

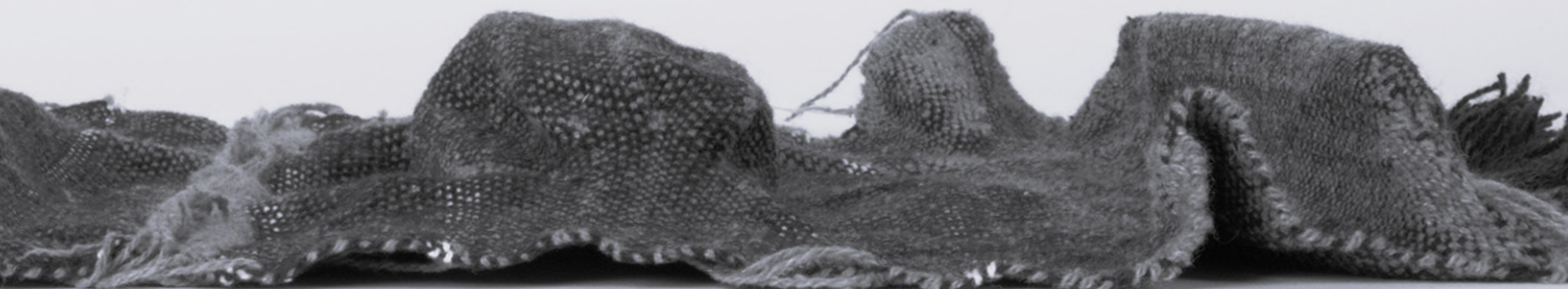
Master Thesis Integrated Product Design

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Unlocking new possibilities in weaving

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Defining methods for weaving 3D fabrics and exploring implementation on standard looms through use of an add-on

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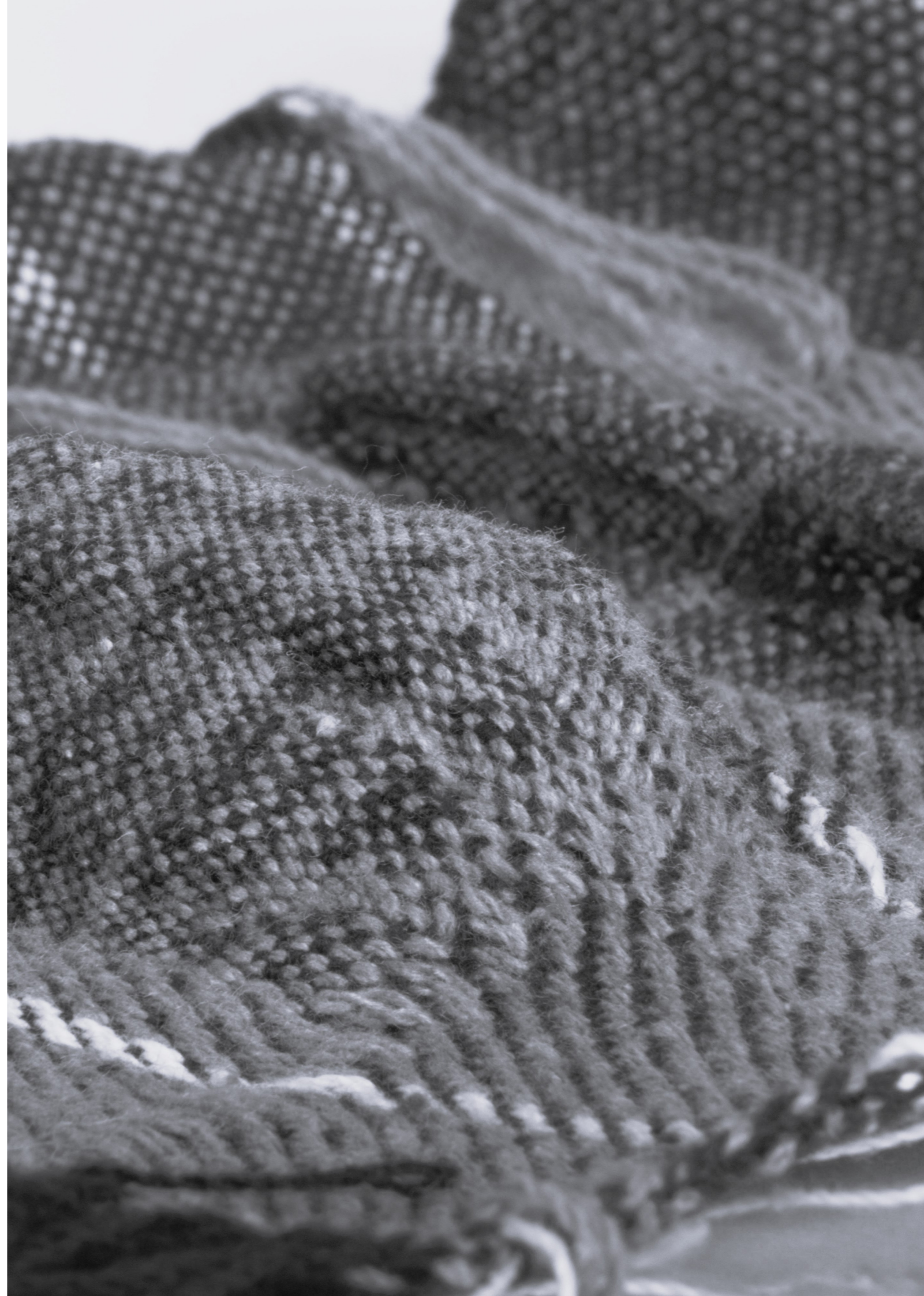
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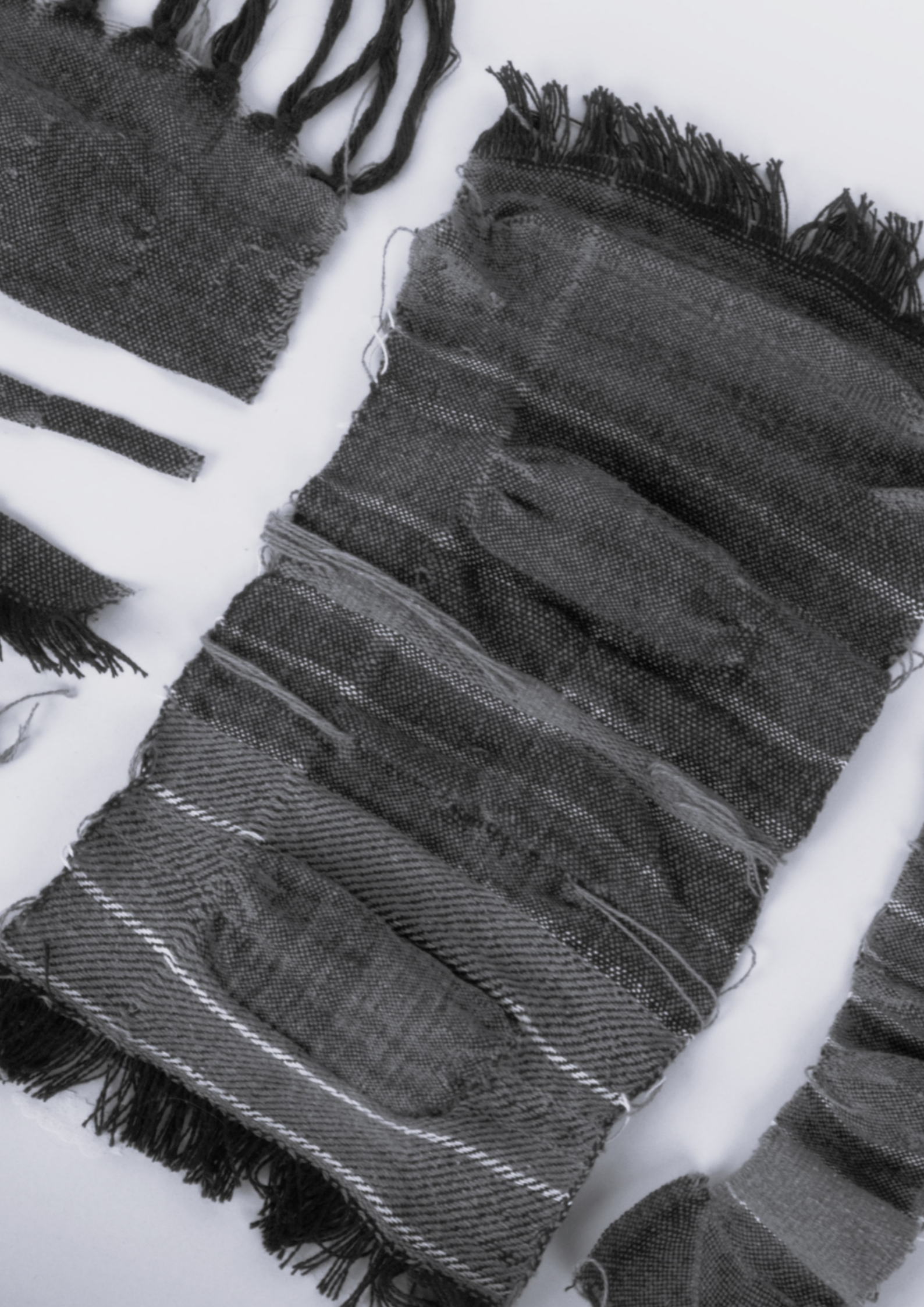


Abstract

Current practices in the textile industry significantly contribute to environmental and social issues. Textile-forms have potential to support the transition towards a more sustainable system, but woven textile-forms are currently rare due to most looms being designed to solely create flat sheets of fabric. The possibilities for woven textile-forms, if the fabric could be shaped directly on the loom, have therefore been left unexplored. This project proposes a way to change the weaving process and the loom to enable the creation of 3D and non-rectangular 2D fabrics. An add-on is introduced that can provide standard looms with the required functionalities, which was validated with a functional prototype for a Magic Dobby shaft loom. The assortment of 3D and non-rectangular 2D fabric samples created with use of the add-on prototype show the potential of the proposed method and tool for creating textile products while requiring less post-processing and eliminating waste.

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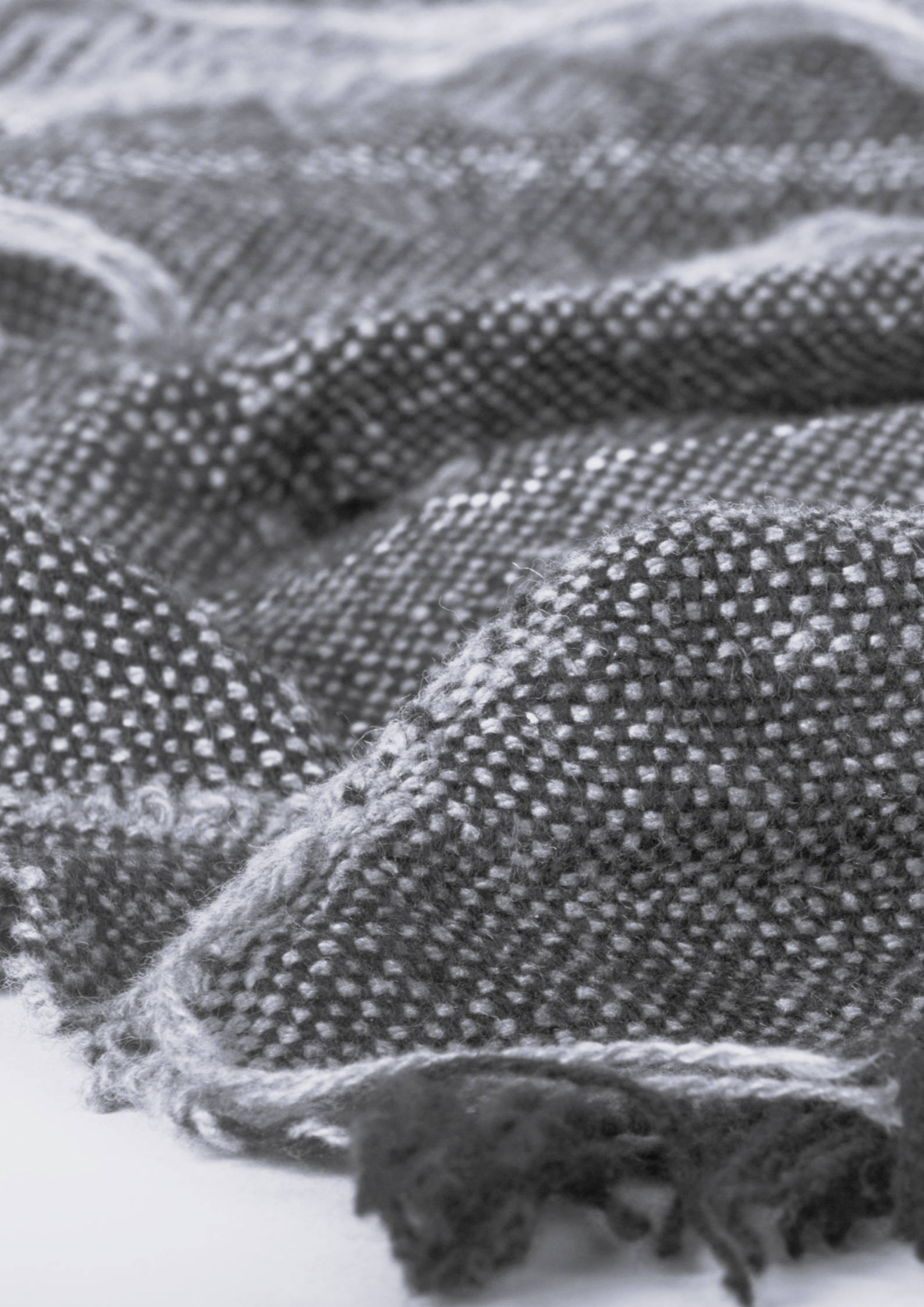
Introduction

A world without textiles would be bare, cold and uncomfortable. On the other hand, our current wasteful and polluting textile production and consumption behavior have resulted in the world facing a plethora of other problems. The textile industry is a massive contributor to global emissions, pollution, resource depletion and social issues (Ellen MacArthur Foundation, 2017). If we want to keep enjoying the benefits of textiles without putting an ever increasing strain on people and the planet, the textile industry must change.

To reduce our overall resource consumption in textiles we should work towards a local, on-demand and zero-waste textile system. Textile-forms, where fabric and form is created simultaneously, could play a major role in this transition (McQuillan, 2020). Woven textile-forms however, are currently rare in industry due to looms mainly being designed to create flat sheets of fabric as fast as possible. The potential of woven 3D fabrics for textile-forms has been left untapped due to standard looms not having the required capabilities and looms specialized for the weaving of 3D fabrics being limited, complex and inaccessible. Motivated by a desire to make the weaving of 3D fabrics available to textile researchers, this project aimed to find and describe methods for weaving 3D fabrics on a shaft loom and validate the methods by designing and testing an add-on for a Magic Dobby loom.

To gain an understanding of weaving and the creation of form, existing methods and tools for creating 2D, 2.5D and 3D fabrics were researched. Based on this research and experimentation with weaving, a weaving taxonomy was created to provide an overview of all the possible ways in which the warp and weft threads can be manipulated within the weaving process. The taxonomy was used to identify which variables need to be changed within the weaving process to accomplish the required placement of warp and weft threads to create a 3D form. It was determined that an inability of warp threads to bulge up on most looms was the biggest barrier to creating 3D fabrics.

A new method was introduced for manipulating warp threads, and as a result the interlaced weft threads, to rise up. An add-on was designed to provide the loom with the required functionalities to enable this method and a functional prototype of the add-on was built for a Louët Magic Dobby shaft loom. Weaving experiments were conducted on the Magic Dobby loom with use of the add-on. A variety of 3D and non-rectangular 2D fabrics were created, showing the potential of the proposed methods and add-on and encouraging further research.



1. Context

Textiles are of undeniable importance to our lives. They provide comfort, protection and a way to express our identity. Given the ubiquitous presence of textiles, it is not surprising that it is one of the largest industries in the world. However, the size and complexity of the current textile industry have resulted in numerous problems. For the benefit of people and the planet an alternative system needs to be developed.

In this chapter the current textile system and its impact are explained and a vision for a more sustainable and ethical system is described.

1.1 The current textile industry

In the last couple of decades the textile industry has massively grown and become increasingly more globalized due to expanding markets and the rise of fast fashion (Ellen MacArthur Foundation, 2017). In the first two decades of the 21st century, the production of textile products doubled and is expected to rise to 145 million tons a year by 2030 (Deckers et al., 2023).

Fast fashion companies entice customers to continuously expand and refresh their wardrobe by releasing new articles of clothing at a high frequency (McKinsey & Company, n.d.). The desire for perpetual economic growth has led the current industry to focus on producing as many products as quickly and cheaply as possible.

1.1.1 Production methods

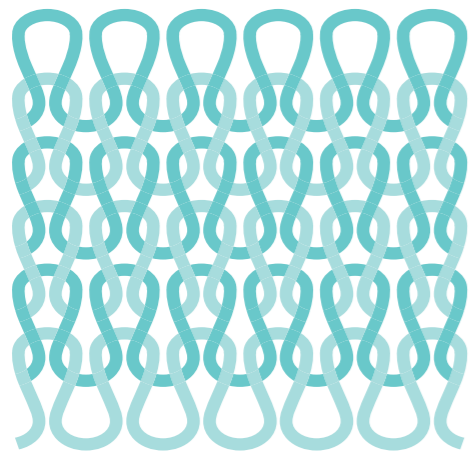


Figure 1: Knitted fabric structure

Textiles are made up of yarns, spun from fibers, which can be categorized into plant, animal, man-made and synthetic fibers (Chemsec, n.d.). The most common methods for turning yarn into fabric is through knitting or weaving. Knitted fabrics are made up of interlocked loops (Figure 1), which give knitted fabrics its inherent elasticity. Knit fabrics are typically very comfortable and therefore used for articles such as socks, shirts and sportswear.

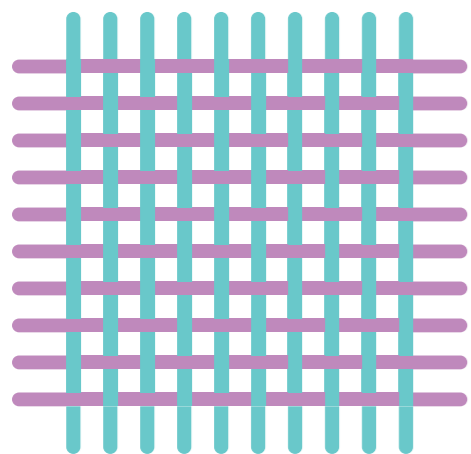


Figure 2 : Woven fabric structure

Woven fabrics are made up of vertical threads interlaced with horizontal threads (Figure 2) and are generally more durable than knitted fabrics. Woven fabrics are often used for pants, dresses and jackets (TAAS INC., 2022). Woven fabrics are also often used for home goods, such as towels and bedding, and for upholstering furniture (Gibbons, 2018).

Most textile products are made out of woven or knit fabric using the cut and assemble method: 2D pieces are cut out of rectangular sheets of fabric and connected, usually through sewing, to create the envisioned 3D shape. While envisioning the 3D form, most designers pay limited attention to how the required 2D pattern pieces will fit together on a rectangular length of fabric. The resulting gaps between the irregular pattern pieces cause 10-20% of the fabric to go to waste (Rissanen, 2013). Despite its wasteful character, cut and assembly is the most common form of production and has been standardized and streamlined to keep up with the high demand for low-cost products. An overview of the cut and assemble process can be seen in Figure 3.



Figure 3: Schematic of the cut and assemble process

1.1.2 Impact of the textile industry

The growth of the textile industry has also increased its strain on the planet. Responsible for an estimated 10% of global carbon emissions, the textile industry is a substantial contributor to human caused climate change. In addition, textile production contributes to serious water pollution and requires a massive amount of raw materials, depleting our resources and harming ecosystems (European Parliament, 2020). Besides its effect on the natural world, the globalized textile industry also has an impact on a social level. In order to produce their products at a low cost, many companies manufacture their goods in countries with low wages and fewer regulations. Issues such as slavery, child labour and unsafe working conditions are sadly common (Ditty, 2020).

Furthermore, the textile industry is responsible for an estimated 92 million tons of solid waste each year (Greenpeace as cited in Hendriksz, 2017). The creation of waste starts in the factory, where on average 25%-35% of the raw materials is lost (Kerr & Landry, 2017 and Runnel et. al, 2017 as cited in McQuillan, 2019). Of the textile products produced, many become waste before they are ever used. This is due to the fashion industry being highly seasonal, trend sensitive and consumer driven, making it difficult to predict demand. Given that fast fashion products are usually cheap to produce, many companies prefer to have an abundance, than to run out of stock (Clero, 2023). Even when products do end up in the closet of a user, some are estimated to be used as little as seven times before being discarded (Remy et al., n.d.). Enticed by the large, low cost and continuously changing offer, many consumers have developed a gluttonous and wasteful attitude towards clothing; they buy more than they need and make limited use of the products (McKinsey & Company, n.d.). Between 2000 and 2015 utilization dropped 36% (Ellen MacArthur Foundation, 2017).

All of this results in about two thirds of the materials used for textile production becoming waste within a year (Kerr & Landry, 2017 as cited in McQuillan, 2019). Only around 1% of that material is currently recycled into new clothing, 12% is downcycled and the rest is incinerated or landfilled (Ellen MacArthur Foundation, 2017).



1.2 Towards a circular textile economy

The current linear economy is often called the take-make-dispose economy. The value of materials and products decreases during their lifespan and is eventually lost. In a circular economy, products and materials are kept in the loop, through methods such as reuse and recycling (Ellen MacArthur Foundation, n.d.).

The circular economy is often hailed as our savior, but it harbors a great pitfall. Within a growth focused economy, any efficiency or material gains will likely be used to produce more in order to continue to feed the expanding market. This so-called rebound effect will lead to the demand for raw materials and energy to continue to increase (Binswanger, 2001). To truly reduce the strain on our planet, Brooks et al. (2017) call on us to question the current profit focused model and strive for an overall reduction in resource consumption.

The difficulty lies in the fact that the current textile system is well established. Its globalized character has created supply chains that are scattered, complex and opaque (Clero, 2023). Actors within this supply chain often have limited control over only a small section of that chain, constraining how much positive change can be made. To truly transform the textile industry to benefit people and the planet, it will not be enough to drop solutions into the existing system. A systemic approach is required in which every aspect of the supply chain is addressed (McQuillan, 2020). This requires the way we produce and consume to be reevaluated.

1.2.1 Systemic change

As a response to the current globalized, wasteful and exploitative textile industry, alternative methods are sought that contribute to the development of a new system that facilitates local, on-demand and zero-waste production (McQuillan, 2020).

Local

Localizing production has a variety of benefits, as explained by Manzini (2013). Localization calls for the distance between where products are designed, produced and used to be as short as possible. The benefits of local production include the ability to use local resources, reduce transportation and improve the self sufficiency of an area. In addition, localization can contribute to efficient production by facilitating better information transfer and collaboration. The production of textile goods can be tuned to what the local community needs and desires.

Localizing production can also drive innovation. Especially micro-factories and fab-labs harbor a lot of potential for innovation by creating a space where creatives can come together to combine traditional craftsmanship with new technologies (Manzini, 2013). Within these micro-factories, designers often become or are in close collaboration with the

manufacturers. This is in stark contrast with the current textile industry, in which designers send their designs off to a far away country with a shallow understanding of how resources will be used (and wasted) to create the form they designed (McQuillan, 2019b). In the micro-factories and fab-labs, groups of innovators can carry out alternative ways of producing, without having to wait for the system and larger infrastructure to change. Jégou & Manzini (2008) describe how these communities are often unique in their ability to align individual interests with social and environmental interests. This makes sense if one considers that it is much harder to ignore the impact of production if it takes place in your own community, potentially motivating designers, manufacturers and consumers to reconsider their behavior.

On-demand

Overproduction is a major problem in the fashion industry, which could be mitigated by enabling on-demand production (Clero, 2023), which refers to only producing goods when they are requested or required (Davies, 2021). Adjusting the supply to align with what will actually be bought and used reduces the amount of resources required and the number of unsold articles that would go to waste. The products that are made on-demand are generally of better quality with higher durability (Christen, 2018). In addition, many on-demand production methods allow customization and personalization, which generally increases utilization due to a stronger emotional connection between the customer and the product (Ellen MacArthur Foundation, 2017). Enabling customers to request a product instead of offering a pre-made selection to choose from, encourages more conscious consumption. The possession of valuable, personalized pieces may also reduce a customer's consumption of fast fashion items (Christen, 2018).

Zero-waste

The large amounts of textile waste generated during the production phase needs to be reduced and ultimately eliminated. Rissanen (2013) describes a zero-waste garment as one that contains all the fabric that was used to create it, with pre-consumer waste having been removed during the design process.

Zero waste can be strived for within standard cut and assembly production methods. This requires designers to design the pattern that will guide the cutting of the fabric in tandem with the 3D form. In a zero-waste pattern the pieces from which the product will be constructed should be placed so they interlock and the material can be used most efficiently. Alternatively, a garment can be constructed by folding and wrapping a rectangular piece of fabric in a specific way. (Rissanen, 2013)

Zero waste can also be achieved by using alternative production methods. McQuillan (2020) introduces the term textile forms, which encompasses textile products made using methods in which form and fabric are created simultaneously. These methods allow material to be placed only where required, eliminating waste from off-cuts. The development of textile forms could support the movement towards a local and on-demand textile system by offering a more efficient way of creating textile products in which both the designer and the user are more closely involved. Textile forms will be discussed more in depth in the following section.

1.2.2 Textile form

Compared to cut and assembly production methods, in which a form is cut out of a previously made rectangular sheet of fabric, textile forms emerge directly as a result of how the molecules, fibers and yarns are placed and treated (McQuillan & Karana, 2023). A schematic of the process can be seen in Figure 4.



Figure 4: Schematic showing how textile forms are created in an additive process

Knitted textile forms are widespread and can be made by hand as well as using industrial machinery. Knitting lends itself well to the production of textile forms because knitted fabrics are built up row by row. A common method for creating knitted textile forms is fully fashioned knitting, in which the pattern pieces are directly knitted in the desired shape and can subsequently be sewn together (Glenmuir, 2023). In whole garment knitting this is taken one step further. Two layers are knitted simultaneously to create a full garment. The company Shima Seiki, for example, has developed a knitting machine with which they can knit seamless and customized clothing on-demand and close to the consumer (Shima Seiki, n.d.), which can be seen in Figure 5.

The creation of 3D forms is often accomplished in knitting by increasing and/or decreasing the number of stitches throughout the knitting process, and by adding extra material in areas through short row knitting. Mariana Popescu uses these methods to create large scale, complex and seamless 3D knitted textiles (Popescu et al., 2018). How a geometry is translated into a knit pattern and the resulting knitted piece can be seen in Figure 6.

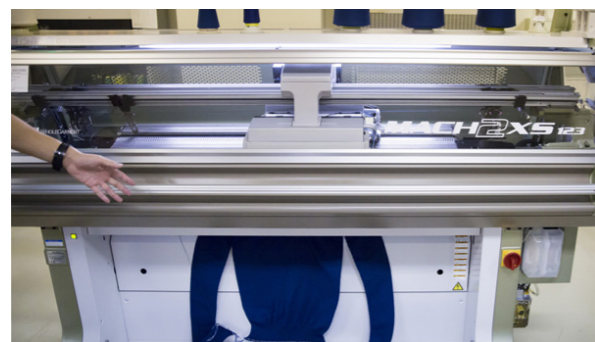


Figure 5: Whole garment knitting on a knitting machine developed by Shima Seiki (BloombergNEF, 2017)

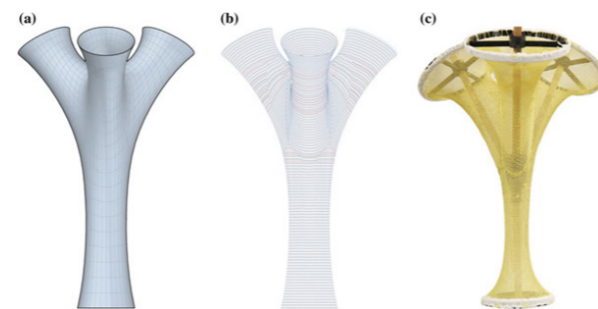


Figure 6: A geometry translated to a knitting pattern and the resulting knitted fabric (Popescu et al., 2018)

Woven textile forms on the other hand are rare compared to ones created using knitting. This is due to the vertical threads being put in place prior to the interlacement of the horizontal threads, leaving little flexibility within the weaving process for shaping. Handlooms as well as industrial looms are designed to weave flat, rectangular fabrics. Although innovation does take place in the textile industry, it is mainly focused on developing looms that can weave fabrics with greater efficiency, at a higher speed, and with a larger diversity of materials and weave structures (Seyam, 2023). Looms are typically not developed for the creation of woven textile forms.



Figure 7: T-shirt embedded within a woven fabric (Leffers, n.d.)

A number of researchers have explored how these standard looms can be utilized to create textile forms with the help of multi-layer structures (Piper, 2019; McQuillan, 2020; Vroom, 2022; Leffers, n.d.). The vertical warp threads on a loom can be separated to allow the weaving of (un)connected layers. These layers can be woven in such a way that when separated and/or unfolded, once the fabric is taken off the loom, a 3D textile form emerges (McQuillan, 2020). This method however, is limited by the loom's ability to only weave 2D layers. (Figure 7 and 8)

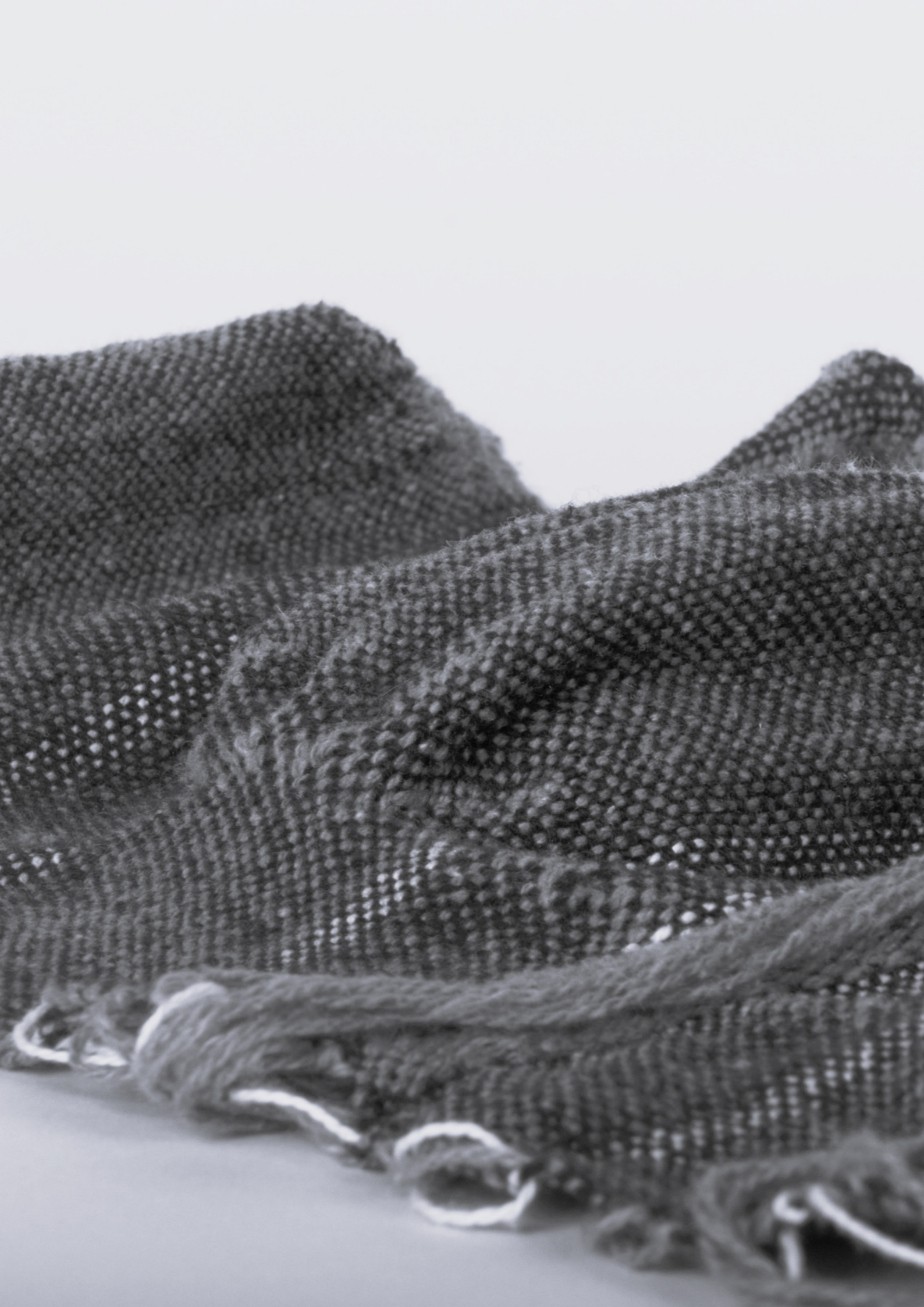


Figure 8: Pants made using multi-layer weaving (McQuillan, 2020)

Sven Steinmetz provides a glimpse into the possibilities for seamless garment construction if 3D forms could be integrated into the fabric. In Figure 9 a top can be seen that was shaped to the wearer's body (Steinmetz, 2024). Unfortunately no information is available on how this was accomplished and based on other work by Steinbach, a high amount of manual steps were likely required during or after the weaving process. The example prompts one to wonder how 3D woven fabrics could be created and what the potential for the textile industry would be if the weaving of 3D fabrics was possible on an industrial scale.



Figure 9: A top shaped to the wearers body during weaving (Steinmetz, 2024)



2. Project description

In this chapter the reason behind this project, the aim of this project, and the way the project was carried out are described.

2.1 Project motivation

As explained above, textile forms could contribute to the development of a more sustainable and ethical textile industry. Woven textile forms however, are greatly lacking in comparison to knitted textile forms, despite woven textile products being widespread and indispensable.

For the development of woven textile forms it would be valuable to be able to shape the fabric into the desired 3D form during weaving. Within the textile industry this is not done due to the limitations of industrial looms. Within the research world, 3D fabrics and their potential for the textile industry have also remained largely unexplored due to a lack of information and tools being available to textile researchers. This project was therefore prompted by a desire to make the weaving of 3D fabrics accessible for textile researchers in order to enable experimentation and further the development of woven textile forms.

2.2 Project aim

The primary objective of this project is to determine how 3D fabrics can be woven on a shaft loom. To fulfill this objective, the project consists of two parts:

Firstly, this research aims to understand how warp and weft threads can be manipulated within the weaving process and what the results of different manipulations are. With this understanding, the goal is to determine how the weaving process needs to be tweaked to create 3D fabrics.

Secondly, this research aims to lay the foundation for making the weaving of 3D fabrics accessible for textile researchers. The focus is placed on exploring how the loom can be given the required functionalities through the implementation of an add-on. The goal is to develop the add-on up to TRL 4, meaning the core functions and mechanisms have been validated in a laboratory environment (Aschenbremmer & Smulders, n.d.). A crude, but functional, prototype is made to provide a proof of concept of the method for weaving 3D fabrics. Testing, including weaving samples on the loom with a prototype of the add-on is carried out by the researcher. This research aims to show that 3D weaving can be made possible on a shaft loom with an add-on. Due to time constraints within this project, the development of the add-on into a user-friendly product for textile researchers is left for further research.

1. Find and describe methods for weaving 3D fabrics

2. Validate a method for weaving 3D fabrics by designing and testing an add-on for a Magic Dobby shaft loom

2.3 Methodology

In order to generate knowledge and come to innovative solutions, the Research through Design (RtD) methodology was used (Stappers & Giaccardi, 2014). In this method the creation of prototypes serves as a research tool. Both the process of creating the prototype and the prototypes themselves can provide new insights. Using the RtD method enables the researcher to benefit from the explorative and iterative nature of design. Given that this project is focused on finding new ways to create fabric, it does not make sense to only explore weaving methods in theory. Quickly putting ideas into practice through prototyping and experimentation can lead to a deeper understanding of the topic and unexpected discoveries. In addition, visualizing ideas and creating physical prototypes can aid discussions and bridge the gap between research and real world application.

2.4 Project structure and approach

An overview of the project and the way each part was approached can be seen in Figure 10.

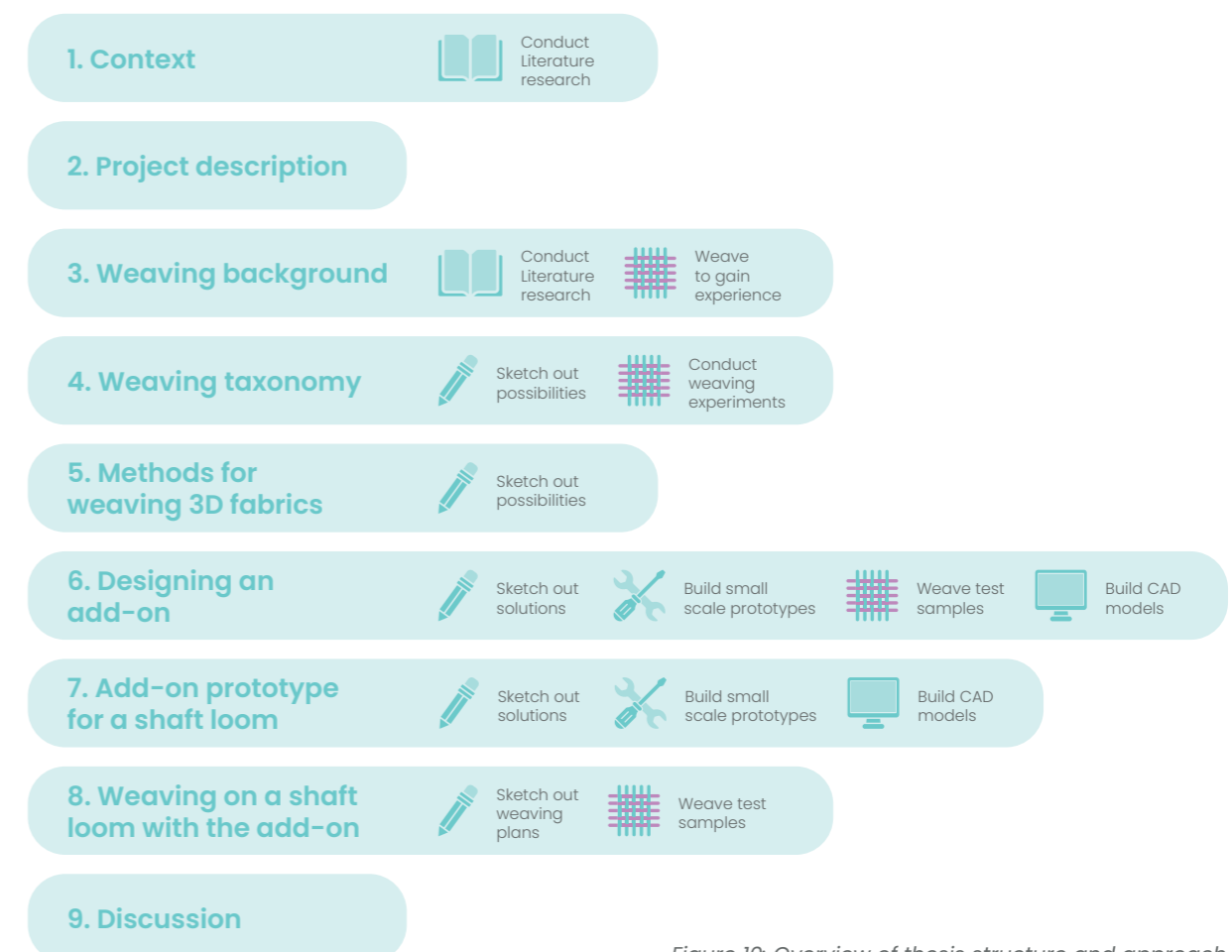


Figure 10: Overview of thesis structure and approach



3. Weaving background

Weaving is one of the oldest known crafts and has played a crucial role in human history. Traces of woven textiles have been found at Paleolithic sites, providing evidence that weaving dates back to at least 25,000 BCE (Adovasio et al., 2001). Tens of thousands of years later, weaving is still one of the main methods for creating textiles today. Within that time, the tools used for weaving have naturally changed with the development of new technology, but the basic principle has stayed mainly the same.

This chapter provides a background in weaving. Existing methods and tools are explained and examples are given of 2D, 2.5D and 3D fabrics. The chapter is concluded with a reflection on the gaps in current knowledge that the research aims to address.

3.1 Fundamentals of weaving

A woven textile is constructed by interlacing vertical threads (the warp) with horizontal threads (the weft). To enable this, the warp is shed: the warp threads are separated to create an opening through which a weft thread is passed. Inserting the weft is also known as picking. The inserted weft thread, or pick, is then beaten up: it is pushed forward, sliding over the warp threads until it lies against the previous weft thread at the edge of the woven fabric, which is called the fell. (Taylor, 2017)

The fundamental weaving steps can be seen in Figure 11.

