part to cover the ends of the legs. It was assumed that the yarn would become very stiff and feel like hard plastic after ironing, it however is stil soft and flexible. The elasticity is reduced.
The 'sock' is knitted by plating the heatshrinking yarn with a polyester, knitting both on front and back of the sock.
The two rod ends could not be kept in the desired configuration by the sock after being shrunk. Further development is required, possibly using multiple plys of the thermoplastic heatshrinking yarn, smaller shape, and a denser stitch structure.

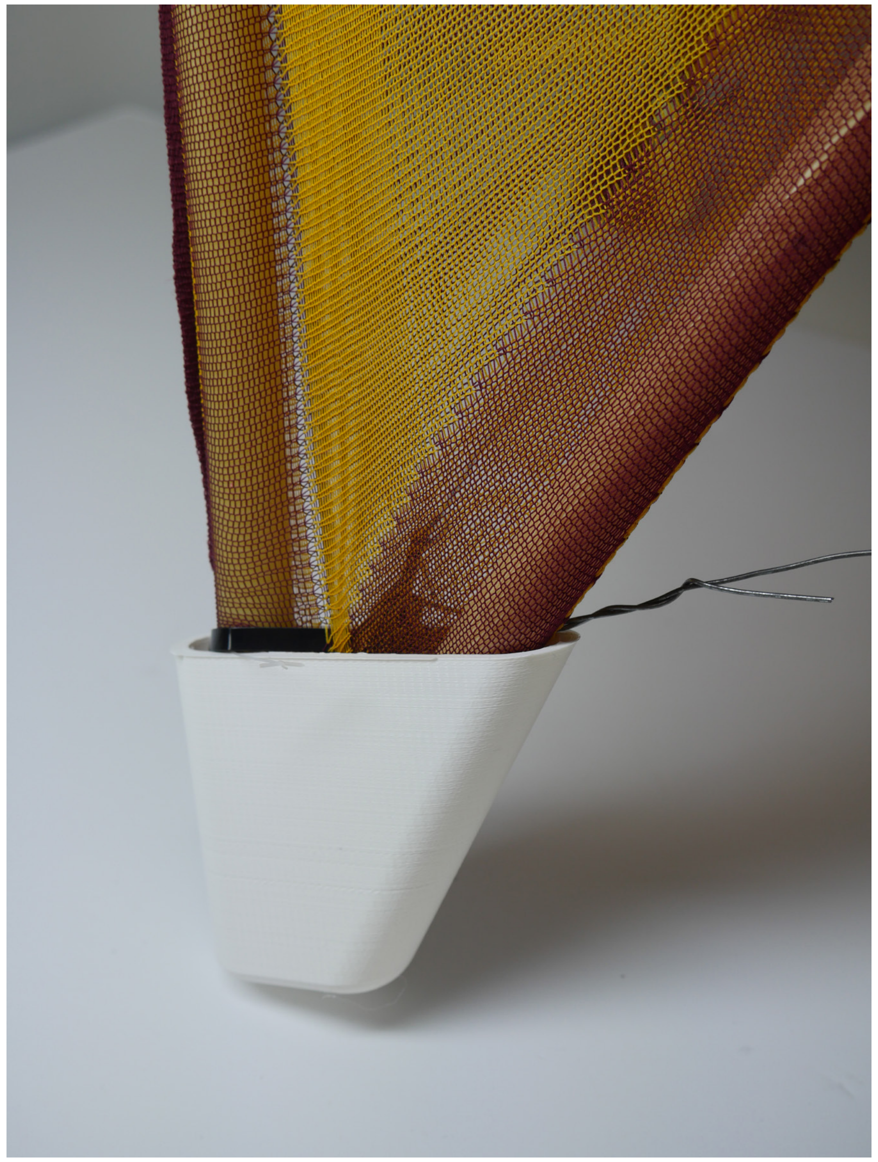




89

The first foot.

The foot is meant to hold the two rod ends into the desired configuration, as indicated by the tunnel placement in the knit.
The foot could be designed to be inside the knit, attaching the two rod ends in a predetermined angle. The knit that goes over will still be the weak point of the object because of the friction between the foot and the floor. Additionally, a foot covered inside the knit is more difficult to attach, and requires a hole in the knit to allow for the wires between the feet to be connected.
Therefore a foot over the knit and rod ends is designed.
A first prototype is presented below, to test the dimensions and angle of the foot. The rod ends stay in place inside the foot and in the desired configuration.
A following iteration will include holes to attach wires on both sides and the front, plus possible material saving solutions to limit the material usage. Topology Optimazation could be utilized to decrease the weight of material used. Due to the short duration of the project this is not explored further.



90

First attempt to knit a spacer segment in the middle of a double jacquard. The nylon continues everywhere, tucking in the circular spcer segment.

The stitchlength is too long, the nylon is sticking out a lot in the double jacquard segments.

91

Iteration on Sample 90, decreased the stitch length of both the polyester and the nylon to eliminate the nylon sticking out of the polyester outer layer.

The transitions in colours of the double jacquard do not look nor feel as expected. Because the nylon is alternating between the front and back bed, both sides feel stiff.

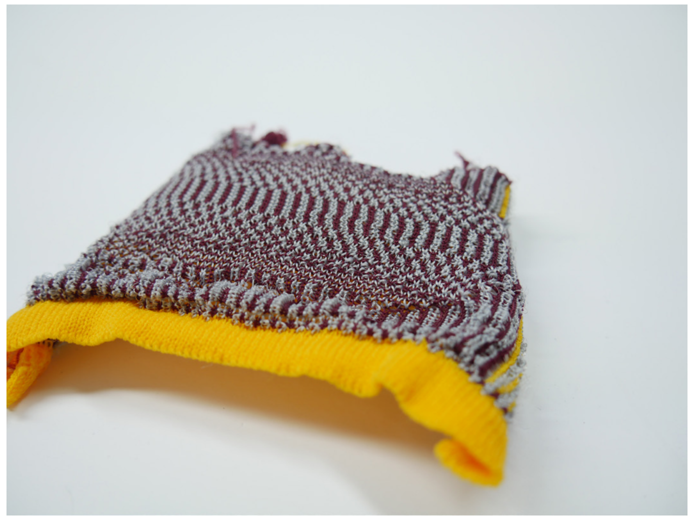
92

Iteration on Sample 90 and 91. Soft handfeel on the yellow/grey side because the nylon is either knitted on the back or tucking between two layers.

The stitchlength of the nylon is small enough for the spacer, however the nylon broke in the double jacquard segment probably because it was too small.

93

Iteration on Sample 90, 91 and 92.
The polyester is knitting all needles everywhere, alternating only with each other and not alternating for the nylon. The nylon is knitted over the polyester, craeting a very irregular double jacquard, very dense.



94

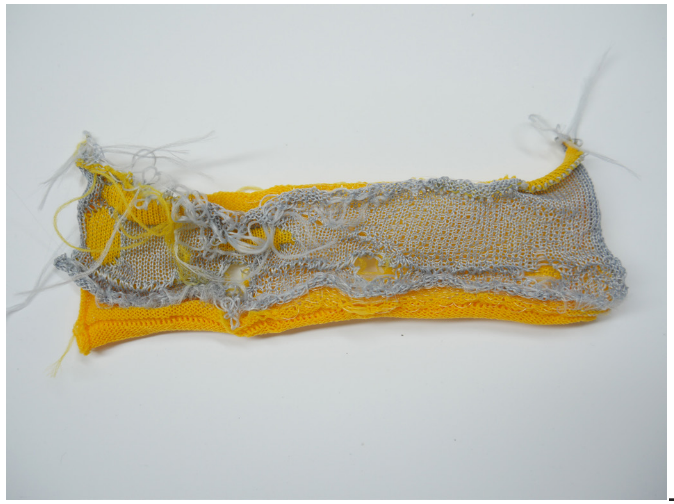
Two attempts to knit nylon only into the ends of a tunnel, leaving the tunnel open, and using only 3 yarn feeders of which 1 nylon cone and 2 polyester.
The nylon cone is fed through a intarsia yarnfeeder.

The first attempt showed that the density decreases because the two polyester colours are alternating knit-float on two needles.

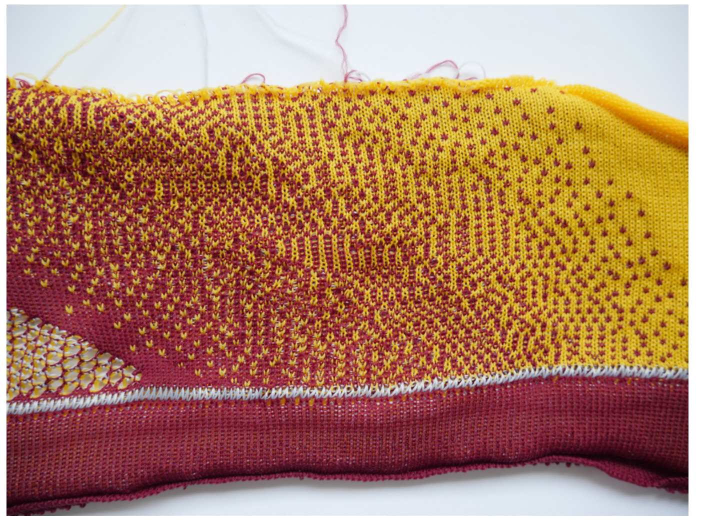
The second attempt did not work well because the grey yarn fluffed up between the beds. However, the colours are seperated and the tunnel still open. Another iteration will be conducted to create a double jacquard with intarsia nylon.

Sample 94 attempt 1

Sample 94 attempt 2



95

Knitting the ends of the tunnels with nylon intarsia, to prevent the nylon to be all over the horizontal tunnel which takes out the stretch.
One nylon cone is on a roll that does not allow the yarn to be taken off by the machine like the other cones.
Multiple solutions were evaluated to be able to still use the cone of nylon. Two cones of nylon are needed to use the intarsia on two seperate spots.
A horizontal axis was used, which led to too much friction. In this sample, the cone is rotated by hand, still leading to a few breakages and an uneven tension.

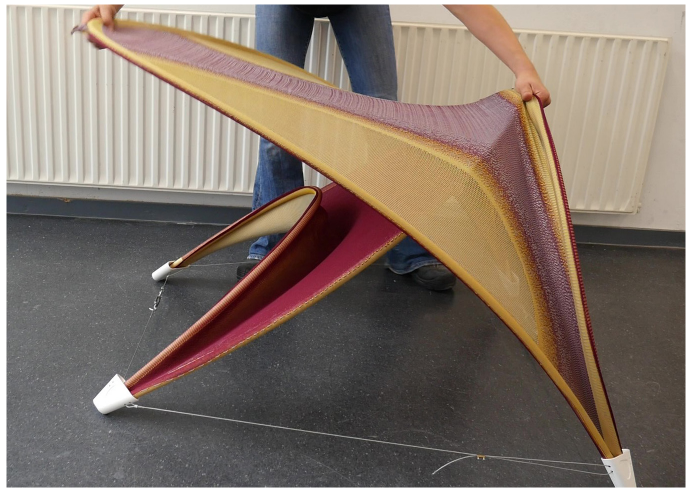
Two roller systems are tested but the friction is still to high.
Since three colours are used for the tunnel, thus on one side alternating knit-float, this already takes out ssome stretch in the horizontal tunnel. Thus is was decided to simply only use one cone of nylon over the full length of the tunnel.

The presented sample has some more flaws: the colours switch as the nylon intarsia area, closing off the tunnel. The grey row that closes the top of the horizontal tunnel but is very loosely knitted because every stitch is knit-tuck.