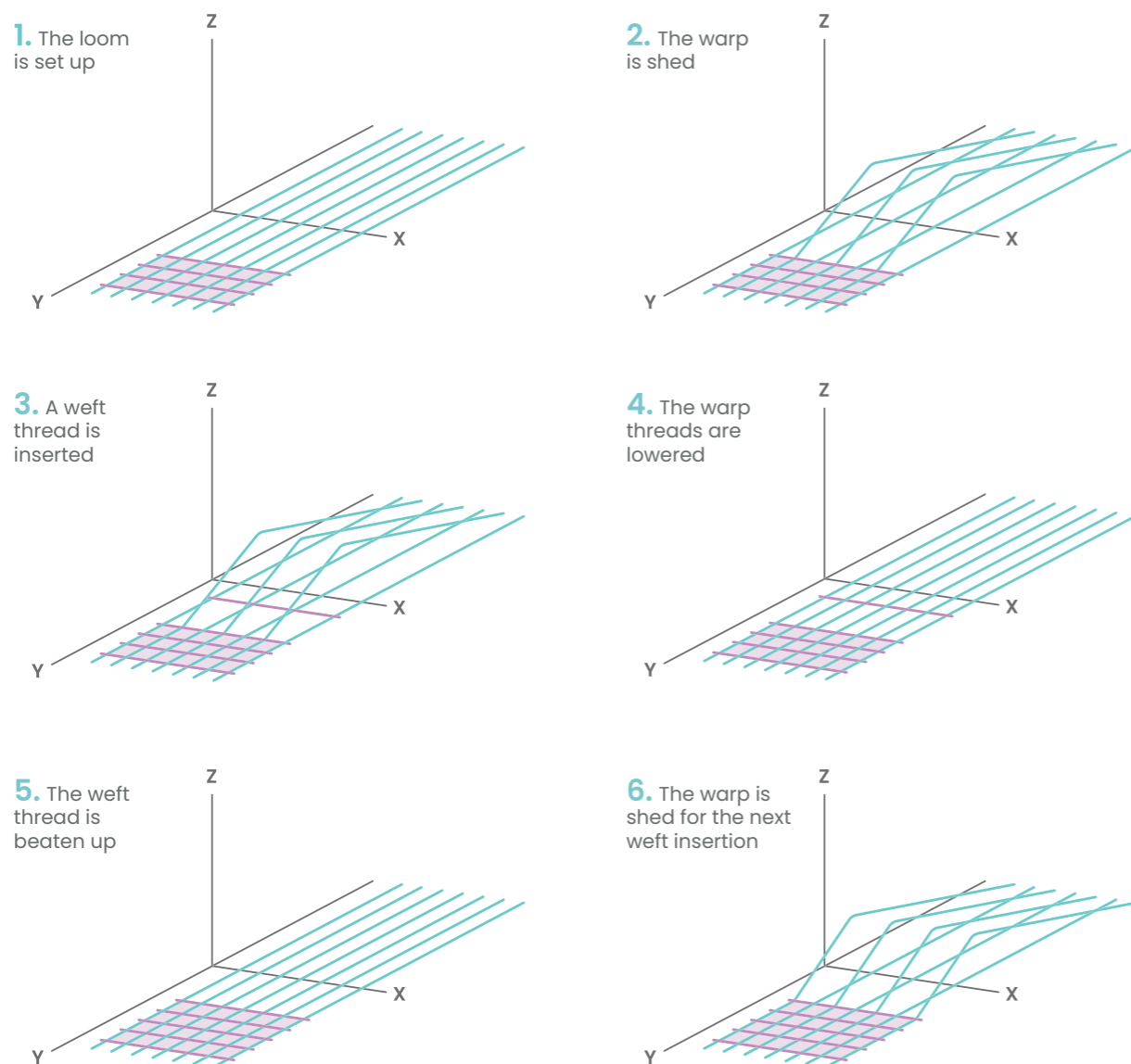


Figure 11: The fundamental weaving steps

3.2 Looms

Looms are made to facilitate the fundamental weaving steps by keeping the warp threads tensioned and raising the warp threads for weft insertion (Shenton, 2014). An illustration of a shaft loom can be seen in Figure 12.

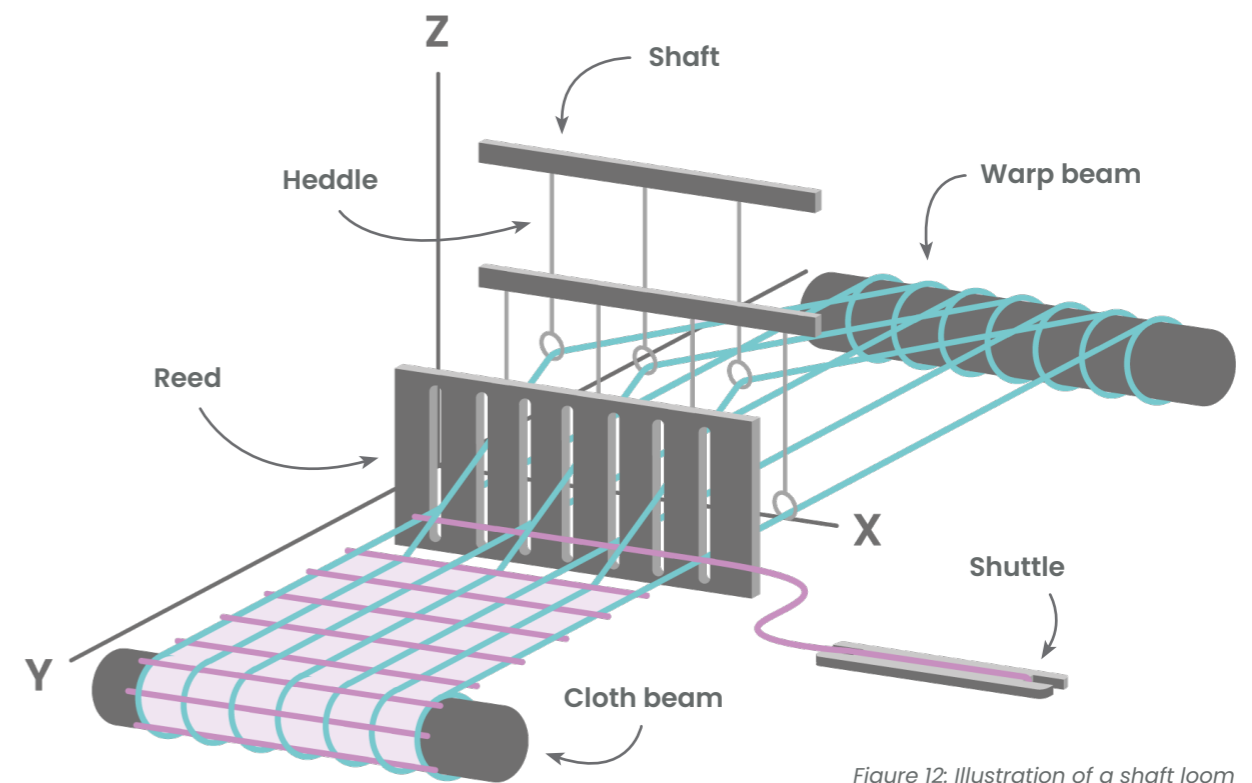


Figure 12: Illustration of a shaft loom

On a shaft loom, the warp threads are divided over heddles attached to different shafts. Shaft looms are available in different sizes: smaller scale table looms and larger floor looms (Handwoven, 2022). Each shaft can be raised and lowered independently to raise all the warp threads attached to that shaft. The complexity of the structures that can be woven on a shaft loom is determined by the number of shafts available, but will always be limited by the fact that the warp threads are controlled in groups. In contrast, on a jacquard loom every thread is controlled individually. This allows very complex structures to be woven (Duvaltex, 2023). Large scale jacquard looms are commonly used to produce textile products on an industrial scale, but a small computer controlled and manually operated jacquard loom, the TC2, has also been developed by Tonrud Engineering for prototyping (Digital Weaving Norway, n.d.).

Looms also differ in the way the weft thread is inserted. The oldest method is using a shuttle, which contains a bobbin with the weft thread and travels back and forth on the loom. Shuttleless looms were later developed to increase the speed of weft insertion. Rapier looms use long rods to carry the weft through the shed, projectile looms use a bullet shaped object to shoot the weft through the shed, and air-jet and water-jet looms use air and water respectively. (Kiron, 2023)

3.3 Materials

A woven fabric is made up of yarns. The choice of material for the warp and the weft will have a large influence on the resulting fabric. The choice of warp material is made when the loom is warped: the warp threads are arranged next to each other along the X-axis and tensioned. A single material can be chosen for the warp, or a combination of multiple materials can be used. While the choice of warp is set after warping, the weft material can be changed throughout the weaving process. A weft thread can either continue between rows (Figure 13) or be cut at the end of a row (Figure 14). This gives the possibility to change the weft type between every row.

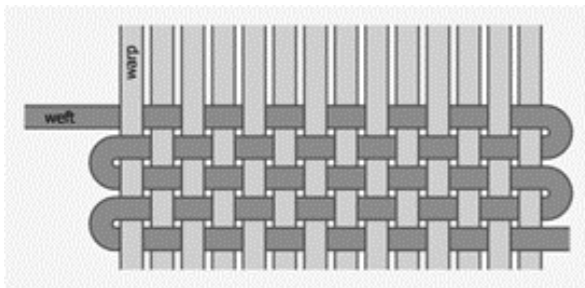


Figure 13: A single weft thread continues from row to row (Nishizaki, 2019)

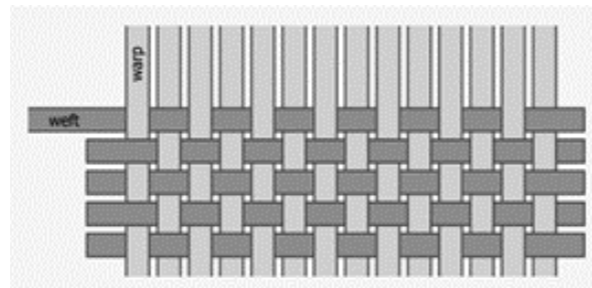


Figure 14: Separate weft threads are used for each row (Nishizaki, 2019)

Combining different materials allows the creation of fabrics with multiple colors and/or textures. An example of a fabric with multiple weft materials can be seen in Figure 15. An example of a multi-colored warp and weft can be seen in Figure 16.



Figure 15: A fabric created with a multitude of different weft materials (Abi, 2015)

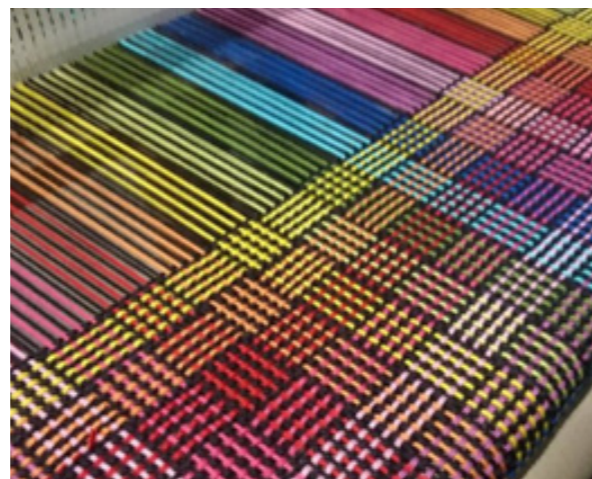


Figure 16: A multi-colored warp interlaced with weft threads of different colors. (DebbieB, 2013)

Combining materials with different properties, such as elasticity or shrinkage in response to heat, can enable the weaver to influence the shape or texture of the fabric after it is taken off the loom. For example, elastic thread can be incorporated into a double cloth to make areas pucker when taken off the loom (Figure 17) (Shenton, 2014).

Hashish (2014) conducted a large amount of experiments with weaving a tubular fabric using a combination of elastic and non-elastic thread. The elastic areas contracted immediately when taken off the loom and shrunk further during wet finishing and heating. Figure 18 shows the result of weaving some sections with elastic thread.



Figure 17: A double cloth made to pucker due to elastic thread being woven into one side



Figure 18: The shape of the fabric once taken off the loom (left) and once washed, dried and heat set (right) (Hashish, 2014)

There are also materials that display a high amount of shrinkage when triggered by an external stimulus, such as heat. McQuillan (2020) utilized heat shrinking yarn to create a tunic (Figure 19) that could be molded into shape by heating the material (Figure 20).

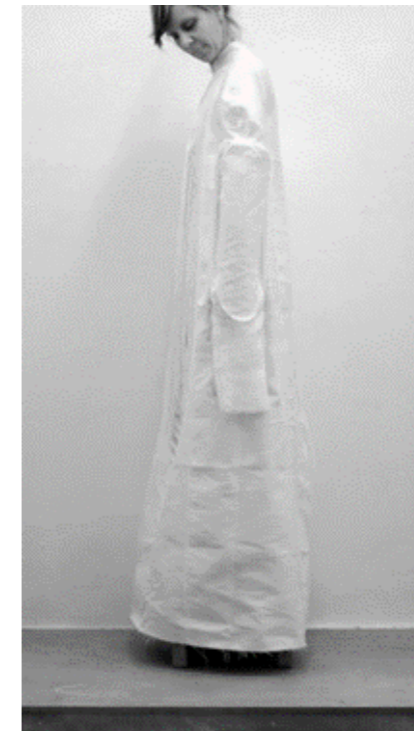


Figure 19: A tunic made from woven fabric with heat shrinking yarns (McQuillan, 2020)

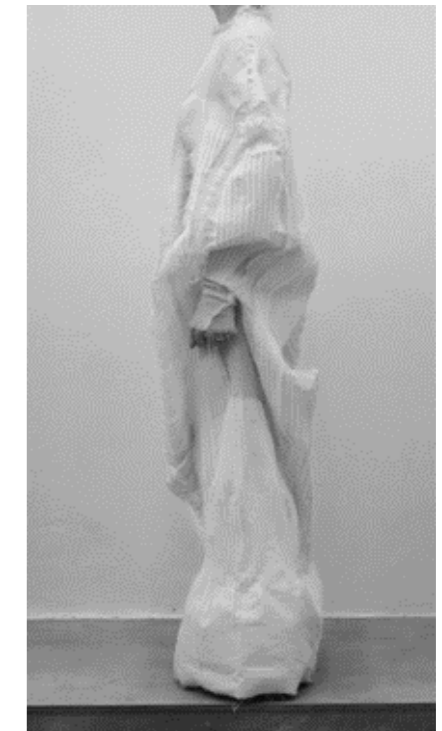


Figure 20: The tunic after shrinking sections using heat (McQuillan, 2020)

3.4 The weaving process

During the weaving process the warp and weft threads can be manipulated in various manners to influence the resulting fabric. Different methods for tweaking the weaving process to achieve different results in 2D, 2.5D and 3D fabrics are explained below.

3.4.1 2D Fabrics

Although every fabric has a certain thickness and texture, most fabrics can macroscopically be regarded as 2D sheets. If the warp and weft threads are interlaced on a single plane and the fabric does not have a significant thickness, it is regarded as a 2D fabric (Gokarneshan & Alagirusam, 2009). Examples of how different variables impact the resulting 2D fabric will be described below.

Weave structures

Every woven fabric is made up of interlaced warp and weft threads. The way in which these threads are interlaced however, can be varied to achieve fabrics with different properties. The manner of interlacement is called the weave structure and can be communicated with a weave diagram (Figure 21). A weave diagram consists of a grid with each square representing a single intersection where a warp and weft yarn cross each other. The color of the square indicates whether the warp or the weft lies on top. Black typically indicates the warp while white indicates the weft. The vertical columns in the grid represent the warp threads, while the horizontal rows represent the weft threads. For each weft row, the cloth diagram indicates with black squares which warp threads need to be raised in the shed to allow the weft to travel underneath. The weave diagram represents a section of the woven structure that can be repeated horizontally and vertically depending on the number of warp and weft threads used in a fabric. (Salolainen et al., 2022)

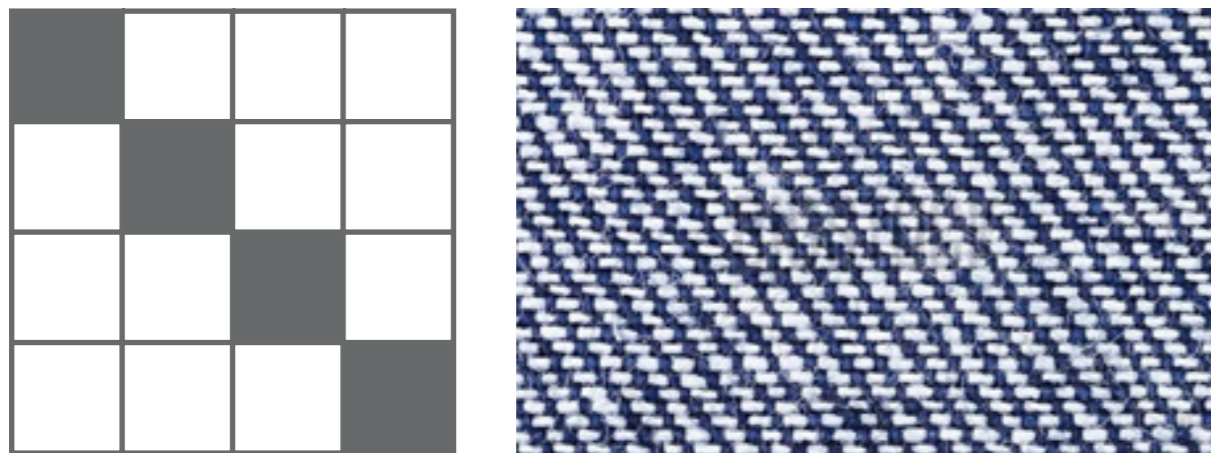


Figure 21: A weave diagram for a twill weave (left) and the resulting fabric (right)

Different weave structures provide different visual effects and give the fabric different properties. In Figure 22 the visual effect of using different types of twill weaves can be seen. The weave structure can also influence the fabric texture. In Figure 22 a honeycomb or waffle weave is shown, which gets its texture from the specific arrangement of the warp and weft floats. A float refers to a portion of the thread that travels over a number of warp or weft threads without interlacing with them. (Shenton, 2014)

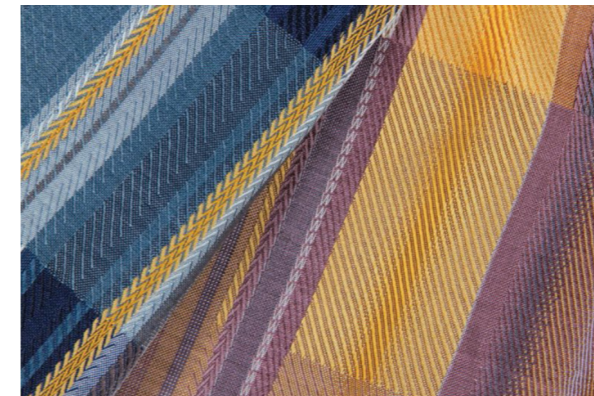


Figure 22: A combination of twill weaves (Shenton, 2014)



Figure 23: A honeycomb or waffle weave (Shenton, 2014)

Supplementary warp and weft insertion

Additional warp and weft threads can be woven into a ground fabric. These threads are not a structural part of the cloth, but can function as a decorative element. Supplementary warp threads usually have their own let off system to allow the threads to move forward at a different pace than the ground warp. Supplementary weft threads can be inserted whenever desired, usually in between two rows of the ground weft. The supplementary threads are brought to the surface of the fabric where desired and left to float underneath the fabric in other areas (Figure 24 and 25). (Shenton, 2014)



Figure 24: Fabric with decorative element created by supplementary warp (Shenton, 2014)

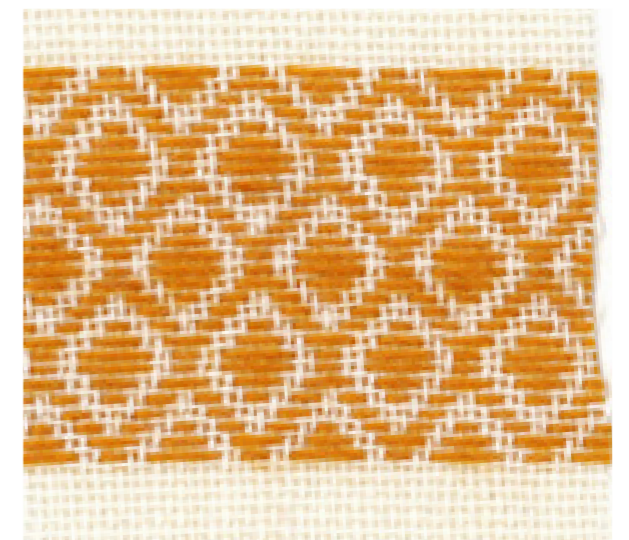


Figure 25: Fabric with decorative element created by supplementary weft (Shenton, 2014)

Warp tension

The warp threads need to be tensioned in order to properly shed the warp and slide an inserted weft thread to the fell. In most standard weaving practices, all the warp threads are let off a common warp beam and kept under equal tension. However, alterations can be made to looms to allow individual or a selection of warp threads to be tensioned differently.

For example, a seersucker fabric is made by winding sections of the warp onto a separate beam. The warp threads on one beam are tightly tensioned while the threads on the other beam are lightly tensioned. This alternating tension causes the fabric to pucker or gather in some areas while remaining smooth in others, as seen in Figure 26. (Richards, 2021)



Figure 26: A seersucker fabric (Shenton, 2014)

A bedford cord is also made with two separately tensioned warps. In this case, the tightly tensioned warp threads float on the reverse of the fabric in some areas (Figure 27). When the fabric is taken off the loom, these tightly tensioned threads relax and contract, pushing the fabric above the floats up (Figure 28). (Shenton, 2014)

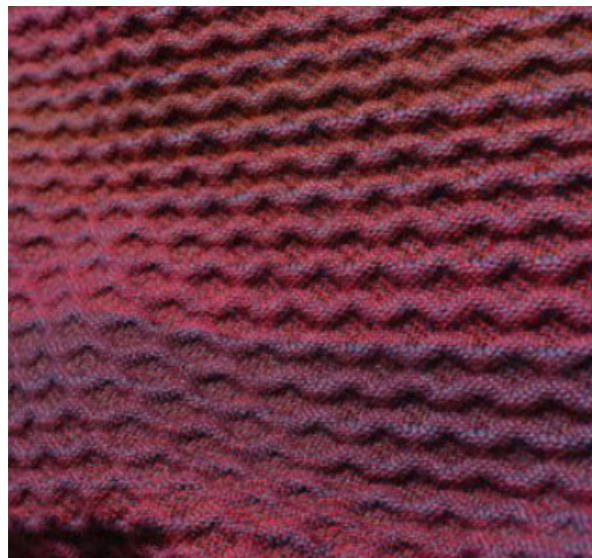


Figure 27: The front side of a bedford cord (Shenton, 2014)



Figure 28: The backside of a bedford cord, where the floats can be seen (Shenton, 2014)

Warp and weft spacing

The spacing of the warp and weft threads can be adjusted to create a more compact or open fabric. A reed is usually used to beat up a newly inserted weft thread (Figure 29). A reed consists of wires aligned in a frame. The spaces between the wires are often referred to as dents. The warp threads travel through the dents in order to maintain their relative spacing. Typically one or two warp threads are guided through each dent. Reeds are produced with different dent densities, allowing a specific reed to be chosen that aligns with the desired warp spacing. The weft spacing is determined by the tension of the warp threads, the weave structure, and the amount of force used to beat up a weft thread with the reed. (Shenton, 2014)



Figure 29: A reed on a shaft loom (Artisan Textiles, n.d.)

Denting plan

A non-uniform warp spacing, in which some threads are crammed closer together and others are more spaced out, can be achieved by following a specific denting plan. The denting plan indicates how many threads should be threaded through each dent. For example, the gauze-like look of a mock leno fabric (Figure 30) is created by varying how many warp threads travel through each dent and/or by leaving some dents empty. The weft spacing is manipulated by changing the amount of force used to beat up a weft thread. (Salolainen et al., 2022)

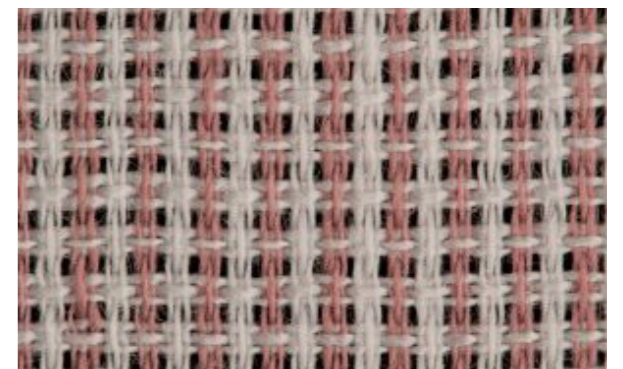


Figure 30: Mock leno fabric (Vintage Fashion Guild, n.d.)

Specialized reeds

The warp spacing can also be varied while weaving with the use of specialized reeds. First of all, there are reeds with dent wires that are angled or curved so that the spacing changes along the height of the reed. As the reed is moved up or down, the warp threads slide through the dents and are pushed into position (Faber, 2002 as cited in Anderson, 2005). A common version is the fan feed (Figure 31), which has dent wires angled to create either one or multiple fan shapes (Ahmad et al., 2023). The fan reed can be used to create undulating effects (Figure 32).

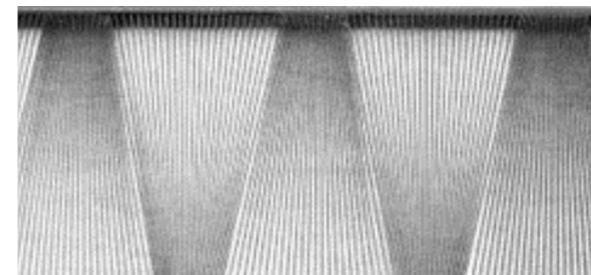


Figure 31: A multi fan reed (Cnaani & Sterman, 2023)



Figure 32: Fabric of which the warp threads have been curved with a fan reed (Cnaani & Sterman, 2023)

More flexibility in changing the spacing between warp threads can be achieved with a rail reed (Figure 33). The dent wires of a rail reed are grouped into modules that can be individually moved and expanded along the X-axis (RailReed, n.d.). An open reed also gives control over the placement of individual warp threads by enabling warp threads to be moved from one dent to another (Figure 34) (RealFibers, n.d.).



Figure 33: A rail reed in use (RailReed, n.d.)



Figure 34: An open reed in use (RealFibers, n.d.)

Weft path

Discontinuous weft

A weft thread does not have to be inserted all the way through the shedded warp, but can enter and exit the shed at any point to only interlace with a section of the warp threads (Figure 35). This is referred to as a discontinuous weft. This technique is often used in tapestry weaving to produce multicolored fabrics (Lo, 2022).

A discontinuous weft can also be used as a supplementary weft to avoid having long floats at the back of the fabric (Figure 36) (Garrity, 2015).

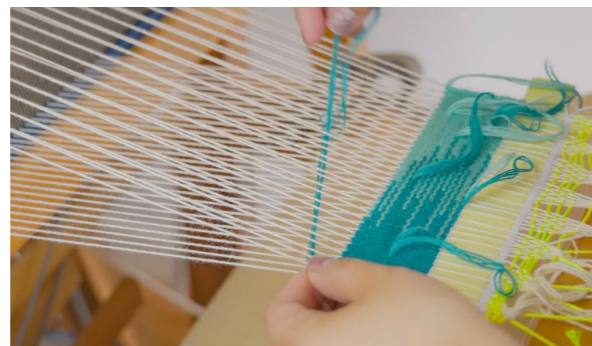


Figure 35: A weaver in the process of inserting a discontinuous weft thread (Lo, 2022)

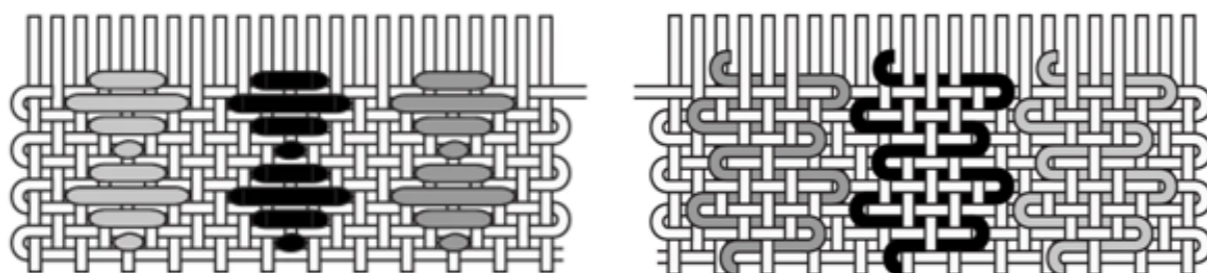


Figure 36: Illustration of the front side (left) and back side (right) of a fabric with decorative elements created with a supplementary discontinuous weft (Garrity, 2015)

Path manipulations

Intricate designs can be made by manipulating how the weft yarn travels through the warp. For example, in Spanish lace the weft thread travels back and forth in a couple of discontinuous rows before continuing along (Figure 37). Another technique for lace weaving is to create little bundles by wrapping the weft yarn around a group of warp threads before threading it through the warp again (Figure 38). (Bunting, 2021a).

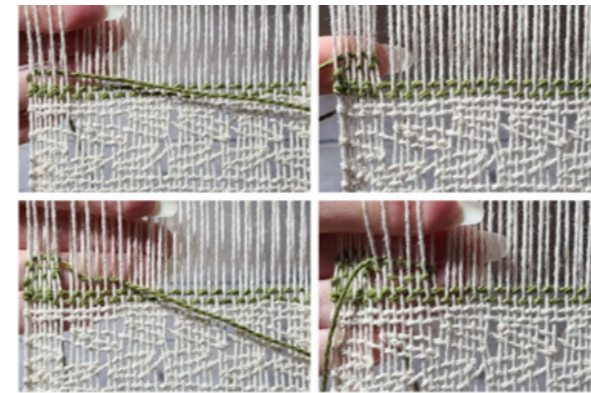


Figure 37: The process of weaving Spanish lace by manipulating the weft to move back and forth through the warp (Bunting, 2021a)

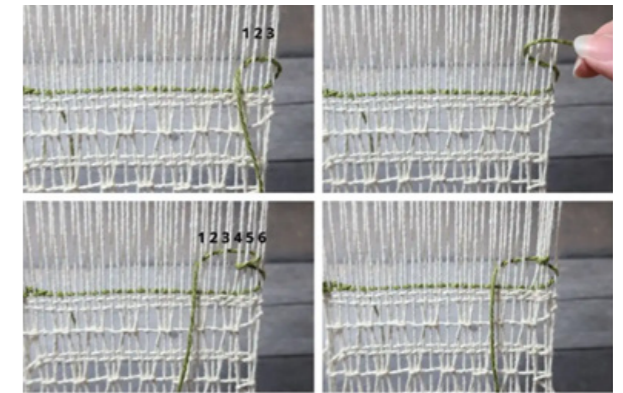


Figure 38: The process of weaving lace by wrapping the weft around groups of warp threads (Bunting, 2021a)

Warp order

The warp threads are placed parallel to each other in a specific order when the loom is warped. Usually, the threads stay in this order throughout the woven fabric. However, in leno weaving, the warp yarns do not stay parallel when interlaced with a weft thread. Instead, they cross over each other. In the simplest form of leno weaving, one regular warp end and one crossing warp end alternate positions with each pass of the weft (Figure 39). (Saha, 2006 as cited in Saha et al., 2017)

Sarah May Johnson takes varying the warp order a step further. She creates intricate patterns using supplementary warp threads that float over the ground fabric before being interlaced with weft threads again, but this time in a different order (Figure 40) (Johnson, 2022).

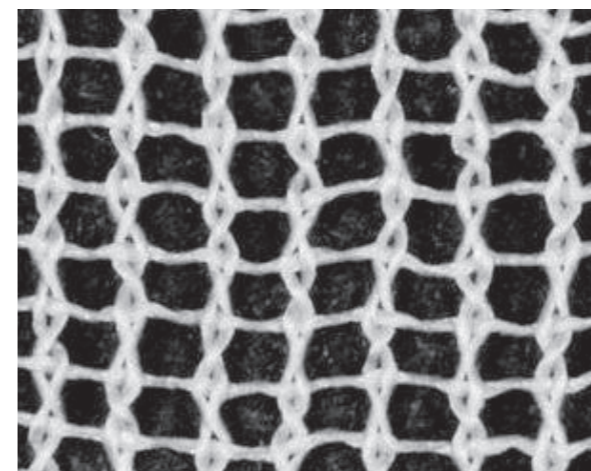


Figure 39: Leno fabric (Saha et al., 2017)

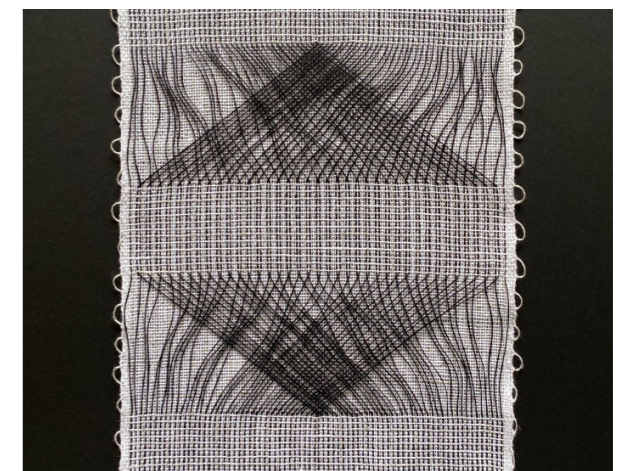


Figure 40: Fabric with warp floats that cross diagonally over the fabric before being incorporated into the ground cloth (Johnson, 2022)

2.4.2 2.5D Fabrics

A 2.5D fabric is defined by Gokarneshan & Alagirusam (2009) as a fabric in which the warp and weft yarns are placed in two mutually perpendicular planes in relation to each other. Examples of methods for creating 2.5D fabrics are explained below.

Raising up weft threads

One way of creating pile fabrics is by looping weft threads out of the fabric plane during insertion. These loops can subsequently be cut or left intact to create a soft, textured fabric. One manual method is to wind a weft thread around a rod that is later removed, as seen in Figure 41. (Kasper et al., n.d.)

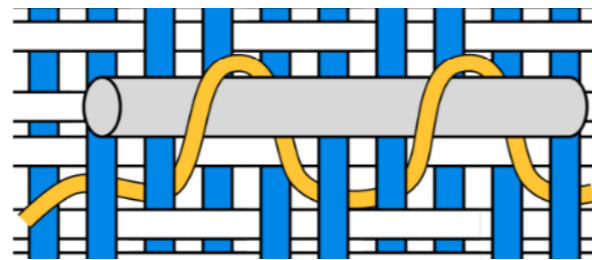


Figure 41: Method for creating pile fabrics by winding the weft around a temporary rod (Kasper et al., n.d.)

Raising up warp threads

Pushing up loosely tensioned warp threads

Terry fabrics can be produced by pushing small sections of warp out of the fabric plane. This is done by dividing the warp over two warp beams: one tightly tensioned, the other loosely tensioned. A weft thread is inserted at a certain distance from the previous row. After two more weft threads are inserted, the reed pushes the whole group forward (Figure 42). The tightly woven warp threads stay in place, but the loosely tensioned warp threads are pushed up into loops. (Adanur, 2001)

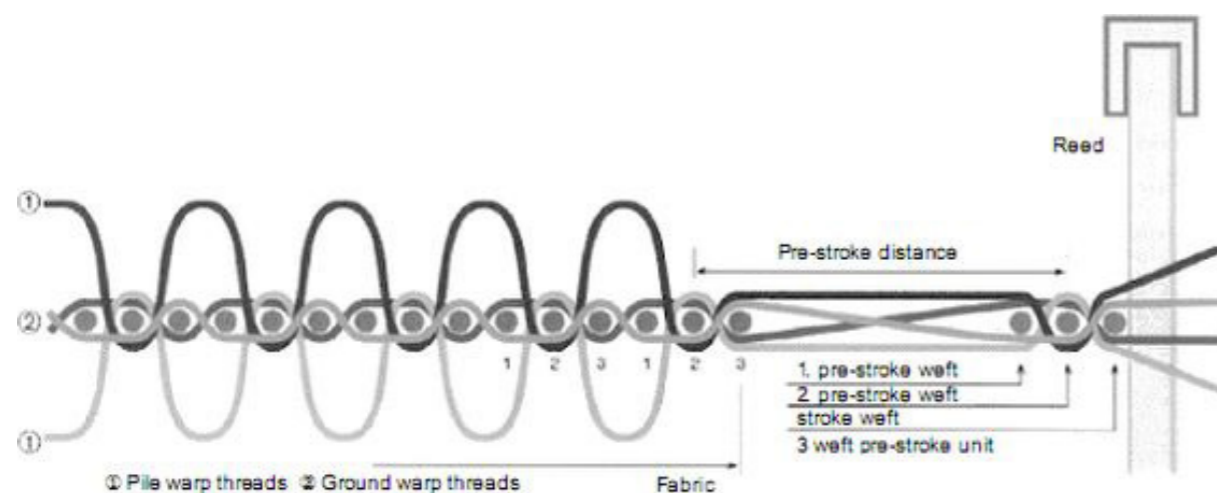


Figure 42: Method for creating terry fabrics by pushing up loops of loosely tensioned warp threads (Adanur, 2001)

Inserting rods under warp threads

Velvet fabrics are also made by creating loops that can later be cut. A traditional method for creating velvets is wire weaving. The ground fabric is woven as usual with a ground warp. The loops are created by lifting the pile warps and inserting a rod through the opened shed. The ground warp can then be shed to continue to weave the ground fabric. After this cycle has been repeated a number of times, the rods can be removed, leaving behind a pile warp (Figure 43). (Ünal, 2012)

The pile warps need to be able to move forward separately from the warp threads of the ground fabric in order to be able to form the loops. For simple velvet fabrics, the pile warps are wound onto a separate warp beam. For more complex patterns, the pile warps also need to be able to move relatively to each other. In traditional velvet weaving a creel system is often used (Figure 44). Every warp thread in this creel system is let off a separate bobbin (Bunting, 2021b).



Figure 43: Velvet created with wire weaving (Artuso, 2017) Figure 44: Traditional creel system (Bunting, 2021b)

A method for setting up a hand loom for velvet weaving was described by (Landry, 2016). Her goal was to make experimentation with velvet weaving accessible to hand weavers (Figure 45). All the warp threads were bound onto a warp beam, but more length than required was let off. This excess length was tensioned through the use of weights that allow the threads to move back and forth while keeping the threads tensioned.



Figure 45: Setup for velvet weaving on a handloom (Landry, 2016)

Van de Wiele has introduced machinery that enables individual let-off and tensioning of warp threads on an industrial scale for the creation of different pile fabrics. For example the Fast Creel, seen in Figure 46, which consists of a large rack of bobbins behind the loom. The tension in each warp thread is controlled with an individual torque motor. (TEXTalks, 2019)



Figure 46: Loom with Fast Creel by Van de Wiele (TEXTalks, 2019)

Van de Wiele has also introduced the Smart Creel, which consists of cells arranged in a matrix (Figure 47). A robot is used to wind yarn onto the cells. The Smart Creel is compact, flexible and efficient. (Seyam, 2020)

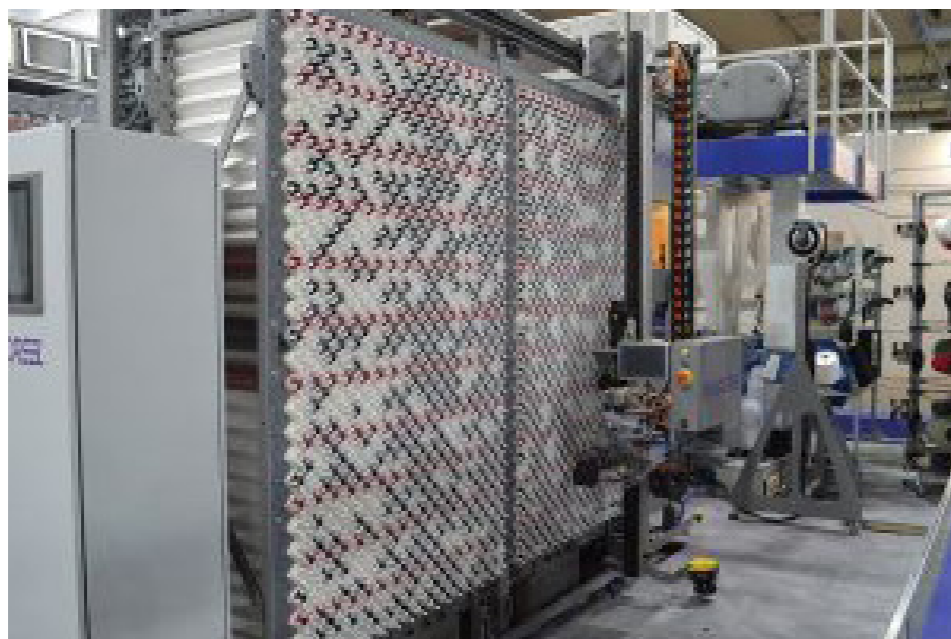


Figure 47: Smart creel by Van de Wiele (Seyam, 2020)

3.4.3 3D Fabrics

When the textile has a thickness or dimensions along the Z-axis that are significant in comparison to the X and Y dimensions, the fabric can be considered 3D (Badawi, 2007). 3D fabrics can be classified into four categories: solid, hollow, shell and nodal (Chen, 2007 as cited in Chen et al., 2011).

A distinction needs to be made between 2D weaving and 3D weaving, both of which can be used to create 3D fabrics. In 2D weaving, two perpendicular sets of yarn are interlaced. The warp threads lie next to each other along the width of the loom and are only raised vertically to allow the weft thread to be inserted at a right angle to the warp. In 3D weaving, a third set of yarns is introduced that run along the Z-axis. Multiple layers of warp are arranged as a grid on specialized 3D weaving looms that are able to shed the warp both row wise and column wide to allow insertion of threads along both the X-axis and Z-axis. (Gokarneshan & Alagirusam, 2009)

Conventional looms designed for 2D weaving, such as dobby and jacquard looms, are less complex and considerably more widely available than 3D weaving looms. Leveraging existing 2D looms for the creation of 3D textiles is therefore more accessible and has the potential to be more practical and cost-effective to implement in large-scale manufacturing than employing specialized 3D weaving looms. This research will therefore solely explore 2D weaving of 3D fabrics.

Studies of 3D fabrics have been clustered based on the method explored (Figure 48).

Method	3D form	Research
Changing the number of warp and weft crossings	Shell	Busgen (1999); Chen & Tayyar (2003)
Changing the spacing between the weft threads	Shell	Cnaani & Sterman (2023); Koppelman & Campman (1964)
Changing the spacing between the warp threads	Shell	Busgen (1999); Bhattacharya & Koranne (2012)
Curving the weft threads out of plane	Shell	Koranne (2014); Kühn (2013)
Weaving multiple layers	Solid, Hollow, Shell, Nodal	Grosicki (1977) as cited in Chen et al. (2011); Lowe (1987); McQuillan (2020); Nuñez & Schmitt (1998), as cited in Ahmad et al. (2023)
Pushing/pulling sections of woven fabric out of the fabric plane	Hollow	Marfurt (1998) as cited in Ünal (2012); Balawi (2020); Mountasir et al. (2011)

Figure 48: An overview of methods for weaving 3D fabrics, the type of form that can be created, and researches exploring each method

Changing the number of warp and weft crossings

Changing the weave structure

The density of crossing points between warp and weft threads in an area influences the surface area of a piece of fabric woven with a certain amount of weft and warp threads. A crossing between a warp and a weft thread restricts the adjacent threads from moving closer together. A piece of fabric woven in plain weave, which has the highest density of crossings between warp and weft will take up a greater amount of space than, for example, a satin weave. The reduced number of warp and weft crossings in a satin weave results in longer floats which allow the threads to move closer together. (Busgen, 1999)

How the warp and weft threads cross each other in different weave structures can be seen in Figure 49 and 50.