96



Bending the bottom panel to the top panel

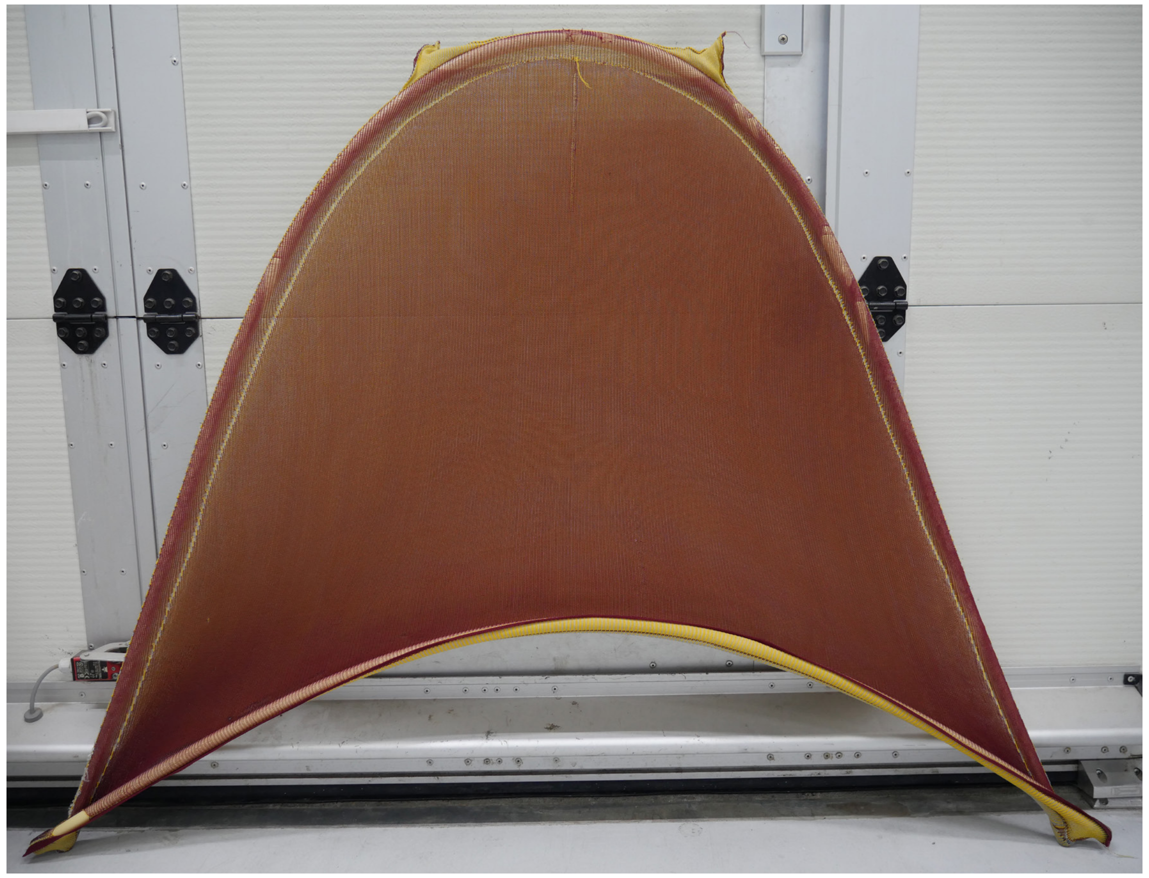

Bending the top panel over the bottom panel


Fixating the crossing rods on the opposite side


Cable slips when load is applied on the object


Size view of Prototype 96

97



98

Appendix B: Concept development

Inspiration

Gianni Pareschi & Ezio Didone

Martin Thübeck

Linda Chi

Daniela González Martínez

Katja Petterson

La silla invisible

William Katavolos

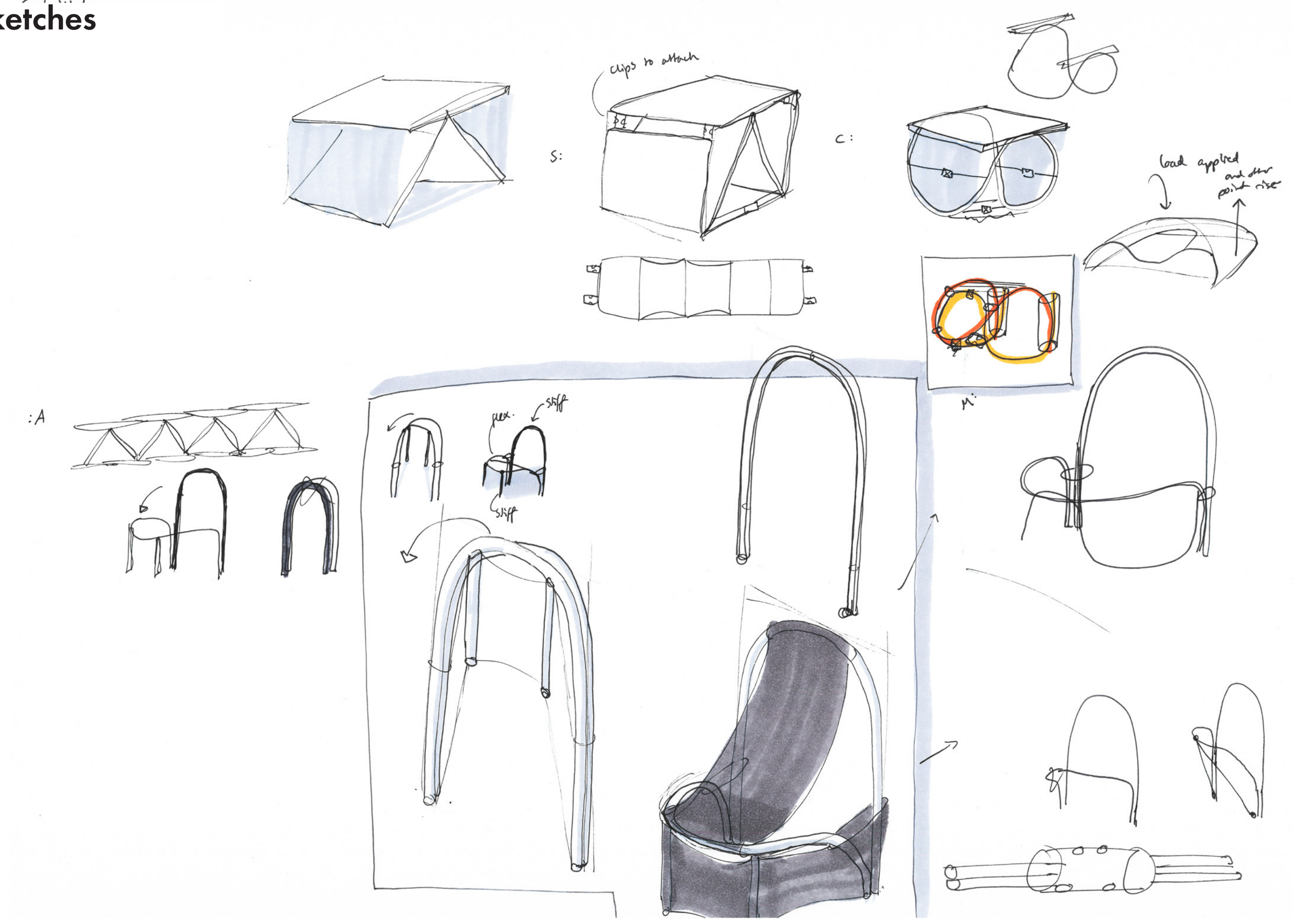
Byron Botker

Verner Panton

Shao Fan

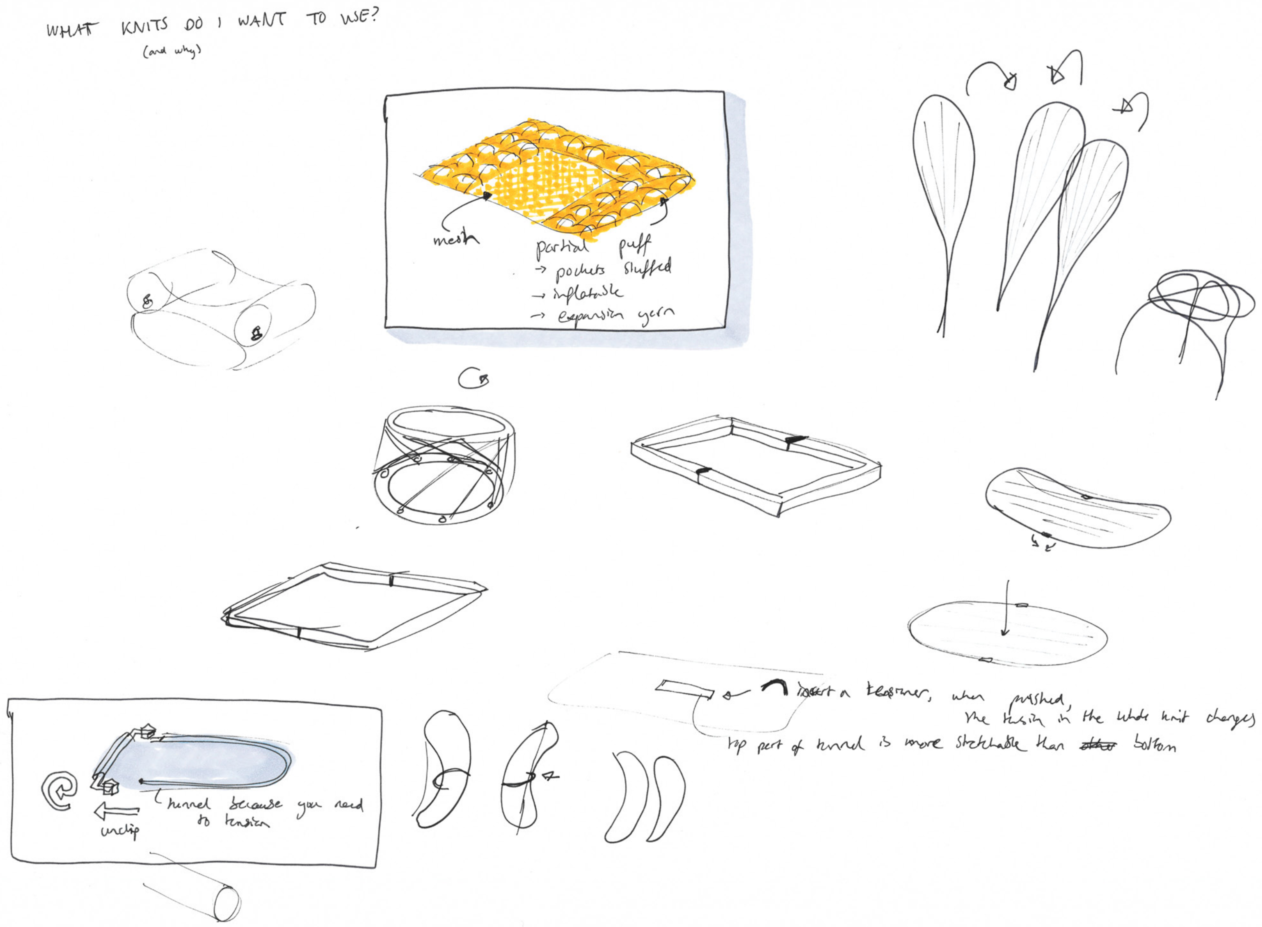
Verner Panton

Sketches

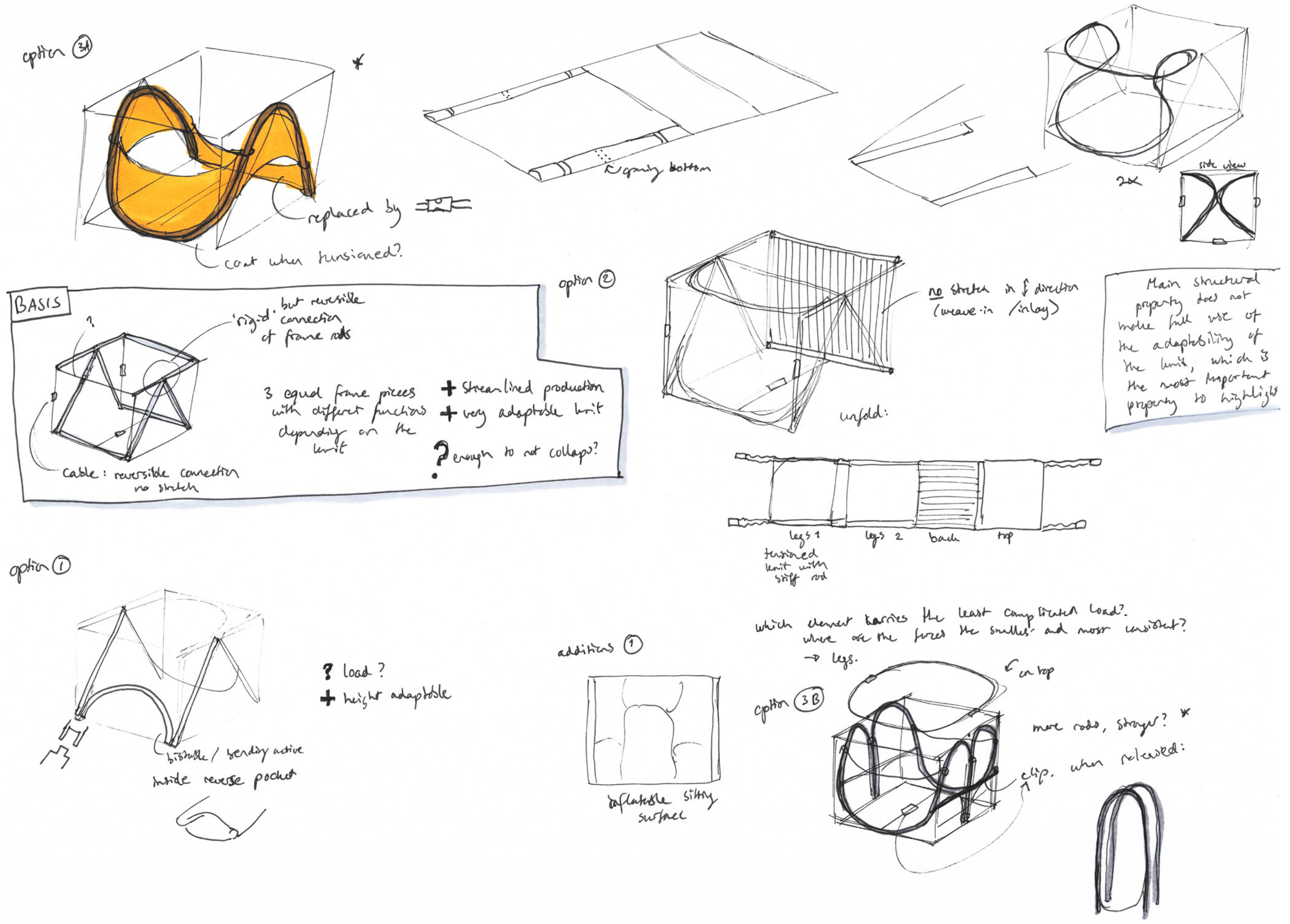


clips to attach
S:
C:
load applied and other point rise
:A
flex.
stiff
stiff
M:

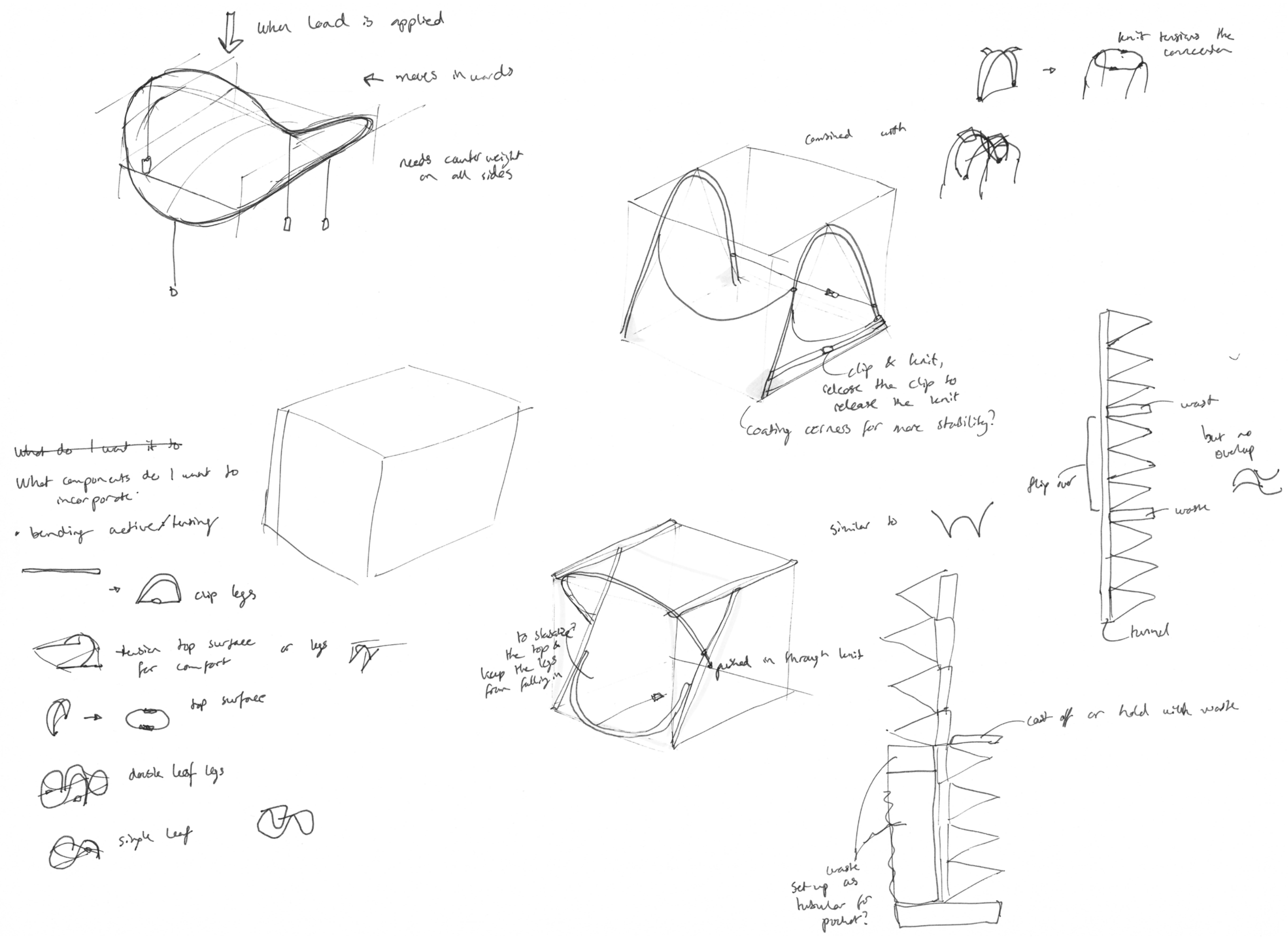
Out of plane
super stretch
non stretch
only ↑ ~ stretch
HOW TO
LEAF SEAT
Release to expand
seat system
non stretch
super elastic

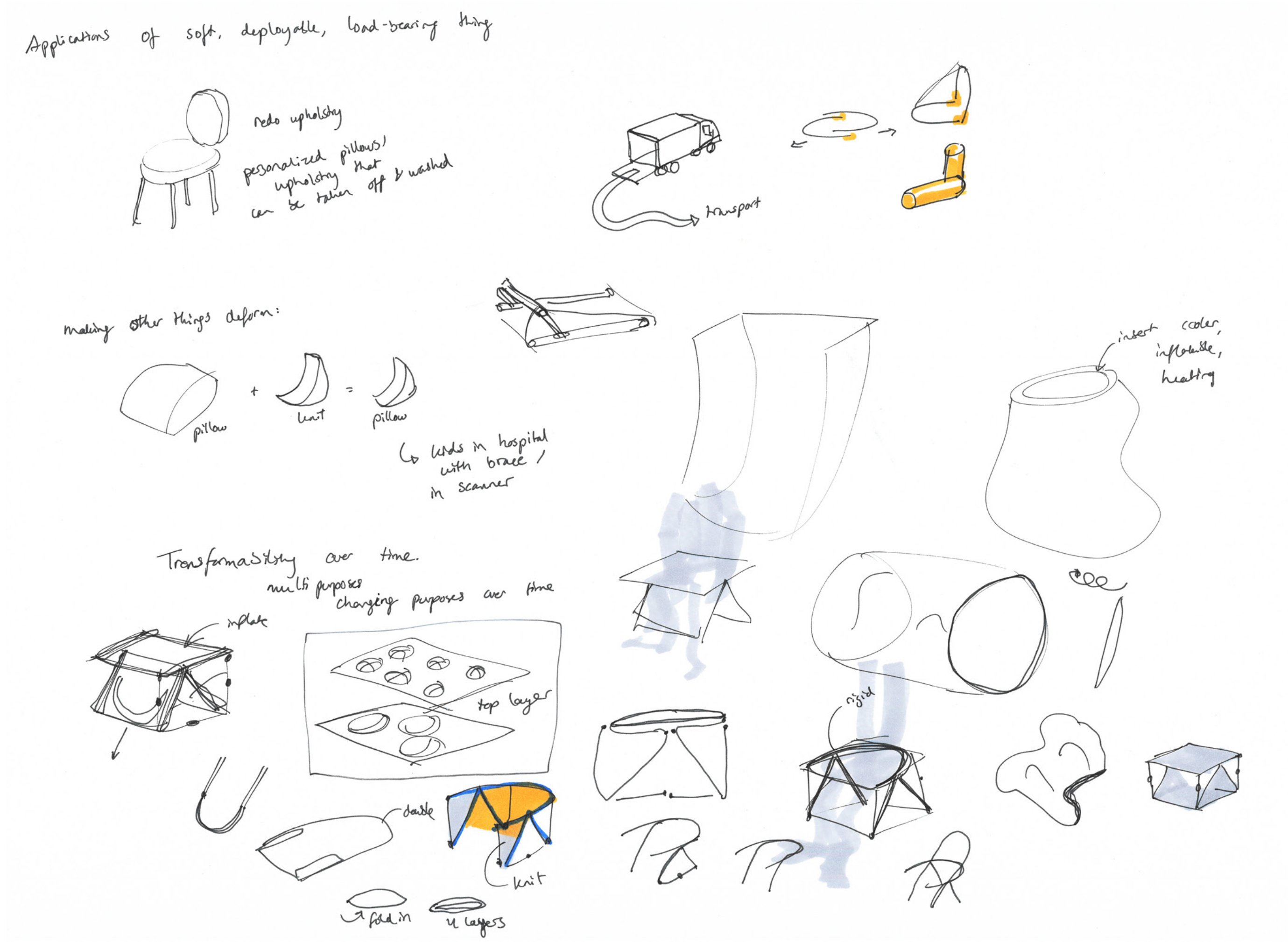


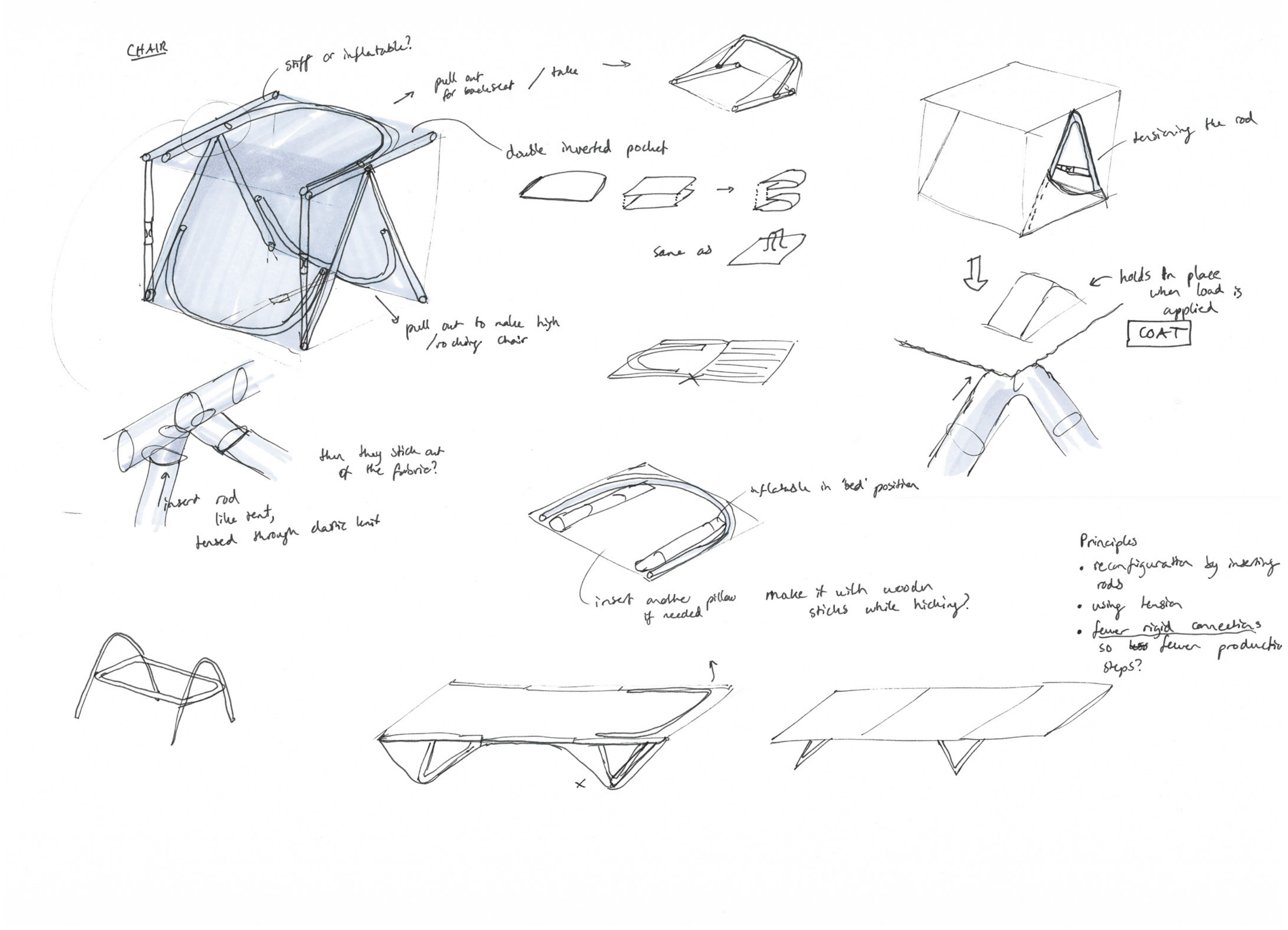
WHAT KNITS DO I WANT TO USE?
(and why)
mesh
partial puff
→ pockets stuffed
→ inflatable
→ expansion yarn
insert a fastener, when pushed, the tension in the whole knit changes
top part of tunnel is more stretchable than bottom
tunnel because you need to tension
unclip