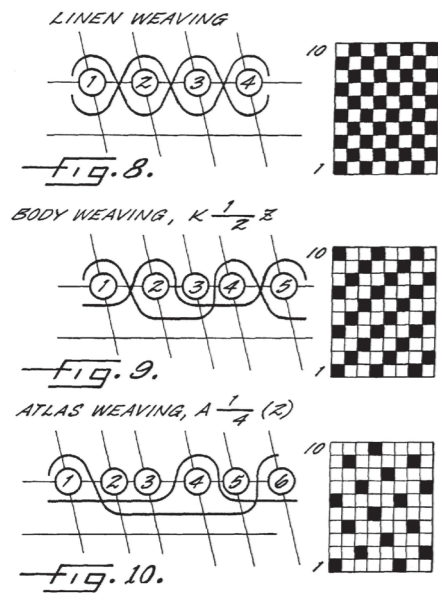


Figure 49: Examples of weave structures with different crossing densities (Busgen, 1999)

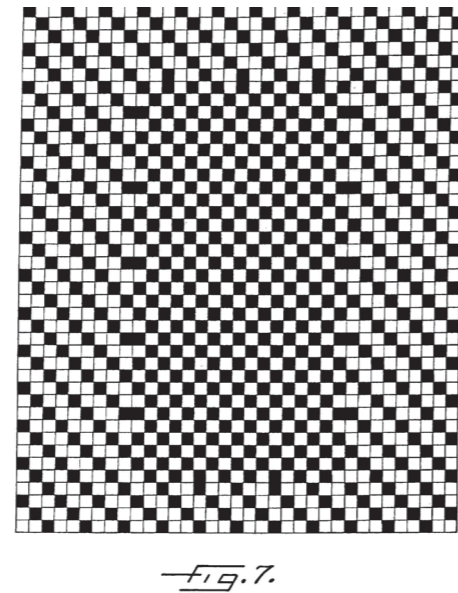


Figure 50: Example of a plain weave surrounded by a twill weave (Busgen, 1999)

Chen & Tayyar (2003) created a domed fabric by enclosing a circle of plain weave in a ring of 2/2 twill, which was in turn enclosed by a ring of 5-end satin. The plain weave bulged up from the fabric, while the satin squeezed together, creating a dome shape (Figure 51).

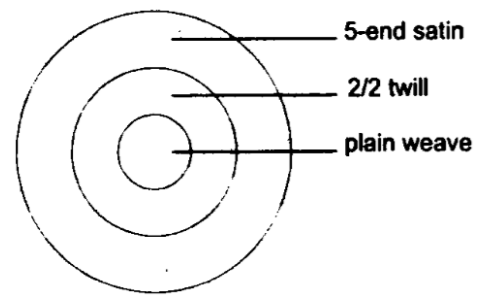


FIGURE 1. A patchy weave design.

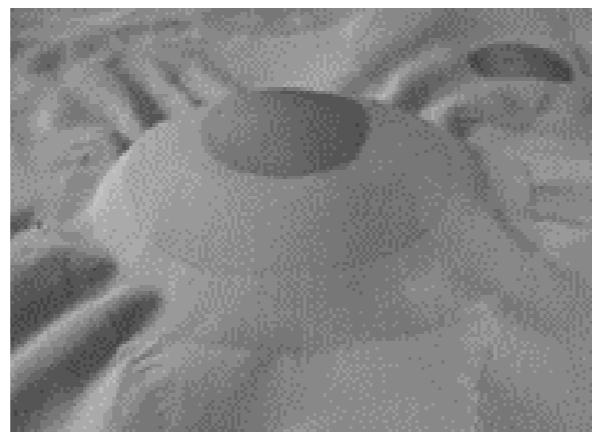


Figure 51: A weave design in which a circle of plain weave is surrounded by a ring of twill and satin (left) (Chen & Tayyar, 2003) and the resulting domed fabric (right) (Chen et al., 2011)

As the areas of the fabric woven in different weave structures grew at different rates, the warp threads in each area needed to be moved forward along the Y-axis separately. Separate let off of warp threads was achieved by using multiple warp beams. In order to retain the tension on all the warp threads, a dome-shaped profile roller was added before the cloth beam to vary the warp take-up (Figure 52).

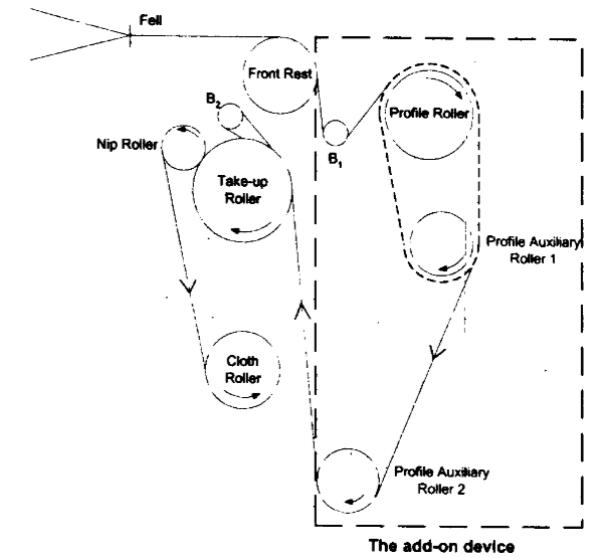


Figure 52: Examples of weave structures with different crossing densities (Busgen, 1999)

Busgen (1999) achieved individual let off of warp threads and varied take-up of woven cloth by using a creel system and a take-up system consisting of rollers split up in individually drivable segments (Figure 53).

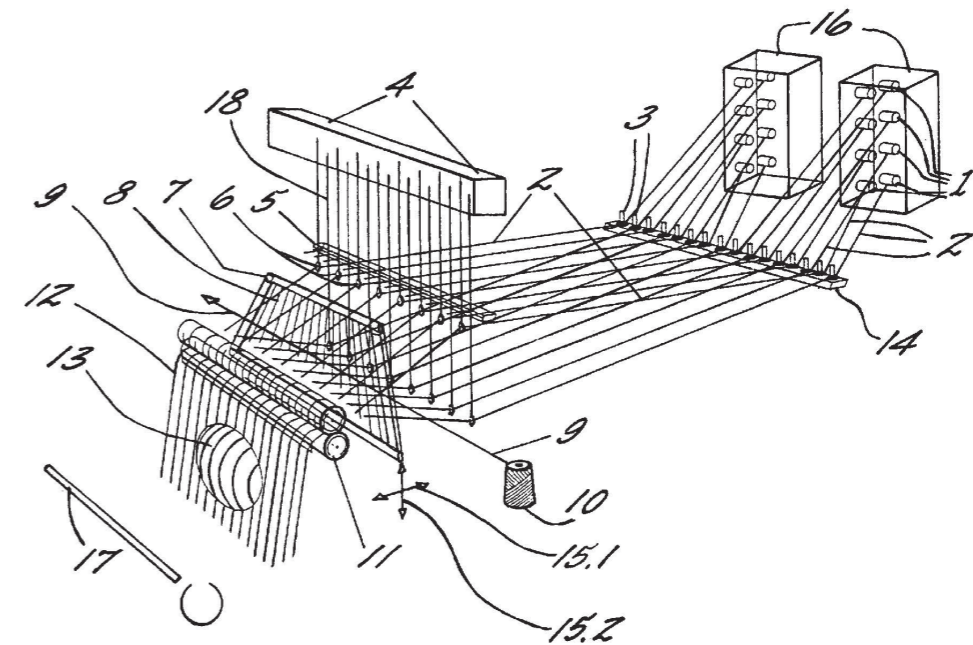


Figure 53: Illustration of a loom with a creel system and individually driven take-up rollers (Busgen, 1999)

Once the fabric is taken off the loom, differences in shrinkage between areas woven in different weave patterns can make the 3D shape more pronounced. The fabric will relax in absence of the tension it was under while being woven. The threads in areas with longer float lengths can move closer together than those in areas with shorter float lengths, causing those areas to shrink more. Areas with longer float lengths have also been observed to shrink more in further finishing steps. (Hashish, 2014)

Inserting/engaging additional threads

The density of warp and weft crossings in an area can also be increased by inserting or engaging additional threads in that area (Figure 54). Busgen (1999) explains how this can be done by engaging a warp or weft thread in some areas while letting it float in others. Instead of floating the threads, it is also possible to weave these threads into a layer beneath the main fabric. The threads can be transferred from that layer to the main fabric when needed. Lastly, floating weft threads can be avoided by adjusting the length of the weft to the width of the section of warp threads with which the thread needs to be interlaced.

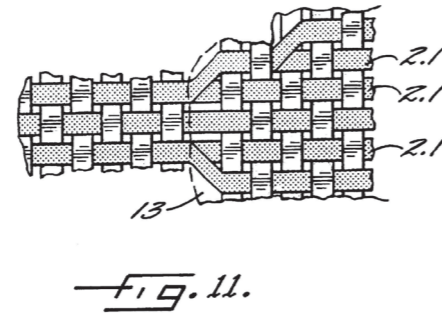


Figure 54: Illustration showing how additional threads can be inserted in used in some areas (Busgen, 1999)

Changing the spacing between the weft threads

Changing the shape of the reed

The reed used to beat up a newly interlaced weft thread is typically made up of dent wires that lie next to each other on a straight line parallel to the X-axis. A standard reed keeps the weft straight and in a perpendicular position to the warp. To allow the weft to be curved and angled while it is beaten up, a variable reed was developed by Cnaani & Sterman (2023). The dent wires of the variable reed can be moved relatively to each other along the Y-axis and are kept in place using cardboard stencils (Figure 55).



Figure 55: A variable reed of which the dent wires can be moved along the Y-axis in order to change the curve of the weft (left) and the resulting fabric while on the loom (right) (Cnaani & Sterman, 2023)

Changing how the weft is curved and angled during beat up throughout the weaving process, enables the weft density to be varied across the fabric. This opens up possibilities for creating 3D forms. The curved weft threads tend to want to straighten once taken off the loom, causing the fabric to bulge up or become wider (Figure 56).



Figure 56: Example of the fabric while on the loom, showing the varying weft spacing (left), and the resulting 3D fabric that emerges when the fabric is taken off the loom (right) (Cnaani & Sterman, 2023)

Another way to change the shape of the reed in order to influence the curve or angle of the weft, is by angling the dent wires forward or backward along the Y-axis (Koppelman & Campman, 1964). A shaped roller pushes against the dent wires to bring them into the desired position for each weft thread that is beaten up (Figure 57).

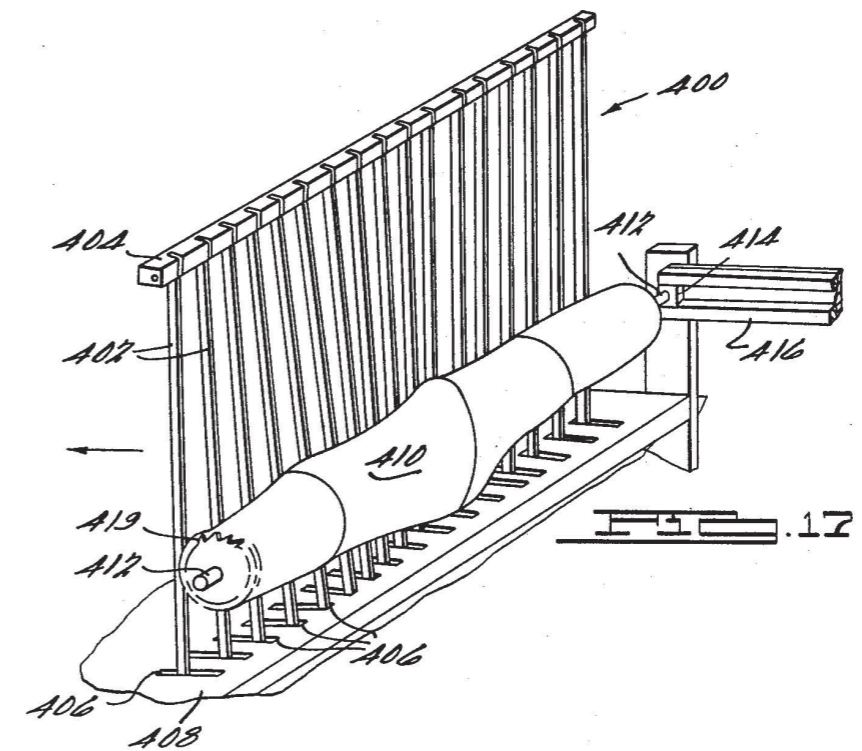


Figure 57: Illustration of a shaped roller that pushes the dent wires forward (Koppelman & Campman, 1964)

Varying warp let off and cloth take up

Instead of beating up the weft in a curved position, the weft thread, after being woven in and beaten up straight, can be pulled into a curved position by varying the take-up of the interlaced warp threads.

The take-up of the woven cloth can be varied using a non-cylindrical take-up beam (Figure 58), shaped to draw specific warp threads forward at different points during the weave process to achieve the desired shape (Koppelman & Campman, 1964).

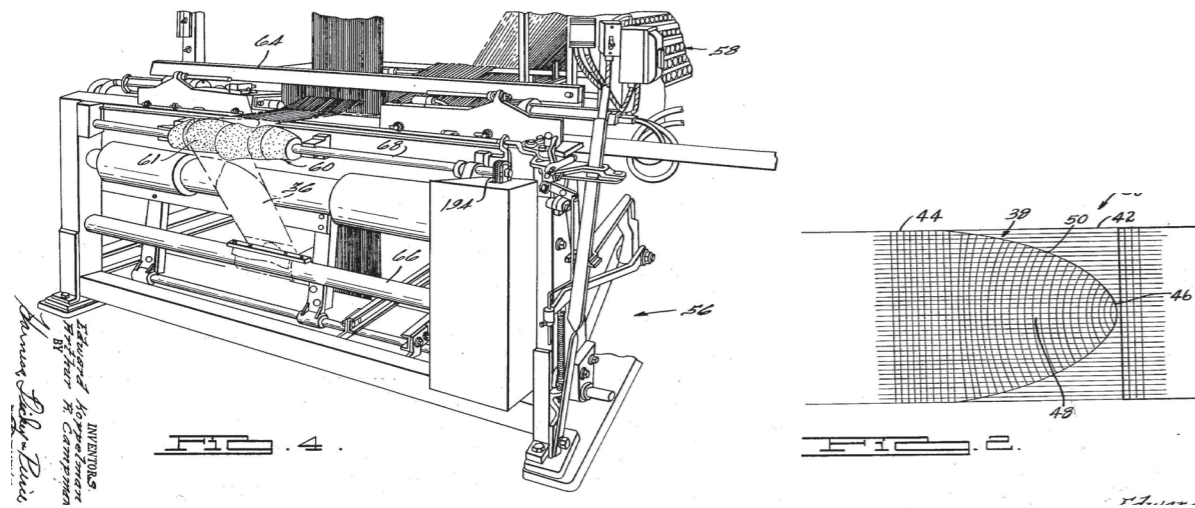


Figure 58: Illustration of a loom with a shaped roller (left) and an illustration of the resulting fabric in which the weft threads have been pulled into a curved position (right) (Koppelman & Campman, 1964)

Varied take up can also be achieved with the take-up system consisting of individually drivable rollers designed by Busgen (1999) In both cases, the warp threads are supplied by a creel system that enables individual let off of warp threads.

Changing the spacing between the warp threads

The spacing between the warp threads can be manipulated as the weave progresses to adjust the curvature of the warp and the warp density. Specialized reeds, such as a fan reed, rail reed or open reed can be used to change the warp spacing.

A single fan reed is utilized by Busgen (1999) to achieve the required spacing between warp threads to achieve his desired 3D form (Figure 53). A reed with dent wires bent into more complex shapes can be used to achieve specific 3D forms. (Bhattacharya & Koranne, 2012) created a custom shaped reed to weave 3D shapes, such as domes and pyramids (Figure 59).

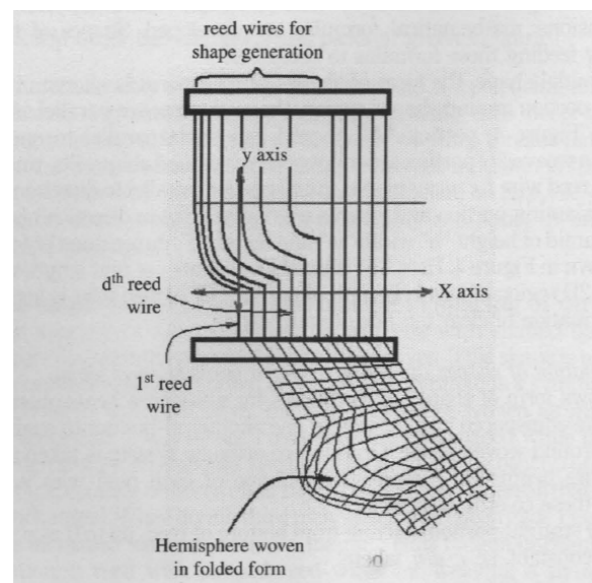


Figure 59: Illustration of a reed with shaped dent wires used to change the warp spacing for fabric shaping (Bhattacharya & Koranne, 2012)

Curving the weft threads out of plane

Curving the weft threads over a mold

Another method for creating a 3D form is directly shaping the weft yarn to the desired out of plane curve during beat up. Koranne (2014) explored this possibility by creating shaped rods that fall in between the warp threads and run through the dents of the reed (Figure 60). They envisioned that the weft threads would be laid over the shaped rods during beat up and would pull the interlaced warp threads up so that the created fabric would follow the curve of the rods. Noticing that the fabric did not adhere to the rods, Koranne (2014) also explored creating shaped slots in fins located between the warp threads. The weft was inserted through these slots, so that the created fabric was restricted from moving either up or down. A dome and a pyramid shape were created using this technique (Figure 61).

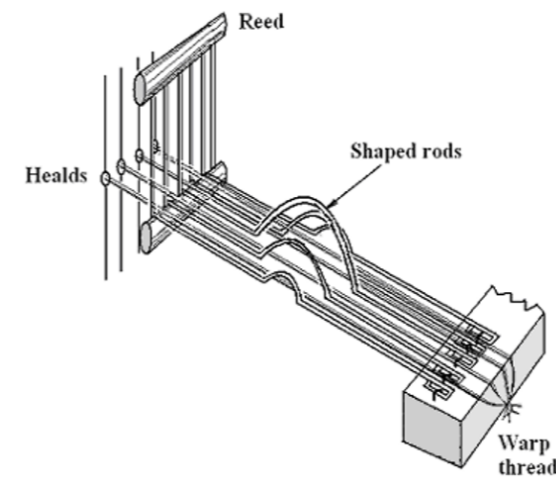


Figure 60: Illustration of shaped rods placed in between the warp threads (Koranne, 2014)



Figure 61: Fabrics with an embedded pyramid and dome shape (Koranne, 2014)

Raising the warp threads during beat up

The weft threads can also be curved out of plane by lifting the warp threads during beat up. The warp threads are lifted to form a specific curve for each weft insertion based on the cross sections of the desired shape. This ensures that the crossing points between warp and weft are located as required for the envisioned 3D shape.

Kühl (2013) proposes each warp thread is inserted through an eye attached to a heddle that can be individually raised or lowered (Figure 62). Alternatively, the weft could be inserted through cut outs in lamellae that can individually be moved up and down (Figure 63). All the lamellae are connected to a bar, allowing the unit to be used as the reed.

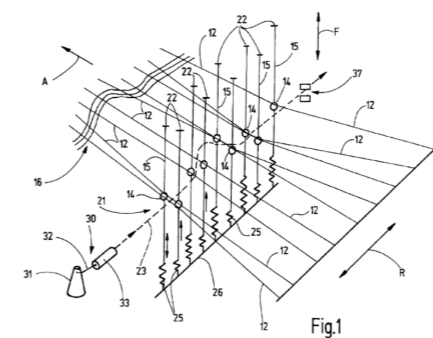


Figure 62: System in which warp threads are threaded through individually controlled heddles (Kühl, 2013)

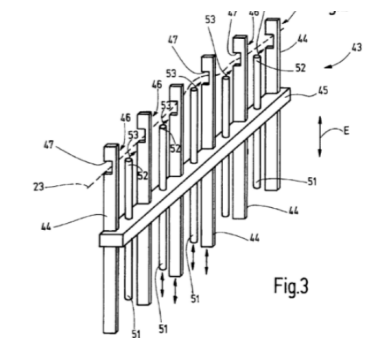


Figure 63: System in which the weft threads are led through individually controlled lamellae (Kühl, 2013)

Weaving multiple layers

Multiple layers of fabric can be woven simultaneously on a conventional loom. This is done by splitting the warp into systems that are separately interlaced with weft threads. Weft threads woven into a different warp group, are stacked on top of each other, instead of placed next to each other (Figure 64). The created layers of fabric can be connected, combined and separated by interlacing threads from adjacent layers. (Taylor, 2017)



Figure 64: Illustration of a multi-layer weave structure showing how the weft threads are placed stacked on top of each other

Weaving multiple connected layers

A fabric with a considerable thickness can be created by splitting the warp up in multiple layers, each with their own set of weft threads. To create a solid fabric, the layers can be connected by interlacing a thread from one layer with the threads of another (Figure 65). Alternatively, an extra set of weft or warp threads can be added that travel through all the layers to connect them (Figure 66). (Grosicki, 1977 as cited in Chen et al., 2011)



Figure 65: Illustration of a multi-layer weave structure in which the layers are connected by a common thread

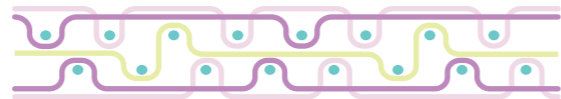


Figure 66: Illustration of a multi-layer weave structure in which the layers are connected by an additional thread

Weaving tubular fabrics

Tubular fabrics can be created by using a continuous weft thread that travels from one warp layer to another at the edges of the fabric (Figure 67).

Nuñez & Schmitt (1998), as cited in Ahmad et al. (2023), explored how tubes with a varying diameter could be produced by engaging or disengaging warp threads at the edges of the fabric (Figure 68).



Figure 67: Illustration of a multi-layer weave structure in which the weft thread continues between the rows and the layers

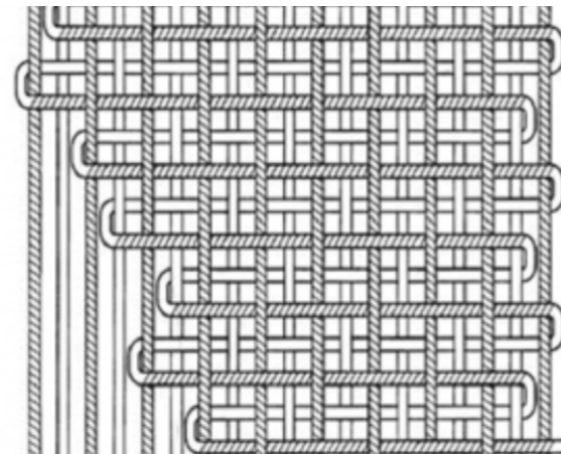


Figure 68: Illustration of a multi-layer weave structure in which the weft thread continues between the rows and the layers

Weaving a 3D fabric in folded form

A single layer can be split in areas of the fabric to create an opening (Figure 69). Multi-layer weaving is also suitable for creating nodal structures. Lowe (1987) created fabrics with an embedded network of tubular members (Figure 70).

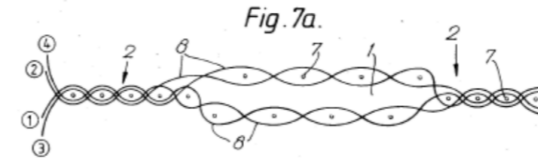


Figure 69: Illustration of a fabric that is partly split into two layers to create an opening (Lowe, 1987)

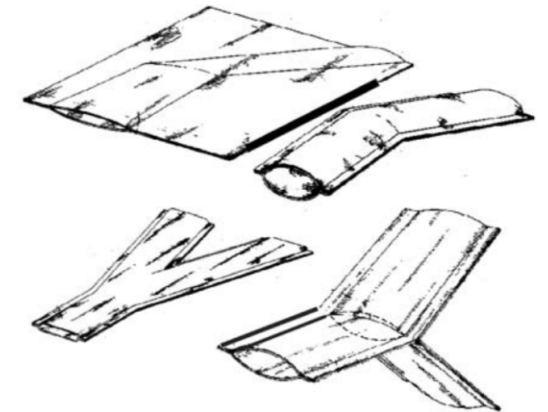


Figure 70: Illustrated examples of nodal fabrics (Lowe, 1987)

Holly McQuillan and Milou Voorwinden (McQuillan, 2020) used the technique of combining and splitting up layers in different ways to create a zero-waste pair of pants (Figure 71).



Figure 71: Illustration of a pair of pants woven using multi-layer structures (McQuillan, 2020)

Pushing/pulling sections of woven fabric out of the fabric plane

Fabrics with embedded hollow spaces can be created by pushing or pulling woven sections out of the fabric plane before continuing the weaving process. For example, horizontal pleats can be created in this manner. The warp is divided into a ground warp and a tight warp, each wound onto their own warp beam (Figure 72).

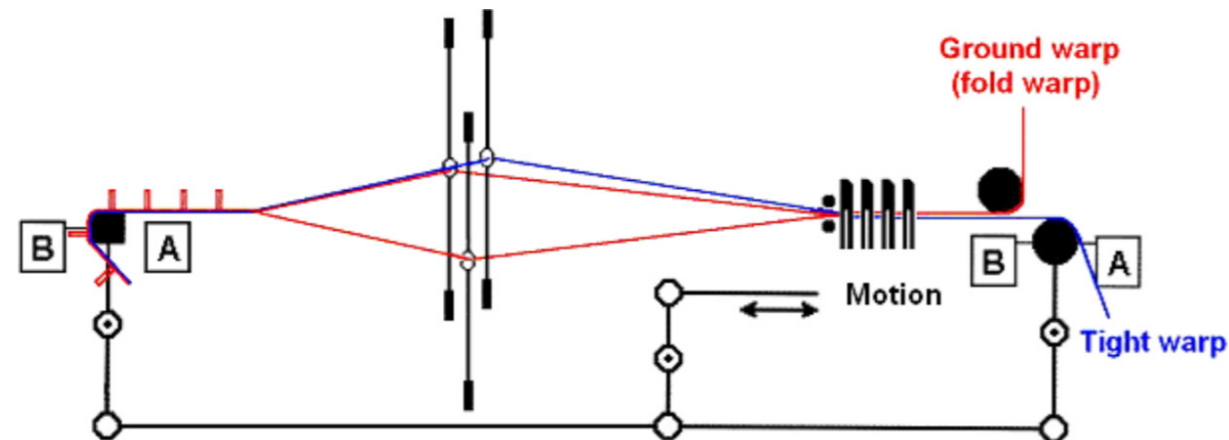


Figure 72: Illustration of a setup for pleat weaving with two differently tensioned warp groups wound onto different warp beams (Kienbaum, 1996 as cited in Badawi, 2020)

The warp threads of the two groups alternate along the X-axis. To create a pleat, a section of cloth is woven with only the warp threads of the ground warp. Once the desired length for the pleat is reached, all the threads are once more engaged in the weaving of the fabric. To push the pleat up, the reed is pushed against the woven fabric. The ground warp is let off its respective beam and bulges up while the tight warp remains static and tensioned. A section of fabric is subsequently woven using all the threads, which restricts the bulging warp threads from being pulled back towards the warp beam or slackening. (Marfurt, 1998 as cited in Ünal, 2012)

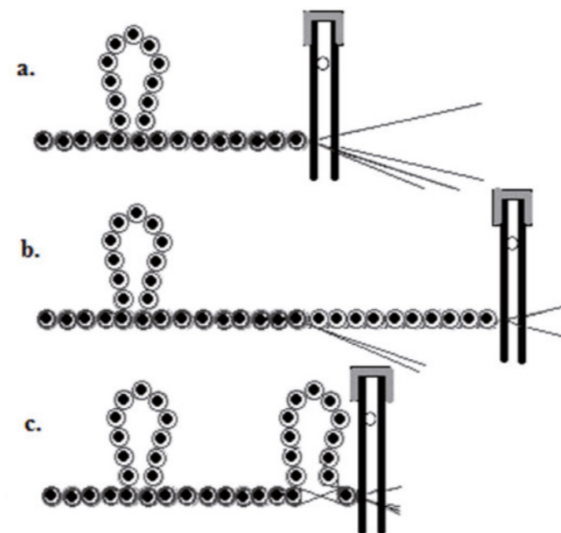


Figure 73: Illustration of the process of creating pleats (Marfurt, 1998 as cited in Ünal, 2012)

The process of weaving a pleat can be seen in Figure 73.

Instead of pushing the woven section forward while the tight warp stays in place, a pleat can also be created by taking the threads of the tight warp, which float under the section woven solely with the ground warp, back up on the warp beam, causing the excess fabric of the ground warp to bulge up. (Balawi, 2020)

The principles of pleat weaving can also be applied to the weaving of spacer fabrics. For example, Mountasir et al. (2011) describes how a u-shaped spacer fabric can be created. The ground fabric is woven as two layers, each layer made up of a ground warp and a tight warp. The walls of the spacer fabric are created by weaving a section using only the ground warp for each layer, intersecting the layers half way through to create a cross. The tight warp is left to float while this section is woven. Once the desired dimensions for the wall are achieved, the floating threads of the tight warp are pulled back, causing the cross to collapse (Figure 74). Once the fabric is taken off the loom, the walls are able to completely straighten.

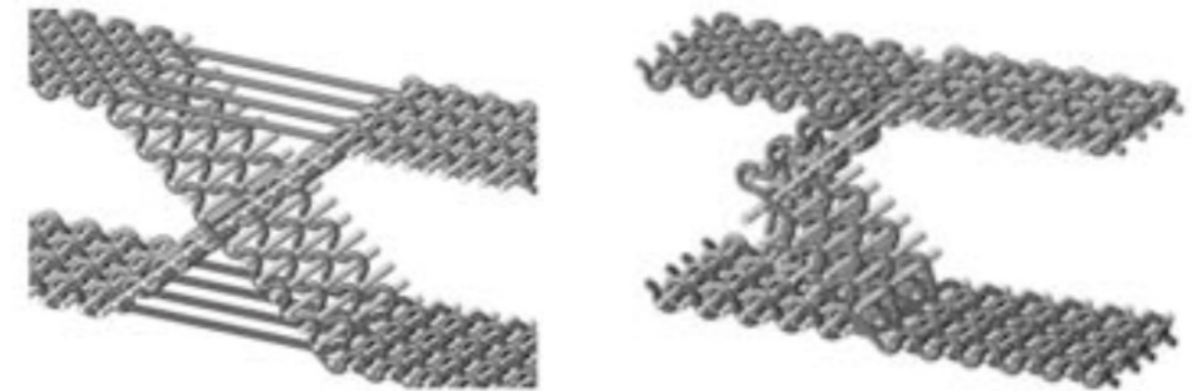


Figure 74: Illustration of the process of creating a spacer fabric (Mountasir et al., 2011)



3.5 Opportunities

Opportunities for this research were identified based on the gaps found in the existing research.

3.5.1 Weaving taxonomy

Weaving is an ancient method of producing textiles for which there are many established methods and tools, making it difficult to get an overview of all the possibilities. Supplied with thousands of years of examples, assumptions about how the weaving process can or should be carried out can easily be made. This can lead to weavers limiting themselves to standard weaving practices, confined by the functionalities of the loom available to them. Looms are created to facilitate the weaving process, but one should not fall into the trap of defining weaving by the functioning of the loom. At its core, weaving is the interlacement of warp and weft threads. If one approaches weaving as such, and disregards the functions and limitations of the loom for a moment, one gains freedom to contemplate how the warp and weft threads can be manipulated during this process of interlacement and consider how this would affect the resulting fabric. Possible adjustments to the loom in order to facilitate the manipulations of the threads, can be addressed afterwards.

The literature research presented in the previous chapter showed that there are ways in which the weaving process can be adjusted to achieve different results. Examples are provided by textile researchers, textile industry players and hobby weavers of how different weaving techniques can be utilized to achieve a desired effect in a 2D, 2.5D or 3D fabric. The creation of the fabrics in these examples requires a combination of different weaving steps and at times the use of an adjusted or specialized loom. Given the perspective that the focus should be placed on the interlacement of warp and weft threads instead of the functionalities of the loom, it was deemed valuable to break down the provided examples to gain a better understanding of how the warp and weft threads are manipulated at different stages of the weaving process.

One could follow the weaving process described by others to achieve the same result. On the other hand, looking at what can actually be done to the threads and using that insight to combine methods of manipulation in a new way could allow the creation of completely different types of fabrics. An opportunity was therefore identified to create a weaving taxonomy that provides an overview of the ways different variables can be changed within varying aspects of the weaving process. This taxonomy based on the core principle of interlacing warp and weft threads could encourage a more open-minded attitude in researchers and weavers and inspire new approaches to weaving, potentially resulting in new types of fabrics. The taxonomy could benefit both this project and other weaving research.

3.5.2 Method for weaving 3D fabrics

Methods for weaving 3D fabrics are currently quite limited. Weaving 3D fabrics in folded form using multi-layer weaving techniques, as explored by Holly McQuillan and Milou Voorwinden for example (McQuillan, 2020), is accessible on jacquard looms but limited by the ability of the loom to only weave 2D layers. On the other hand, methods for creating 3D fabrics, especially shell fabrics that have areas that rise up out of the fabric plane, are limited or inaccessible.

First of all, methods that require the threads to be curved and stretched during weaving in order to jump into shape once taken off the loom, are limited by the weft and warp materials' properties. Secondly, many of the looms designed or adjusted to weave 3D fabrics lack flexibility due to the use of tools made specifically for a certain shape. For example, the use of a profile roller, a mold or a specialized reed. Lastly, the looms are often complex and inaccessible. For example, the loom designed by Busgen (1999), which has a large number of individually driven take-up rollers and thus requires a high amount of electronics and complex programming. Specialized 3D looms add a further layer of complexity and are mainly intended for technical and medical textiles.

Most of the methods and tools explored and designed by others are not transferable to a standard shaft loom, leaving shell weaving unexplored by most weavers and textile researchers. An opportunity was therefore identified to explore methods for shell weaving and develop a way to enable the creation of 3D fabrics on a shaft loom without the need for large alterations to the loom or complex tools. Furthermore, given that the existing methods are generally limited to creating specific 3D shapes, there is also an opportunity to find more flexible shaping methods. The proposed taxonomy is intended to offer guidance in the exploration of how warp and weft threads can be manipulated to be positioned in order to create a desired 3D fabric.



4. Weaving taxonomy

A taxonomy was created that aims to provide an overview of the possibilities within weaving. The taxonomy was not based on the functionalities and limitations of specific weaving looms, in an aim to break free from assumptions about what is currently possible or common practice within weaving. Instead the focus was placed on the warp and weft threads and the variables that can be changed in the process of interlacing the threads.

The taxonomy was created based on the insights gained by analyzing how the warp and weft threads are manipulated in different existing weaving methods, as described in Chapter 3. Taking literature research and weaving experience as a starting point, the taxonomy was expanded by brainstorming what else could be done with the warp and weft threads through sketching and experimenting with weaving. Examples of experiments can be found in Appendix A.

The taxonomy and the way it can be used are described in this chapter.

4.1 Taxonomy

To bring structure to the taxonomy, the variables were categorized into different aspects of the weaving process: warp setup, warp tension, weft selection, interlacement, weft insertion, weft beat up, weft tension, weft row interactions and warp movement. An overview of these categories and their subcategories can be seen in Figure 75. The possibilities in each subcategory are explained in the next section.

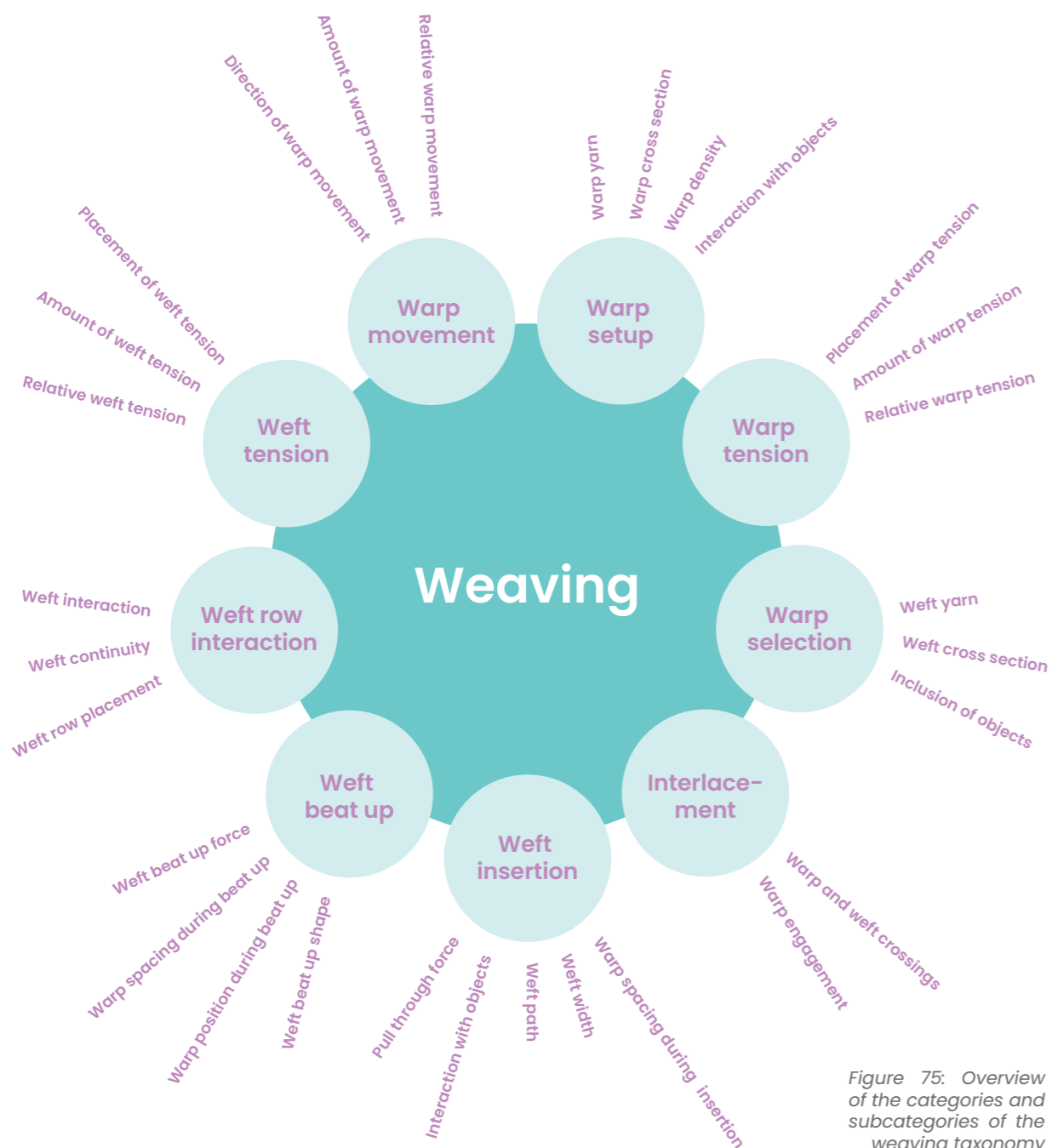


Figure 75: Overview of the categories and subcategories of the weaving taxonomy

4.1.1 Warp setup

In weaving, weft threads are typically interlaced one by one with a set of warp threads. These warp threads are generally set up prior to the weaving process. The variable that can be adjusted during set-up can be seen in Figure 76.

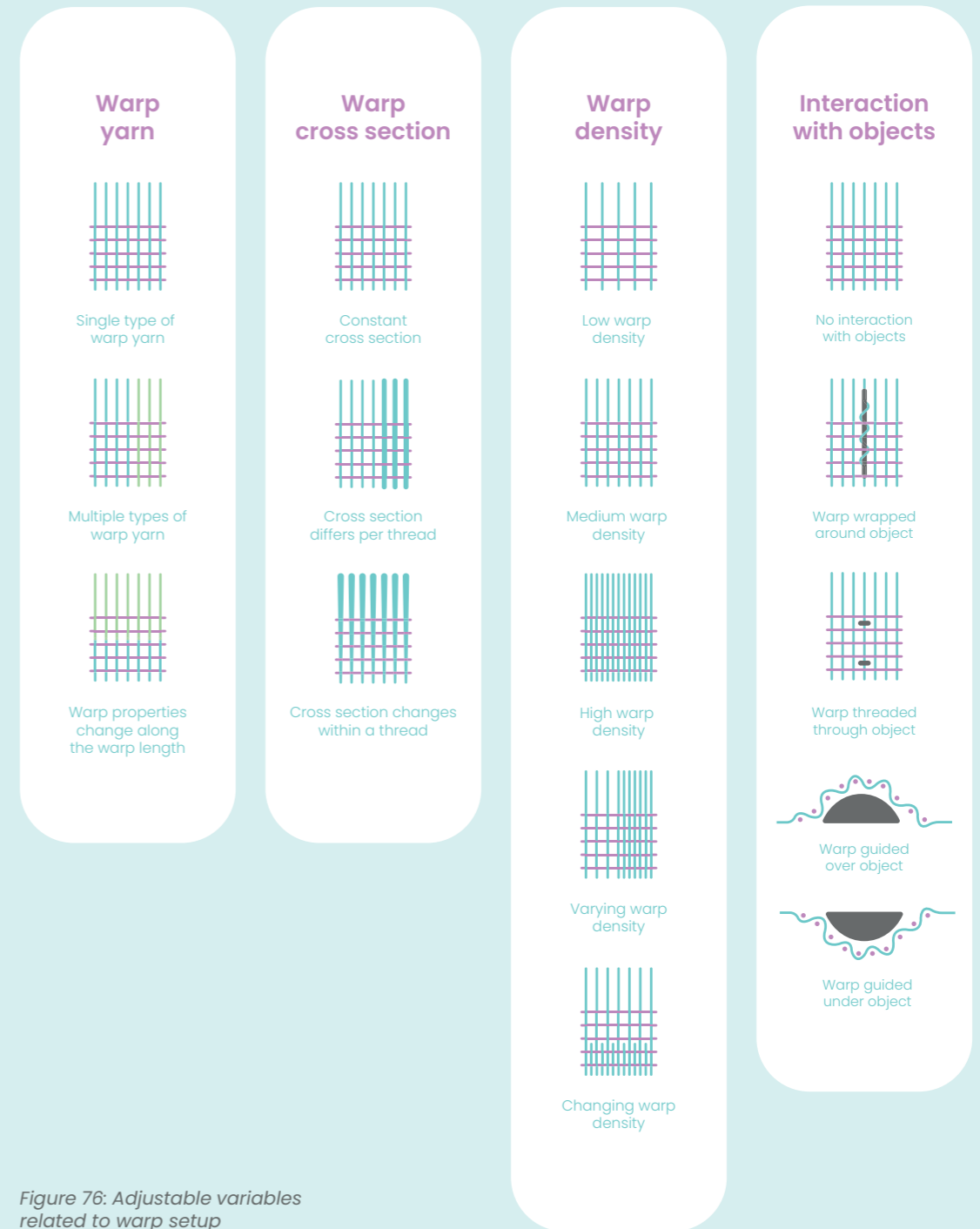


Figure 76: Adjustable variables related to warp setup

4.1.2 Warp tension

To ease the interlacement of weft threads with the warp threads, the warp threads should be tensioned. The warp threads are usually all tensioned equally from end to end, but Figure 77 also shows other possibilities.

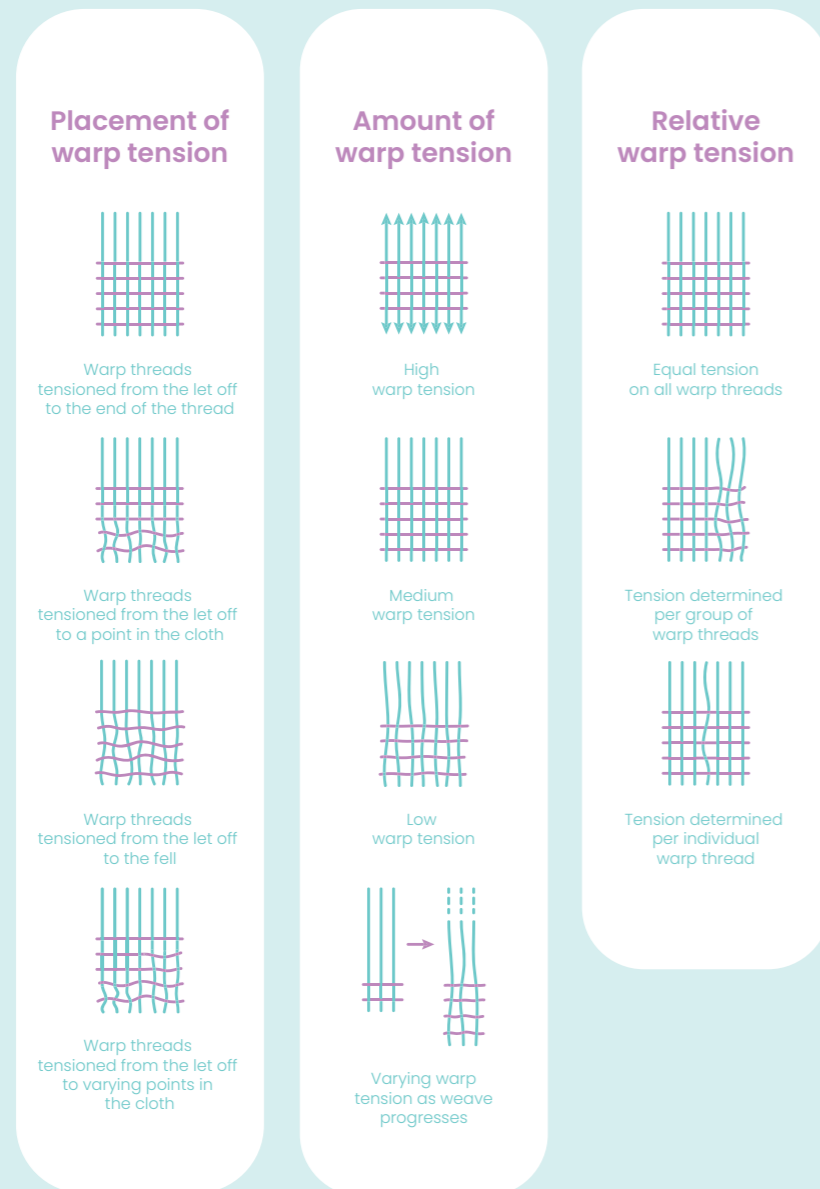


Figure 77: Adjustable variables related to warp tension

4.1.3 Weft selection

The weft is inserted row per row, leaving a lot of flexibility during the weaving process to change the weft (Figure 78).



Figure 78: Adjustable variables related to weft selection

4.1.4 Weft insertion

After the warp is shed, the weft is inserted through the created opening between the warp threads. Variables that can be changed during weft insertion can be seen in Figure 79.

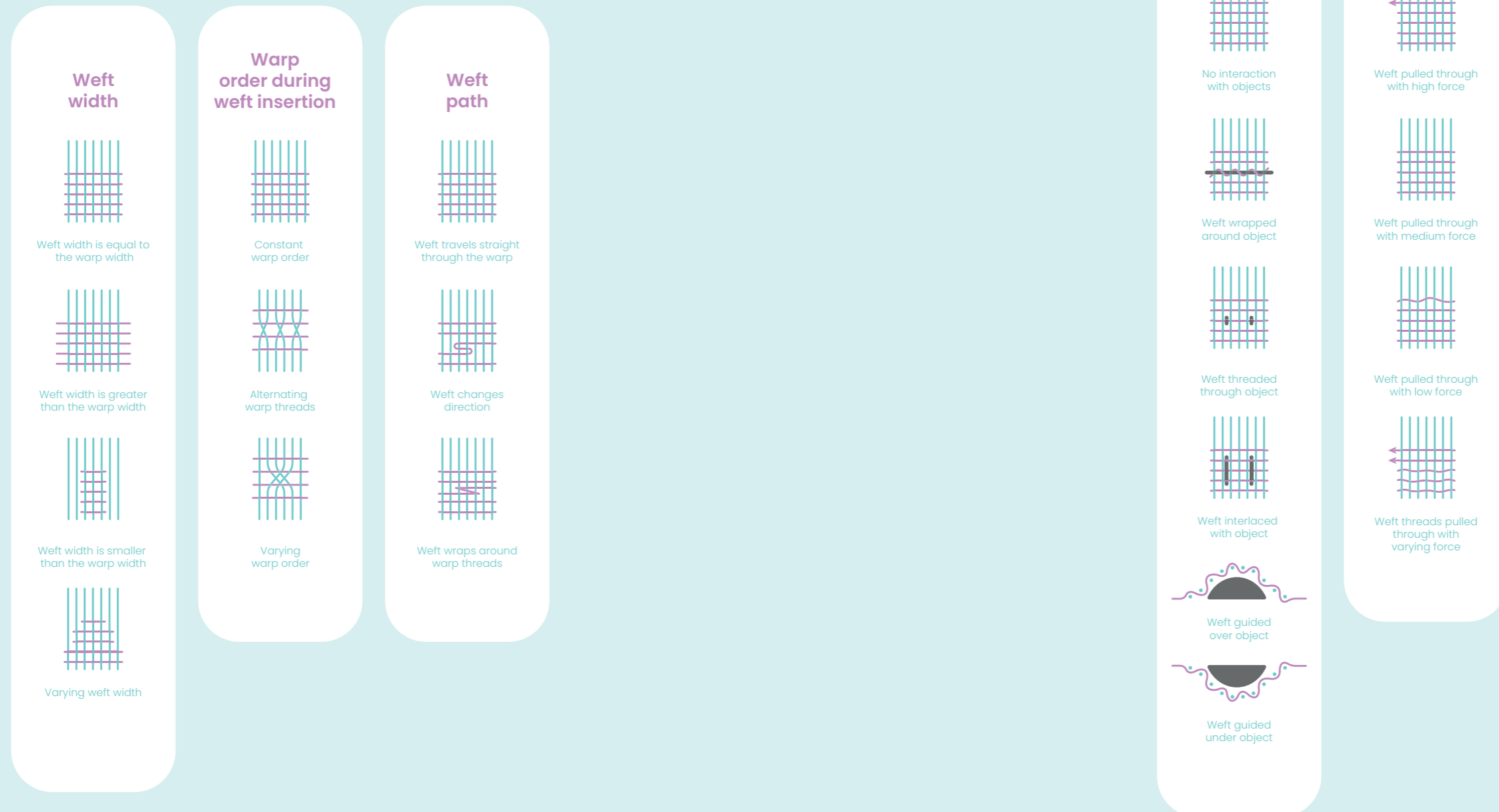


Figure 79: Adjustable variables related to weft insertion

4.1.5 Interlacement

The interlacement of warp and weft threads is the foundation of weaving. In each row, the weft thread travels over some warp threads and under others. To facilitate the interlacement of a weft thread, the warp is shed. The way the warp is shed for each row determines the weave structure. The variables related to the shedding of the warp and the resulting interlacement of the warp and the weft, can be seen in Figure 80.

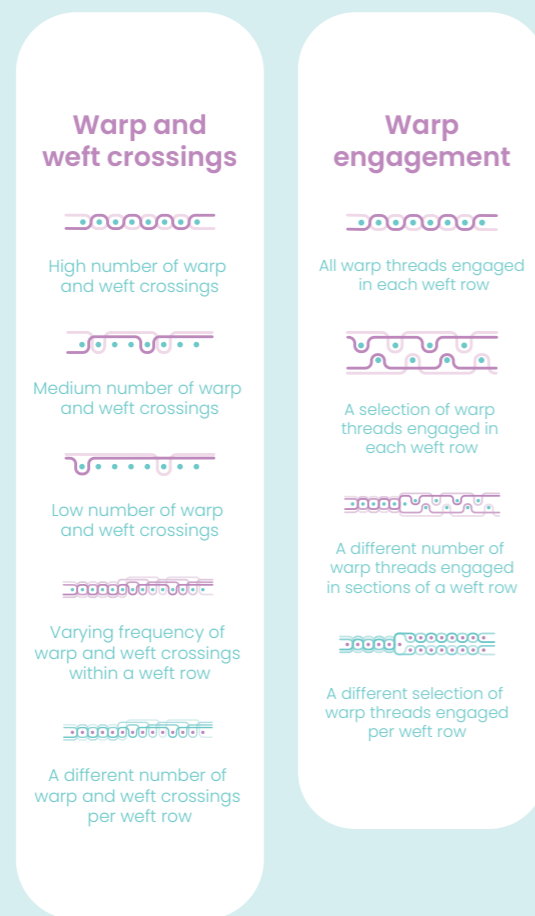


Figure 80: Adjustable variables related to warp and weft interlacement

4.1.6 Weft beat up

Once inserted, the weft needs to be pushed against the previous row to create a neat fabric. Adjustments that can be made during beat up can be seen in Figure 81.

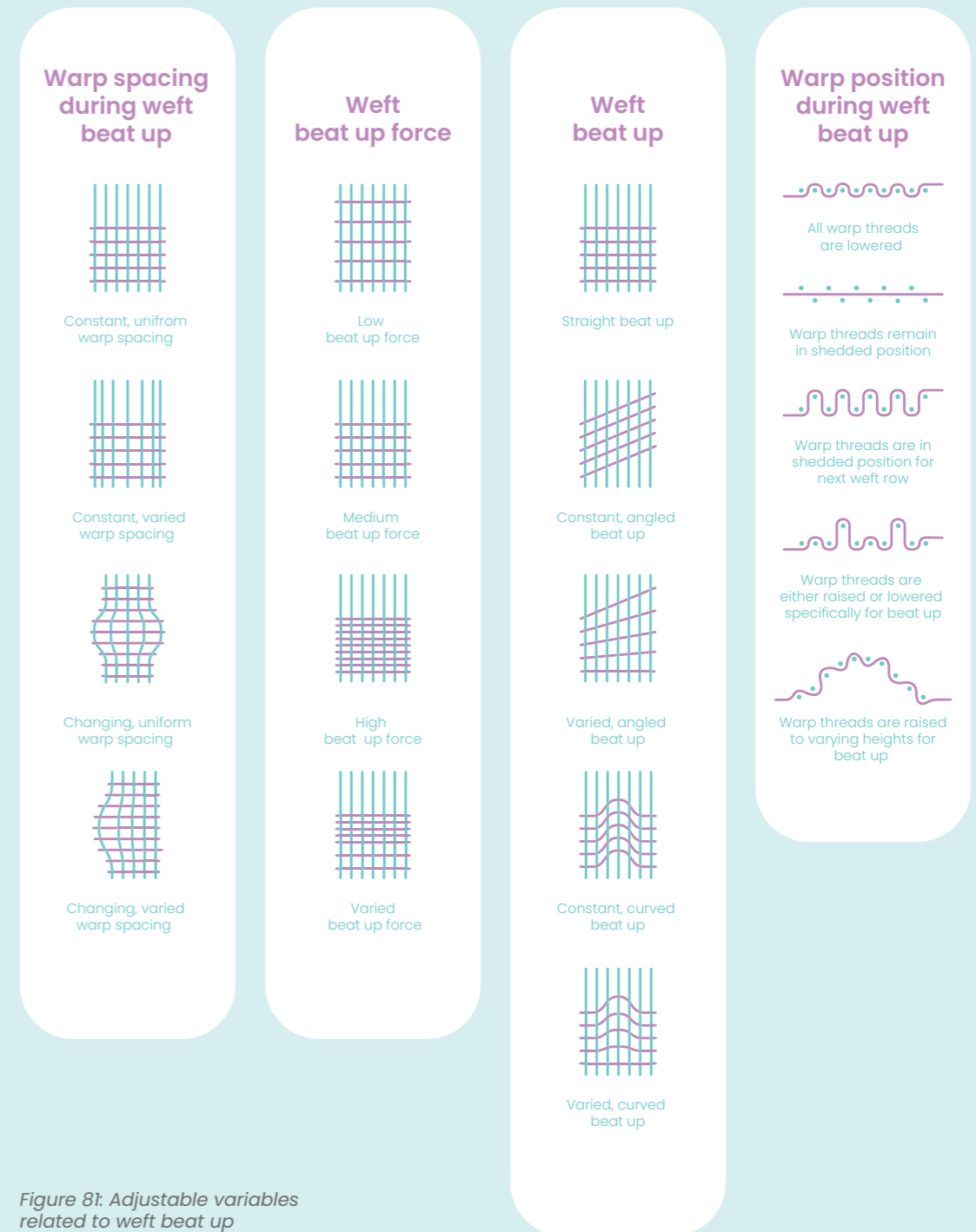


Figure 81: Adjustable variables related to weft beat up

4.1.7 Weft row interactions

Once inserted, the weft needs to be pushed against the previous row to create a neat fabric. Adjustments that can be made during beat up can be seen in Figure 82.

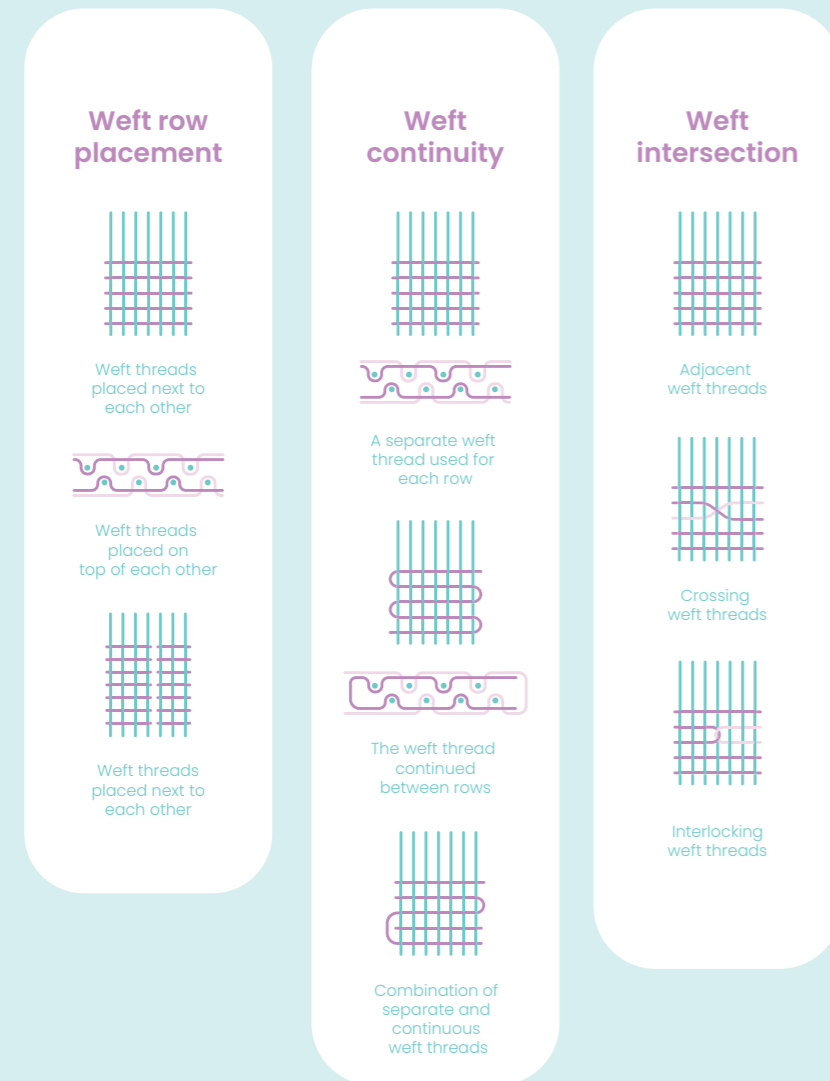


Figure 82: Adjustable variables related to weft row interactions

4.1.8 Weft tension

Unlike the warp, the weft threads do not need to be tensioned during weaving, but it might be desired in some situations. Figure 83 shows different options.

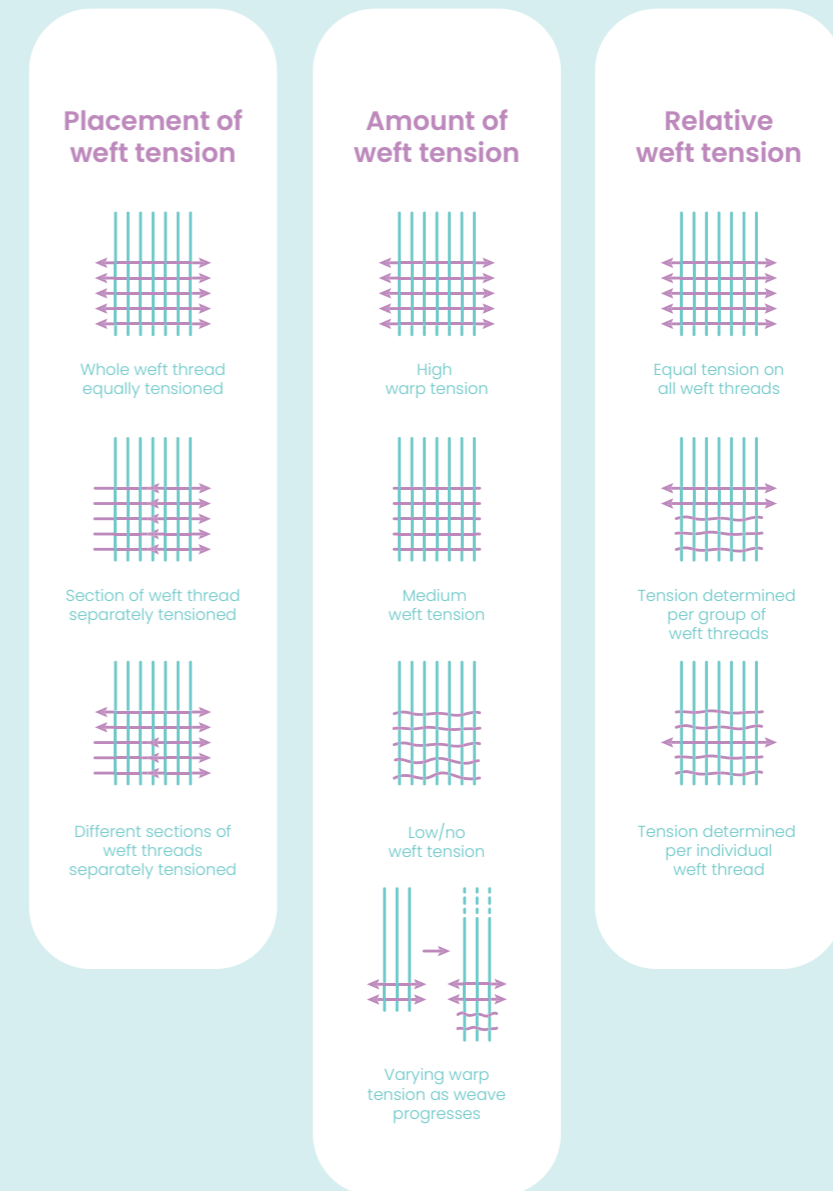


Figure 83: Adjustable variables related to weft tension

4.1.9 Warp movement

Weft rows are woven in one after another. Adjustments can be made to influence how two consecutive weft rows are placed relatively to each other or connected (Figure 84).

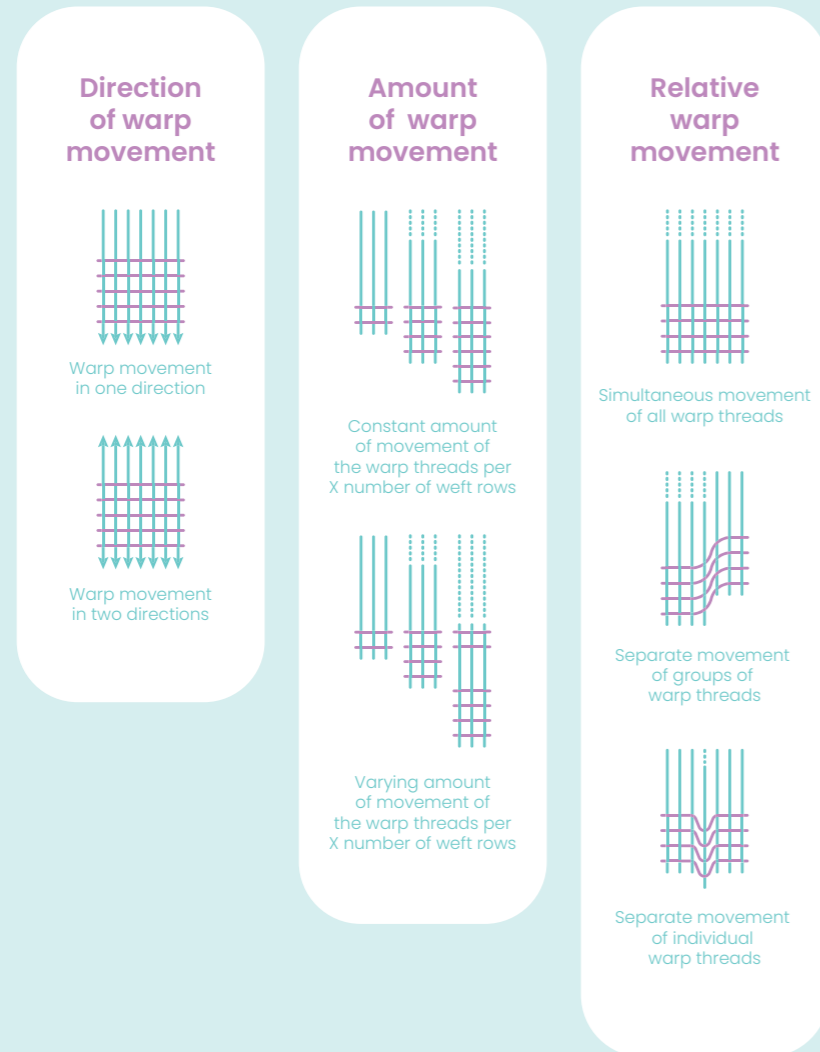


Figure 84: Adjustable variables related to warp movement

4.2 Use of taxonomy

The taxonomy, structured with categories and subcategories, serves as a guide for planning how a sample is to be woven. Figure 85 shows how an option can be selected from every category, of which the combination enables a specific sample to be woven. This enables a systematic approach in which every aspect is considered. The taxonomy was used in this research to pinpoint which variables need to be changed in order to create a 3D fabric. Figure 85 provides a sneak peak, but the methods for weaving 3D fabrics will be explained in more detail in the following chapter.

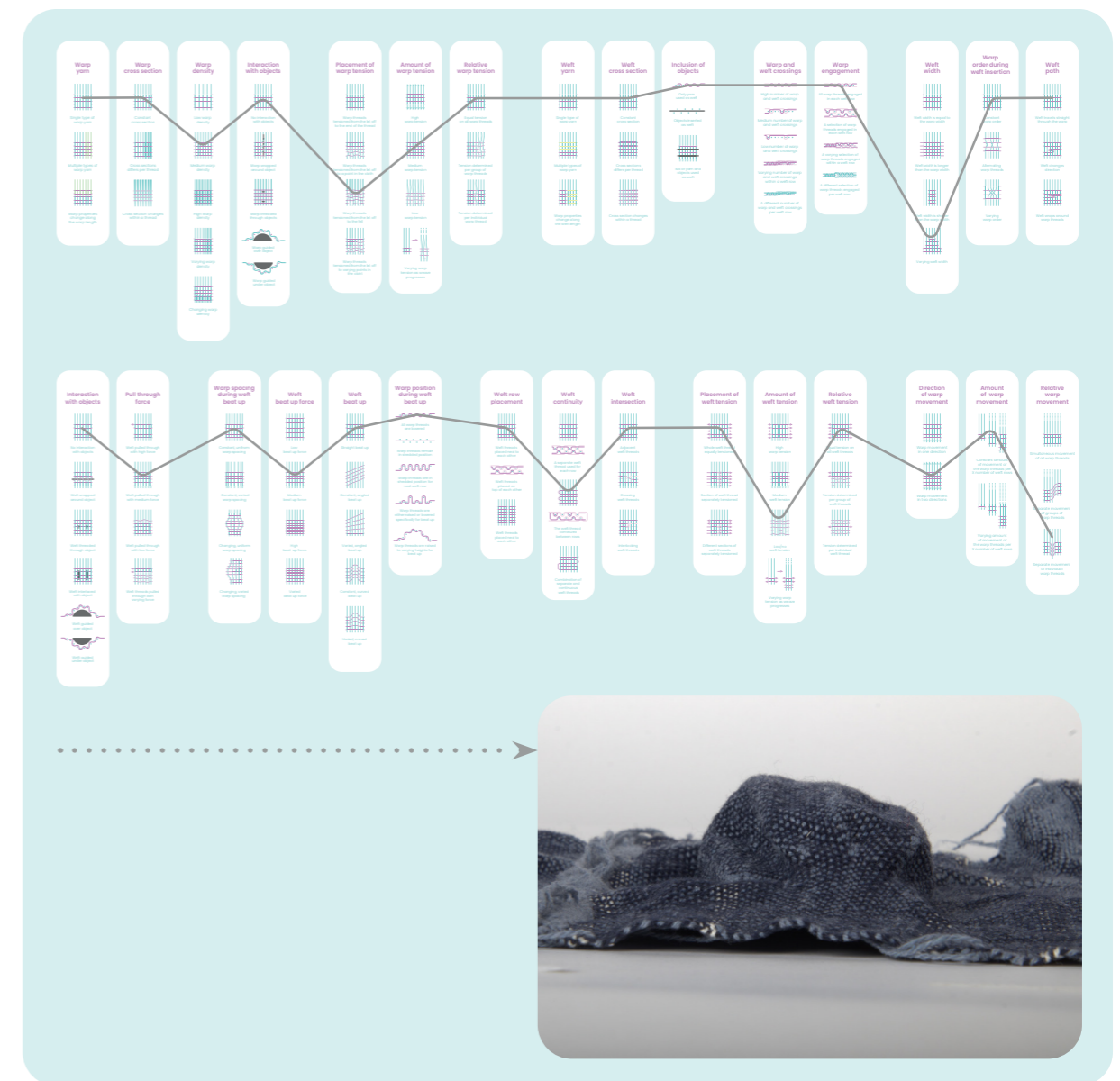


Figure 85: Example of how a option can be chosen from every subcategory to formulate a plan for weaving a specific sample



5. Methods for weaving 3D fabrics

In this chapter the way the warp and weft material needs to be placed to create a 3D fabric is explained. The taxonomy introduced in the previous chapter is used to explain existing and newly found methods for placing the weft and warp threads as required. The chapter concludes with a reflection on which methods have potential to be explored further and how the weaving process and loom need to be adjusted to facilitate these methods.

5.1 Required material distribution in 3D fabrics

3D fabrics, more specifically shell fabrics, have areas that extend out of the XY plane. This entails that the length of some weft and warp threads is longer than the distance between the endpoints of that thread along the X and Y-axis respectively. This extra length bulges up, as seen in Figure 86.

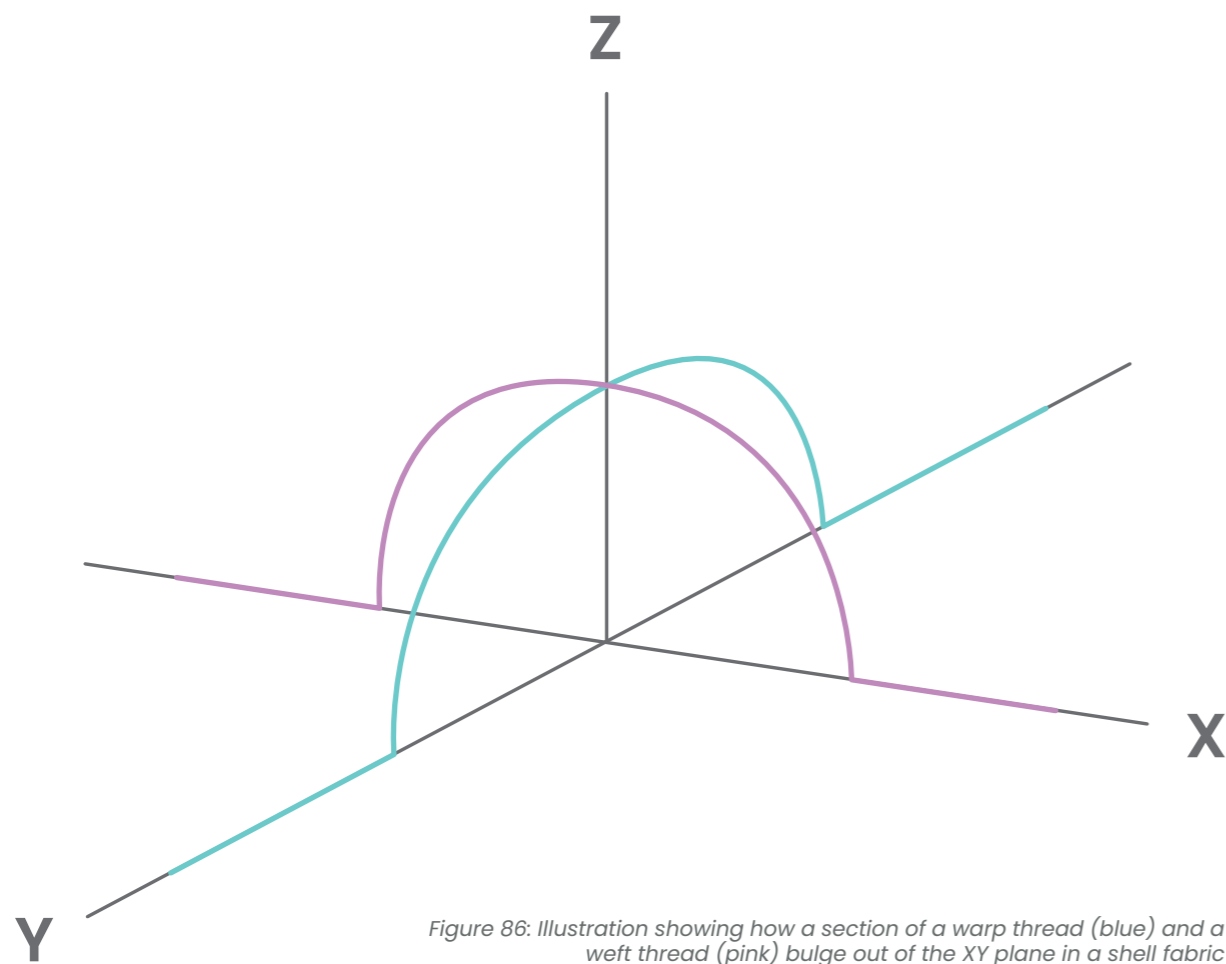


Figure 86: Illustration showing how a section of a warp thread (blue) and a weft thread (pink) bulge out of the XY plane in a shell fabric

During weaving, interlacing threads need to be distributed differently over the excess length that will bulge up in comparison to other threads that will remain flat or bulge less. Ways of placing the weft threads along the length of a bulging warp thread are shown in Figure 87.

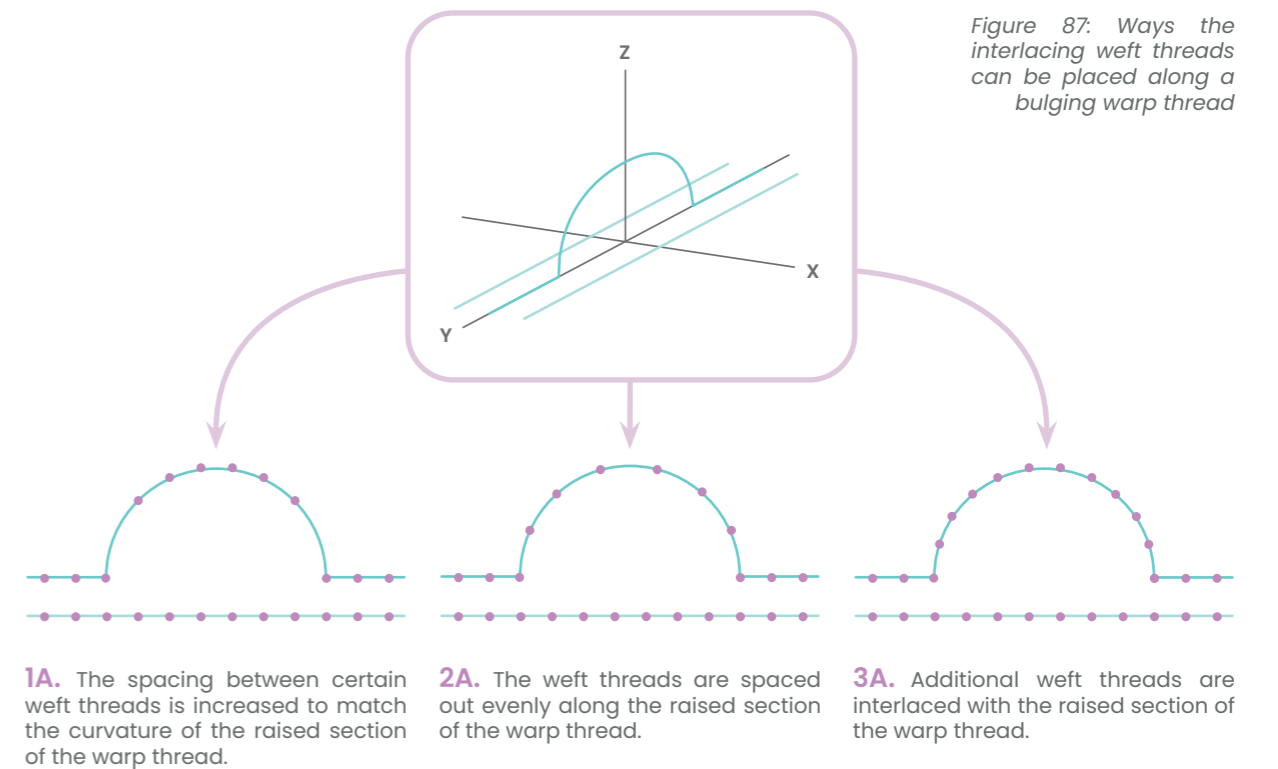


Figure 87: Ways the interlacing weft threads can be placed along a bulging warp thread

- 1A.** The spacing between certain weft threads is increased to match the curvature of the raised section of the warp thread.
- 2A.** The weft threads are spaced out evenly along the raised section of the warp thread.
- 3A.** Additional weft threads are interlaced with the raised section of the warp thread.

Figure 88 shows how the interlacing warp threads should be placed interlacing along a bulging weft thread.

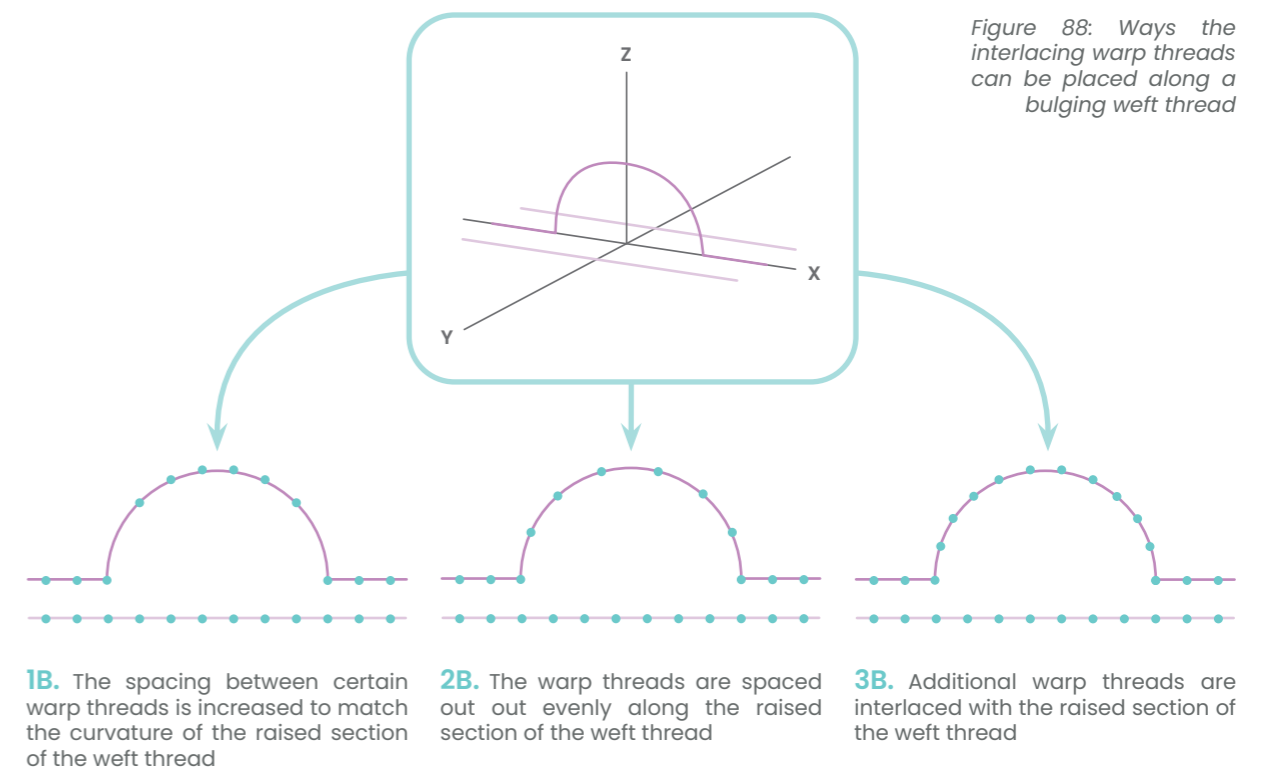


Figure 88: Ways the interlacing warp threads can be placed along a bulging weft thread

- 1B.** The spacing between certain warp threads is increased to match the curvature of the raised section of the weft thread
- 2B.** The warp threads are spaced out evenly along the raised section of the weft thread
- 3B.** Additional warp threads are interlaced with the raised section of the weft thread

To create a shell fabric, both warp and weft threads need to curve out of the fabric plane. How the interlacing threads are placed along the length of the curving threads can be determined separately for the warp and the weft. Different combinations lead to fabrics with different distributions of crossing points, as seen in Figure 89.

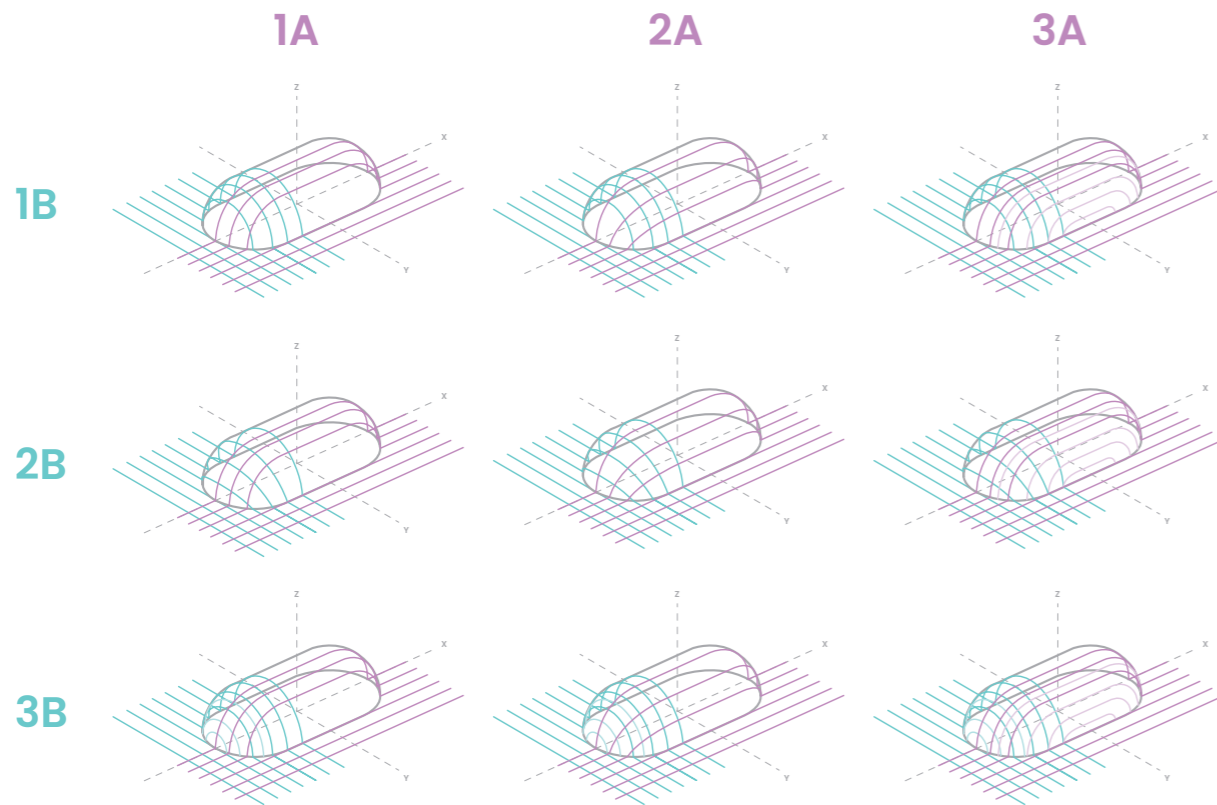


Figure 89: Overview of how different combination of methods for placing the warp and the weft threads respectively leads to different distributions of crossing points

5.2 Methods for weaving 3D fabrics

Ways in which the material placement in a 3D fabric can be achieved by adjusting variables within the weaving process are described in the following section.