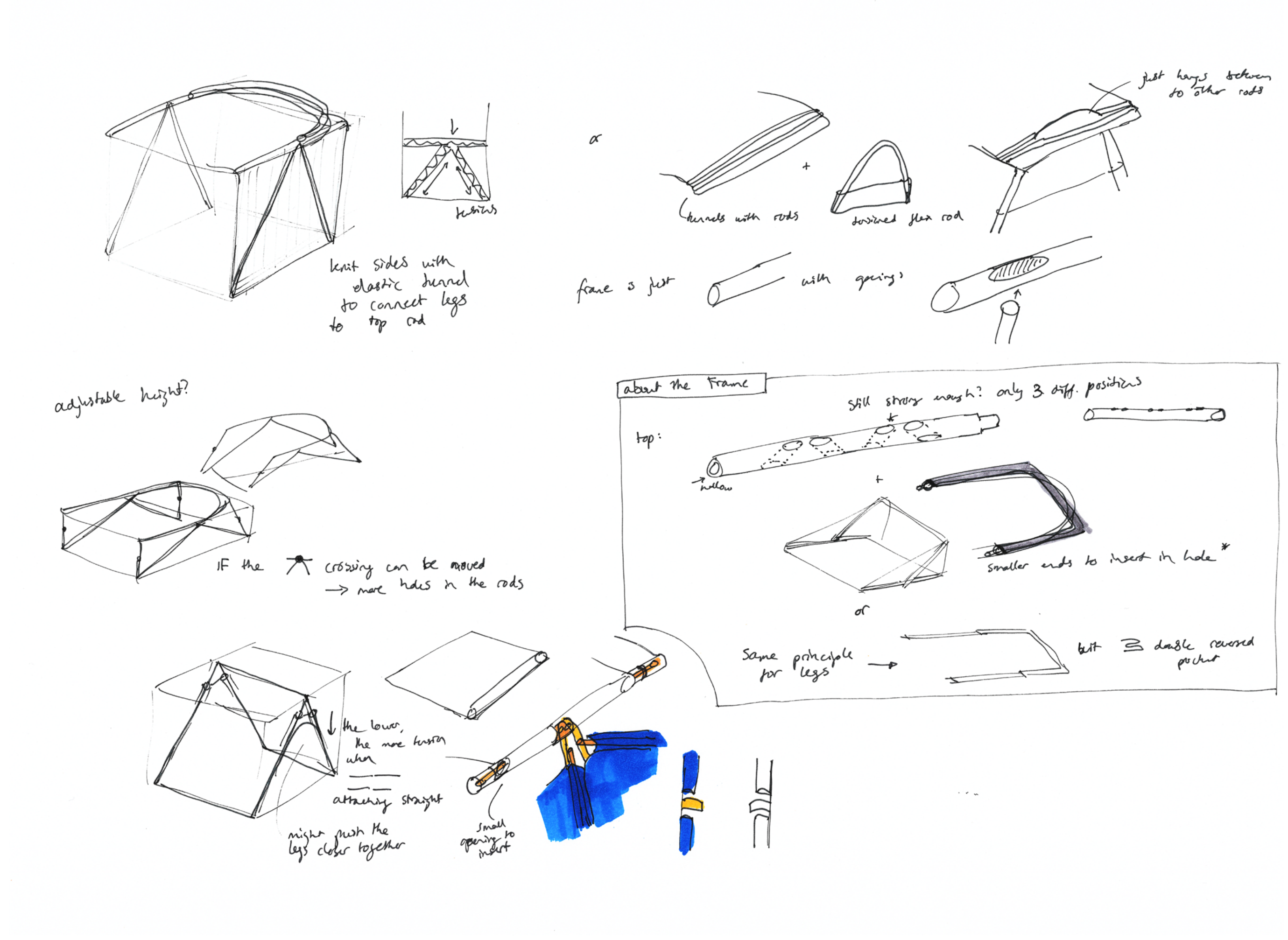


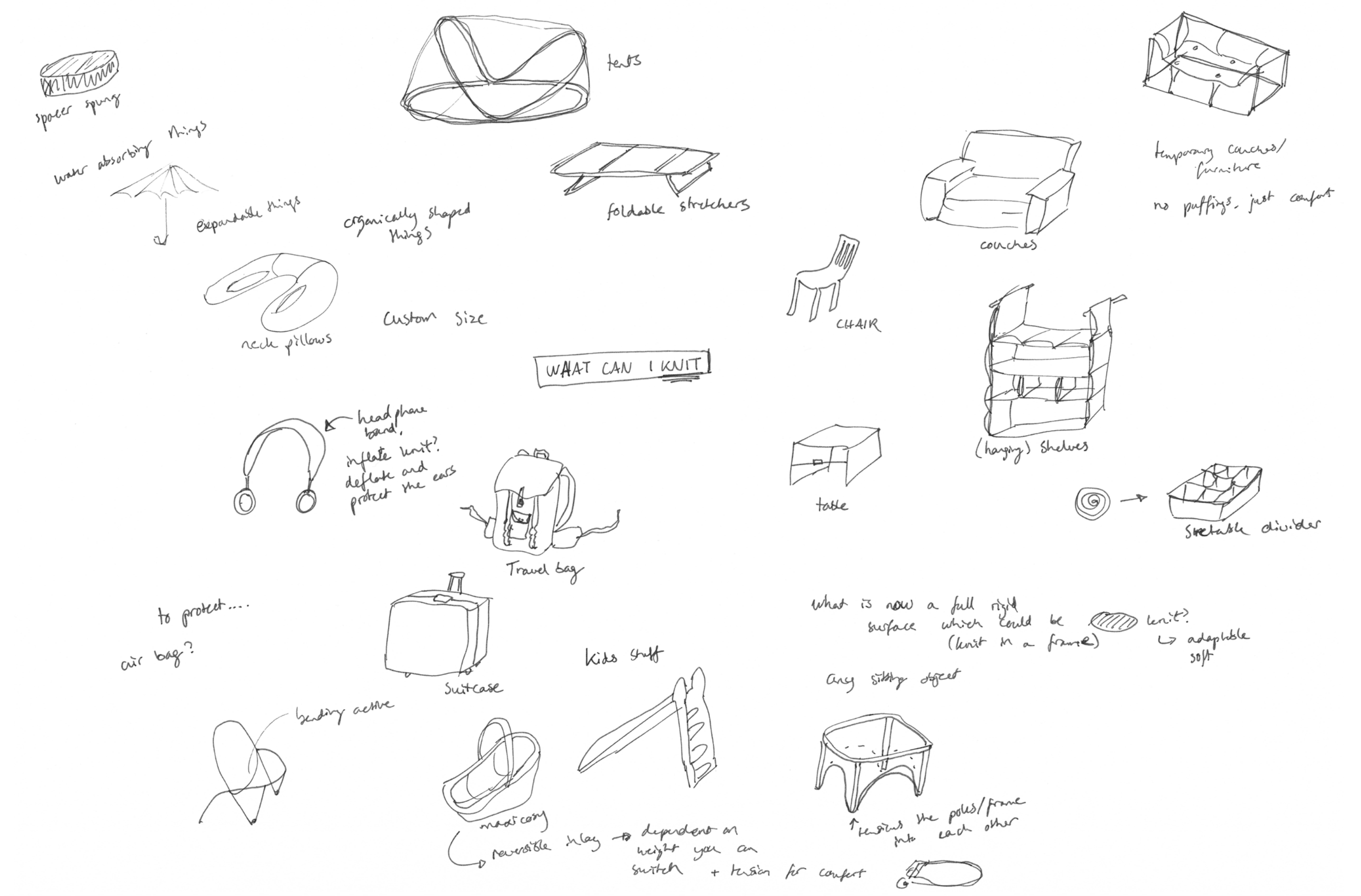
option 3A
replaced by
coat when tensioned?
BASIS
'rigid' but reversible connection of frame rods
3 equal frame pieces with different functions depending on the knit
+ streamlined production
+ very adaptable knit
? enough to not collapse?
cable: reversible connection no stretch
option 2
no stretch in ∫ direction (weave in / inlay)
Main structural property does not make full use of the adaptability of the knit, which is the most important property to highlight
unfold:
legs 1
legs 2
back
top
option 1
? load?
+ height adaptable
bistable / bending active inside reverse pocket
additions 1
inflatable sitting surface
which element carries the least compression load? where are the forces the smallest and most consistent?
→ legs.
option 3B
on top
more rods, stronger?
clip. when released:

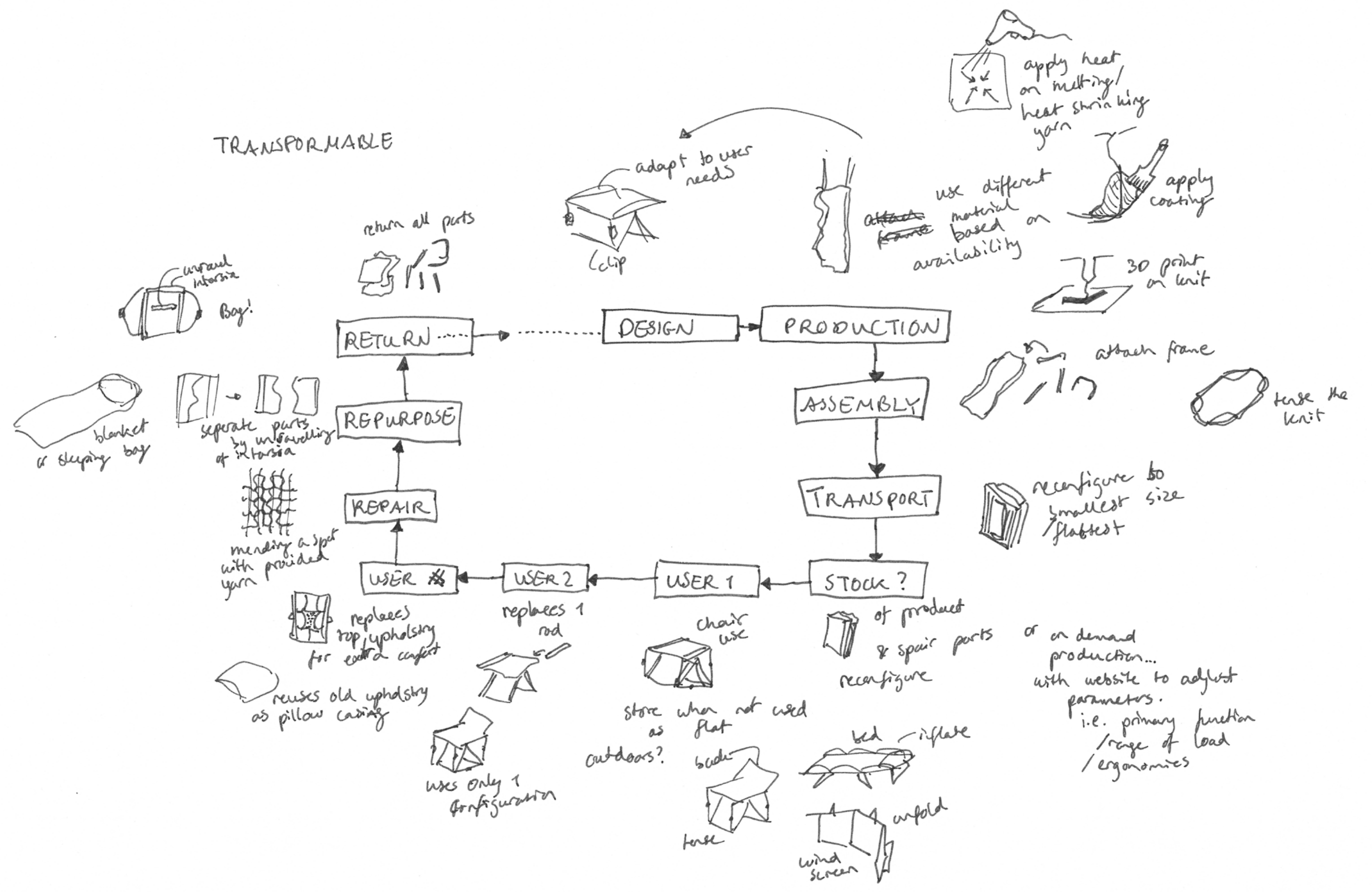

when load is applied
moves inwards
needs counter weight on all sides
knit tension the connection
combined with
clip & knit, release the clip to release the knit
coating corners for more stability?
What components do I want to incorporate:
• bending active/tensioning
clip legs
tension top surface for comfort
or legs
top surface
double leaf legs
single leaf
similar to
to showcase? the top & keep the legs from falling in
pushed through knit
waste
but no overlap
flip over
waste
turned
cast off or hold with waste
waste
set up as tubular for pocket?

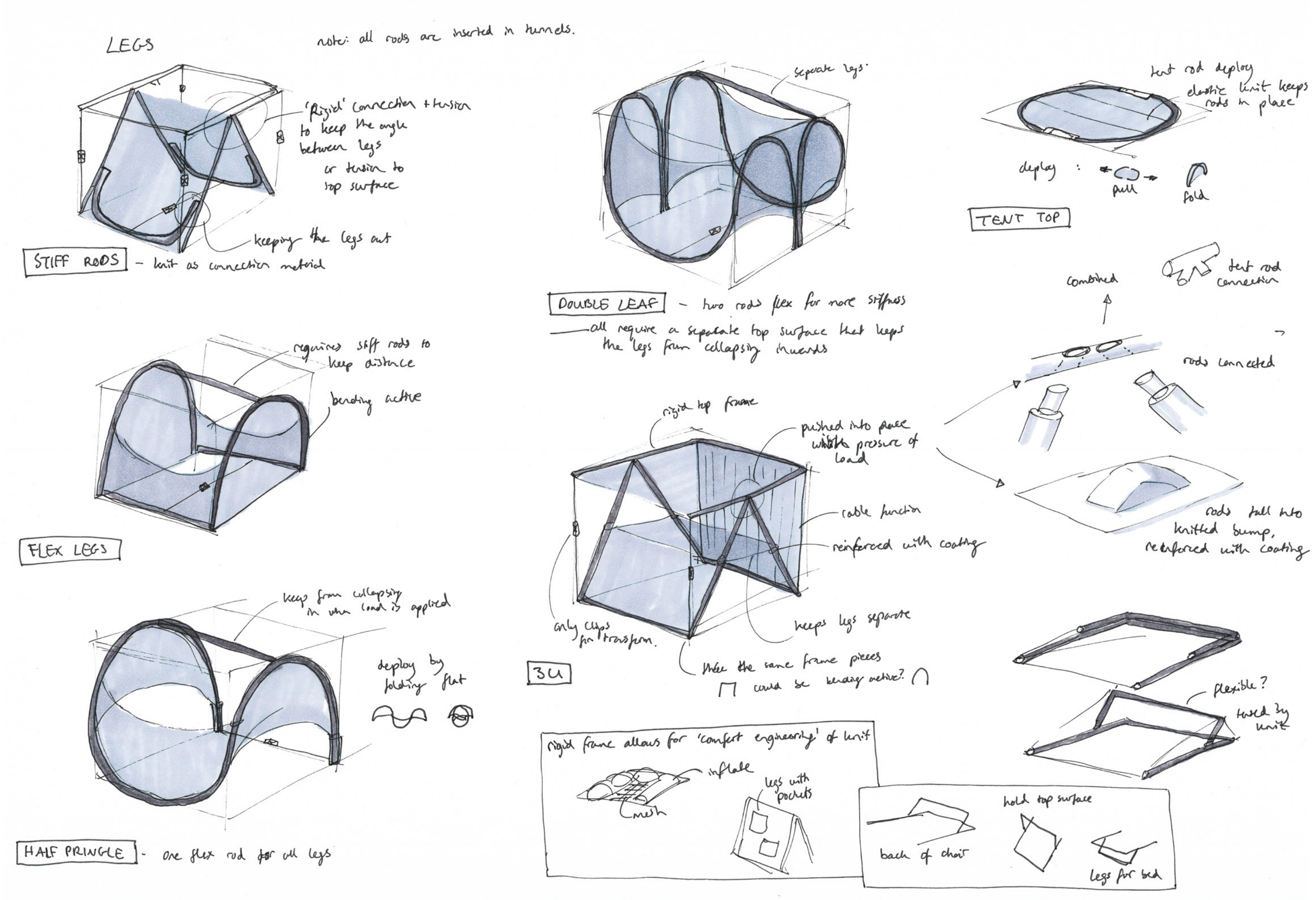

Applications of soft, deployable, load-bearing thing
redo upholstery
personalized pillows/upholstery that can be taken off & washed
transport
making other things deform:
pillow
knit
pillow
↳ knits in hospital with brace / in scanner
insert cooler, inflatable, heating
Transformability over time.
multi purpose
changing purposes over time
inflate
top layer
double
knit
fold in
4 layers
rigid

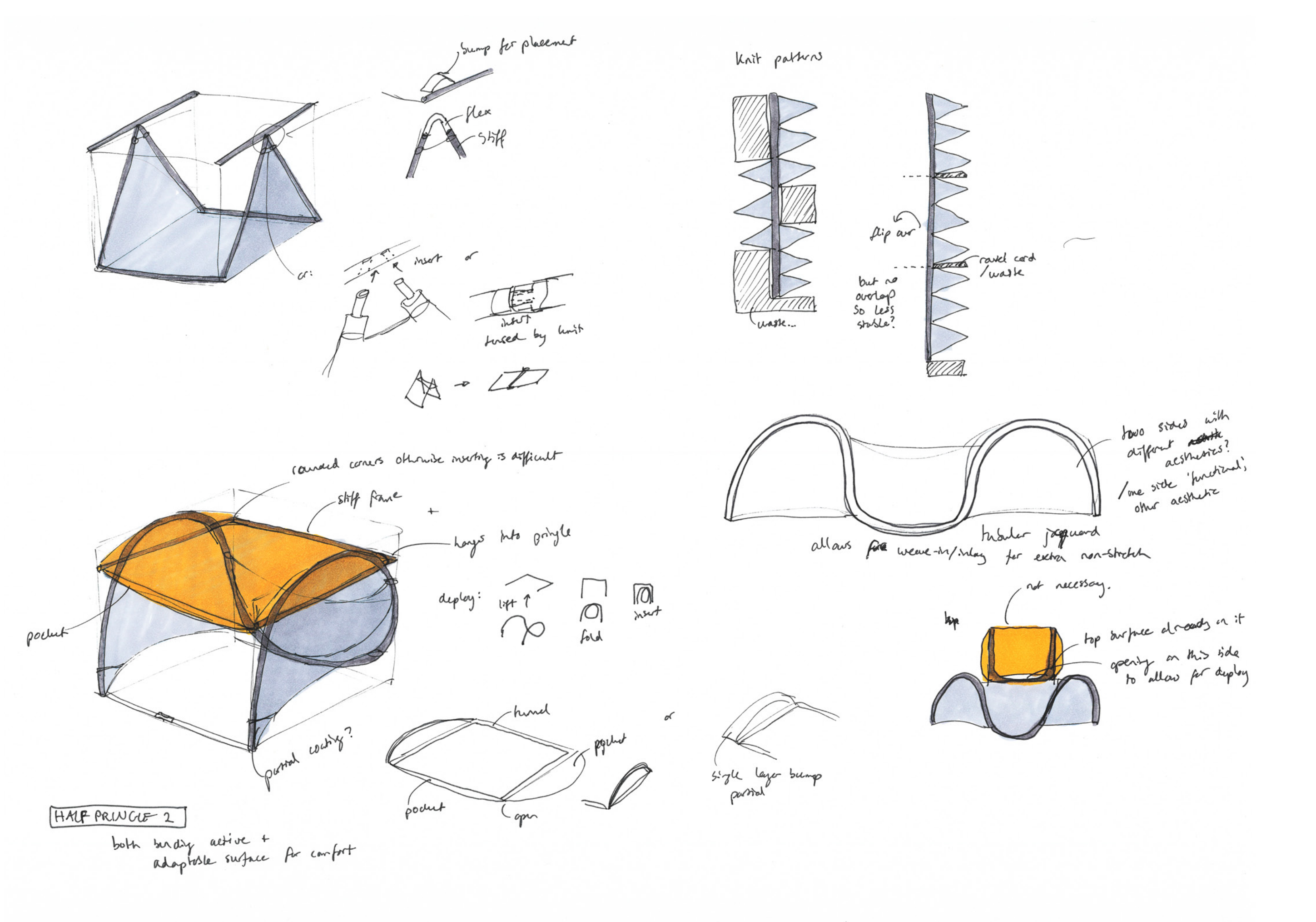

CHAIR
stiff or inflatable?
pull out for bookshelf / table
double inverted pocket
same as
pull out to make high / rocking chair
tensioning the rod
holds in place when load is applied
COAT
then they stick out of the fabric?
insert rod like tent, tensed through elastic knit
inflatable in 'bed' position
insert another pillow if needed
make it with wooden sticks while hiking?
Principles
• reconfiguration by inserting rods
• using tension
• fewer rigid connections so fewer production steps?


knit sides with elastic tunnel to connect legs to top rod
or
tunnels with rods
tensioned flex rod
just hangs between to other rods
frame is just
with opening
adjustable height?
If the crossing can be moved → more holes in the rods
about the frame
top:
still strong enough? only 3 diff. positions
hollow
smaller ends to insert in hole
or
same principle for legs
both 3 double crossed pocket
the lower, the more tension
attaching straight
might push the legs closer together
small opening to insert


tents
spacer spring
water absorbing things
expandable things
organically shaped things
foldable stretchers
couches
temporary couches/furniture
no puffings, just comfort
neck pillows
custom size
CHAIR
WHAT CAN I KNIT
(hanging) shelves
table
stackable divider
Travel bag
to protect....
air bag?
suitcase
kids stuff
bending active


TRANSFORMABLE
adapt to user needs
clip
return all parts
RETURN
DESIGN
PRODUCTION
REPURPOSE
ASSEMBLY
REPAIR
TRANSPORT
USER 3
USER 2
USER 1
STOCK?
apply heat on melting/heat shrinking yarn
apply coating
use different material based on availability
3D print on knit
attach frame
tense the knit
blanket or sleeping bag
reconfigure to smallest size/flattest
replaces top upholstery for extra comfort
reuses old upholstery as pillow casing
uses only 1 configuration
store when not used
outdoors?
bed
inflate
unfold
wind screen
or on demand production...
with website to adjust parameters.


LEGS
note: all rods are inserted in tunnels.
separate legs.
tent rod deploy
TENT TOP
STIFF RODS
- knit as connection material
DOUBLE LEAF
- two rods flex for more stiffness
FLEX LEGS
bending active
rigid top frame
3U
HALF PRINGLE
- one flex rod for all legs
rigid frame allows for 'comfort engineering' of knit
inflate
mesh
legs with pockets
back of chair
hold top surface
legs for bed
flexible?
rods connected
combined


bump for placement
flex
stiff
insert
knit pattern
slip over
ravel cord / waste
waste...
rounded corners otherwise inserting is difficult
stiff frame
pocket
partial coating?
HALF PRINGLE 2
both bending active + adaptable surface for comfort
tunnel
pocket
open
not necessary.
deploy:
lift
fold
insert

Concept "klapstoel"

The design of the tunnels allows for reconfiguration of the rods and thus for different geometries.

Inspiration
This concept is inspired by an old fashioned folding chair.

Principle
The core of the concept is the knitted joints, the reversible connection between two rigid materials that functions as a joint.
The knitted fabric is a tubular jacquard containing tunnels in which rigid rods are inserted. The jacquard allows for many tunnels, so the placement of the rods defines the final geometry of the object.

Transformability
The chair is transformable through kit-of-part: the rods can be seperated from the fabric. The placement of the tunnels is designed so rods can be added and removed to create different geometries of the object. For transportation some rods can stay in place while the other rods are rolled into the fabric to keep everything together.

Adaptability
The knit itself is a crucial part of the construction of the object. The knit in between the rods should be designed such that the knitted fabric hold the rods in the right position when a load is applied on top of the chair.

Recyclability
The knit and rods are seperable to allow recycling. The knitted fabric is knitted with different yarn materials, which compromises the recycling of the knit itself. The rods can be made of wood. The rods do not need any alterations except from the length, so they can be re-used for other purposes.

Production process
The fabric is knitted flat to be able to create a wide range of knit structures within the fabric, without compromising the density. Rods of varies lengths are provided to create the different configurations.

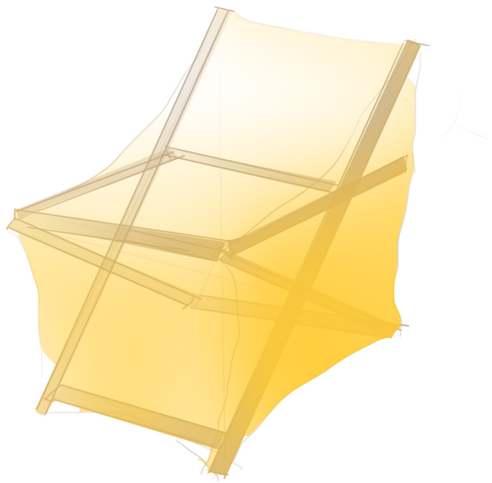


Figure XX Adding more rods in the back for more support

Further development through prototyping
As shown, the rods are connected through tunnels. As observed in Sample 47 and 48, the insertion of the rods can be challenging on the longer segments, however holes can also be used to connect the rod and fabric. Prototyping is necessary to determine where tunnels, holes or even small pockets at the ends are most suitable to make the construction work.
The exact knit structure in between the tunnels or holes defines the final geometry when a load is applied. Determining the structures is a process of trial-and-error, or require computational modelling of different knit structures, which is not within the scope of this project.

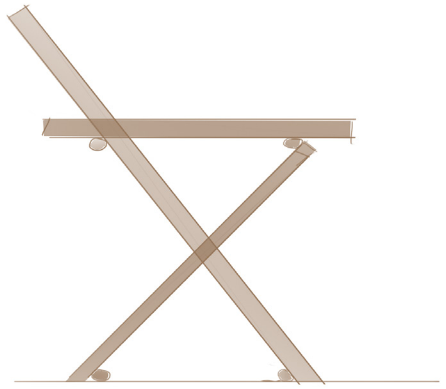


Figure XX Side view of the chair

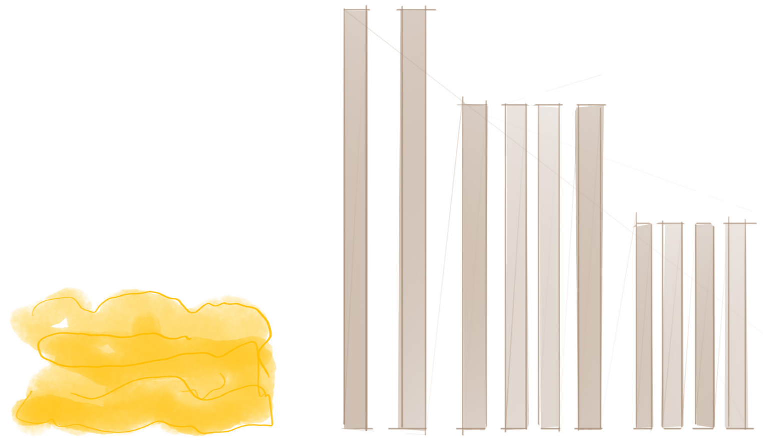


Figure XX The components: one knitted structure and ten rods

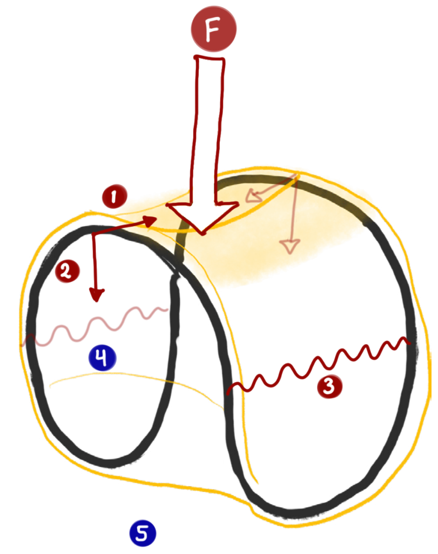
Figure XX The knit as flat. The yellow segments are tubular, the white parts can vary in knit structure, according to the necessary elasticity

Concept “Pringle”

Inspiration
Inspiration for this concept comes from the construction and deployability of tents, and the work of Alhquist et al. (2015) Both use GFRP rods to tense a knitted fabric. Tents such as pop-up tents of Queshua use a bending active mechanism to create a bistable construct. The hollow rods are connected through a rigid metal part and an elastic thread for easy deployement. The rods shape the fabric, and the fabric shapes the rod. This concept uses this principle of co-dependence to create a sitting object.

The concept can be executed in two manners.

Figure 1 Pringle



Concept 1A Flexible rods
Principle
The object consists of a knitted ‘skin’ in which a GFRP rod is inserted into tunnels, a bending active structure. The rod has two configurations, undeployed, when the rod segments are seperated, and deployed, rods are connected and restricted in shape by the knitted skin.