5.2.1 Material placement

As explained above, in order to manipulate warp and weft threads to rise out of the fabric plane, the placement of the interlacing threads along the section of the warp or weft thread that needs to bulge up must be adjusted.

Using the taxonomy as a guide, ways in which variables could be used and combined to achieve different placements of interlacing threads have been defined. Some of these methods have been explored by other researchers, as explained in Chapter 3, while others newly came forth from experimentation with the taxonomy.

Changing the weft spacing

In Figure 90 to 92 methods for changing the weft spacing are described using the taxonomy. For each method the way the most important variables need to be changed is explained.

Curving the weft during beat up

Vary the angle or curve of the weft threads during beat up with a variable reed.

(Cnaani & Sterman, 2023)
(Koppelman & Campman, 1964)

Weft
beat up

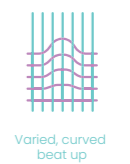


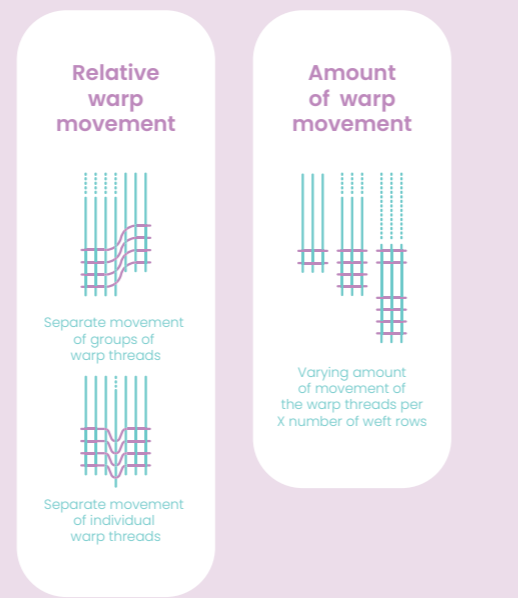
Figure 90: Changing the weft spacing by curving the weft during beat up

Curving the weft by moving the warp threads individually

Move individual or groups of warp threads forward along the Y-axis at different speeds. The interlacing weft threads will be pulled into a curve, influencing the spacing between the curved thread and a following weft thread beaten in straight.

(Koppelman & Campman, 1964)

Figure 91: Changing the weft spacing by moving the warp threads

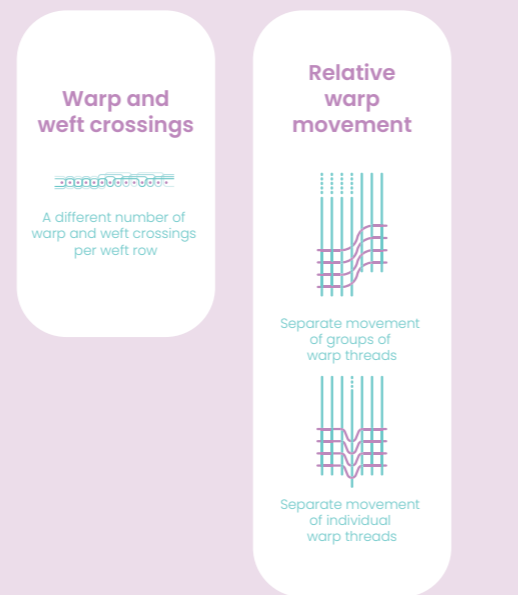


Using weave structures to change the weft spacing

Influence how the warp threads travel over and under the weft threads by changing the weave structure. If the warp thread crosses from over to under between two adjacent weft threads, the threads are pushed apart. If the warp stays under or above both weft threads, the threads can move closer together. The differences in spacing of the weft threads results in a curved fell. With a normal reed, each weft thread is beat up straight. Beating up a straight weft against a curved fell would result in unwanted gaps between the weft threads. Therefore, the fell should be straightened by moving individual or groups of warp threads forward.

(Busgen, 1999)

Figure 92: Changing the weft spacing by changing the weave structure



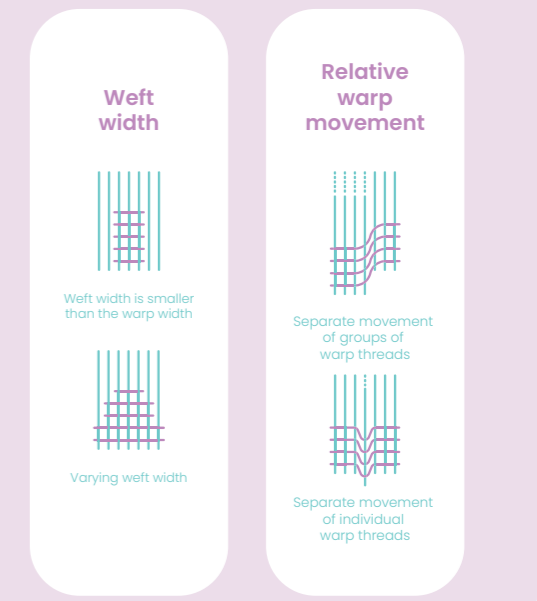
Interlacing additional weft material

In Figure 93 to 96 methods for interlacing additional weft material with specific warp threads are explained.

Interlacing discontinuous weft rows

Weave in discontinuous weft rows to vary the number of weft threads each warp thread interacts with. To keep the fell straight to avoid unwanted gaps between weft threads, the interlaced warp threads should be moved forward individually or in groups.

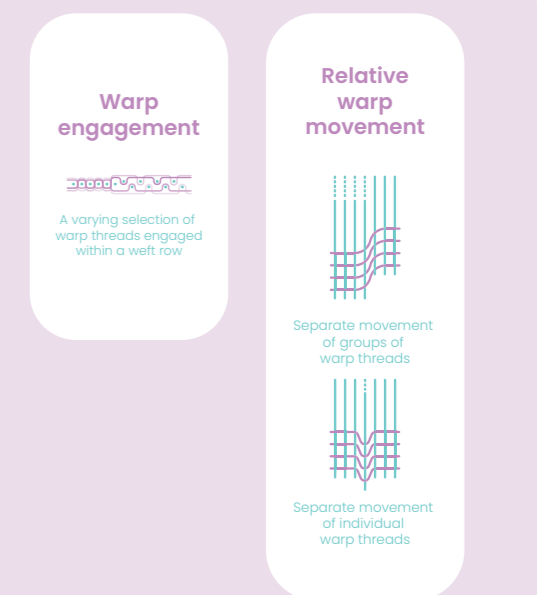
Figure 93: Interlacing additional weft material with some warp threads using discontinuous weft



Dividing the warp and weft over multiple layers

Within a weft row, change whether all the warp threads or only a selection of the warp threads are engaged. By changing which warp threads are engaged in each weft row, the number of weft threads each warp thread interacts with is influenced. To keep the fell straight the interlaced warp threads should be moved forward individually or in groups.

Figure 94: Interlacing additional weft material with some warp threads using multi-layer weaving



Manipulating the weft path

Change the path of the weft so that it doubles back in the warp in order to influence how often each warp thread interacts with the weft. To keep the fell straight the interlaced warp threads should be moved forward individually or in groups.

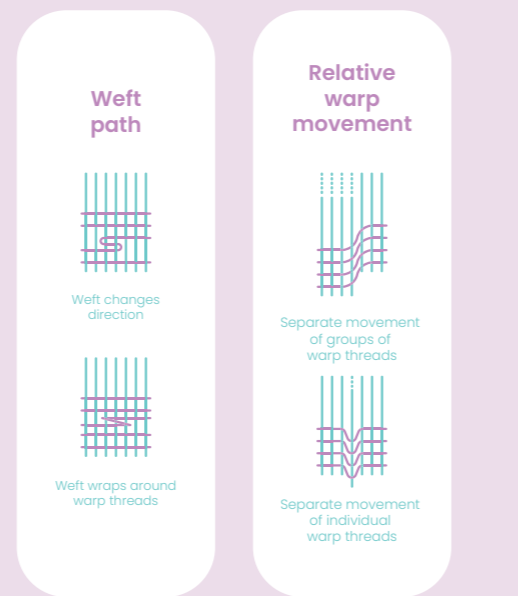


Figure 95: Interlacing additional weft material with some warp threads by changing the path of the weft

Using weft threads with a varying cross section

Weave in different types of weft threads, including some that have a changing cross section. While the number of threads is technically not increased, the amount of material in some areas is. To keep the fell straight the interlaced warp threads should be moved forward individually or in groups.

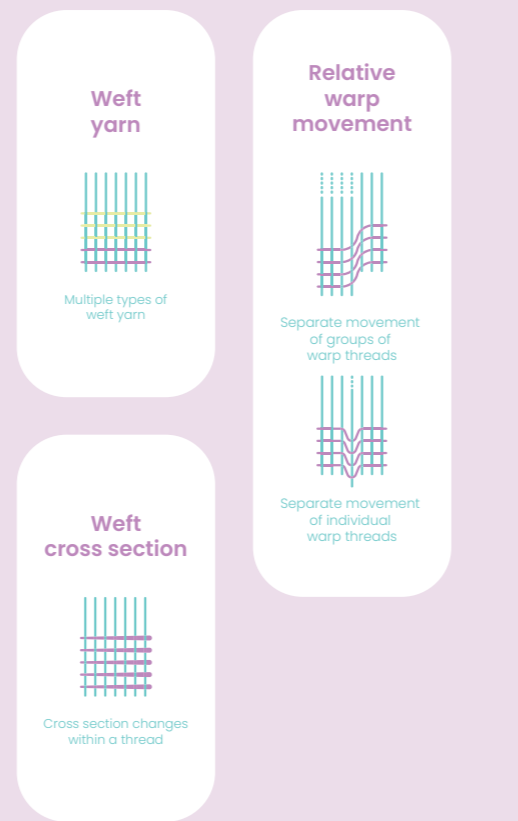


Figure 96: Interlacing additional weft material with some warp threads by using weft with varying cross sections

Changing the warp spacing

In Figure 97 to 99 methods for changing the weft spacing are described using the taxonomy. For each method the way the most important variables need to be changed is explained.

Using weave structures to change the warp spacing

Influence how the weft threads travel over and under the warp threads. If the weft thread crosses from over to under between two adjacent warp threads, the threads are pushed apart. If the weft stays under or above both warp threads, the threads can move closer together.

(Busgen, 1999)

Figure 97: Changing the warp spacing by changing the weave structure

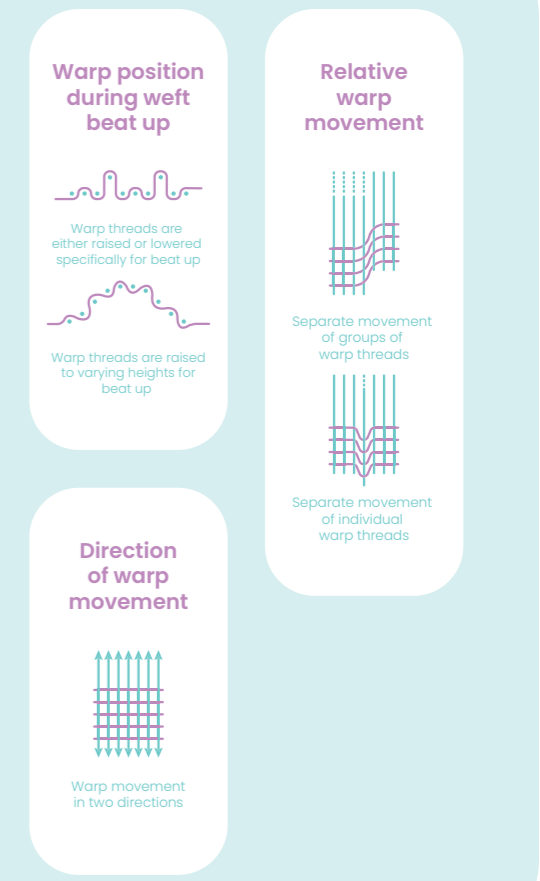


Lifting up warp threads during beat up

Lift up the warp threads during weft beat up to increase the distance between warp threads. Lifting up warp threads requires separate movement of warp threads, if the elasticity of the thread is not sufficient. When the warp threads are lowered again, the extra length moved forward needs to be pulled back again to restore equal tension.

(Kühi, 2013)

Figure 98: Changing the warp spacing by lifting up warp threads during beat up



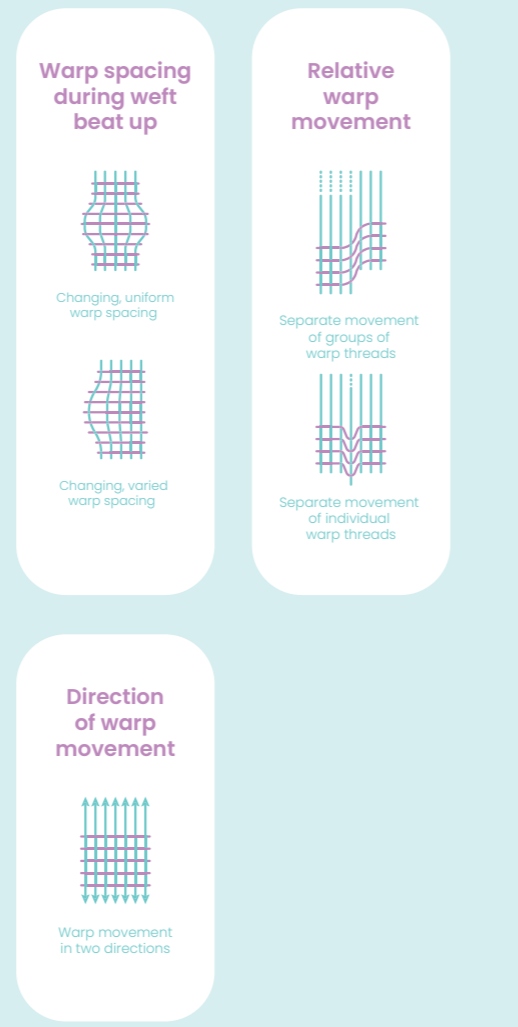
Changing the warp spacing during beat up

Change the spacing between the warp threads during weft beat up using variable reeds, in order to influence the total length of the weft and the distribution of the weft length over the warp threads. As the spacing between warp threads is increased, the distance the threads have to travel to the fell is also increased, requiring separate movement of warp threads. When the spacing is brought back to neutral, the extra length moved forward needs to be pulled back again.

Separate movement of the warp threads is not required if the warp threads have enough elasticity to compensate for the extra distance.

(Bhattacharya & Koranne, 2012)
(Busgen, 1999)

Figure 99: Changing the warp spacing by pushing apart the warp threads during beat up



Interlacing additional warp material

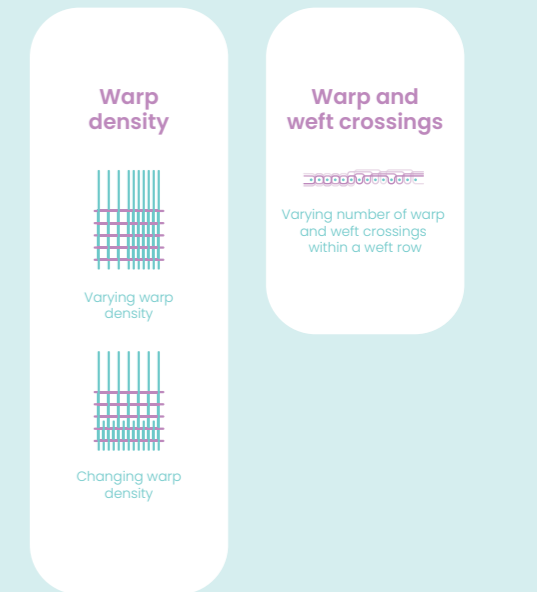
In Figure 100 to 102 methods for interlacing additional warp material with specific weft threads are explained.

Changing the number of warp threads on the loom

Add additional threads in areas while setting up the loom or remove/add warp threads throughout the weaving process. The spacing between all the warp threads should be equalized along the length of the weft thread to achieve a bulging effect. To achieve equal spacing in the areas with additional threads in comparison to the rest of the fabric, the frequency of warp and weft crossings can be increased to push the threads apart.

Changing the frequency of warp and weft crossings is not necessary if the thickness of the weft itself is enough to push the warp threads apart in areas with a higher warp density.

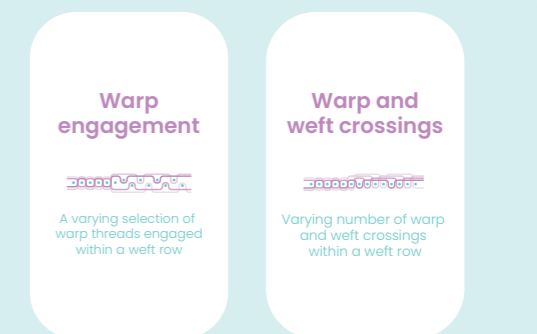
Figure 100: Interlacing additional warp material with some weft threads by placing the thread on the loom



Dividing the warp and weft over multiple layers

Manipulate the weft thread to engage more warp threads in some areas than in others. To achieve equal spacing in the areas with additional threads in comparison to the rest of the fabric, the frequency of warp and weft crossings can be increased to push the threads apart.

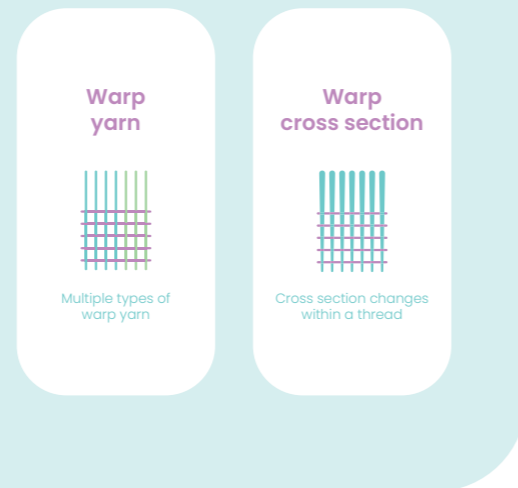
Figure 101: Interlacing additional warp material with some weft threads using multi-layer weaving



Using warp threads with a varying cross section

Use different types of warp threads, including some that have a changing cross section. While the number of threads is technically not increased, the amount of material in some areas is.

Figure 102: Interlacing additional warp material with some weft threads by using warp with varying cross sections



5.2.2 Warp tension

The length of a bulging thread within a shell fabric must be longer than that of a thread that lies flat. In most of the methods described above this extra length is embedded in the fabric during the weaving process by varying how much each warp thread is moved forward along the Y-axis between weft insertions.

Typically, the warp threads in the woven cloth, or at least a section of it, remain under tension while the fabric is on the loom. The tension keeps the warp threads straight and flat. When the warp threads are moved relatively to each other along the Y-axis, the interlaced weft threads must curve and stretch to accommodate for the additional distance between their crossing points with the warp threads. For example, Figure 103 shows a situation in which the center warp threads have been moved forward in varying amounts to allow for the interlacement of additional discontinuous weft threads. The weft threads that were woven in prior to the warp threads moving have been stretched into a curve because of the warp movement. When the tension on the warp threads is released, the curved weft threads will be able to relax and straighten. The additional lengths of warp that have been moved forward will be pushed up, resulting in the desired 3D fabric.

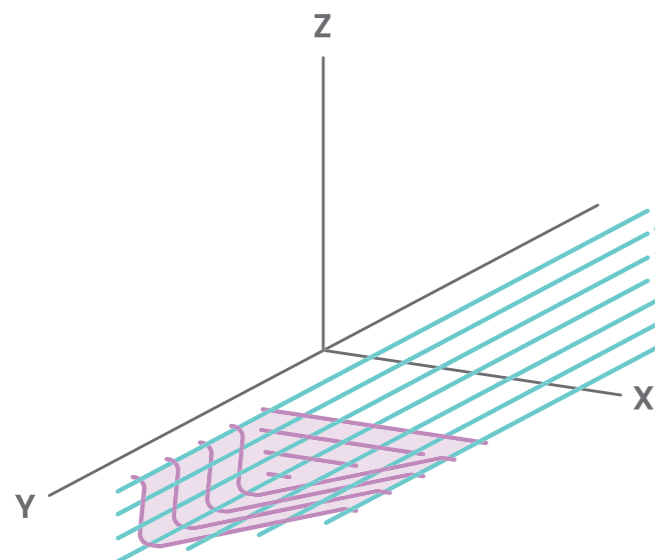


Figure 103: Illustration of loom setup in which the warp threads and the woven cloth are tensioned. The center warp threads were moved forward to make room for discontinuous weft rows, causing previous weft rows to curve and stretch

Although shell fabrics can be created despite the woven cloth being under tension while on the loom, the size and shape of the 3D fabric is limited by how much the weft threads can be stretched and how much tension they can withstand. It is therefore interesting to look at alternative placements of tension on the warp, besides tensioning the full warp threads. Different options are described in the taxonomy (Figure 104).

The option to solely tension the warp threads up to the fell is especially interesting. The unwoven part of the warp threads needs to be tensioned to effectively shed the warp and beat up the weft threads. No tension however, is required on the woven cloth behind the fell. Removing the tension on the cloth allows the warp and weft threads to bulge and curve as they naturally would. If additional weft threads were interlaced and warp threads were moved forward in the same manner as described in the example above, but this time without keeping the woven cloth tensioned, the 3D shape of the envisioned shell fabric would emerge immediately on the loom. This can be seen in Figure 105.

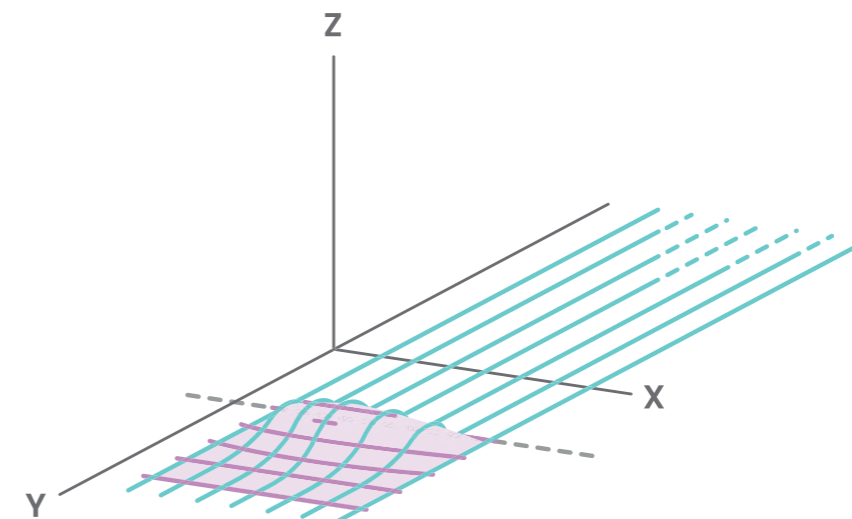


Figure 105: Illustration of loom setup in which the warp threads are tensioned up to the fell and the woven cloth is untensioned. The center warp threads were moved forward to make room for discontinuous weft rows, causing the warp and interlaced weft threads to bulge up

Placement of warp tension

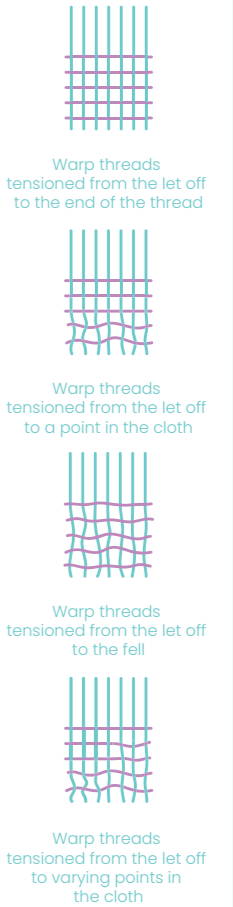


Figure 104: The different ways of tensioning the warp threads

The tensioned unwoven warp threads behind the straight fell provide a clean slate. The previously woven cloth puts no limitations on what can be woven. It was therefore concluded that tensioning the warp solely up to the fell is essential for having a high degree of form freedom in shell weaving.

5.3 Facilitating the methods for weaving 3D fabrics

As described above, weaving 3D fabrics requires adjustment to the placement of warp and weft threads, and benefits from removing any tension on the woven cloth. To facilitate the presented methods, changes need to be made to the weaving process and the loom.

5.3.1 Possibilities and limitations of current looms

The methods for changing the warp placement along a weft thread, and as a result the weft length in areas, are already quite accessible. For example, available reeds or weave structures can be used to change the warp spacing, and multi-layer weave structures can be utilized to change the number of warp threads interlaced with certain weft threads. On the other hand, manipulating a warp thread to rise out of the fabric plane by changing the weft spacing or inserting additional weft threads requires adjustments to the weaving process that are not typically possible on a loom.

The only relatively accessible method for raising up warp threads is changing the curvature of the weft thread during beat up, but even this method requires a specialized variable reed, such as the one presented by Cnaani & Sterman (2023), which is not readily available. Besides, this method relies on the warp and weft threads remaining flat and tensioned during weaving and jumping into shape once the fabric is taken off the loom, which limits the possibilities for 3D shaping. In addition, changing the curvature of the weft to influence the spacing has a big influence on the integrity of the fabric and is therefore not preferred.

All the other methods for manipulating a warp thread to rise up require individual movement of the warp threads. Unfortunately, this is not possible on most looms. In addition, the woven cloth is usually kept tensioned on the loom, restricting the warp threads from bulging up. The tension on the warp threads in the woven cloth also results in the methods for raising weft threads having limited effect, because the flat and tensioned warp threads will keep the interlaced weft threads down. In comparison, adjusting the loom and the weaving process to enable warp threads to bulge up would result in the weft threads also rising up, due to them being pulled along by the interlaced warp threads. If the methods for raising weft threads are simultaneously applied, the length of the weft thread and the placement of warp threads along that length can be adjusted to the desired 3D shape, but weaving a 3D fabric can already be achieved without doing so.

In conclusion, the inability of warp threads to rise up while the fabric is on the loom seems to be the biggest barrier to weaving 3D fabrics. A focus was therefore placed on adjusting the weaving process and loom to facilitate the presented methods for raising up warp threads without restricting the implementation of already accessible methods for adjusting the weft length to the desired fabric form.

5.3.2 Adjustments to the weaving process

In Chapter 5.2.1 different methods were described to manipulate a warp thread to rise up out of the fabric plane. Of these methods, interlacing additional weft material with some of the warp threads is especially interesting, because it enables the creation of a fabric with a constant density. In Figure 106 the steps required to force a warp thread to bulge up by interlacing discontinuous weft rows and moving individual warp threads are described. The previously woven cloth is not tensioned in this situation.

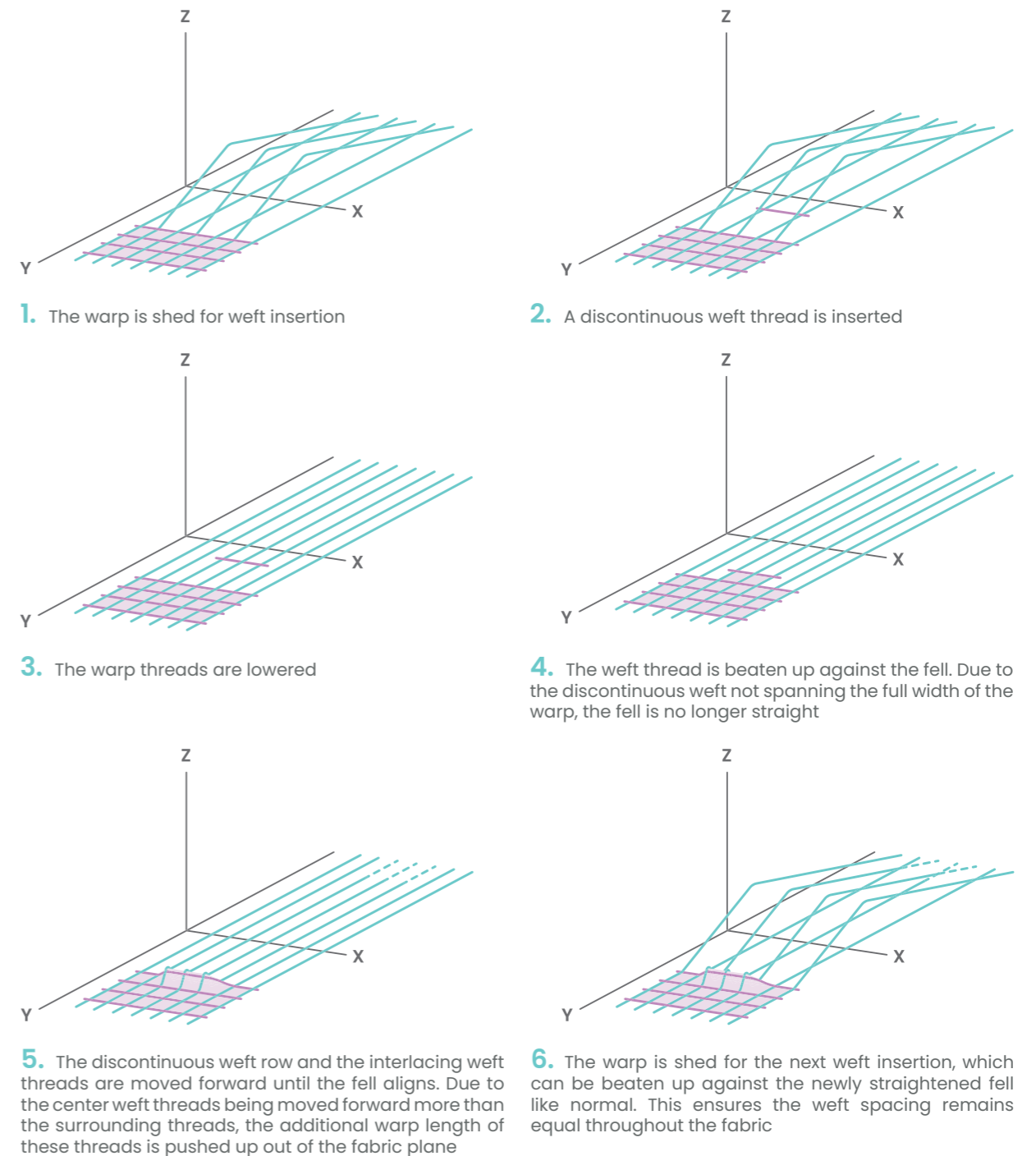


Figure 106: Illustrated weaving process of forcing a warp thread to bulge up by interlacing discontinuous weft rows

The example in Figure 106 shows how discontinuous weft rows can be used for shell weaving. However, as explained in Chapter 5.2.1, there are other ways of distributing the weft threads differently over some of the warp threads. Each of these methods results in a curved fell (Figure 107). Straightening each of these fells would cause the interlaced warp threads to be pulled forward along the Y-axis in the same manner as described above.

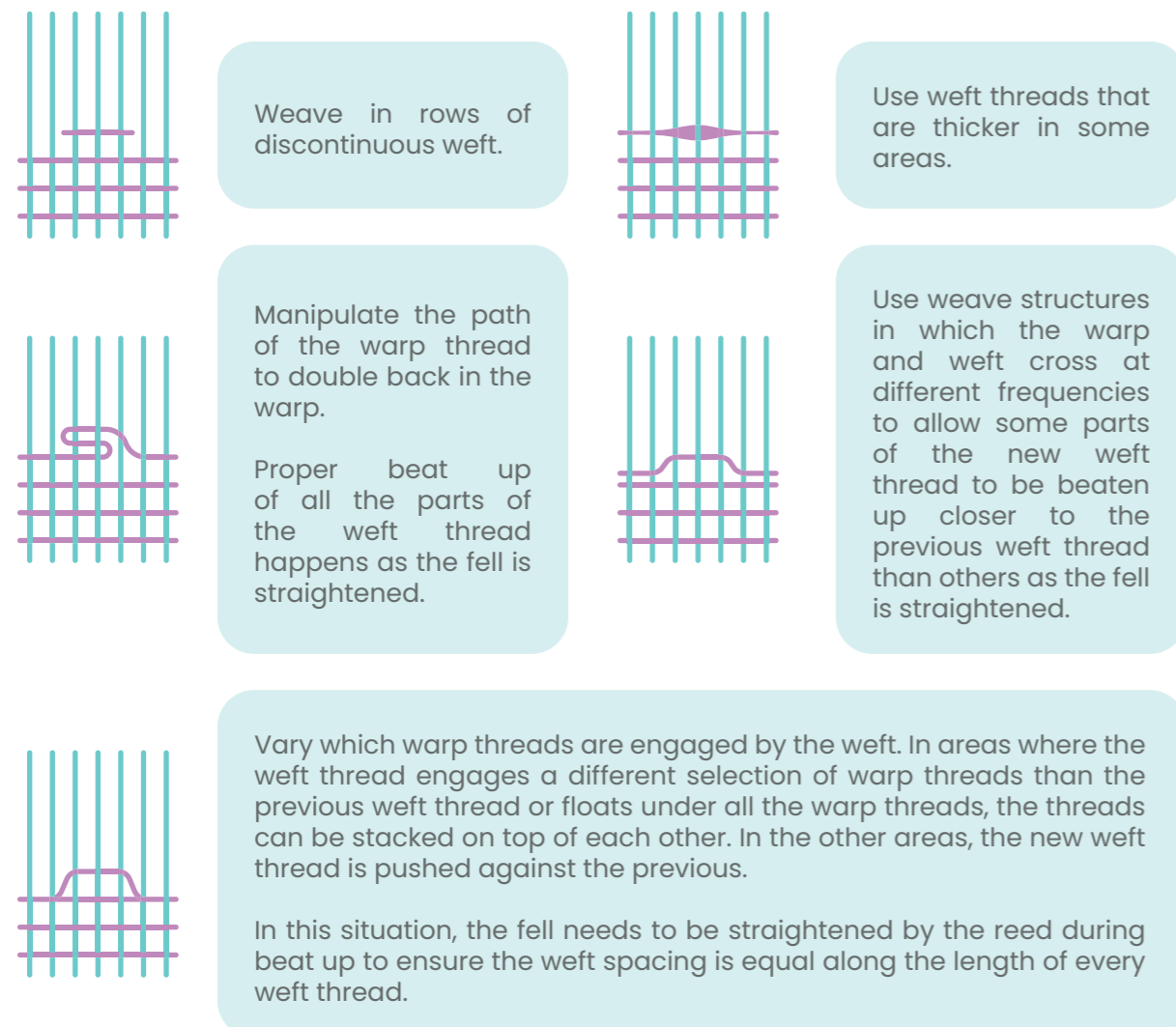


Figure 107: Overview of different methods for distributing the weft material differently over some warp threads, which all result in a curved fell

5.3.3 Need for an add-on

As explained in Chapter 3.4.3 some looms have been developed or adjusted for weaving 3D fabrics, but they are complex and inaccessible. In addition, tensioning the warp solely up the fell has not been explored at all.

Instead of looking into the development of a completely new type of loom, adding the functionalities required for shell weaving to existing prototyping looms would make shell weaving significantly more accessible for research and experimentation. The process of designing an add-on to provide the loom with the necessary capabilities will be described in the following chapters.



6. Designing an add-on

To put the theorized methods for creating shell fabrics into practice, concepts for a loom add-on were developed and tested through prototyping on a rigid heddle loom. These concepts were analyzed to decide how to best proceed in building a large-scale prototype for a Louët Magic Dobby Electronic shaft loom.

This research encompasses only the initial phase of development of the add-on and therefore mainly focused on finding ways to provide the add-on with the required functionalities to weave 3D fabrics.

6.1 Looms

The goal of this research is to put the theorized methods for weaving 3D fabrics to the test on the Magic Dobby loom. However, in order to quickly test ideas a small rigid heddle loom was designed and built. Both types of looms are explained below.

6.1.1 Rigid heddle loom

The rigid heddle loom can be seen in Figure 108. The heddle only facilitates plain weave: half of the warp threads are either raised or lowered by the rigid heddle. The beams of the loom can easily be taken out, making room for alternative or additional parts. Furthermore, extra bolt holes were added to the side to allow easy attachment of components. This provided flexibility for prototyping.

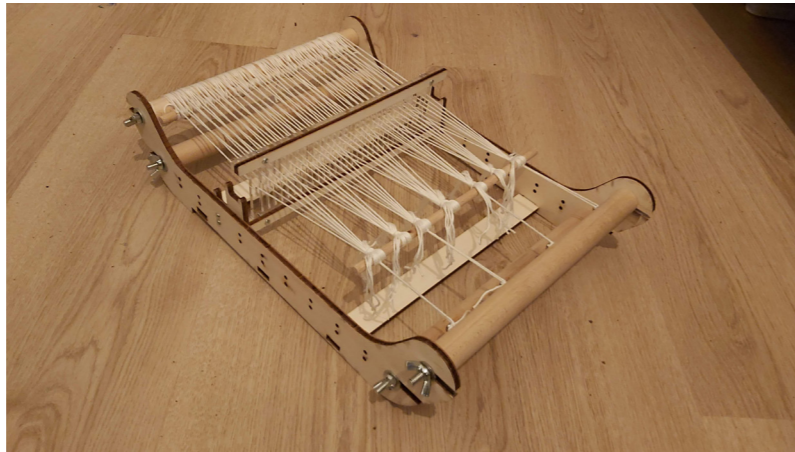


Figure 108: Rigid heddle loom

6.1.2 Magic Dobby loom

A Louët Magic Dobby Electronic loom with a 70cm weaving width was available for this research (Louët, n.d.). The loom can be seen in Figure 109. The Magic Dobby loom has 24 shafts which can be controlled using a computer and different weaving software. Interesting for this project is the fact that additional warp beams can be added to the Magic Dobby loom. For this research, three warp beams were available.



Figure 109: Louët Magic Dobby Electronic loom

6.2 Add-on requirements

To facilitate the shell weaving process, the add-on must give certain extra functionalities to the loom (Figure 110), without restricting the loom's main function: shedding the warp for weft insertion. The add-on must enable the following:

1. Movement of the warp threads relative to each other in both directions along the Y-axis
2. Movement of the weft threads and their interlaced warp threads as required to restore a straight fell, meaning the last intersection point of every warp thread with a weft thread lies on a common line parallel to the X-axis
3. Placement of tension on the unwoven warp threads up to the fell while keeping the fell straight and in place at a specific point along the Y-axis

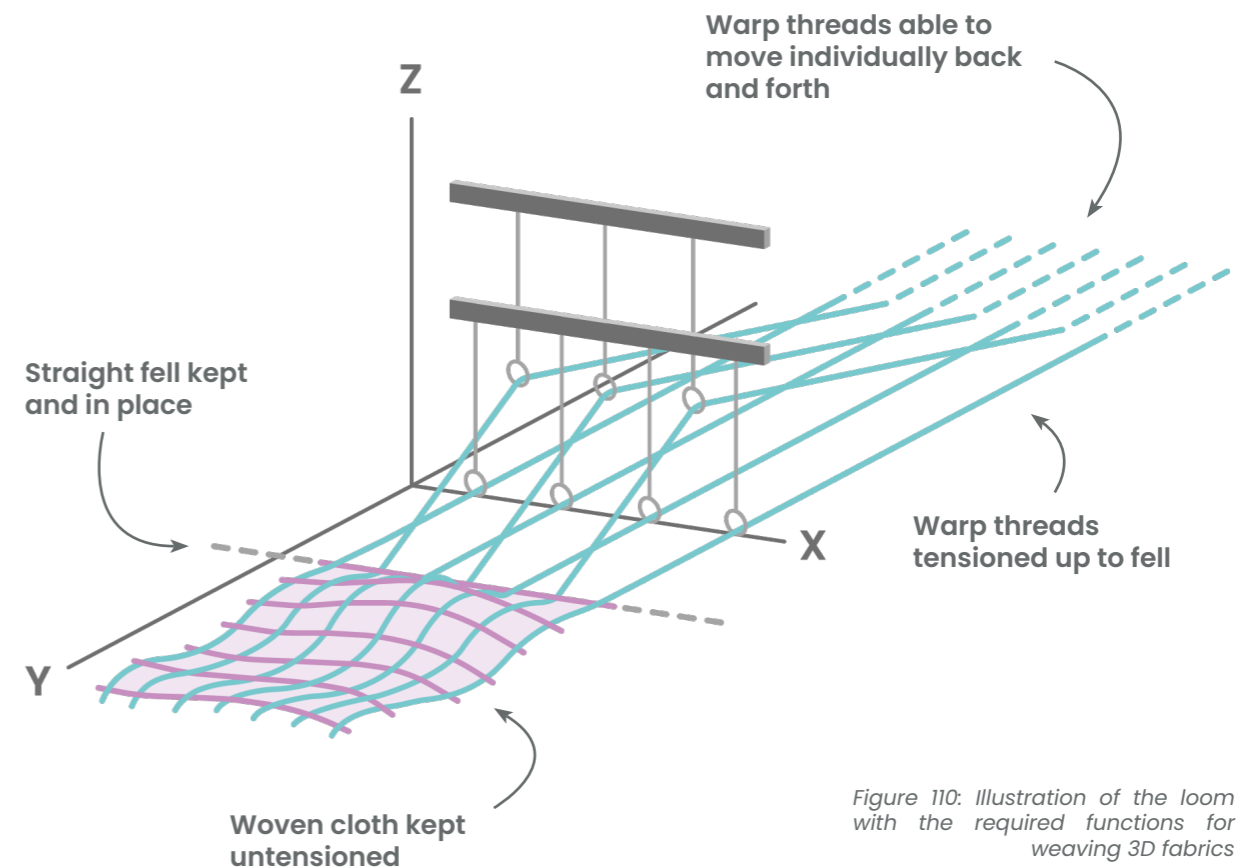


Figure 110: Illustration of the loom with the required functions for weaving 3D fabrics

The add-on is designed to be used on a Louët Magic Dobby shaft loom, requiring the following to be possible:

4. Attachment of the add-on to a Louët Magic Dobby loom without requiring permanent alterations to the loom

For the purpose of this research the loom has been warped with cotton yarn. Relatively thick yarn and a medium warp density was chosen in order to create larger samples while keeping the number of threads that need to be moved or manipulated individually manageable. The minimum tension was determined based on what the researcher observed to be a suitable tension for weaving when the warp and cloth beams were used to tension the warp threads on the Magic Dobby loom.

At a minimum, the add-on should function with the warp setup used for this research and should therefore:

5. Accommodate at least 240 warp threads
6. Accommodate a warp density of at least 8 ends per cm
7. Accommodate a warp tension of at least 0.30N

To weave 3D forms, it must be possible to use the add-on in combination with other weaving techniques. The following must be possible while using the add-on:

5. Varying the weave structures within a weft row
6. Varying the weave structures between weft rows
7. Varying the number of layers within a weft row
8. Varying the number of layers between weft rows
9. Varying the width of the weft rows
10. Manipulating the path of the weft during insertion
11. Using a fan reed or rail reed

6.3 Add-on wishes

To guide the development of the add-on, wishes were formulated.

The objective of this research is to find an accessible way to weave 3D forms on a shaft loom, the following values were kept in mind while designing the add-on:

1. Simple
2. Low-cost
3. Robust
4. Ease to install and use
5. Require no additional electronics
6. Require minimal extra actions from the weaver

The intention is to design the add-on in such a way that it can be used on a variety of looms with different warp setups. It is therefore strived for that the add-on can:

8. Accommodate as many different warp densities as possible
9. Accommodate as many different types of warp yarn as possible
10. Accommodate as big a range of warp tensions as possible
11. Easily be redeveloped for different types of looms

The use of the add-on requires changes to the weaving process, but should not negatively impact the resulting fabric. The following is kept in mind:

12. The likelihood of the add-on damaging threads or the woven fabric should be as low as possible
13. The likelihood of the add-on affecting the look, feel or integrity of the woven fabric should be as low as possible

6.4 Concepts: Individually moving warp threads

On most looms, including the available Magic Dobby loom, the warp threads are typically wound onto a warp beam and let off simultaneously. In order to allow warp threads to move relatively to each other along the Y-axis to support the weaving of 3D fabrics, the let-off system needs to be adjusted.

There are looms designed or adjusted for other purposes, such as velvet weaving, that do allow individual movement of (groups of) warp threads. Different methods and tools, such as extra warp beams, creel systems and weights were explained in Chapter 3. Existing creel systems offer a lot of flexibility, because every thread is let-off a separate bobbin, but are generally complex to set up and require a large amount of space. Inspiration was therefore taken from a simpler setup described by Landry (2016), whose research was carried out to make individual movement of warp threads accessible for hand weavers.

The concept can be seen in Figure 111. After being let off the warp beam, the warp threads are first guided backward to wrap around another beam before entering the loom. Excess length is let off the warp beam and tensioned with weights in the space between the two beams. The weights allow this excess length to be pulled forward while remaining tensioned. If the force pulling the thread forward is released, the weight pulls the excess length back, avoiding the thread slackening. The tension on the threads can be changed by increasing or decreasing the weight.

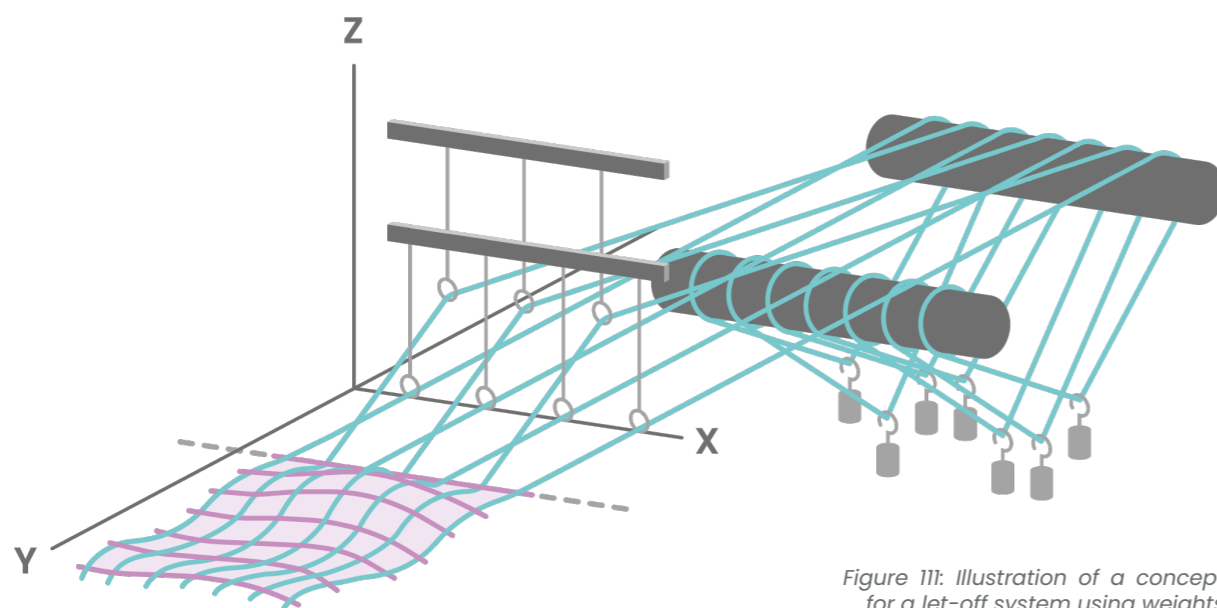


Figure 111: Illustration of a concept for a let-off system using weights

All the threads are simultaneously let-off the warp beam as they normally would be. The amount of excess length let off and weighed down by the weights is the amount the warp threads can move forward. A drawback of storing all the threads on the same warp beam is that once the excess length of even one thread runs out, all the threads need to be let-off more if the weaver desires to move that thread forward again. This puts some limitations on what can be woven and the order in which different forms are woven. The threads need to be balanced out at some points to avoid the excess length of some threads getting too long while others run out.

Dividing the warp threads over multiple warp beams can help mitigate this problem by allowing groups of warp threads to be let off separately. As mentioned before, two extra warp beams can be added to the Magic Dobby loom. Figure 112 gives an impression of a setup with three warp beams.

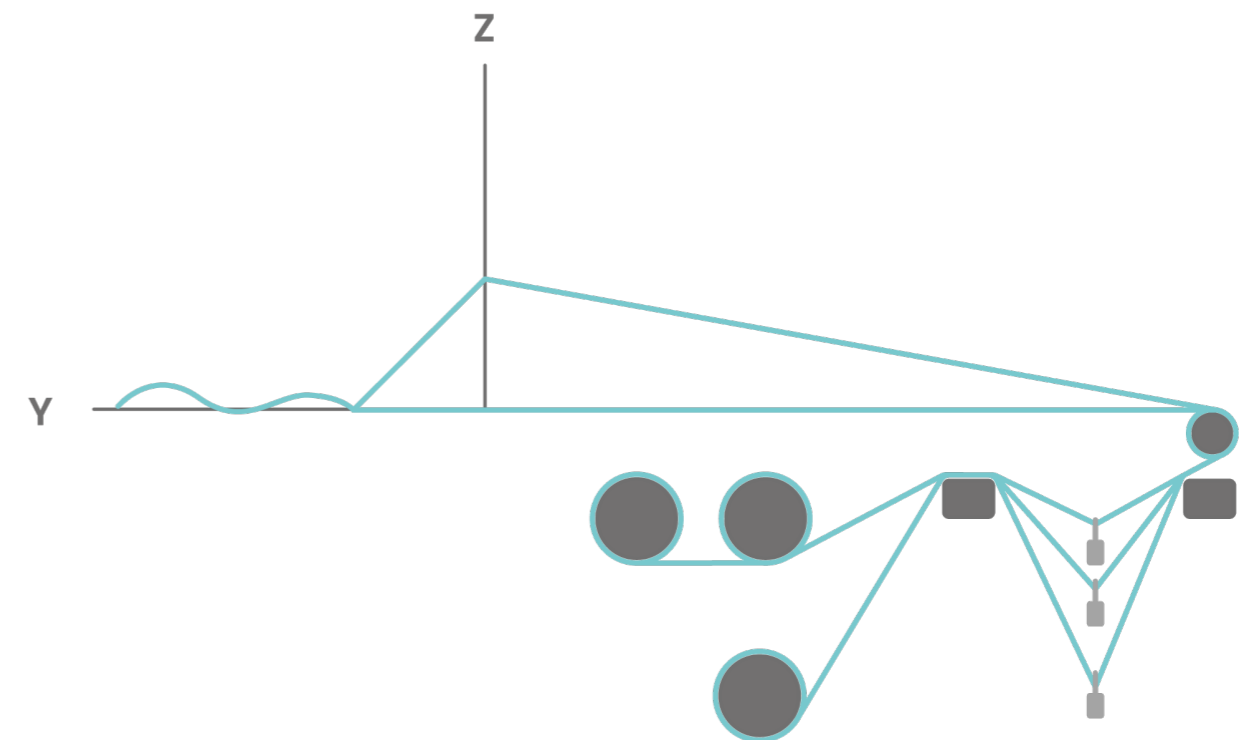


Figure 112: Illustration showing the loom from the side. The warp threads coming off three separate beams curve over and around common beams at the back of the loom. Weights are hung onto the threads in the created space

6.5 Concepts: Straightening and fixating the fell

Besides the adjustments that need to be made at the back of the loom to allow individual movement of warp threads, adjustments also need to be made to the front of the loom. The threads need to be moved the right amount to straighten the fell. The fell must subsequently be kept in place to enable the weaving process to continue.

6.5.1 Comb

In the first concept, a comb is used to move the weft and keep the fell in place. The teeth of the comb are inserted in between the warp threads in order to press against the weft (Figure 113).

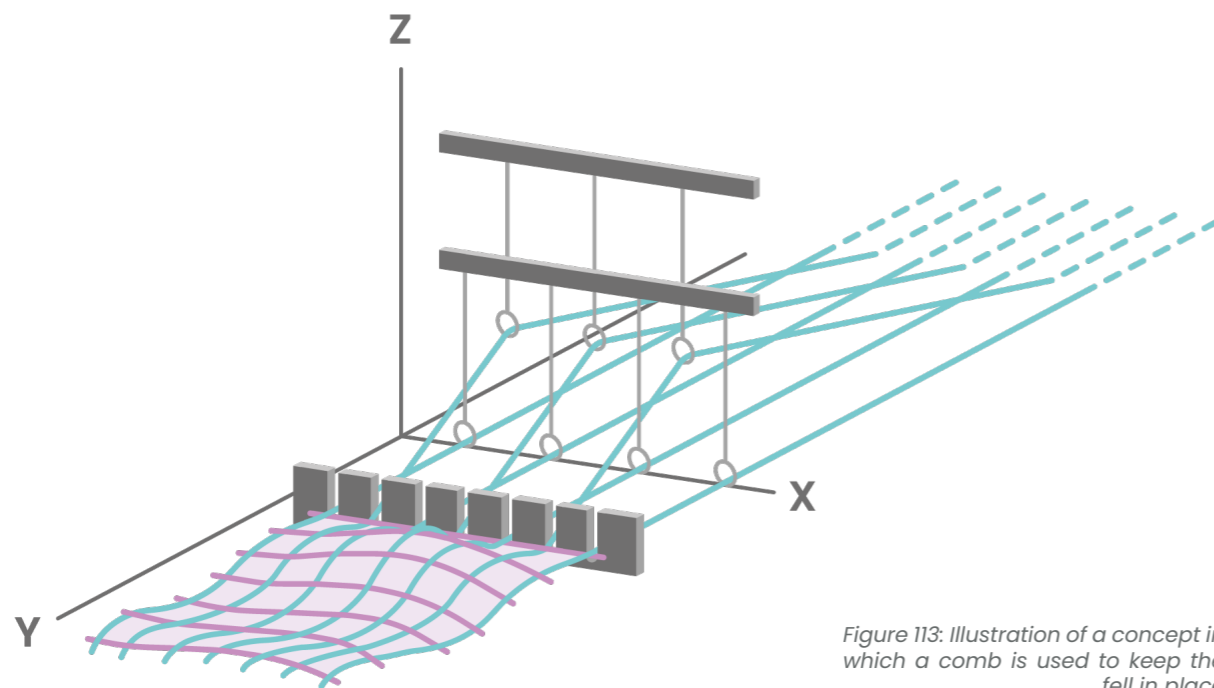


Figure 113: Illustration of a concept in which a comb is used to keep the fell in place

Weaving process

How the comb is used in the weaving process can be seen in Figure 114.

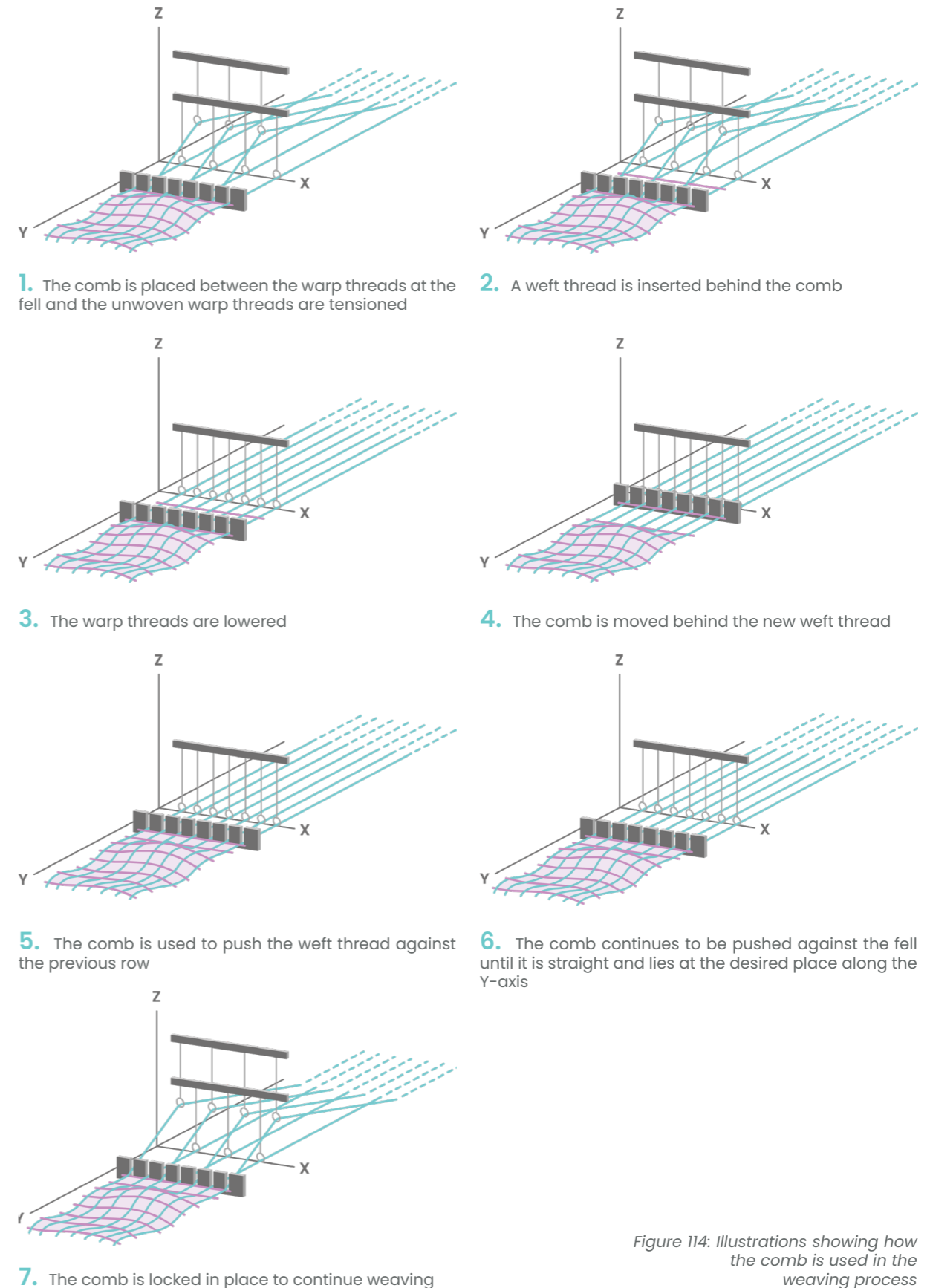


Figure 114: Illustrations showing how the comb is used in the weaving process

Prototypes and experiments

The concept of using a comb to keep the fell aligned and in place was first tested on the rigid heddle loom (Figure 115). The simple comb was made out of metal wire that was bent into teeth and clamped between two pieces of wood. The comb was tied to the bottom front beam of the rigid heddle loom in order to control the comb's movements by turning and locking the beam. The sides of the comb were guided between two pieces of wood to keep the comb from rotating.

A simplified method for allowing the warp threads to move individually was constructed. At the back of the loom the warp threads have been clamped in between two pieces of wood, which are pressed together with nuts and bolts. When the bolts are unscrewed and the pressure on the threads is released, each warp thread can move individually.

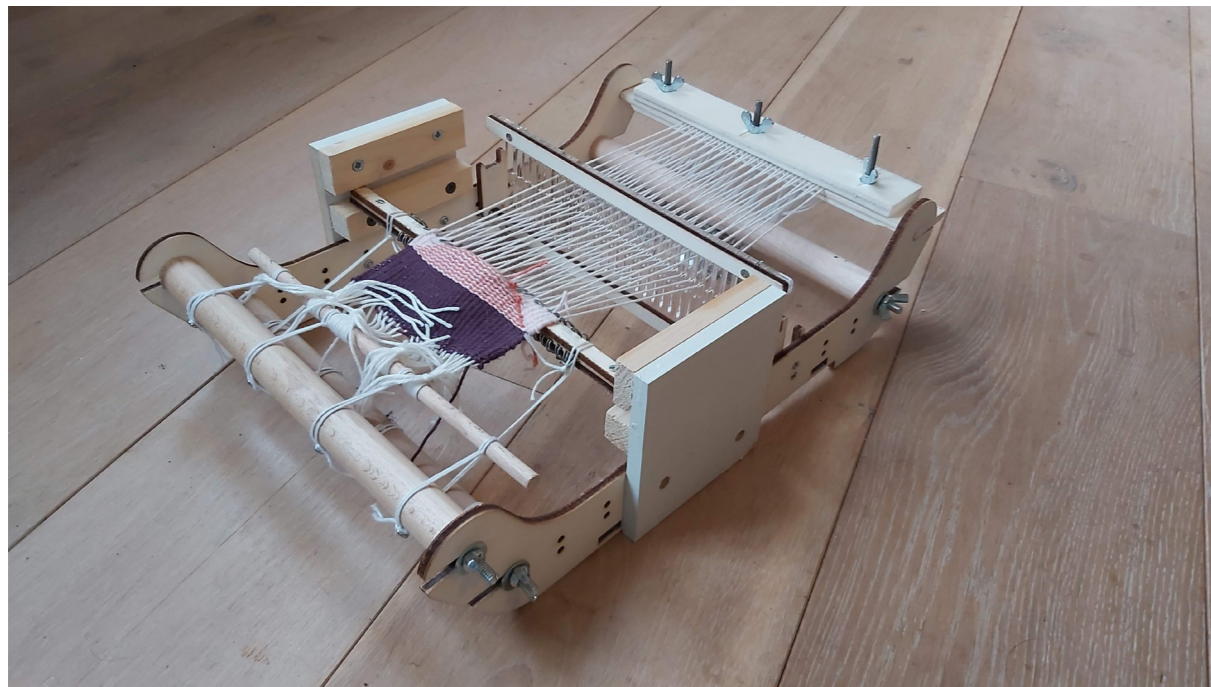


Figure 115: Prototype of the comb on the rigid heddle loom

Several samples were woven on the rigid heddle loom with help of the comb. To create 3D areas additional weft rows were interlaced with certain warp threads through the use of discontinuous weft. During the weaving process, the comb is moved to hook behind the most recently inserted weft thread every time the fell needs to be realigned. An example of how the comb is used in the weaving process can be seen in Figure 116. A detailed explanation can be found in Appendix B.

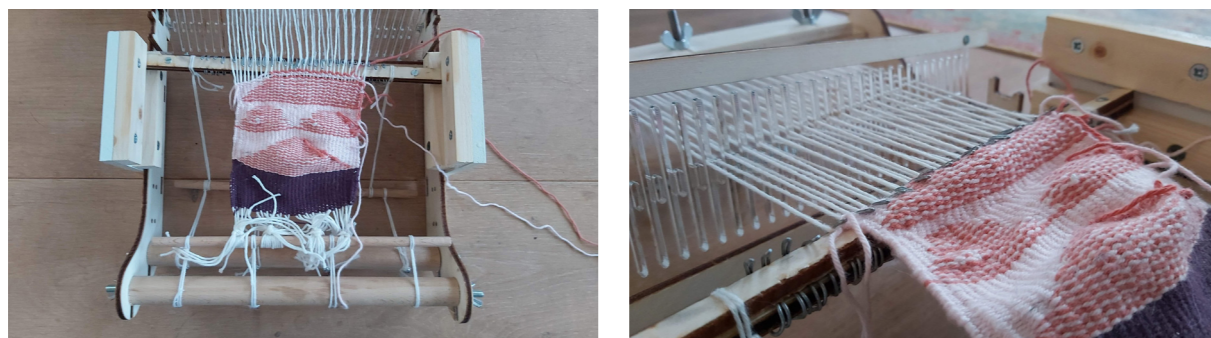


Figure 116: Example of how the comb hooks behind a newly inserted weft row and pulls the material forward

Samples made on the rigid heddle loom with the comb can be seen in Figure 117.



Figure 117: Samples created on the rigid heddle loom with comb prototype

6.5.2 Clamp

In the second concept the reed is used to move the weft and align the fell. A clamp is used to keep the fell in place (Figure 118). The clamped section of the woven fabric should be as thin as possible to obstruct the bulging of the threads as little as possible.

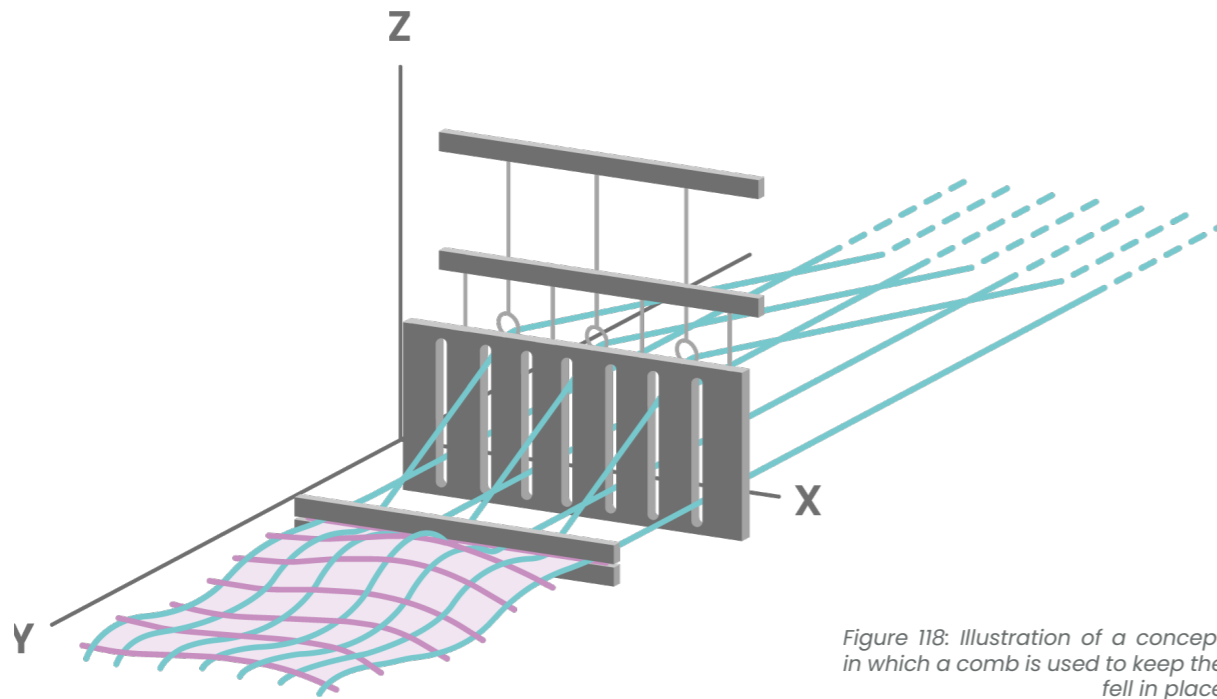


Figure 118: Illustration of a concept in which a comb is used to keep the fell in place

Weaving process

How the clamp is used in combination with the reed can be seen in Figure 119.

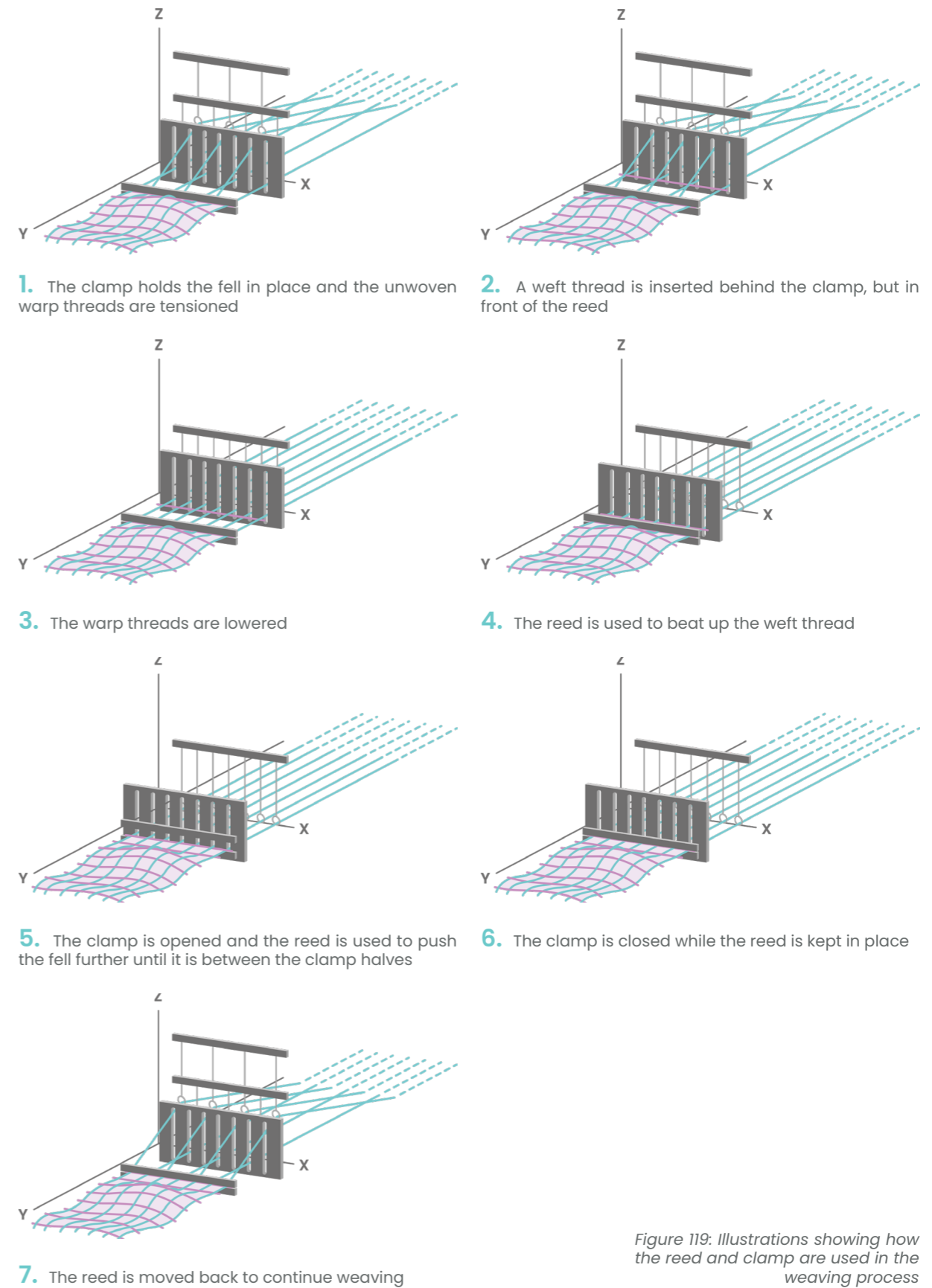


Figure 119: Illustrations showing how the reed and clamp are used in the weaving process

Prototypes and experiments

The concept was tested on the rigid heddle loom. A clamp was made from two pieces of wood: one rectangular lath and one angle profile. An angle profile is used because the wide side provides space to apply force, while only the thin edge is pressed against the lath. This way, the clamped area of the fabric is kept to a minimum. The clamp was attached to the sides of the loom and the halves of the clamp were pressed together using bolts and nuts (Figure 120).

After the warp was clamped in place, the threads were divided into four groups. Each group was weighed down to ensure it could move forward separately from the other groups, while the warp threads always remained tensioned up to the clamp (Figure 121).



Figure 120: Prototype of the clamp on the rigid heddle loom



Figure 121: Loom setup with warp threads tensioned with weights

In Figure 122 an example of how the clamp is used on the rigid heddle loom is shown. Due to the weights having to fall over the side of a table, the weaver is standing on the other side of the loom than they normally would. A detailed explanation can be found in Appendix C.

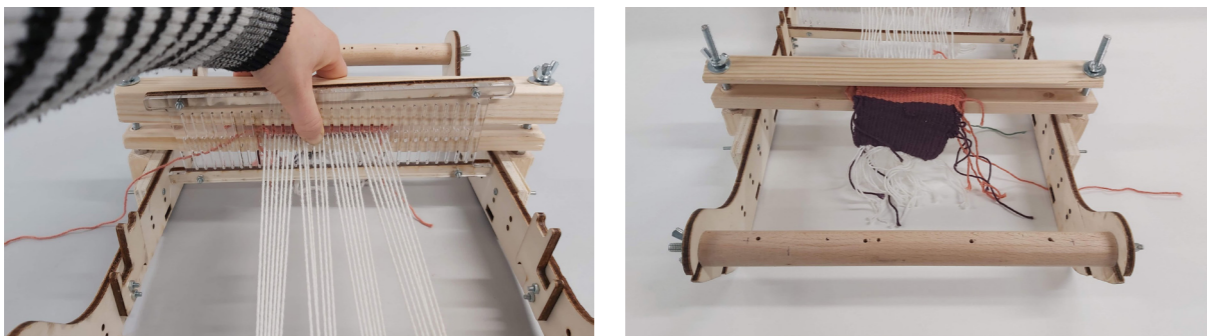


Figure 122: Example of how the reed is used to push the woven fabric between the clamp halves (left) and how the woven fabric hangs untensioned on the other side (right)

The sample made on the rigid heddle loom with the clamp can be seen in Figure 123.



Figure 123: Sample created on the rigid heddle loom with clamp prototype

6.6 Potential for further development

The clamp and comb concepts were compared based on the requirements and wishes in order to judge which one has the most potential for further development, which can be found in Appendix D and of which the conclusion is described below. The potential of the proposed let-off system in comparison to other existing solutions is also analyzed in the following section.

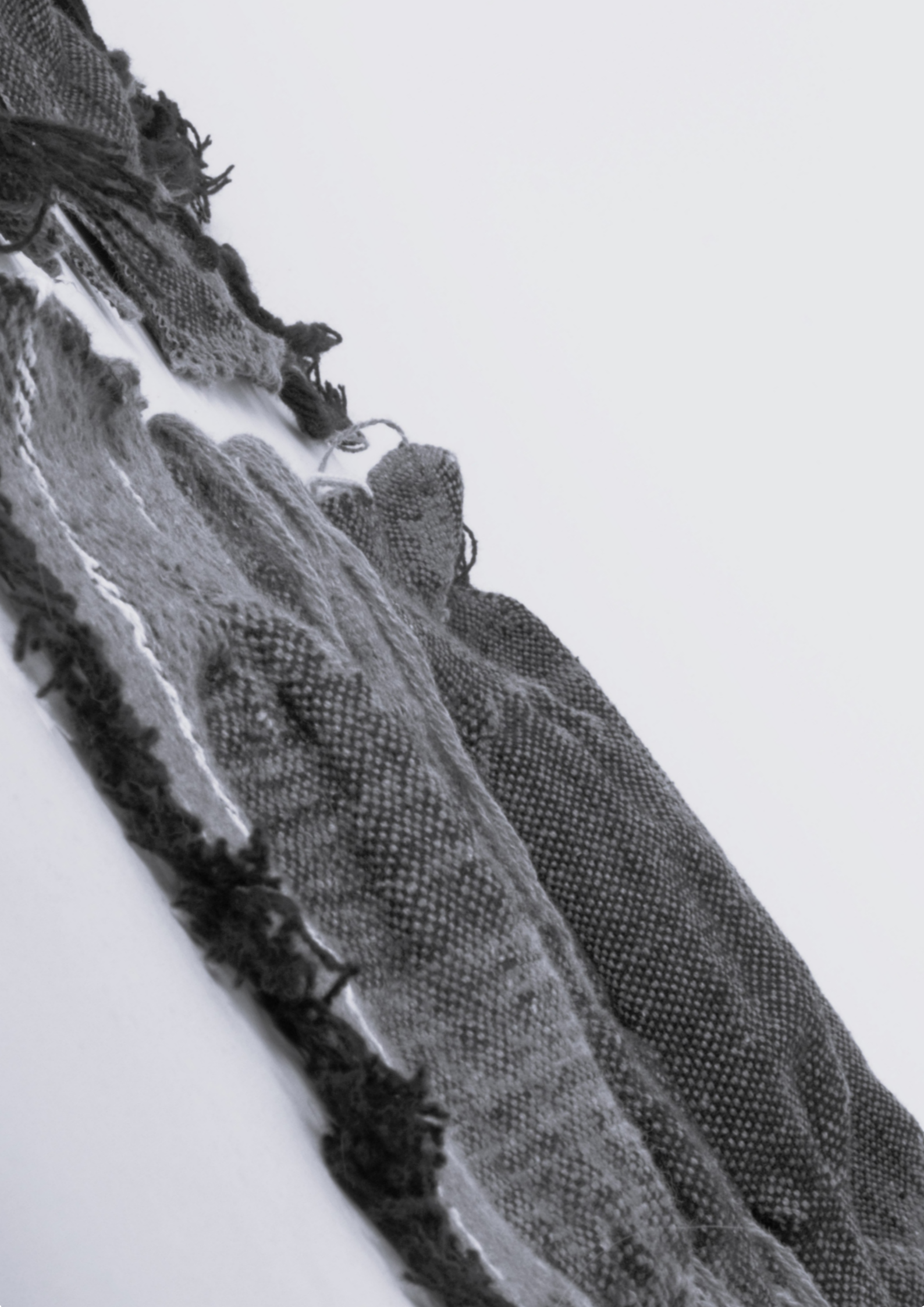
6.6.1 Individually moving warp threads

A concept for a let-off system was introduced in which excess warp length is let off the warp beam and subsequently weighed down. This allows individual warp threads to move forward while staying tensioned. Storing the warp threads on warp beams instead of using a creel system, in which every thread comes off a separate bobbin, limits the amount of flexibility. However, the proposed concept offers enough freedom to move individual warp threads to allow experimentation, which is the focus of this research. The concept will therefore be developed further as part of the add-on prototype.

6.6.2 Straightening and fixating the fell

Two concepts were introduced: a comb and a clamp. Through prototyping and experimentation it was validated that both a comb and a clamp can provide the loom with the necessary functionalities. Both concepts require further development, but it was concluded that the clamp has more potential. The comb is very reliable in keeping the fell in place due to it blocking the weft no matter the weave structure or thickness of the fabric. However, the chances that repeatedly inserting the comb will damage the threads and/or affect the spacing of the warp threads are quite high. Furthermore, removing the comb, inserting it and using it to move the weft threads to realign the fell are a lot of additional steps in the weaving process that currently take some manual fiddling to get right. Lastly, the thin teeth of the comb will likely be very fragile unless a very stiff and strong material can be used, which requires more material research and will likely make the comb expensive to produce.

The clamp provides a number of benefits over the comb. First of all, the clamp can easily be developed to be simple and robust. Secondly, the reed is used to move the weft to align the fell, which requires the same actions as the weaver would normally carry out to beat up the weft. Opening and closing the clamp can be done simultaneously with moving the reed. Furthermore, the clamp is pressed onto the woven fabric and nothing is inserted in between the threads, which means it does not influence the fabric in any way and is not affected by the density, spacing or number of warp threads. The downside of the clamp is that it is more difficult to keep the fell in place using friction than it is by blocking the weft, as the comb does. A way needs to be found to press the clamp halves together with enough force along its whole width when the size of the clamp is increased. Furthermore, ways to compensate for variations in the fabric thickness at the fell need to be found, for example through the use of rubbers. Although there are challenges that need to be addressed, the simplicity, robustness and versatility of the clamp make its development into a functional prototype for the shaft loom interesting and feasible.



7. Add-on prototype for a shaft loom

In order to validate the methods for weaving 3D fabrics on a larger scale, a prototype of the add-on was constructed for the Magic Dobby shaft loom. In the previous chapter it was concluded that a clamp could be a simple and robust tool for keeping the fell in place. This concept was therefore expanded upon. In this chapter the final iteration of the prototype is presented, including why certain design choices were made.

7.1 Final prototype

The add-on consists of two large parts: the fell clamp at the front of the loom and the let-off frame at the back of the loom. Figure 124 and 125 show the final iteration of the add-on prototype installed on the Magic Dobby shaft loom. The components of the add-on and their functionalities will be elaborated on in the next sections.



Figure 124: Fell clamp installed on the front of the Magic Dobby loom

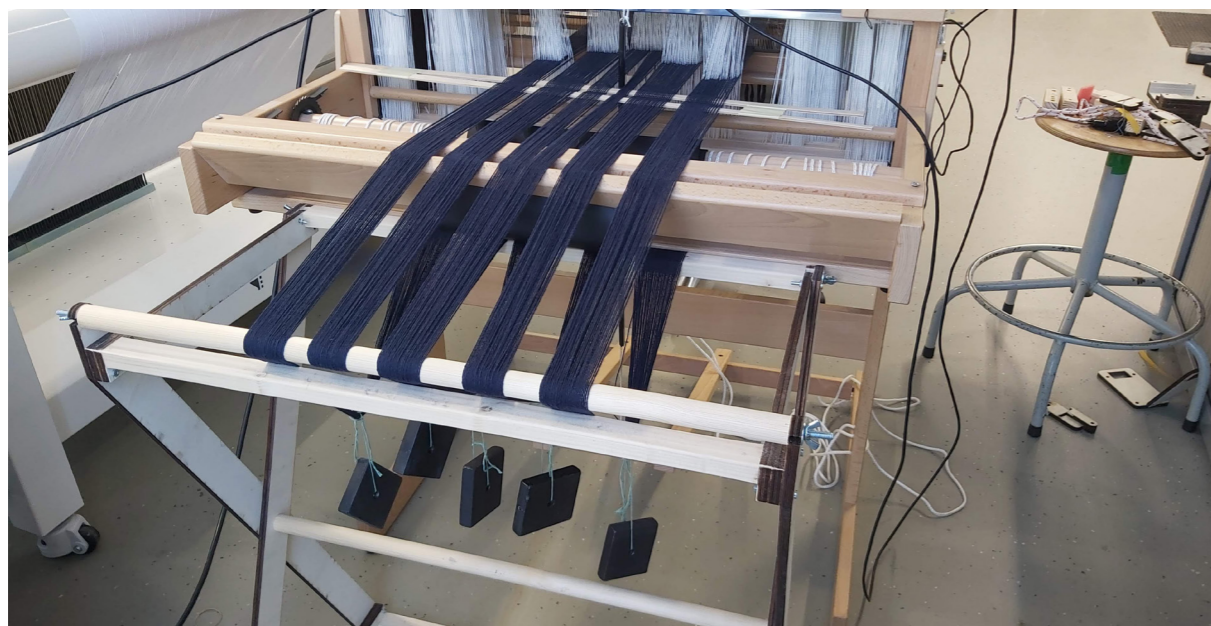


Figure 125: Let-off frame placed at the back of the Magic Dobby loom

7.2 Fell clamp

The fell clamp's main functionality is keeping the fabric in place at the front of the loom. In Figure 126 an exploded view of the fell clamp can be seen in which the parts of the clamp are indicated.

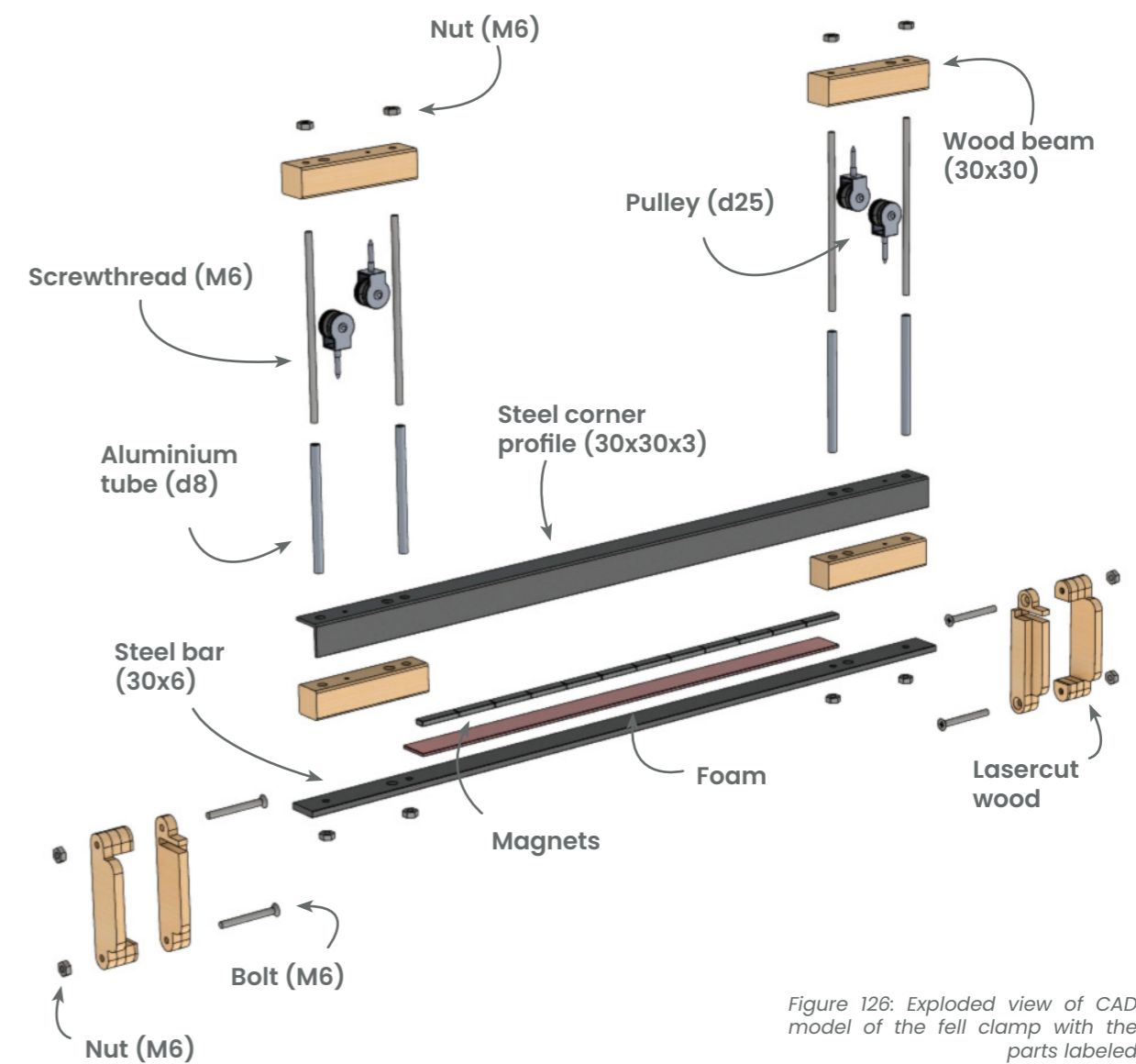


Figure 126: Exploded view of CAD model of the fell clamp with the parts labeled

7.2.1 Clamp

The most important part of the add-on is the clamp. The clamp consists of two steel parts: a steel lath and a steel angle profile. Magnets have been attached to the bottom clamp half using double sided tape. These magnets ensure the steel top clamp half is automatically pulled tight against the bottom half, securely keeping the fabric fixated in between. A layer of foam has been added underneath the magnets to compensate for any irregularities in the magnets or slight thickness variations in the fabric. The cross section of the clamp with the fabric in between can be seen in Figure 127.