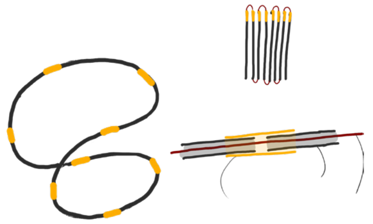


Figure 2: Tent rod deployement

Figure 3: Frame

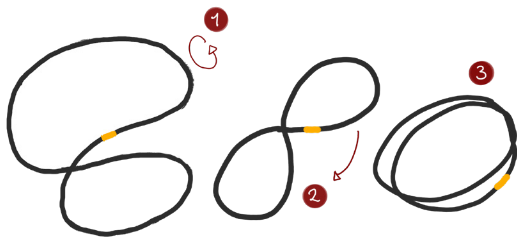


Figure 4: Queshua tent deployement

Figure 5: Tensions and forces when sitting down. F = force direction of person sitting down. 1 = the rod moves inwards towards the sitting person. 2 = the rod moves down and forces the vertical segments outwards. 3 = the fabric relaxes. The knit is designed to counter these forces. 4 = the knit can not stretch in the horizontal direction to counter 2. 5 = the knit can not stretch in the indicated direction to counter 1.

Feasibility
Experimentation with actual tent rods lead to a few conclusions. To let the knit control the rods and vise versa, they need to be connected through either tunnels or holes. This connections determines how the rods can be deployed. The more connection points between the knit and rods, the more difficult it becomes to mimic the deployement of the Queshua tent, see Figure 4. Inserting the rods in a continues tunnel results in the most control over the deployed geometry but will require undeployement by disconnecting the rod segments.

The actual tent rods are very flexible which serves its purpose for a tent where the rods are holding up a cloth to create a shelter. The only load from above are the weather conditions. In this concept, the rods need to be stiff enough to withstand the load of a person sitting down on it, and not too stiff so the construction can actually be tensioned by the fabric and the rods can still be bended into the undeployed configuration.
This requires a computational modelling of the stiffness of the rod (straight and in the defined bending angle), and analysis of the stiffness of the designed knitted fabric. The whole knitted structure is designed to compensate for the downward force of a person sitting down on the top surface, see Figure 5.

Adaptability
The balance between the stiffness and elasticity of both the knit and the rods have consequences for the design process. If the knit structure were to be adjusted, the material or construction of the rods should be reevaluated too. This increases the required time for adaptation.
One might want to adapt the knit structure for personal preferences, or to alter the aesthetics of the product.

Concept 1B Stiff rods
Principle
The object consists of a knitted ‘skin’ in which stiff metal rods are inserted into tunnels. The rod are single curved with squared ends that connect to each other in a certain angle to prevent rotation.

Feasibility
The stiffness of the frame leaves room for different knit structures on all sides of the object. The knit and frame are still co-dependent in the sense that the frame in itself is not a sitting object yet, where the knit is neither without the frame.
The object can be rotated for different sitting surfaces and experiences.

Adaptability
The fine balance between knit and frame in concept 1A is eliminated in 1B. The knit is adaptable to a users preferences, within the boundaries of the required strenght of the knit.

Production process
The production of this frame is specific for the geometry of this product. The production might be more costely and time consuming then the production of the tent rods. However, the wider range of design possibilities of the knit structure might compensate for it.

Concept “Balance”

Inspiration
This concept is inspired by the use of pockets by Mariana Popescu, tensegrity structure and Sample 38

Principle
The sitting object consists of three plates and a knit structure with pockets in which these are inserted. The tension of the knit and the configuration and interconnection of the pockets are balanced such that the top surface stays in place when a person would sit on it. This way the knit is reversibly rigidified, forming a temporary connection with the plate material.

Transformability
The object can be transformed by removing the top panel and folding the knit around the bottom two. Or the knit can be designed as such that different segments can be seperated and then folded flat. See Figure 6

Adaptability
These ‘plates’ can have variations in material, sizes and geometries. As long as the core principle is taken into account, the structure will be load bearing (see Figure 9).

Recyclability
he knit can be seperated from the rigid material so the material can be reused.

Production process
The knit is restricted by two principles of flat bed knitting. First, knitting more than 2 layers requires to knit on every other needle. Second, when knitting a pocket using front and back bed, transfers can only happen when knitting on every other needle. Inlays can be used in this concept to reduce the stretch, but this requires transfers. Therefore the structure should be knitted in two pieces, see Figure 7.

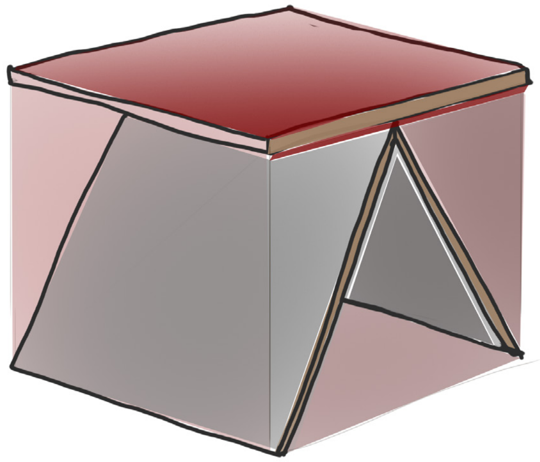


Figure 6 (above) The final sitting object, with the (below) plate material that is inside the red pockets

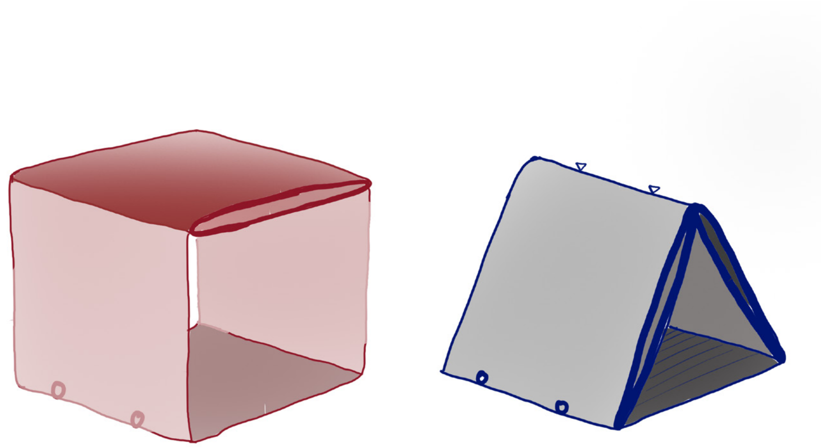


Figure 7 Knitting in tw pieces

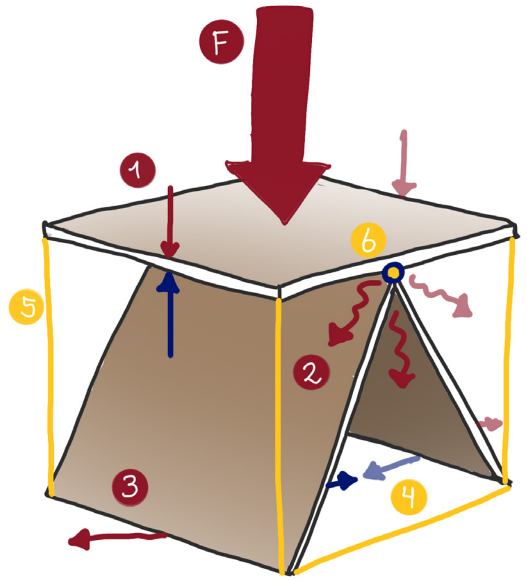


Figure 9 Forces when sitting down

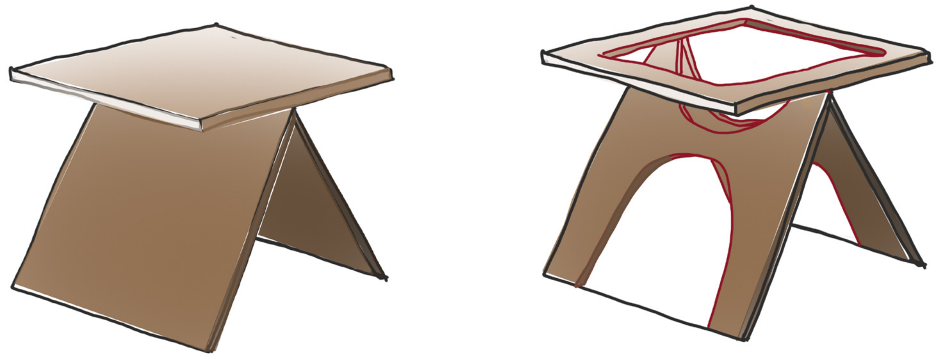


Figure 8 Possible reduction on the plate material

Appendix C Material properties

All data in this appendix is sourced from GRANTA EduPack. (GRANTA EduPack, 2022)

Polyamide yarn - Nylon 6

Mechanical properties

Young's modulus	4	-	5	GPa
Specific stiffness	3,51	-	4,39	MN.m/kg
Yield strength (elastic limit)	* 600	-	1,05e3	MPa
Tensile strength	600	-	1,05e3	MPa
Specific strength	* 526	-	921	kN.m/kg
Elongation	16	-	19	% strain
Flexural strength (modulus of rupture)	* 600	-	1,05e3	MPa
Shear modulus	* 1	-	2	GPa
Bulk modulus	* 1,2	-	1,3	GPa
Poisson's ratio	* 0,35	-	0,36	
Shape factor	1			

General information

Designation

Polyamide (PA6), fiber (Nylon-6)

Tradenames

Nylon 6, Nylon 6,6

Typical uses

Clothing including hosiery, fishing lines and nets, guitar strings, tire cords, tents, parachutes, carpets and brushes.

Composition overview

Compositional summary

Nylons are a family of synthetic thermoplastic polymers based on aliphatic or semi-aromatic polyamides (-NH-(CH2)5-CO-)n.

Form	Fiber
Material family	Plastic (thermoplastic, semi-crystalline)
Base material	PA6 (Polyamide/nylon 6)

Polyester yarn

General information

Designation

Polyester, fiber (Dacron)

Tradenames

Dacron, Terylene; Fiber V, Trevira, Polyester; Polyethylene terephthalate (PET), Fleece

Typical uses

Thread, rope, sails, tyre cord, ties, seat-belts, fire hose and geotextiles. Domestic uses include curtains, carpets, mattresses, pillows, seat cushions and custom upholstery, clothing, particularly dress fabrics, fleece, rain-wear, suits and shirts.

Composition overview

Compositional summary

Dacron is a condensation polymer obtained from ethylene glycol and terephthalic acid.

Form	Fiber
Material family	Plastic (thermoplastic, semi-crystalline)
Base material	UP (Unsaturated polyester resin)

Mechanical properties

Young's modulus	3	-	6,1	GPa
Specific stiffness	2,17	-	4,41	MN.m/kg
Yield strength (elastic limit)	* 573	-	730	MPa
Tensile strength	573	-	730	MPa
Specific strength	* 414	-	528	kN.m/kg
Elongation	18	-	28	% strain
Flexural strength (modulus of rupture)	* 573	-	730	MPa
Shear modulus	* 1	-	2	GPa
Bulk modulus	* 2	-	4	GPa
Poisson's ratio	* 0,34	-	0,36	

Glass fiber pultruded rod

General information

Designation

Polyester (UP) matrix, continuous glass fiber (E-glass) pultruded rod, manufactured by pultrusion (wet resin process), parallel to rod axis

Tradenames

Pultex 1500, Extren 500, Bedford

Typical uses

Access Systems,
Bridges, Cooling Towers, Grating, Handrail, Mezzanines, Platforms, Brooms, Brushes, Flag
Poles, Golf Equipment, Gymnastic, Equipment, Hoes, Ladders, Mops, Playgrounds, Rakes, Shovels

Composition overview

Compositional summary

Polyester resin, glass fiber

Material family	Composite (polymer matrix)			
Base material	UP (Unsaturated polyester resin)			
% filler (by weight)	65	-	75	%
Filler/reinforcement	Glass			
Filler/reinforcement form	Unidirectional lay-up			
Polymer code	UP-GF70			

Composition detail (polymers and natural materials)

Polymer	25	-	35	%
Glass (fiber)	65	-	75	%

Price

Price	* 1,49	-	1,65	EUR/kg
Price per unit volume	* 2,84e3	-	3,47e3	EUR/m^3

Physical properties

Density	1,9e3	-	2,1e3	kg/m^3

Mechanical properties

Young's modulus	35	-	45	GPa
Specific stiffness	17,4	-	22,7	MN.m/kg
Yield strength (elastic limit)	690	-	828	MPa
Tensile strength	690	-	828	MPa
Specific strength	341	-	419	kN.m/kg
Elongation	2			% strain
Elongation at yield	2			% strain
Compressive modulus	35	-	45	GPa
Compressive strength	414	-	483	MPa
Flexural modulus	41	-	45	GPa
Flexural strength (modulus of rupture)	690	-	828	MPa
Shear modulus	* 14	-	18	GPa
Bulk modulus	* 40,7	-	42,7	GPa
Poisson's ratio	* 0,33	-	0,35	
Shape factor	5,7			
Hardness - Vickers	* 9,9	-	21,5	HV
Hardness - Rockwell M	* 60	-	66	
Hardness - Rockwell R	* 95	-	105	
Elastic stored energy (springs)	5,84e3	-	8,88e3	kJ/m^3
Fatigue strength at 10^7 cycles	414	-	497	MPa

Impact & fracture properties

Fracture toughness	* 48,4	-	59,2	MPa.m^0.5
Toughness (G)	57,7	-	90,3	kJ/m^2
Impact strength, notched 23 °C	* 130	-	159	kJ/m^2

Polyvinyl Chloride

General information

Designation

Poly Vinyl Chloride (Rigid, Molding); Type I

Tradenames

Axiall; Etinox; Evicom; Exelene; Geon; Guang; Inovyn; LG; Marpol; Mexichem; Novablend; Oncolor; Prime; Resilience; Shanghai; Silver; Small; Sumikon; Sunfrost; TPC; Tuf-Stif; Vital-Line; Westlake

Typical uses

Pipe and pipe fittings, building products, bottles, film, records, floor tiling.

Included in Materials Data for Simulation	✓
Materials Data for Simulation name	Plastic, PVC (rigid)

Composition overview

Compositional summary

Compound of PVC, (CH2CHCl)n, with stabilizer (commonly tin-based)

Material family	Plastic (thermoplastic, amorphous)
Base material	PVC (Polyvinyl chloride, rigid, unplasticized)
Polymer code	PVC

Composition detail (polymers and natural materials)

Polymer	100			%

Price

Price	* 0,946	-	1,07	EUR/kg
Price per unit volume	* 1,23e3	-	1,6e3	EUR/m^3

Physical properties

Density	1,3e3	-	1,49e3	kg/m^3

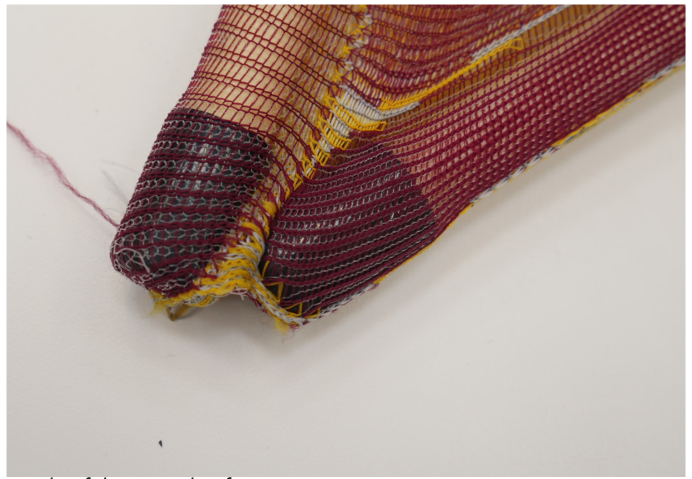
Mechanical properties

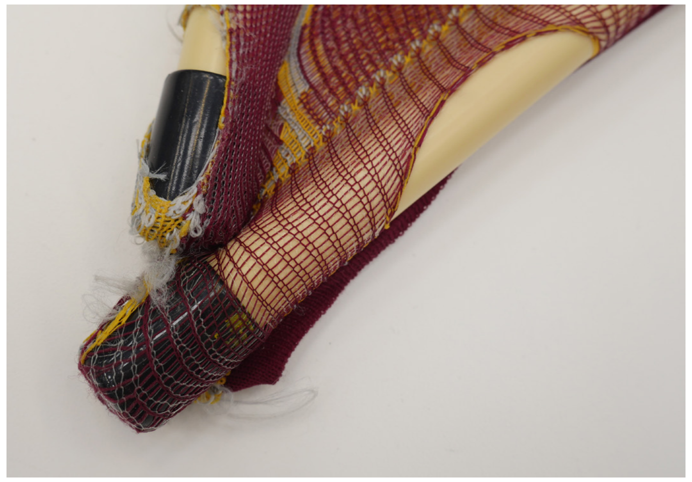
Young's modulus	2,48	-	3,3	GPa
Specific stiffness	1,76	-	2,4	MN.m/kg
Yield strength (elastic limit)	41,4	-	52,7	MPa
Tensile strength	41,4	-	52,7	MPa
Specific strength	29,3	-	38,5	kN.m/kg
Elongation	40	-	80	% strain
Compressive modulus	* 2,41	-	3,3	GPa
Compressive strength	* 37	-	44,3	MPa
Flexural modulus	2,7	-	3,4	GPa
Flexural strength (modulus of rupture)	83	-	92	MPa
Shear modulus	* 0,883	-	1,18	GPa
Bulk modulus	* 3,94	-	5,79	GPa
Poisson's ratio	* 0,395	-	0,405	
Shape factor	6			
Hardness - Vickers	* 12	-	16	HV
Hardness - Rockwell M	* 72	-	90	
Hardness - Rockwell R	105	-	130	
Hardness - Shore D	80	-	85	
Elastic stored energy (springs)	294	-	495	kJ/m^3
Fatigue strength at 10^7 cycles	* 16,6	-	21,1	MPa

Impact & fracture properties

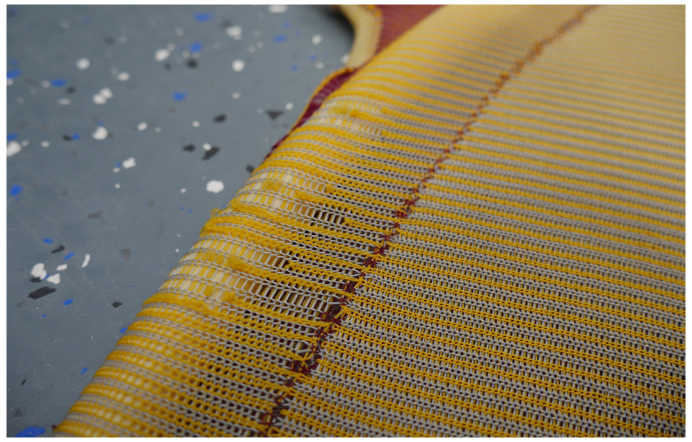
Fracture toughness	* 3,63	-	3,85	MPa.m^0.5
Toughness (G)	4,19	-	5,69	kJ/m^2
Impact strength, notched 23 °C	3,8	-	5,4	kJ/m^2
Impact strength, notched -30 °C	* 1	-	2	kJ/m^2
Impact strength, unnotched 23 °C	590	-	600	kJ/m^2

Appendix D Technical Evaluation





Ends of the tunnels after test 1



Damage to panel 2 after test 1

Manual repair to panel 2 after test 1

Elongation of GFRP tubes

Appendix E User evaluation

Notes during interviews (Dutch)

Participant 1
Man, 26 jaar, student IPD; Nederlands;

* eerste indruk, de kleuren doen denken aan Afrikaanse setting, dus safari, vorm doet denken aan een tent, dynamisch, alsof ie weg kan springen, levendig, doet denken aan een kikker, maar kikkers zijn dik, dit is dun en slank, behendig;
Ik weet dat het een stoel is, hij is te klein om onder te liggen, dus ik zou er wel op willen zitten, maar ziet er niet uit alsof ie mij zou houden. Ik zou helemaal naar achter leunen, ziet eruit alsof ie helemaal naar beneden uit; het vouwt om je heen, lekker loungen, helemaal doorbuigen; dit zakt door, dit wordt een soort rugleuning; door die strook in het midden , dat is solide, daar moet je zitten, de rest is doorzichtig dus dat is minder 'echt'
Mooie kleuren, oker geel en aardsig;
of luchtige kleuren, dn had je iets zweverigers gedacht.
het ziet eruit als een strandstoel, omdat het zo luchtig en relaxed is.

licht gewicht, oeh', de klemmen zijn dik, de witte voeten zijn goed weggewerkt;

het is ook nice om eronder te liggen; bijna vis achtige, heel smooth, de poten heel mooi
de mesh is war ruwer, als je zit te loungen er zo met je hand overheen kan gaan, ontspannende textuur; midden is gwn stof op spanning; de onderpaneel ook nice maar iets minder interessant want iets gladder.

nu te klein om in te liggen, het is best groot voor een stoel; twee keer zo lang was prima lang voor een ligbed geweest, ik wil erin kunnen liggen.
Die ronde vibe is wel leuk.

die blokken negeer ik heel hard nu, beter zwart bekleden;

in een museum zou het niet werrassend zijn, in een lounge hoek zou het heel nieuw zijn.

Ik wist dat het gebreid; het is wel gek; het is heel erg dun, mn omeder breidt truien,; ik zou zeggen dat dit gewoven is; dat is wel sick;

Participant 2
Man, student IPD, Nederlands

denk niet dat je erop kan zitten; denk eerder dat het heel groot kan zijn en dat het een tent is;
in kleedmakerszit,

dit is een andere steek,

het voelt niet als iets waar ik op kan zitten, ik denk dat het doorscheurt,
ik denk dat mn sleutels er doorheen zagen

de klemmen kijk ik omheen, omdat ik weet dat het een prototype is;

de stof is lekker zacht, het voelt als een kous, lingerie, het voelt sensueel, ook een beetje visnet, nautisch, voelt iets ruwer (eroner, emeer een steunkous, voelde hij zelf niet direct aan)

brei voorkennis: wel ooit de machine gezien, van Mark uitleg gekregen.

Heb je trektesten gedaan?
Verbaasd dat dit neit te modelleren is; anisotroop materiaal?

Participant 3
multisensory, een rasp effect, en dan weer smooth;

denk niet dt je erin kan zitten,

de hele vorm van het ding doet helemeaal niet denken aan een stoel dus denk je niet dat je erin gaat zitten; de bedoeling i s niet duidelijk, meer een kunst object, geen idee hoe ik erin zou gaan zitten, maar wel heel vet, de orientatie van de rest van je lichaam geen idee;

als je dit voelt, heel koel, aan de ene kant als ik dit zie flexe gaat dit mn gewicht niet houden, de bovenste gaat mn gewicht niet houden, maar als je dan de onderste voelt wel; wel uper cool dat die stok zo flext, geeft een extra dimensie;
grafisch ontwerp ervan heel cool, een soort space-age ruimtevaart stoel voor een ruimteadmiraal of ie aan de goede of de verkeerde kant staat of niet; het heeft ook iets heel kalms, sereen, door de stroming van de lijnen, het stroomt mooi, het nis niet hoekig, er zit uberhaubt geen rechte hoek is, mooie curves,

kijkt naar de onderkant, oh dit is ook weer heel anders;

van deze kant een stranger things monster,

de klips weer genegeerd;

verteld over opklappen; veranderd niet het beeld ervan, ik zou m niet anders gebruiken; het ziet er niet uit als een stoel die je buiten gaat gebruiken, laat staan meenemen; waarom? omdat ie heel mooi is, je gaat ook niet je perzisch tapijt meenemen op vakantie, dan neem je je picknick kleed mee;

dat stofje is heel open en fragiel, ik verwacht niet dat het de bedoeling is om meerdere keren in en uitgeklapt te worden, dan is het na een tijdje stuk

Translated notes grouped on theme

First impression
"Tent" (P1, P2, Passenger)
"Could be a scale model of something very large" (P1, P2, Passenger)
"Dynamic, like it can jump away, lively, slender, agile" (P1)
"Tensegrity?" (Passenger)
"Interesting" (Passenger)

Fuctionality: sitting
"It does not look like it would hold me" (P1, P2, P3)
"Sit on the middle, that looks solid, the rest is transparant thus less stable"(P1)
"beach chair, light and relaxed" (P1, Passenger)
"I would sit cross-legged, I don't know where to leave my legs otherwise" (P2)
"Quite large for a chair, but too small to lay down on, I want to be able to lay down" (P1)
"I don't know how I would sit in it, what direction to put my legs" (P3)
"I would lean back in it, like a lounge chair that will bend and fold around you"(P1)
"It does not feel like something I can sit on, I think it will tear" (P2)
"When I feel it, I see the object bend so I don't think I can sit on it" (P3)
"Anything sharp in my backpocket will cut the knit when I sit" (P2)
"The top panel does not feel like it can hold me, but the bottom one does" (P3)

Functionality: deployement
"I would not fold it, it does not look like I can use it outside, let alone transport it" (P3)
"It is so beautiful, just like I would not take my persian tapestry with me when I go camping, I could not take this chair with me anywhere" (P3)
"The fabric feels open and fragile, I don't expect it to be designed to fold and deploy multiple times, then it is damaged after a while" (P2)
"Feels very light weight"(P1)

Motif
"Colours look African, safari-like. Could also have more air colours, because it almost floats." (P1)
"Very cool graphics" (P3)

Shape and geometry
"The sitting height is very important, when a chair sags, elder people should still be able to get out of the chair" (DEJA VU)
"The roundness is fun" (P1)
"In a museum this would not look very out-of-place, but in a lounge corner it would be very novel" (P1)
"The overall shape does not look like a chair to me so I don't think I can sit on it. The function is not clear when looking at it, it looks more like an art piece." (P3)
"kind of space-age space travel chair, and at the same time very calm, serene, peaceful, because of the flowing lines, no straight corners at all, everything is curved" (P3)
"The bending of the tubes is very cool, it does give an extra dimension to it" (P3)
"I attempt to look through the clamps, they are very large and bulky, and I know it is only a prototype" (P1, P2, P3)

3D knitting
"I know it is knitted. It is strange, it is very thin and I know knitting from my mom who makes sweaters, so I would assume this is woven" (P1)

Thoughts while touching the chair
"Fish skin texture" (P1)
"Smooth" (P1, P3)
"The mesh feels coarse, I feel like touching it while lounging in the chair" (P1)
"Coarse" (P3)
"Relaxing texture" (P1)
"The center just feels like tensioned fabric" (P1)
"The bottom panel feels nice but less interesting, just smooth" (P1)
"It feels soft like stockings, like lingerie, quite sensual" (P2)
"Fishnet" (P2)
"Nautical" (P2)
"Rough" (P3)

No participants touched the bottom panel without it being suggested to them.