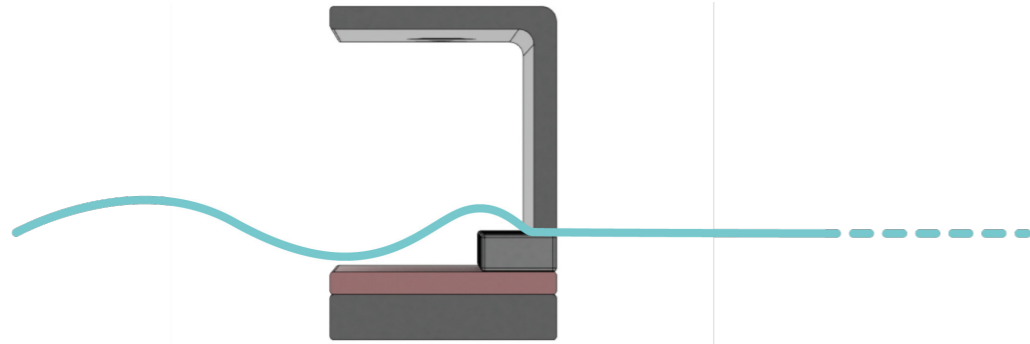


Figure 127: Cross section of the clamp with warp drawn in

7.2.2 Loom attachment

On either side of the loom, the clamp is inserted into two wooden pieces that are clamped around the sides of the loom with bolts (Figure 128). The clamp is kept in place through friction and no permanent alterations to the loom are required.



Figure 128: CAD model showing how the clamp is attached to the side of the loom

7.2.3 Pulley system

A pulley system is used to open the clamp. A rope is threaded through the clamp halves and led around the pulleys as seen in Figure 129. When one presses down on the rope with their foot, the top clamp half is pulled up. When the pressure on the rope is removed, the top clamp half falls down due to gravity and is pulled against the bottom clamp half by the magnets. The pulley system offers two significant benefits. First of all, a pulley system reduces the effort required to lift the weight of the clamp. Secondly, opening and closing the clamp with the foot leaves the hands free to move the reed forward and keep it in place in the meantime.

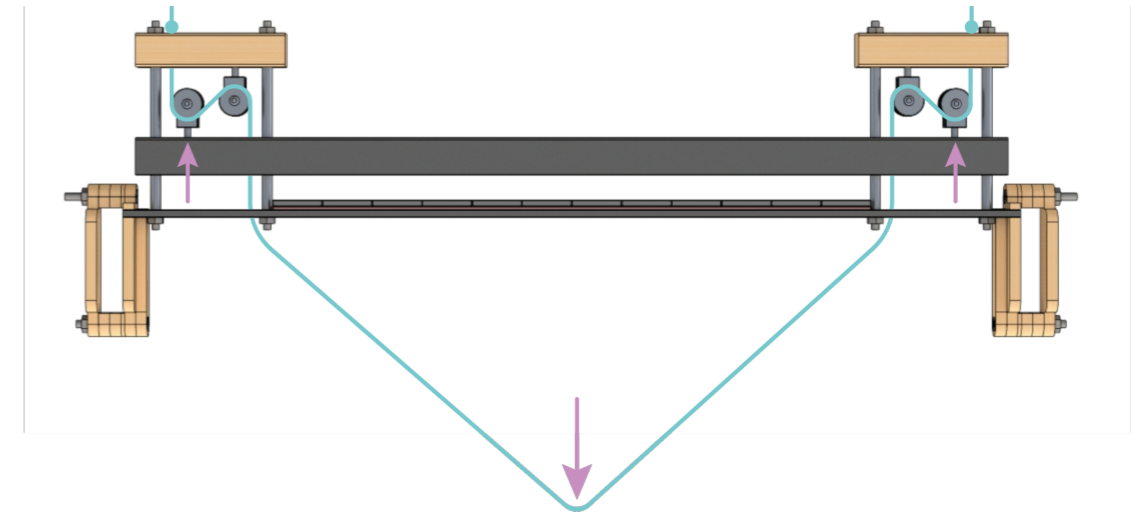


Figure 129: CAD model of the clamp with rope drawn in to show how pressing down on the rope causes the clamp top open

7.3 Let-off frame

A frame was built over which the warp threads could be led after coming off the warp beam. In Figure 130 an exploded view of the let-off frame can be seen.

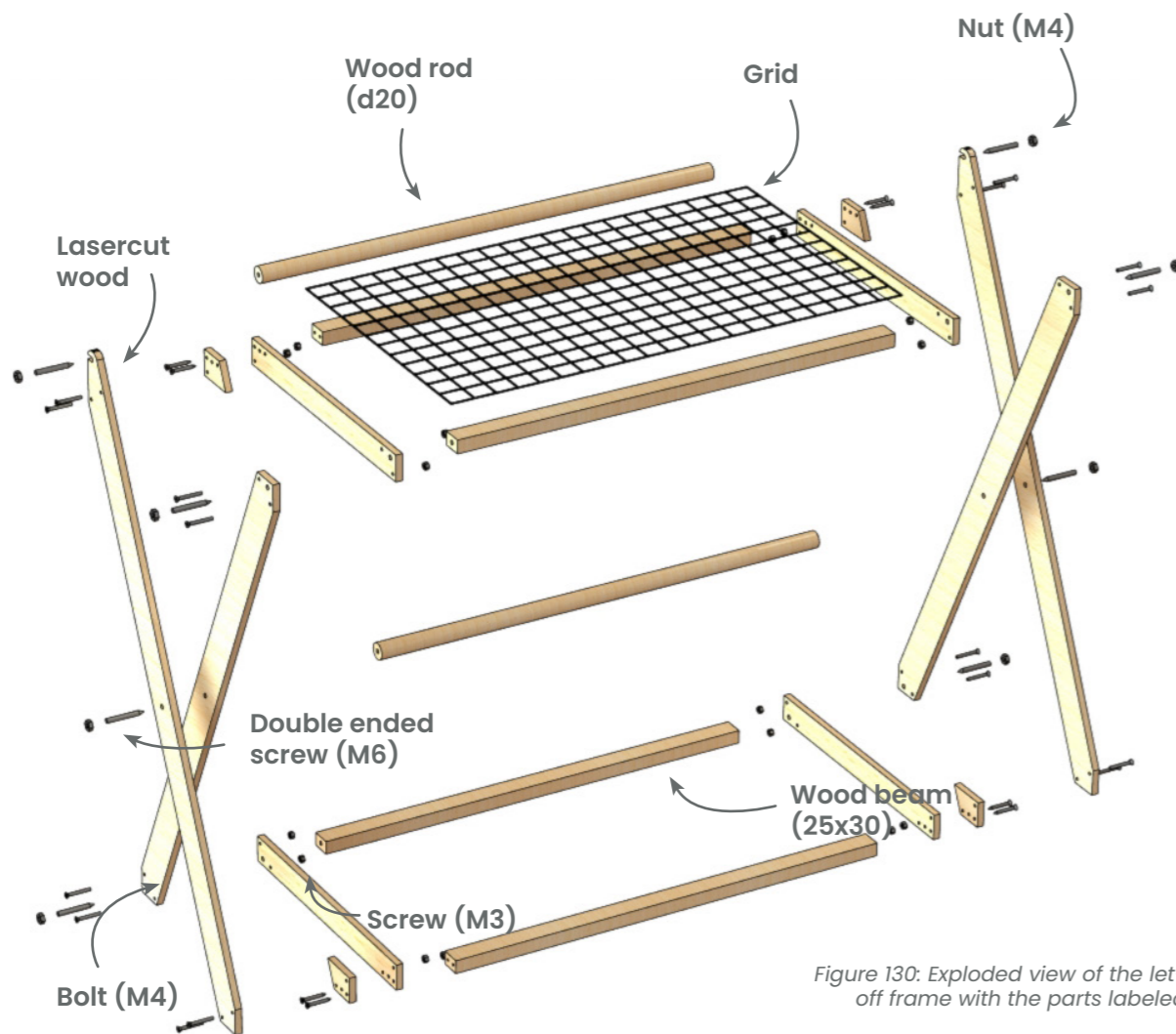


Figure 130: Exploded view of the let-off frame with the parts labeled

7.3.1 Warp path

The warp threads can be stored on one or multiple warp beams as normal. Usually, the threads would travel straight from the warp beam, over the back beam and into the loom. The let-off frame can be placed behind the loom and enables the path of the warp threads to be lengthened. The warp threads travel over the frame and around the back rod before traveling back towards the loom (Figure 131). In the space between the two beams of the let-off frame excess warp length, that has been let-off the warp beam, can be stored and tensioned using weights.

The image shows one warp beam for clarity, but warp threads originating from multiple beams can be led over the same let-off frame. The available Magic Dobby loom has three warp beams.

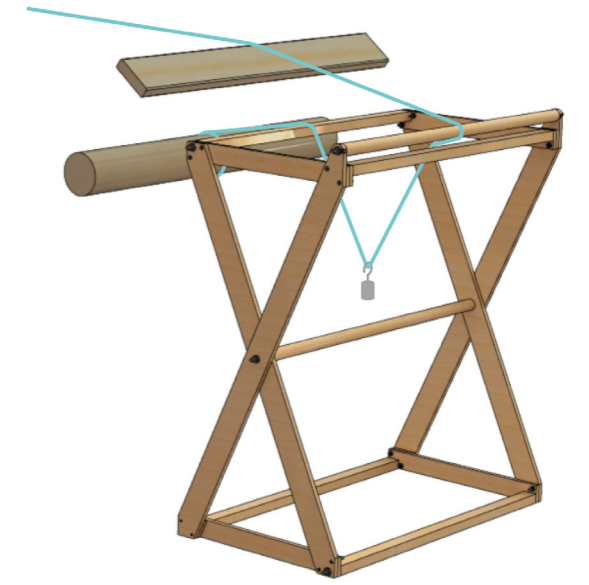


Figure 131: CAD model of the let-off frame with a warp beam onto which the warp threads are stored and the back beam of the loom over which the threads are led to enter the loom. A warp thread has been drawn in

7.3.2 Thread separation

To avoid the threads getting tangled, a grid can be added to the let-off frame. The warp threads can be divided over the holes in the grid so that they stay separated (Figure 132).

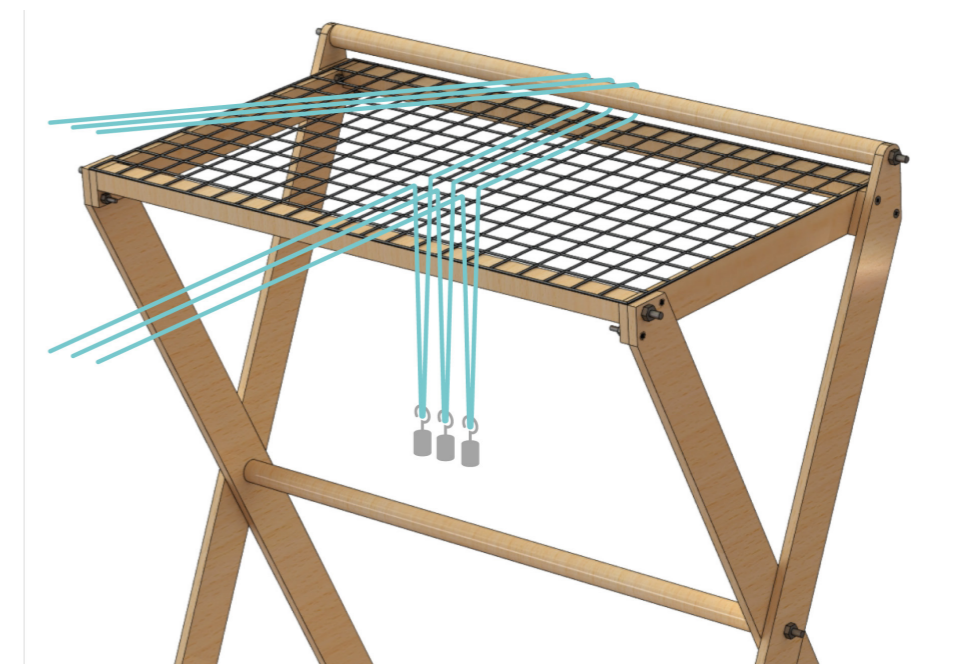


Figure 132: CAD model of the let-off frame with grid. Three warp threads have been drawn in to show how each thread is inserted through a different hole

7.3.3 Warp tension

Every warp thread is fixated on both ends. It is wrapped around a warp beam on one end and clamped in place on the other. Due to both ends being fixated, the thread can be tensioned using weights. Figure 133 shows a side profile of a warp thread tensioned on the let-off frame without a grid.

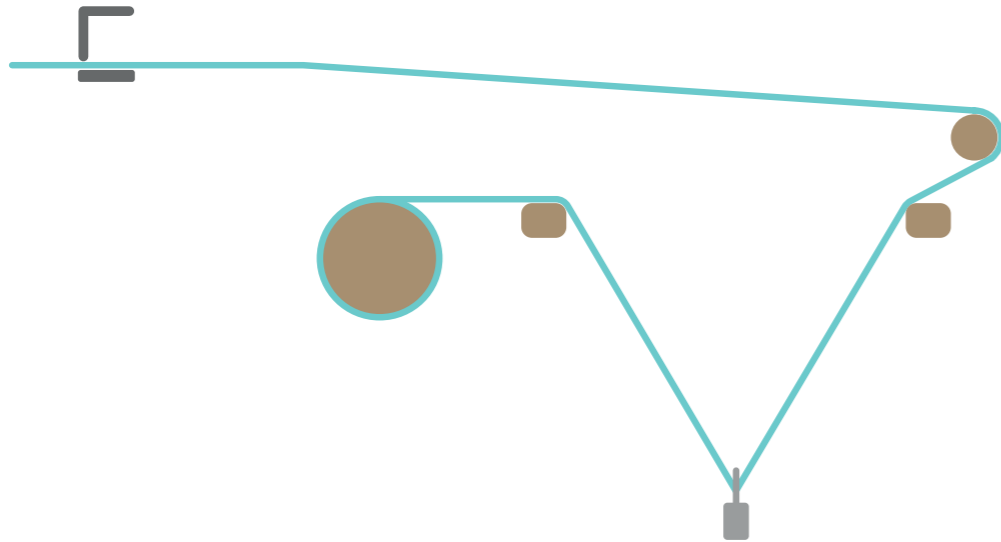


Figure 133: Illustration of the let-off frame without a grid from the side, showing how the warp thread is pulled down by the weight in between the two beams of the let-off frame

The tension in the threads is a result of the weight and the angle of the threads. The forces at play can be seen in Figure 134. The weight is hung in the middle of the section of the warp thread that lies between the two beams of the let-off frame. The angle in which both sides of the thread travel up towards the beams is equal on both sides of the weight. This results in both sides of the thread being equally tensioned.

Based on the laws of equilibrium, the vertical component of the tension in both sides of the thread must counteract the downward force of the weight.

$$2 * T * \sin(\alpha) = m * g$$

The tension can thus be calculated as follows:

$$T = (m * g) / (2 * \sin(\alpha))$$

As the weight is pulled up due to the warp thread being pulled forward, the angle decreases, which results in the tension in the thread increasing (Figure 135).

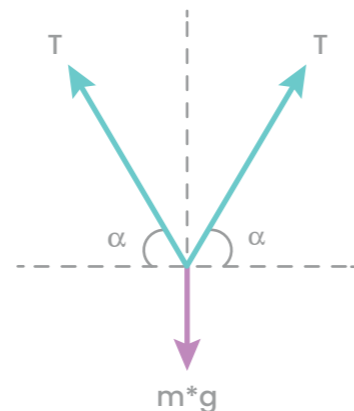


Figure 134: Visual of the forces in the warp threads due to the weight

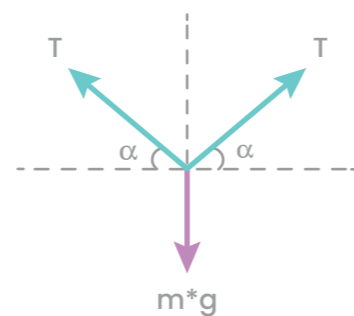


Figure 135: Visual showing how the angle changes as the weight is pulled up

A changing tension in the threads during the weaving process is usually not desired. Especially when warp threads are pulled forward at different speeds and thus end up having different tensions relative to each other. This problem can be mitigated through use of the grid. The weight pulls the thread down through one of the holes in the grid (Figure 136). As can be seen in the image, the weighed down section of the thread is nearly straight.

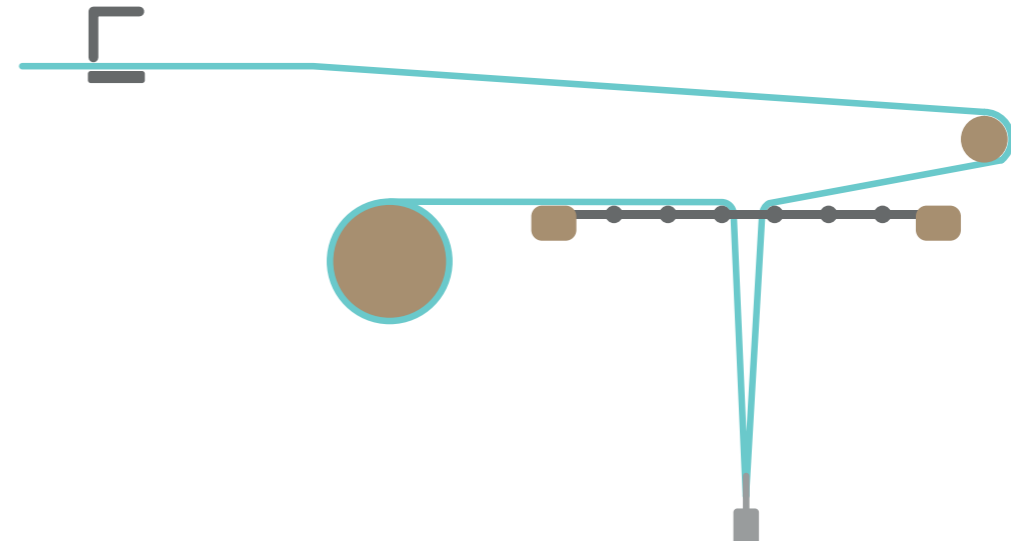


Figure 136: Illustration of the let-off frame with a grid from the side, showing how the warp thread is pulled down by the weight in between two wires of the grid

As the thread is pulled up the angle of the threads barely changes for the majority of the way up (Figure 137). This means that changes in tension will also be less dramatic. The downside of keeping the threads straighter is that more weight is required to achieve the desired tension in the threads.



Figure 137: Visual showing how the angle barely changes when the weight is pulled up

A weight can be hung onto every thread or the threads can be grouped together and tensioned with a common weight. If multiple threads are tensioned with one weight, the weight needs to be divided over the number of threads when calculating the tension.

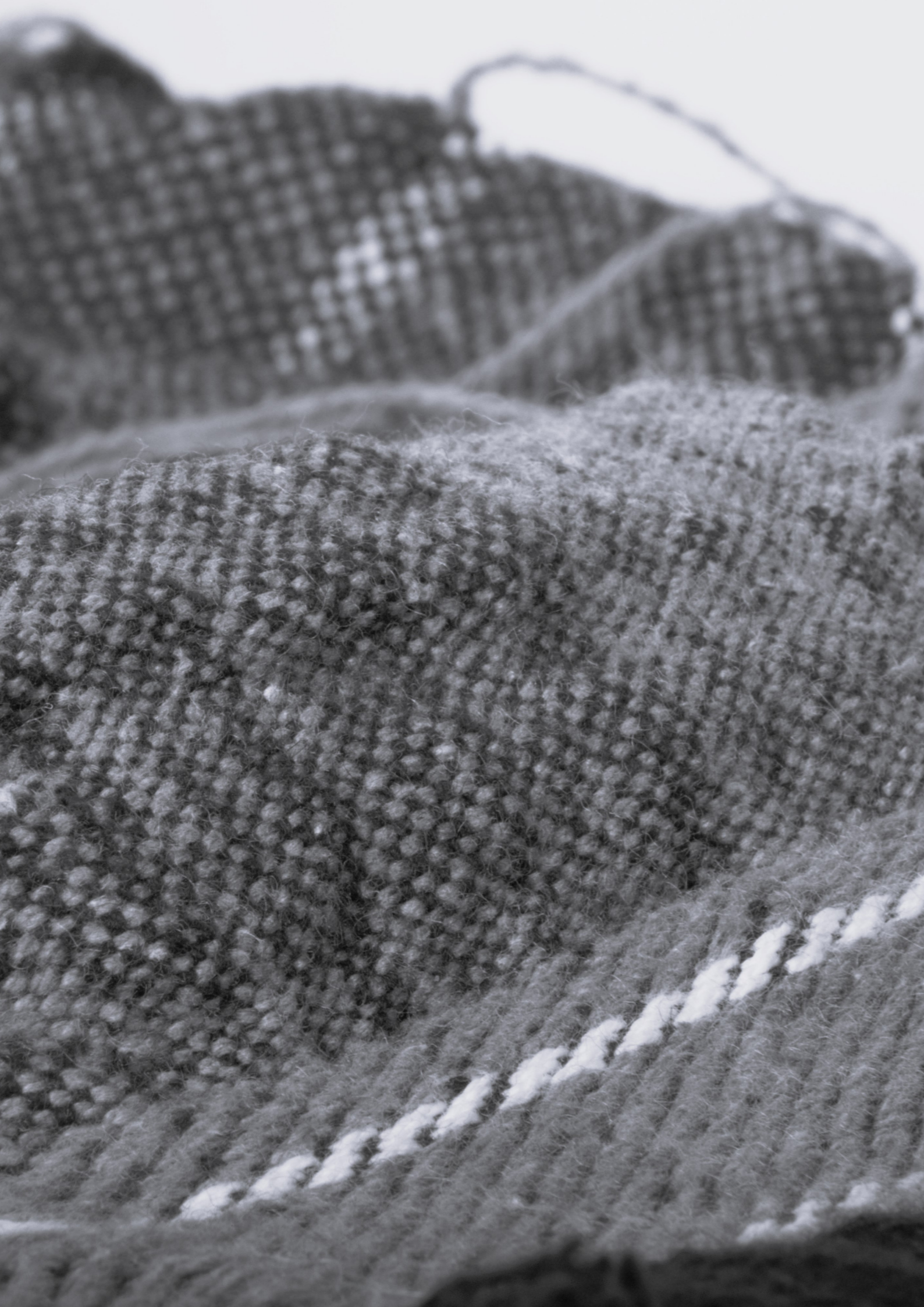


7.4 Functionality tests

During the prototyping process, tests were carried out to see if the add-on prototype could fulfill the functions required to weave samples. These tests are described in detail in Appendix E.

First of all, it was confirmed that the reed can be moved forward enough to straighten the fell, and that the warp threads are able to move along accordingly. Secondly, the tests validated that the clamp was able to keep a fabric with a constant thickness in place even when the warp threads were tensioned up to 0.30N and the warp was shed for weft insertion. However, the clamp was not able to properly keep a fabric with a varying thickness in place. The thinnest section tended to slip out of the clamp. Lastly, the ability of the weights to keep the warp tensioned and the grid to keep the threads separated when they move relatively to each other was verified.

Once it was established that the add-on prototype was able to fulfill the major requirements, weaving experiments could be carried out on the shaft loom with add-on, which will be described in the following chapter.



8. Weaving with the add-on

As explained in Chapter 5, the spacing between the weft threads or the number of weft threads that are interlaced with certain warp threads can be adjusted. It was hypothesized that a 3D form can be created by moving the warp threads so that the fell aligns. Warp threads that are moved forward more than the surrounding threads will rise up out of the fabric plane, pulling along the interlaced weft threads. A prototype of an add-on for the Magic Dobby Shaft loom was introduced in Chapter 7 that was made to facilitate this process.

To put the add-on to the test and explore how the theorized methods can be used in practice to create different fabric forms, a variety of weaving experiments were conducted on the Magic Dobby loom using the add-on. How these experiments were carried out, the resulting fabric samples and the observations made during weaving will be explained in this chapter.

8.1 Setup of the Magic Dobby shaft loom with add-on

In order to carry out the experiments, the Magic Dobby loom had to be warped, the add-on had to be installed and the threads had to be tensioned using weights.

8.1.1 Warping the loom

Prior to the installation of the add-on and the weaving of samples, the loom was warped following a standard warping procedure (Shenton, 2014). A weft material was also chosen.

Warp material: cotton (dark blue)	Number of warp threads: 240
Weft material: cotton (light blue)	Warp density: 8 ends per cm

The Magic Dobby Shaft Loom can be equipped with three warp beams. The 240 warp threads were divided over these three beams, as seen in Figure 138, in order to enable groups of warp threads to be let off separately.

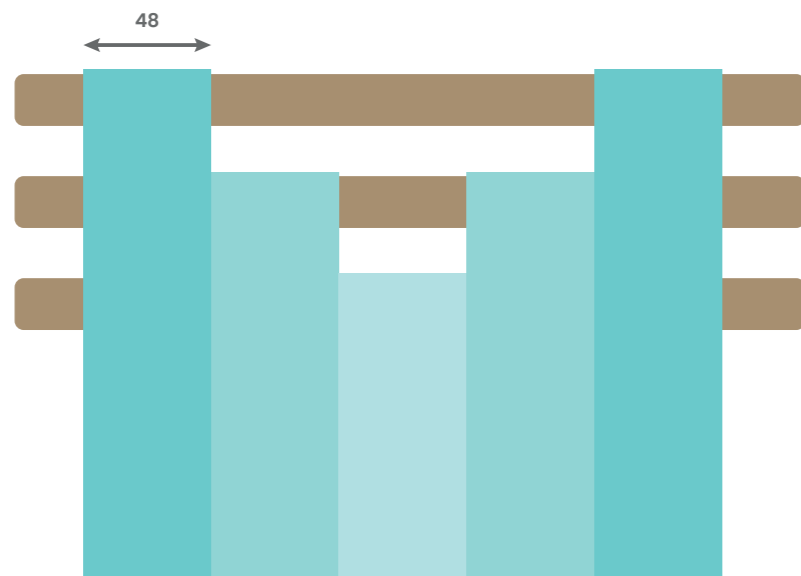


Figure 138: Illustration of the warp divided into five equal groups and wound onto three warp beams

To enable the shedding of the warp, the threads were led through the heddles of different shafts. 20 of the 24 shafts of the Magic Dobby were used. The warp was divided into five equal groups, based on the way the threads were divided over the warp beams. Each of these groups was threaded through the heddles of four respective shafts. This was done to allow each warp group to be shed differently to facilitate the weaving of different structures, providing more options for experimentation. The treading plan can be seen in Figure 139. Each group contains 48 threads, meaning each section of four threads in the treading plan needs to be repeated 12 times.

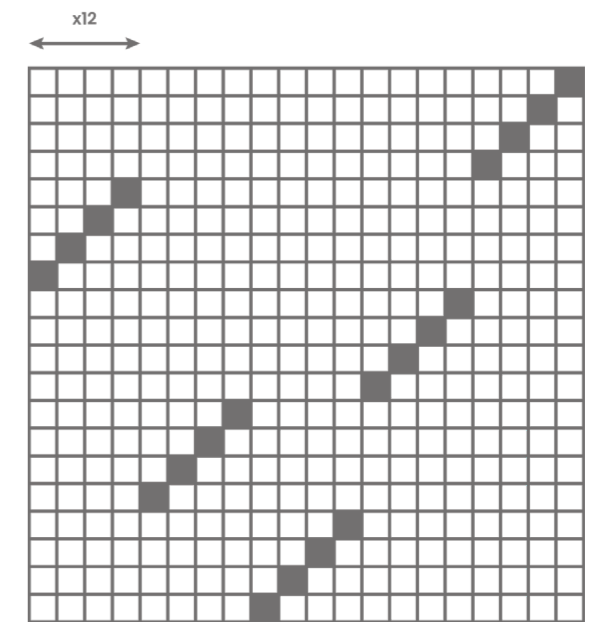


Figure 139: Treading plan used to set up the loom

After being thread through the heddles, the warp threads were thread through a reed with a dent density of four dents per cm. Two warp threads were led through each dent.

8.1.2 Installing the add-on

It is possible to install the add-on on the loom before or after the loom is warped, which provides flexibility. In this research, the add-on was installed after the warp was already in place.

To keep the warp threads in place at the front of the loom during warping and the installation of the add-on, the threads were attached to a rod that was in turn attached to the cloth beam. To install the fell clamp, the top and bottom half were separated. The bottom half of the clamp was slid under the warp threads and inserted into the wooden loom attachment pieces that were then clamped to the sides of the loom. The top half of the clamp was placed on top of the threads and attached to the bottom half with bolts. How the threads lie between the two clamp halves can be seen in Figure 140. Once the clamp is closed, it takes over the function of keeping the threads in place. The cloth beam can be left on the loom to loosely store the woven fabric.



Figure 140: Picture showing how the two clamp halves are placed under and on top of the warp, which is kept in place by the rod attached to the cloth beam

The let-off frame was installed after the warp was already in place. The frame was first placed behind the loom. To draw the warp threads over the frame, the rod at the back of the let-off frame was detached and inserted behind the warp threads. The warp threads were then let-off the warp beam so that the rod could be pulled back and reattached to the let-off frame, consequently pulling the warp threads into place (Figure 141).



Figure 141: Picture showing how the beam of the let-off frame is inserted under warp threads, pulled back and attached to the let-off frame

8.1.3 Tensioning the warp threads with weights

As explained in Chapter 7.3, weights can be hung onto the warp threads at the back of the loom to allow the threads to move relatively to each other while remaining tensioned. Two different setups were used for the tests experiments.

In the first setup (Figure 142), the warp threads were split up into five groups and each was weighed down with a 500gr weight, enabling the groups to move relatively to each other.

In the second setup (Figure 143), each thread was weighed down individually with a 30gr weight made from a M8x50 bolt with three nuts in order to enable every thread to move separately. The bolts were inserted through a safety pin, which was in turn clipped onto the warp threads.



Figure 142: Setup 1 in which the warp threads are divided into five groups, each weighed down with a 500gr weight



Figure 143: Setup 2 in which each individual thread is weighed down with a 30gr weight

8.2 Method

The way the experiments were conducted, the result and observations made during the weaving process are explained below.

The fabric in each sample was shaped using discontinuous weft rows. How the material was placed in each experiment was documented with a weaving plan.

8.2.1 Weaving process

Weaving discontinuous weft rows is an easy way to vary the number of weft threads interlaced with each warp thread. A benefit of using discontinuous weft rows in comparison to other methods for changing the weft number or spacing is that it does not require the use of different weave structures. A simple plain weave can be used, which makes it easy to see what is happening in the fabric. Another benefit is that weft threads are added without changing the spacing between the threads, which should result in a fabric with a uniform density. Keeping the weave structure constant also results in a fabric with a constant thickness. As explained in Chapter 7.4, the add-on prototype functions better when the thickness of the fell does not vary along the width of the fabric. For these reasons, the weaving experiments carried out in this research focussed on the use of discontinuous weft rows in combination with the add-on to create different fabric forms.

The Magic Dobby loom used for the experiments is computer operated. The software used to program the loom is Fiberworks Silver v4.2.

The general weaving process can be seen in Figure 144.



1. The weaver weaves in a number of discontinuous weft rows above the clamp. The weft rows can be woven in one after another, without a need for straightening the fell, as long as the width of each row is equal or smaller than the previous row.

The discontinuous weft rows result in a fell that is no longer straight. If the weaver desires to weave in a weft row that is wider than the previous, the fell needs to first be straightened. This needs to be done to allow the weft thread to be beaten up properly so that it lies against the full fell and equal spacing between the weft threads is maintained.

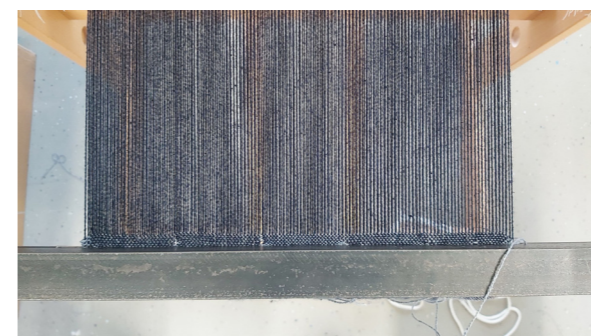


2. To straighten the fell, the weaver pulls the reed forward against the weft. Simultaneously, the weaver opens the clamp with their foot.

The reed is used to move the weft threads and the interlaced warp threads forward. At the same time the warp threads are pulled back by the weights, pulling the fell against the reed. This results in the fell becoming straight where it lies against the reed.



3. The weaver continues to move the reed forward until the straightened falls lies in between the two open clamp halves. Once the fell is in place, the weaver closes the clamp.



4. Clamped in place, the fell stays straight when the reed is moved away.

The next weft row can be woven in and beaten up against the straight fell.



5. As the weaving process progresses, the fabric form starts to appear.

Figure 144: The general process of weaving a shaped fabric with the use of the add-on by interlacing discontinuous weft rows

8.2.2 Weaving plan

Description of the weaving plan

The way weft threads of varying lengths are woven into the warp determines the shape of the resulting fabric. To communicate the number of weft and warp threads and the width and weave structure of every weft row, a weaving plan was made for each experiment. The concept of a weaving plan was inspired by patterns used for short row knitting, which is also sometimes referred to as knitting with suspended stitches (Underwood, 2009). In knitting one can choose to only knit a portion of the stitches on a row while the other stitches are held to be re-introduced later. Only engaging a portion of the warp threads when inserting the weft is very similar. Patterns used for short row knitting were used as inspiration for how different forms could be created on the loom.

In Figure 145 an example of a weaving plan is shown. The plan consists of a grid in which each vertical line of squares represents a warp thread and every horizontal line represents a weft row. The colors of the squares on each row communicate the length of the inserted weft thread and its location in the warp. The blue squares represent the unwoven warp threads and the pink squares represent the interlaced warp and weft. For clarity, the number of warp threads and weft rows in different sections is indicated on the bottom and on the right. When a section is repeated a certain number of times, it is indicated on the left. A legend is provided to communicate the meaning of the colors. The legend also indicates which weave structure is used.

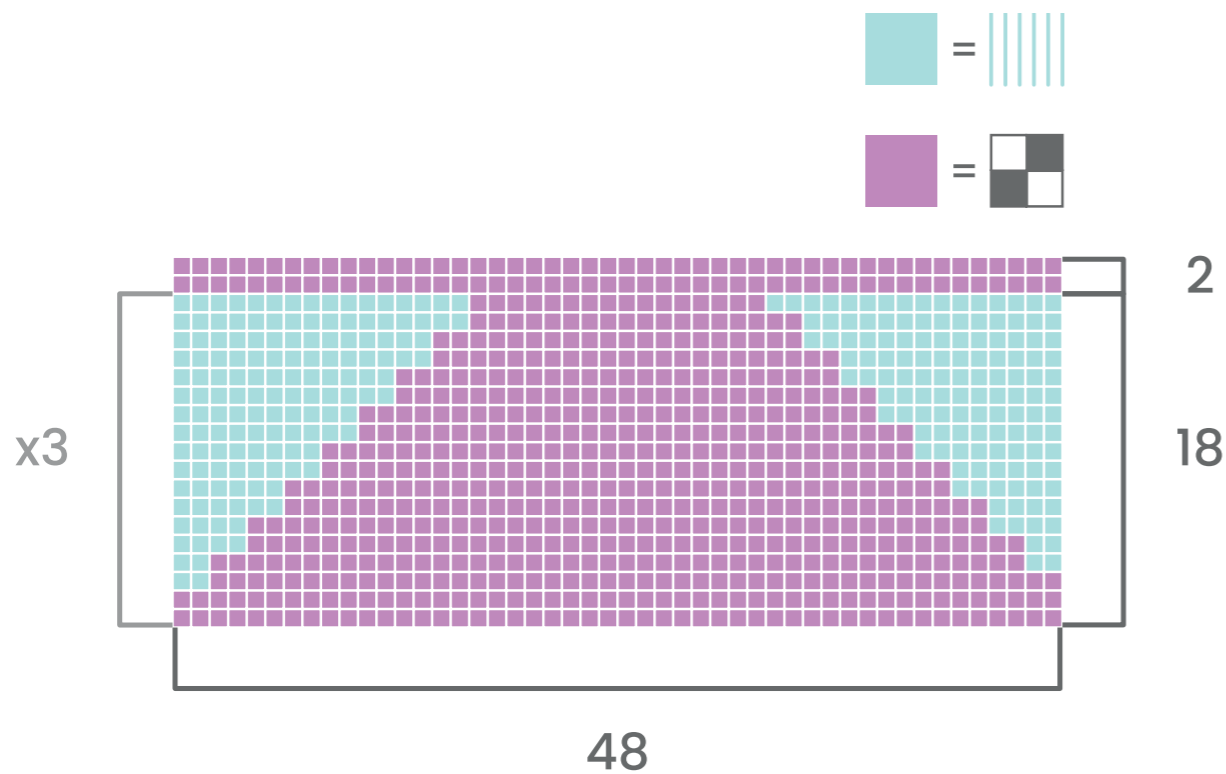


Figure 145: Example of a weaving plan

The weaving plan is a 2D representation of the final fabric form. The gaps between the pink weft rows would normally mean warp threads would float in between those rows. The use of the add-on however, enables the fell to be realigned to allow the next weft thread to be pushed against the last. The fabric form can thus be read from the weave plan by imagining the shape that would emerge if all the pink sections were pulled against each other.

Weave structures

In the weaving plans, different shades of pink are used to communicate the use of different weave structures (Figure 146).

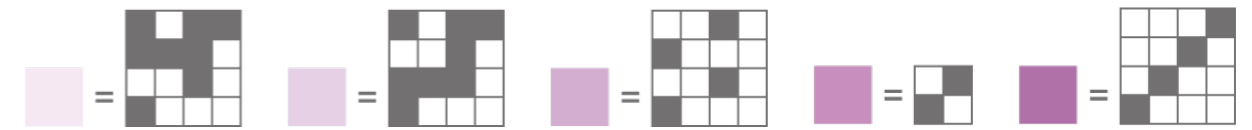


Figure 146: The different weave structures used in the experiments

The weaving plan shows that the fabric is built up out of weft rows. One can decide whether to use a separate thread for each row or to continue the weft thread between rows. In most of the experiments a continuous weft thread was used. A shuttle was used to store and insert the weft.

Weft path

Figure 147 shows how the weft travels from row to row in a given weaving plan. In the weaving plan, the width of the weft decreases every two rows. Continuing the weft thread from row to row while decreasing the width, results in a pyramid shape of which the sides have a slight offset to each other. When there is a large difference in width between two rows, it is generally more convenient to cut the weft and reintroduce it in the next row.

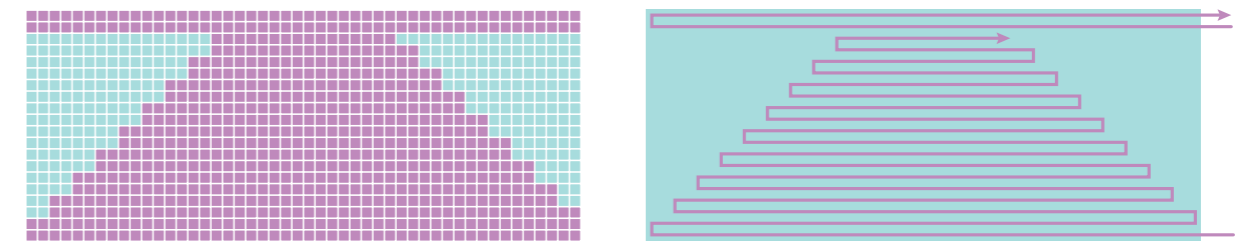


Figure 147: Visual showing how the weft travels from row to row (right) for a given weaving plan (left)

In some of the experiments, multiple weft threads were woven in on the same row. This is indicated in the weaving plan with a thicker line between two sections. Figure 148 shows how three separate weft threads travel from row to row.



Figure 148: Visual showing how a gap in the weaving plan (left) indicated the use of separate weft threads (right)

Simplification for legibility

For the sake of the legibility of this report, it was chosen to slightly simplify the visualization of the weaving plans of the experiments (Figure 148). The grid was removed to avoid the lines cluttering the image, especially in samples with a high number of warp threads and weft rows. The full weaving plans can be found in Appendix F.