Appendix F Material Experience Vision

The Material Experience Vision (MEV) expresses what role the material might play in relation to a product, its user and the context. (Karana, 2015) This enables to reflect upon the unique qualities of the material and then translate them into product offerings. Experiential characterization of the material are expressed on multiple levels: sensorial, interpretive (meanings), affective (emotions), and performative (actions, performances).

Defining this Material Experience Vision is of importance in this project not because knitting is new, but because the application is new. The general associations with knitting might not be in line with the novel application of the production technique, which might make implementation difficult. The functional aptness is often taken for granted, but the material should also be socially and culturally accepted and make sense. To qualify a material not for what it is, but also for what it does. By defining the Material Experience Vision, the gap between the 'old' and 'new' application could be bridged.

A short historical analysis of hand knitting is presented which inspired for the MEV defined afterwards.

Resilience
The ability to adapt and adjust according to different situations is crucial in today's world. People nowadays seem to be less resilient compared to those from 50 years ago because their support networks have become smaller, despite the influence of social media. However, knitting, which has evolved over time and can be produced industrially, demonstrates adaptability. The interconnectedness of knitted loops makes the fabric vulnerable, similar to how our society depends on other countries for certain products. If one loop breaks, it affects the surrounding stitches. Yet, knitting remains resilient because it is stretchable, flexible, and can be easily picked up and continued with just a loop and yarn. It can be attached to various objects as long as there are loops or holes to work with.

Construction as aesthetics.
Through this object I want to demonstrate that wanting to make products sustainable requires more than just using organic cotton instead of regular cotton. It requires to rethink the purpose of a product, designing with low-waste production in mind, whether the design can be altered easily to accomodate for possible changes in the environment, in terms of functional properties, aesthetics. The aesthetics of the sitting object should follow from this line of thinking. The technical requirements determine the material, texture, shape and form of this sitting object. If there are options within these parameters that are technically equally appropriate, than the aesthetics can be an argument for one option of the other.

Knitting creates a bond
A knitting club connects people with similar interests, and forms a community to share not only practical knitting knowledge, but to share about other issues in the personal life's of the knitters to. It enables the people to benchmark their feeling, so get something off their chest. The clubs are about sharing knowledge and experiences, not about the result of the knitting itself. It is a celebration of learning, crafts, and connecting people and experiences.
Knitting is a reflection of a family, everyone is made of the same material, and is connected, and is a support network for each other, but when one falls, many go down with them. It is the opposite of the individualistic society, it shows the vulnerability and the interconnectedness and dependence of things. When a yarn breakes somewhere in the knitted fabric, the consequences are felt over the whole fabric, just like the butterfly effect.

Adaptability: a curse and a blessing
We are with more and more people, who feel a need to distinguish themselves from others, mostly through fashion items or experiences to be shared on social media. The 'uniqueness' is so much 'in fashion', that is becomes mainstream again to wear 'random' looking items. The uniqueness is a uniform. Since fashion is a uniform, why not wear the same garment that is actually of value to that person, instead of low-priced items that do not have anything to do with your personality.
A personality is not static, so the changing expression of a garment could be desired.

Personalization is good when it is used for a lifetime, not when it is used to just be slighly unique within a trend. The adaptability seems to invite for more production because every time you want something slightly different, it is easily made. This does not contribute to a sustainble use of products. The knit should be designed at the start in a personal way, adapted to personal needs, so it will stay relevant for longer. Not to 'reprint' upholstry when a new colours arrangement is desired.
The adaptability is very purposeful to increase comfort for specific needs. Scaling up or down in size, adding a little room in a certain spot, changing the surface for ergonomic preferences.

Historical analysis of hand knitting

Throughout history, hand knitting has been used as practice by women as a necessity to provide and make money, but also as demonstrative method to express and discuss political opinions, and dissatisfaction with current practices.

late 18th century

Abolitionism movement during which women came together in sewing circles (also knitting) to exchange ideas about politics. (Stitch by Stitch, a Brief History of Knitting and Activism, 2017)

mid-19th century

'Fancy' knitting by ladies of decorative objects to show their skills (The History of Hand-knitting · V&A, n.d.) It was an hobby for some women, and a necessariy means to earn money to survive for others.

1914-1917

Women, men and children knitting in 'knitting circles' to keep the soldiers warm in the 1st World War

1920s

Knitted fashion items became popular because of Coco Chanel and Jean Patou

1930s

Knitting becomes a necessity again during the Interbellum: handknitting is cheaper than buying a (hand or machine) knitted garment. Socks are designed for repair of the knit with replacable toes. The knitting machine became popular but is still expensive.

1940s

Women were encouraged to knit to contribute to the war, to 'kit out' their men, sometimes tucking notes into the garments to message the soldiers.

1950s and 1960s

Machine knitting becomes more popular and makes knitwear more varied and affordable. Knitting is still seen as a useful skill, not just as a hobby.

1980s

Great decline of popularity of hand knitting, since machine knitted apparel became less expensive than buying the material to knit yourself.

1990s

The internet allows knitters to share patterns, knowledge and experiences, and have direct access to material instead of through the local shops.

2000s onwards

Increase in popularity of hand knitting as part of general increasing interest in DIY and crafts, as a countermovement to the increase of massproduction.

2007

Cassidy and Jessica Forbes founded Ravelry, a website that connects knitters and crocheters all over the world, with almost 3 millions active users this year.

"Grandmother"

Aesthetics
The knit is thick, 'itchy', made of wool with intricate Fair Isle patterns. The fabric feels very strong, robust, and dense.

Meaning
The garment is not in style, looks old-fashioned, and is forced upon you because your beloved grandmother has put time, effort and love into it. Precise, meticulous, nostalgic.

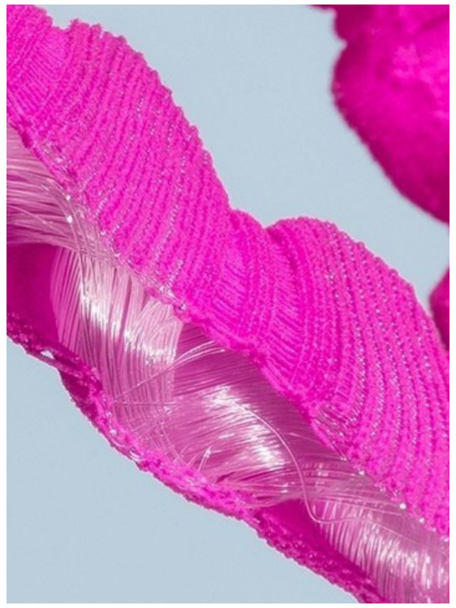
Emotions
The grandmother is happy to have made a nice sweater for her children and grandchildren, it is a nice way to spend the day, knitting and watching television, and they children are happy with the warm, durable sweaters of high quality wool. At the same time she feels obliged to do so, it reminds her of her youth when she had to sew her own clothes because buying them was much more expensive.

"Insta-knitter"

Aesthetics
Fluffy yarns, multiple colours, large stitches, droopy shapes.

Meaning
Hand-made as meditative practice, and creative expression through a 'unique' product. Craftsy, natural look, intuitive.

Emotions
The maker feels calm and peaceful while knitting, clearing their mind. They feel content with themselves to have made a nice looking garment, so it feels like a win-win. Possibly even thinking of their sustainable contribution by not buying a mass-produced garment.



"Knit engineer"

Aesthetics
Flashy colours, intricate structures of multiple layers, direct shaping of the knit, using an industrial knitting machine.

Meaning
The 3D printing of fabrics, developing novel applications of knits and materials. Total control, luxary, futuristic, very novel and much variety.

Emotions
From interviews it was learned that many peopole don't know whether a fabric is knitted or woven, they express a great surprise and excitement when they learn that shirts are always knitted and that even shoes are knitted.
The maker feels avant-garde, pioneering in the knit industry finding novel applications.

Attempts to explain this research project to fellow students and friends, lead to the realisation that many are not very familiar with what knitting is and how it can be used. Different associations distilled from the conversation are presented on the right as three persona's defined by the aesthetics, meaning and emotions.

The wide range of expressions of knitting is reflected in the many possible MEV's stated below.

"I want the user to feel **hopeful** that by reinterpreting and rethinking old production techniques and their applications, we can come up with applications to improve sustainability of current products. The beauty is in the simplicity of the solution and the fact that it is not 'high tech' thus still **relatable**."

"I want the user to feel **content** with their modest but vital contribution to a more sustainable society, doing what is within their power, just like the grandmother in the family providing her grandchildren with warm clothes for the winter, **caring** and **thoughtful**."

"I want the user to be **intrigued** by the overall look of the product, to feel **curious** to know how it is made. This can be conveyed by making the construction part of the aesthetics. Form follows function, aesthetics follows construction."

Most importantly, I want the user to feel safe when sitting down in the chair, and to be surprised by the fact that the chair is knitted.

The Material Experience Vision will be used to evaluate the final prototype of the sitting object. During development, design decision will be based on the demands of the list of requirements. The expression of the MEV is considered of lower priority in this research. The aesthetics will result from this 'structural' perspective.

Appendix G Other applications

The designed demonstrator could inspire to develop different objects using the design space for 3D knitted, load-bearing, transformable structures. From small product scale to large architectural scale, the developed textile hybrid development and production process can make objects personalized, adaptable in form and design, and transformable. (Figure 11)
For example knitting a backpack with padding adjusted in size and thickness to the user's needs and wishes.
The ARCHETYPE.98 could be enlarged with a foot rest and sunshade, including a padded segment for the head to rest.
Even tents could be knitted, streamlining the production process by directly integrating tunnels for the tentpoles.
Larger architectural structures, protecting people from weather conditions, could be knitted with different material properties for each segment to adjust for the structural performance required, combining rigid and flexible material properties.

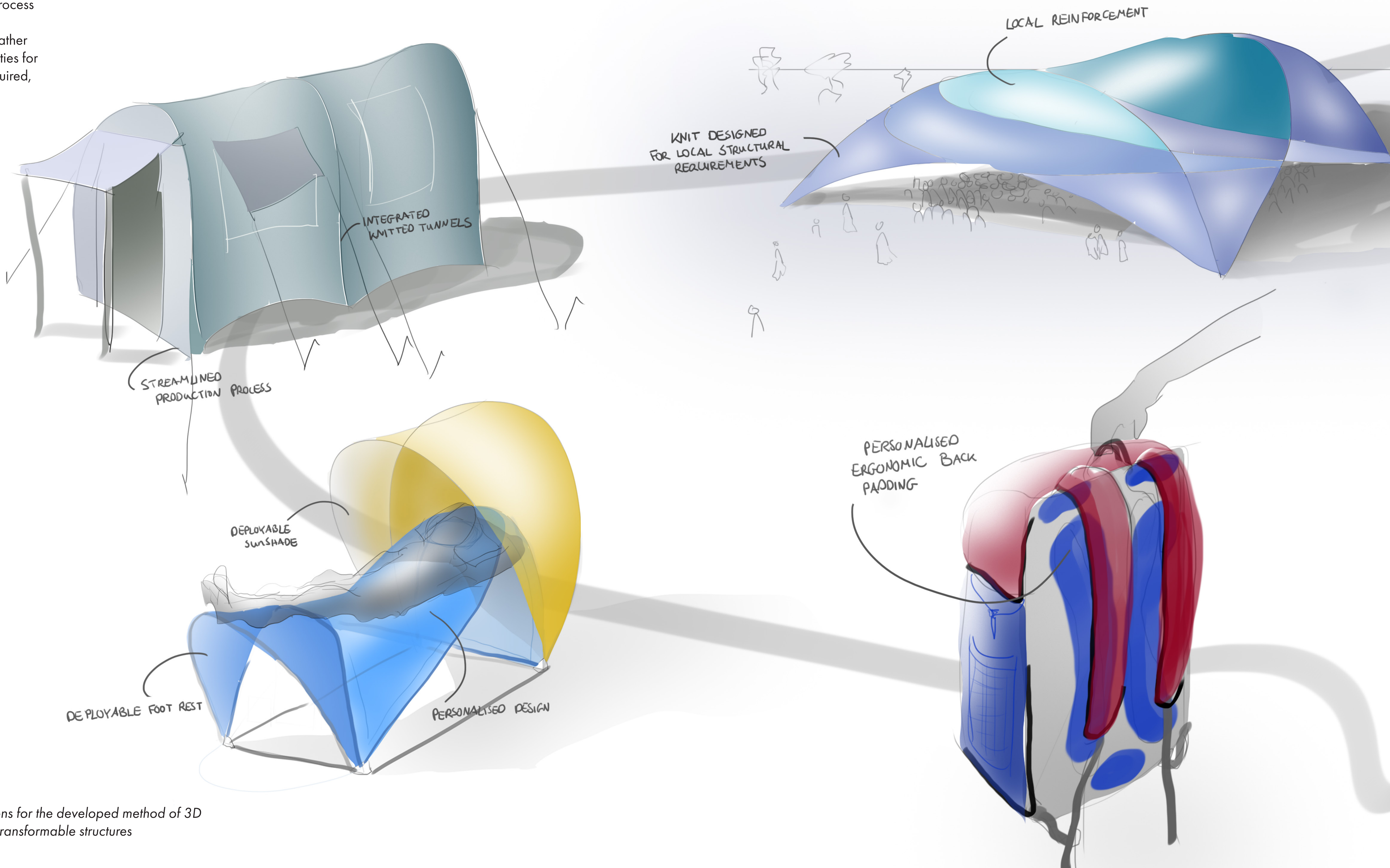


Figure 11 Other applications for the developed method of 3D knitting for load-bearing, transformable structures