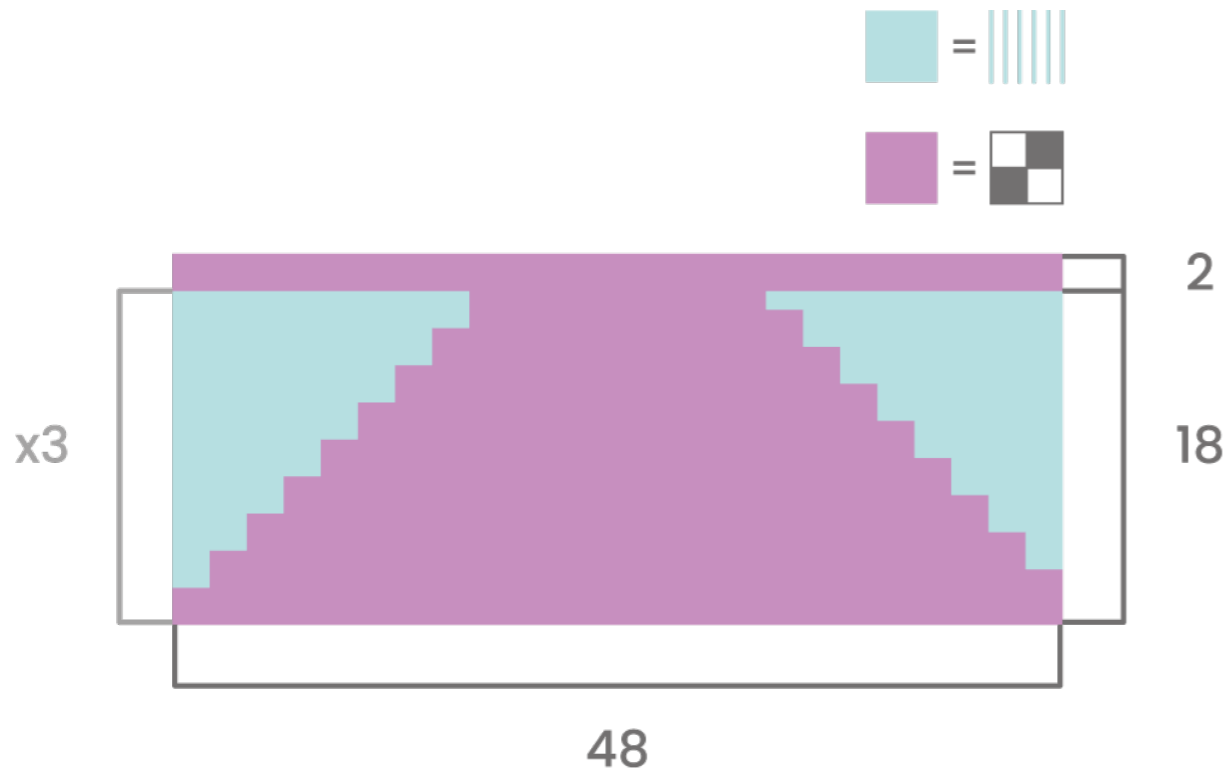


Figure 148: Example of a weaving plan simplified by removing the grid

8.3 Experiments

The experiments are described in chronological order below, including why the experiments were carried out and the resulting fabric sample.

Experiment 1-3 were carried out with the first setup, in which the warp was split into five groups. Only being able to move the groups as a whole put limitations on the shapes that could be woven, but provided enough flexibility to get an initial idea of what types of fabrics could be woven with the add-on. Experiment 4-13 were carried out with the second setup in which every thread could move individually. This allowed more complex forms to be woven.

8.3.1 Overview of explored possibilities

The experiments showed that the add-on offers a variety of possibilities for creating both 2D and 3D fabrics by interlacing discontinuous weft rows in specific ways. Figure 149 gives an overview of the possibilities that were explored.

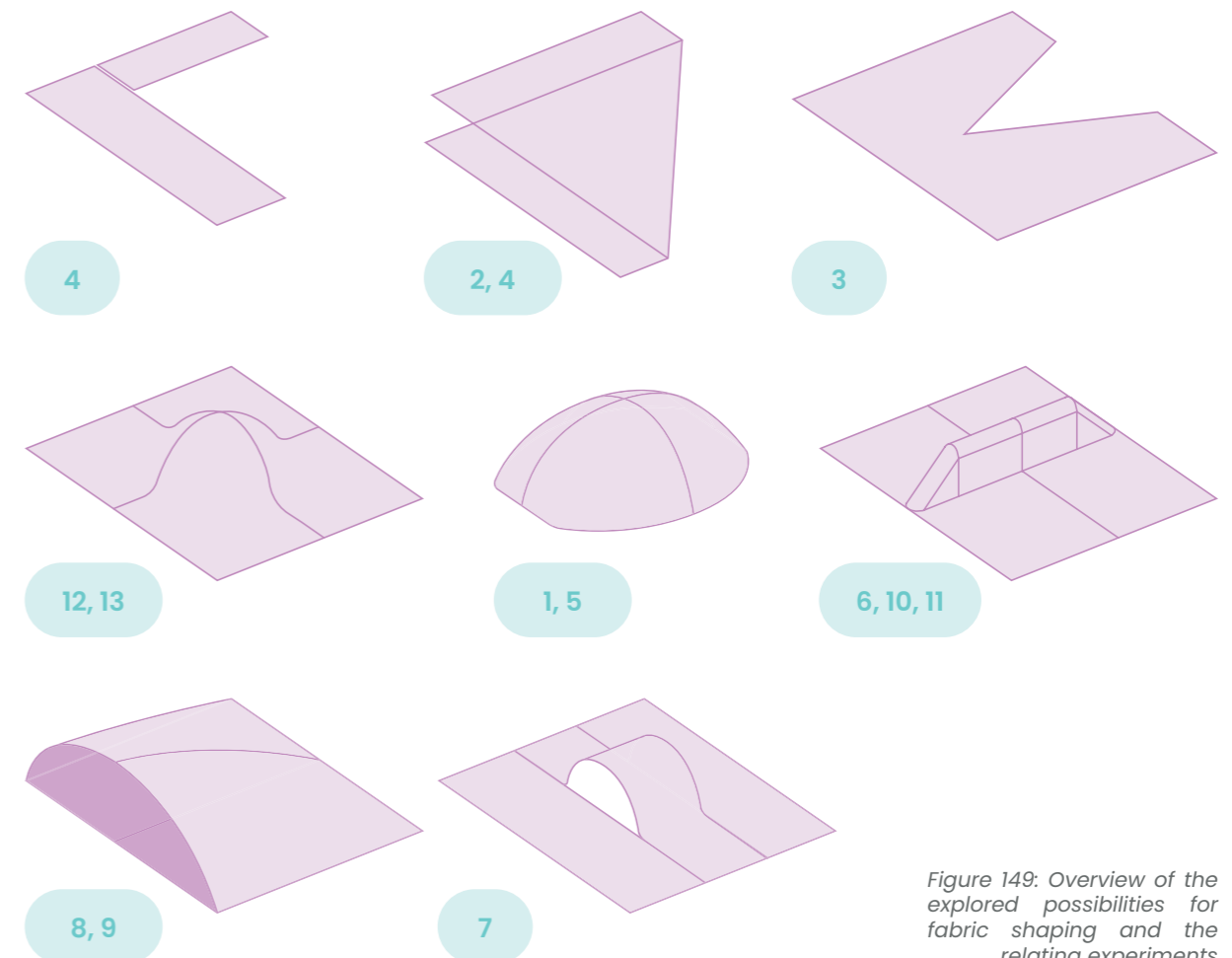


Figure 149: Overview of the explored possibilities for fabric shaping and the relating experiments

8.3.2 Experiments in detail

Thirteen experiments were conducted. Each is explained below and the full, detailed weaving plans can be found in Appendix F.

Experiment 1: Dome

The first experiment was conducted to confirm that a 3D fabric could be woven on the shaft loom with the help of the add-on prototype.

Weaving plan

The goal of the experiment was to cause warp threads in the center three sections to rise up out of the fabric by adding additional discontinuous weft rows. The weaving plan can be seen in Figure 150.

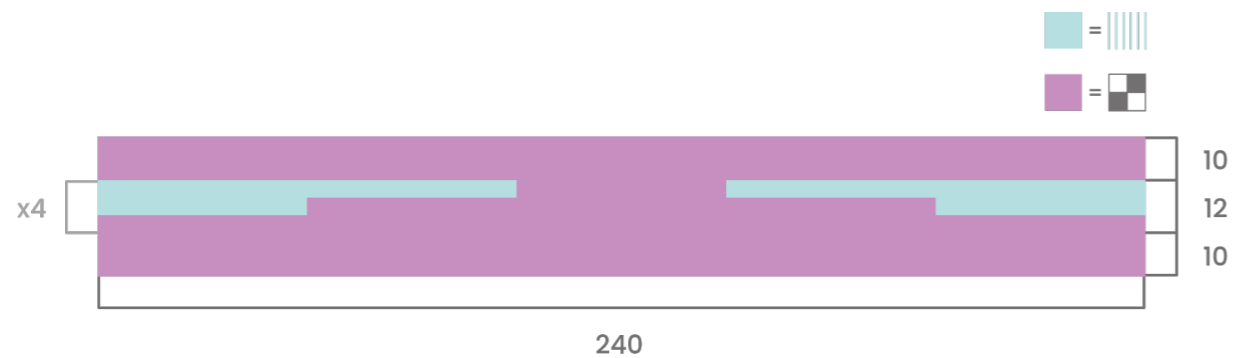


Figure 150: Weaving plan for a dome

Process and results

Figure 151 shows the sample while still on the loom and Figure 152 and 153 show the sample after it was taken off the loom.



Figure 151: The woven dome while still on the loom



Figure 152: Top view of resulting fabric with dome



Figure 153: Side view of resulting fabric with dome

Experiment 2: Triangular fabric

The second experiment was conducted to gain insight into how the add-on could be used to create a non-rectangular 2D fabric.

Weaving plan

A plan was created with the goal of weaving a triangular fabric, as seen in Figure 154. Moving from left to right, increasingly more weft material was inserted in each warp section.

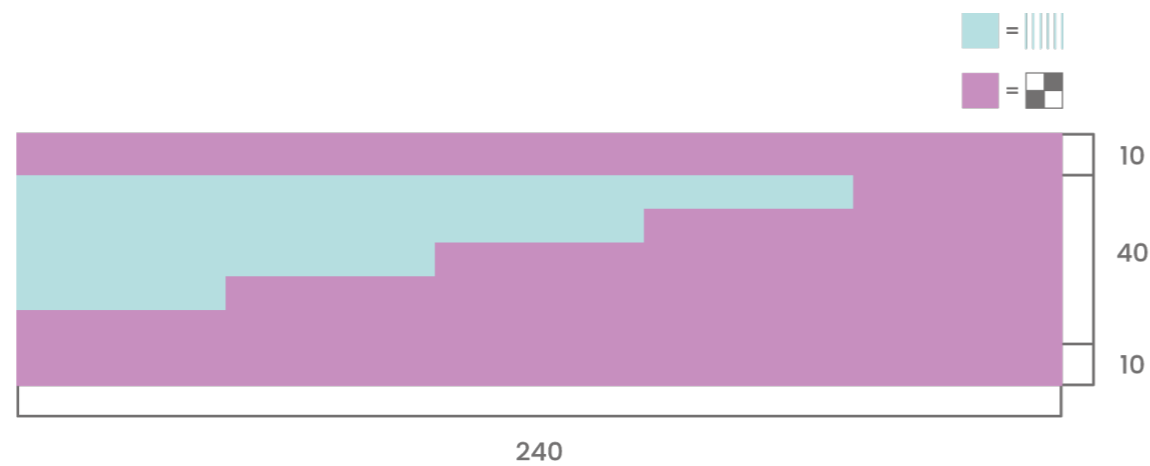


Figure 154: Weaving plan for a triangular fabric

Results

The resulting sample can be seen in Figure 155.



Figure 155: Resulting triangular fabric

Experiment 3: Fabric with cut-out

In this experiment an idea was explored that fabrics with interesting shapes, such as cut-outs, could be made without using floats that later need to be removed.

Weaving plan

The weaving plan in Figure 156 shows how the weft was distributed over the warp. When the weave plan was carried out while using the add-on to realign the fell, the two slanted lines created by the discontinuous weft rows were woven against each other, with no floats in between.

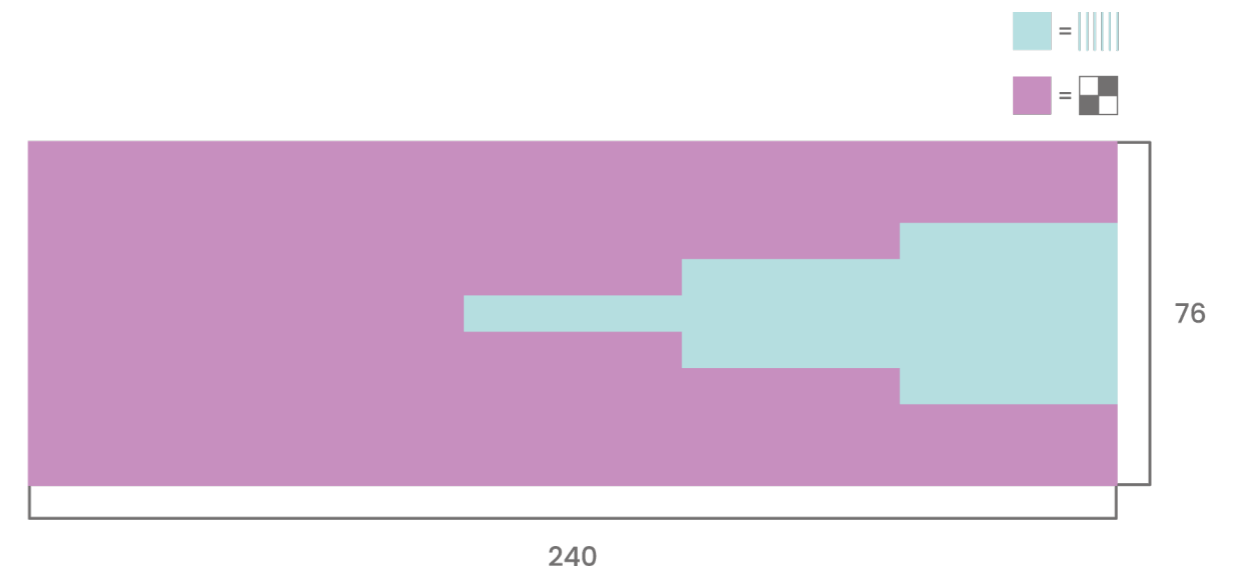


Figure 156: Weaving plan for a fabric with a cut-out

Results

The way the fabric comes off the loom can be seen in Figure 157.

As mentioned above, the two slanted lines in the weave plan were moved against each other in the weave process. After the fabric was taken off the loom, the fabric was cut along this line to open up the fabric into the envisioned shape with cut out (Figure 158). Glue was used to strengthen the edges and avoid fraying.



Figure 157: The sample after being taken off the loom



Figure 158: The sample after it was cut open

Experiment 4: Curving strip of fabric

In order to make optimal use of the warp threads on the loom and weave as many different samples as possible, an experiment was conducted to see if only a portion of the warp threads could be used while the rest of the threads remained unwoven on the loom. The experiment was expanded to see if the separated section of the warp could be curved.

Weaving plan

First of all, two unconnected pieces of fabric were woven by using two separate weft threads in the first 10 rows. Subsequently rows of weft with decreasing width were woven into the warp threads of the separated strip of fabric. As can be seen in the weaving plan (Figure 159) this was repeated twice to create a curve.

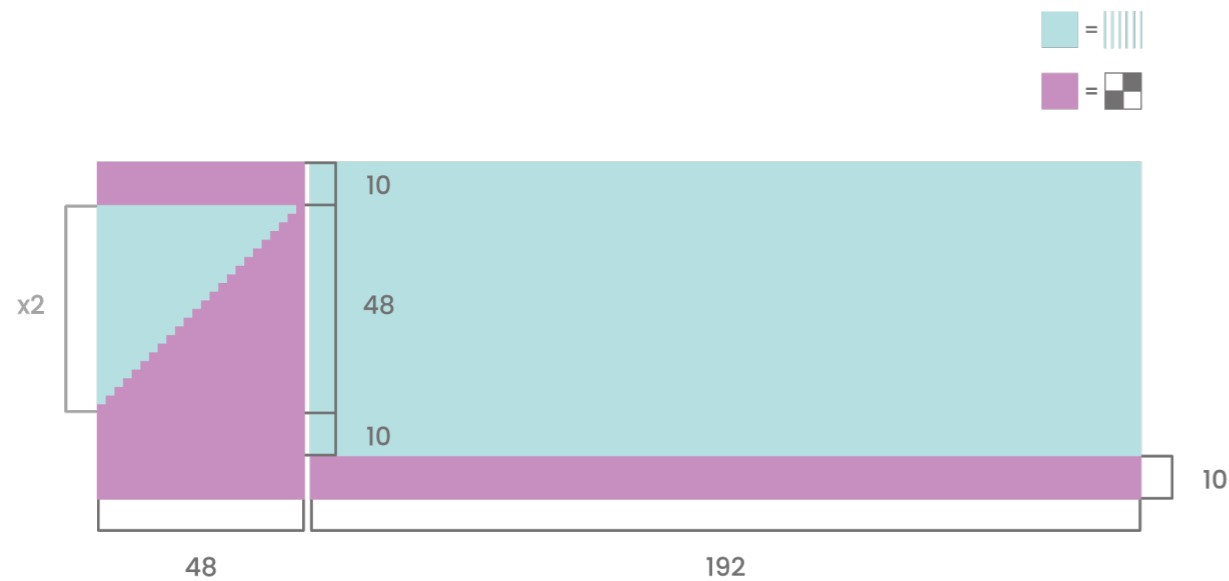


Figure 159: Weaving plan for a curving strip of fabric

Process and results

Figure 160 shows the separated strip of fabric next to the rest of the warp threads that were no longer used after the first 10 weft rows. The image shows how the fabric strip has already started curving left after the first repeat of the weaving plan.

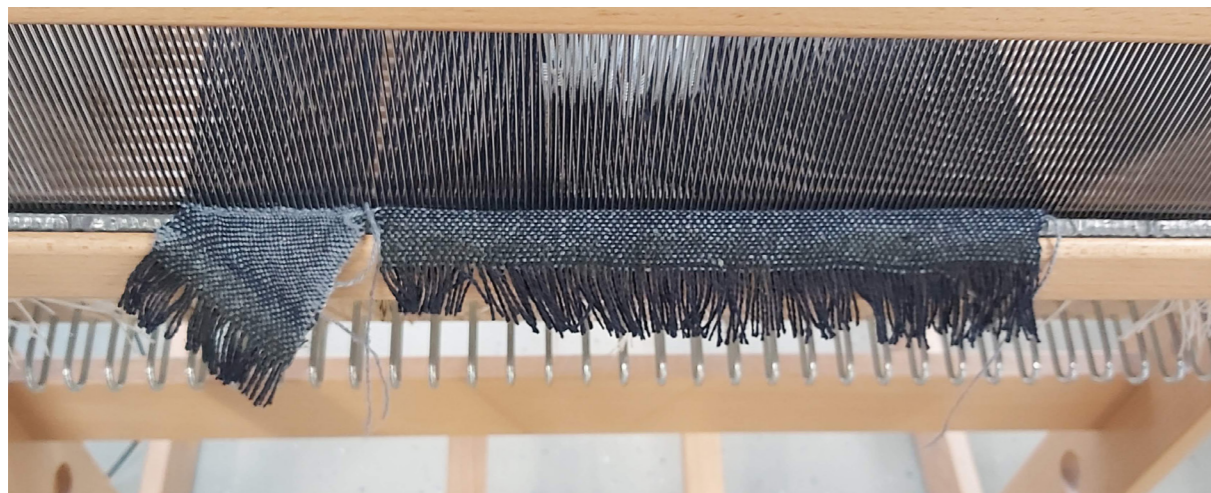


Figure 160: The curving strip of fabric while on the loom

Figure 161 shows the curving sample after it was taken off the loom.

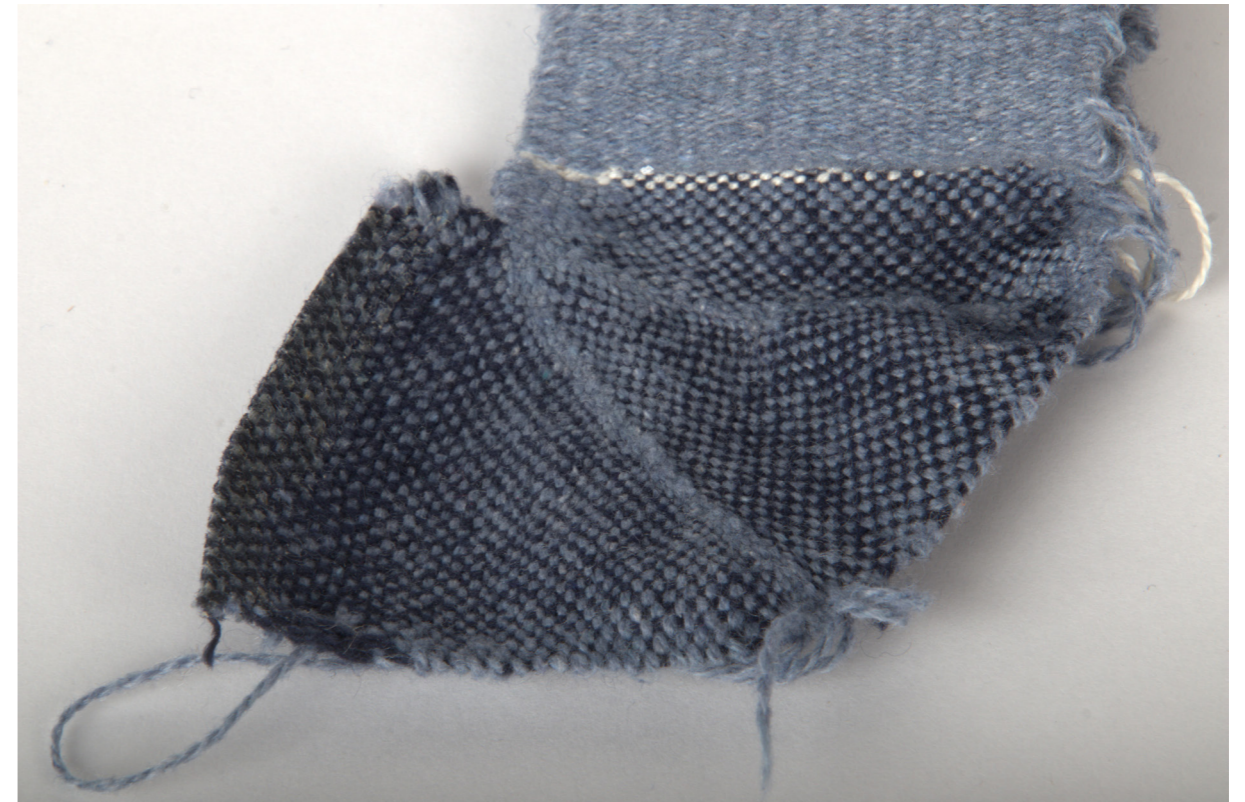


Figure 161: Resulting curved fabric

Experiment 5: Dome

This experiment was conducted to see if a short row knitting pattern for a dome could be translated to weaving. It was chosen to continue only using the warp threads of the strip of fabric that was split off from the rest of the warp threads, as explained in the previous experiment. The use of fewer threads allowed a more pronounced dome to be created in a shorter amount of time and reduced the amount of material needed for the experiment.

Weaving plan

The weaving plan in Figure 162 shows how the weft material was distributed. The weaving plan only shows the warp threads of the separate fabric strip. It is important to note that the section of the weaving plan was repeated three times to build up the dome.

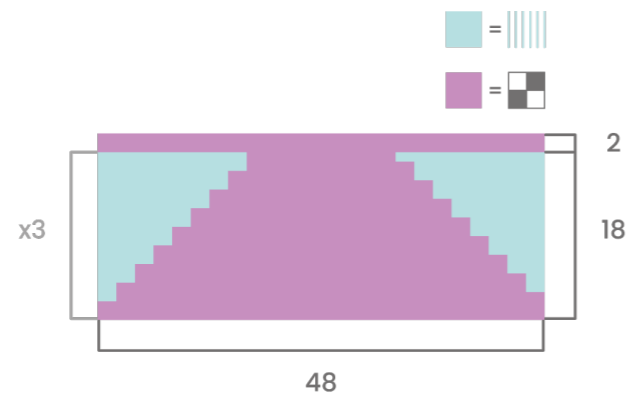


Figure 162: The weaving plan for a dome

Results

Figure 163 shows the dome after the fabric was taken off the loom.



Figure 163: Resulting domed fabric

Experiment 6: Ridge

The next experiment was carried out to see if the weaving plan for the dome could be tweaked to create a ridge that rises straight up from the fabric. Once again, only the 48 warp threads of the separated strip were used.

Weaving plan

The weaving plan in Figure 164 shows how the weft material was placed to build up the sides of the ridge.

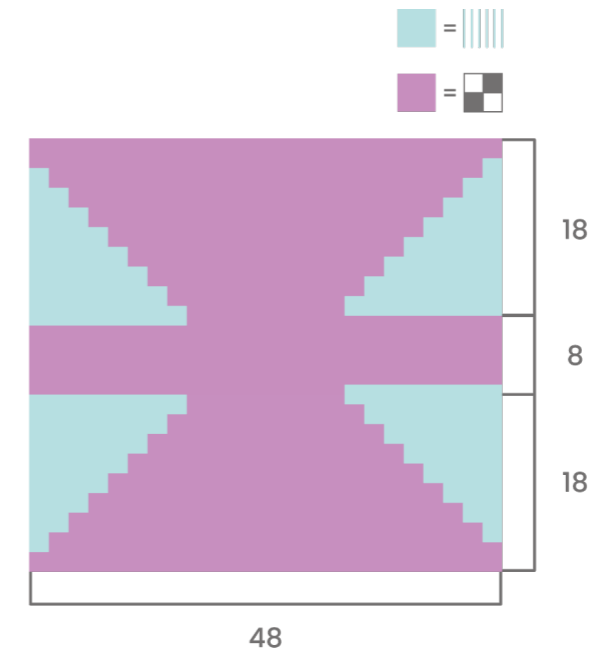


Figure 164: Weaving plan for a ridge

Results

The resulting sample can be seen in Figure 165.



Figure 165: Resulting domed fabric

Experiment 7: Loop

In this experiment the possibility of weaving a separated strip of fabric and pushing it up out of the fabric plane to create a loop was explored.

Weaving plan

The weaving plan shows that after 14 rows, three separate weft threads were woven into the same row to split the fabric up into three pieces. Additional weft threads are added to the middle section of the warp to create the fabric strip that will be pushed up when the fell is aligned (Figure 166).

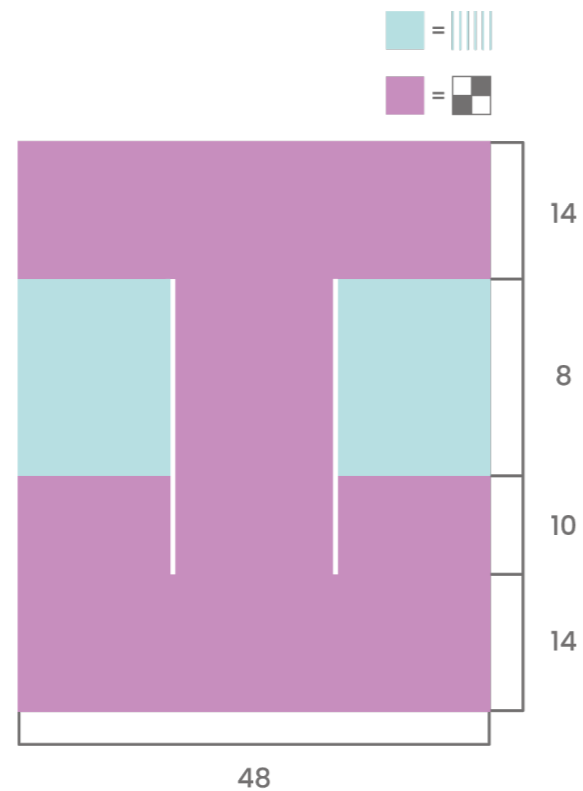


Figure 166: Weaving plan for a loop

Results

The resulting sample with loop can be seen in Figure 167.



Figure 167: Resulting fabric with loop

Experiment 8: Double layer pocket

This experiment was conducted to explore how weaving two layers of fabric with different shapes could be used to create a 3D form.

Weaving plan

The weaving plan can be seen in Figure 168. It is important to note that, as opposed to the previous experiments, multiple weave structures were used in this experiment.

First a section of double weave was woven. The two layers were connected on the left side and separated on the right. This was done by using a continuous weft thread and changing the shedding order of a conventional double plain weave. Changing the shedding order allowed the weft thread to travel back and forth in one layer before continuing to the next layer.

After the section of double weave, extra weft rows were added to the top layer. Changing the way the warp was shed in each row ensured that the weft threads were only interlaced with the warp threads of the top layer. The number of extra weft threads interlaced with the warp threads was increased from left to right. This was done to keep the size of the two layers mostly equal where they connect on the left and create a big difference where they are separate on the right. The process of weaving a section of double weave and adding more material to the top layer was repeated three times.

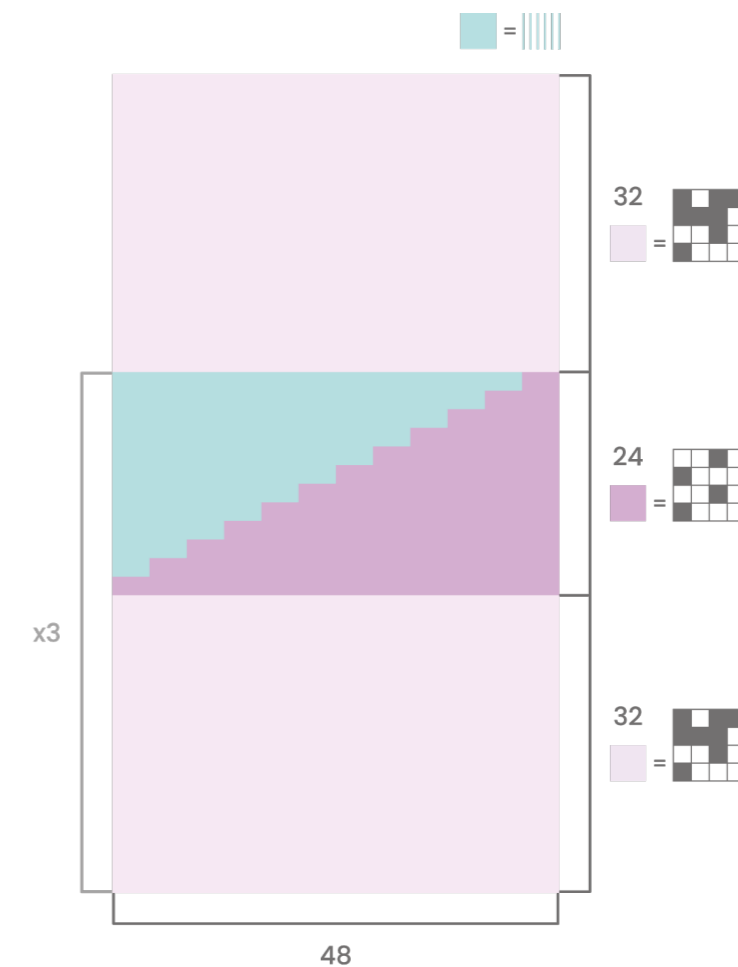


Figure 168: Weaving plan for a double layer pocket

Process and results

Figure 169 shows how the amount of weft material in the top layer is greater than in the bottom layer.

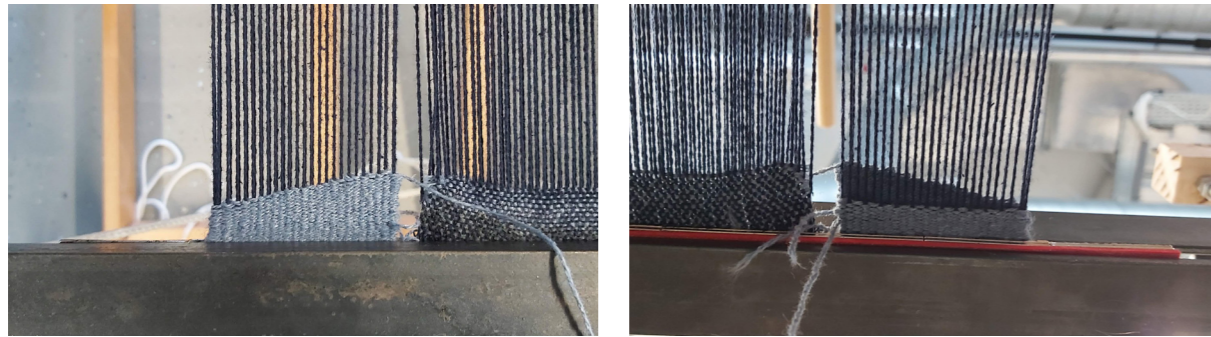


Figure 169: Top view of the fabric in process (left) and bottom view (right), showing how extra material was added to the top layer

The resulting pocket with a larger top layer can be seen in Figure 170.



Figure 170: Resulting pocket

Experiment 9: Double layer dome

The concept of weaving two differently shaped layers simultaneously was explored further in this experiment. The goal of the experiment was to create a hollow shape by weaving a double layer fabric of which the top layer rises up into a dome while the bottom layer remains flat.

Weaving plan

Similarly to the previous experiment, the weaving plan shows a combination of sections woven in double weave and sections in which additional weft threads are woven into the top layer (Figure 171). More weft material was added in the center to create a dome shape, similarly to what was done in Experiment 5. The two layers were connected on both sides due to the use of a continuous weft thread that traveled from one layer to the other.

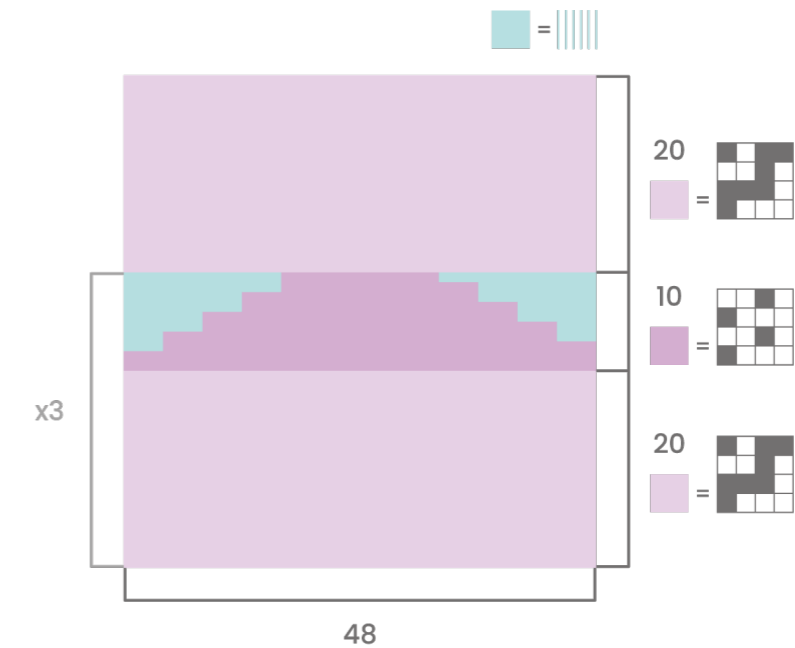


Figure 171: Weaving plan for a double layer dome

Process and results

The resulting double layer fabric can be seen in Figure 172.



Figure 172: Resulting double layer dome

Experiments 4-9 were all woven using only 48 warp threads of the total 240 (Figure 173). After this sample was woven, the length of these threads was no longer sufficient to weave samples with these threads. The woven fabric strip and the remaining length of the warp threads were therefore removed from the loom so that the following experiments could be carried out with the remaining 192 threads without any obstacles.

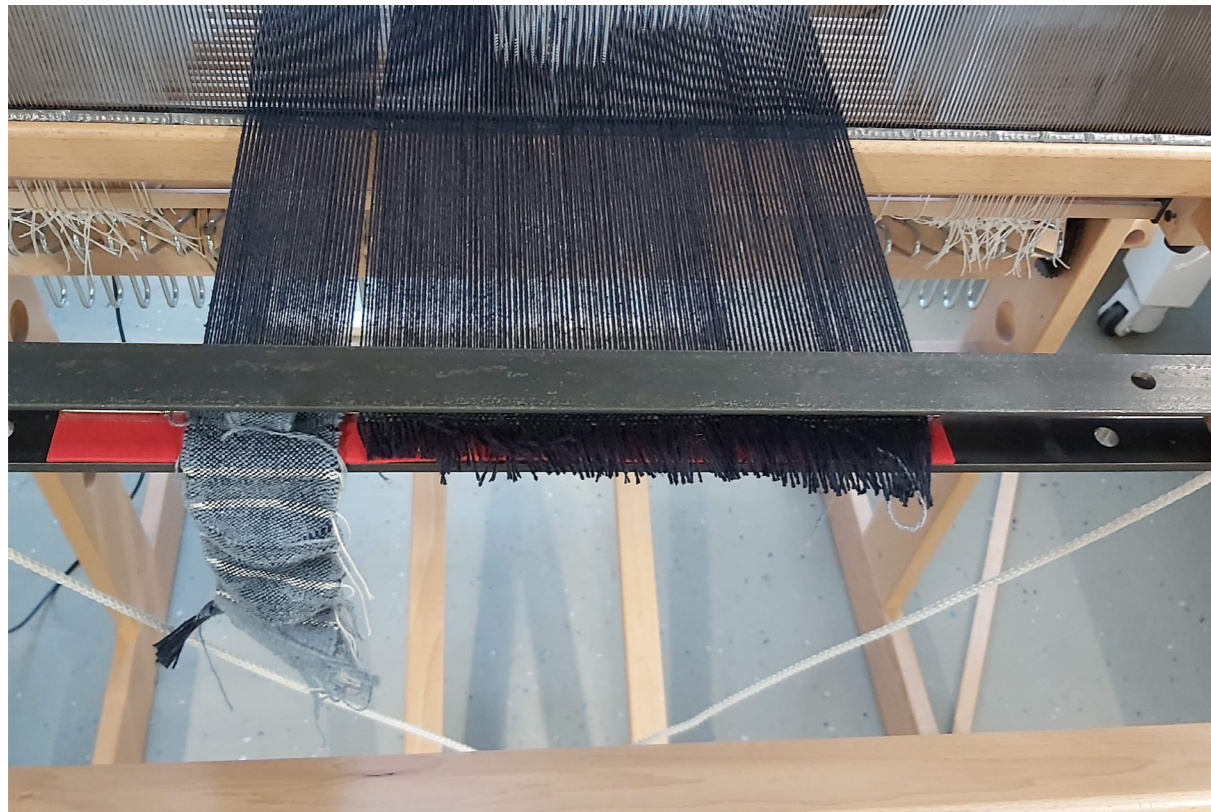


Figure 173: The fabric strip created in Experiment 4-9 while on the loom next to the section of the warp not used

Experiment 10: Corners

The following three experiments were carried out with all 192 warp threads that remained on the loom in order to create a few larger scale samples while utilizing the ability to move every thread individually.

First of all, an experiment was conducted to see if sharp corners could be made. This was inspired by a short row knitting pattern for a box.

Weaving plan

Figure 174 shows the weaving plan. Using the add-on during weaving enables the slanted lines to be pulled against each other to create the envisioned corners.

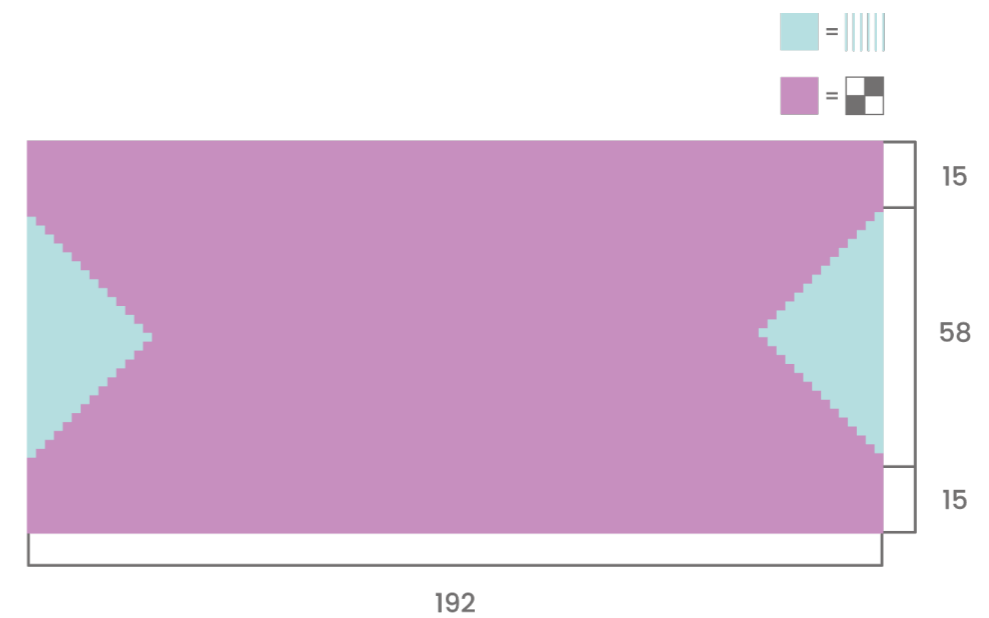


Figure 174: Weaving plan for a fabric with corners

Results

Figure 175 shows the resulting fabric.



Figure 175: Resulting fabric with corners on a table (left) and draped over a square shape (right)

Experiment 11: Two ridges

The goal of this experiment was to see if multiple bulging areas could be created.

Weaving plan

The weaving plan can be seen in Figure 176.

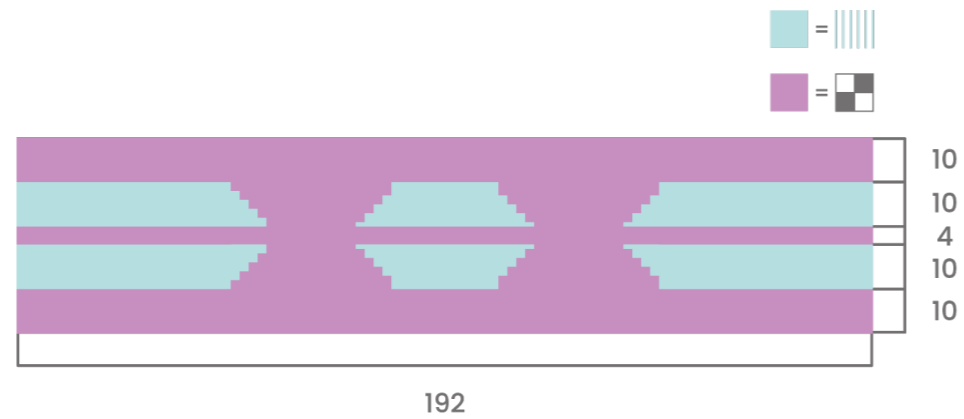


Figure 176: Weaving plan for a fabric with two ridges

Process

Instead of using two separate weft threads to build up the two ridges, a continuous weft thread was used. The thread was left to float underneath the warp in between the two shapes (Figure 177).

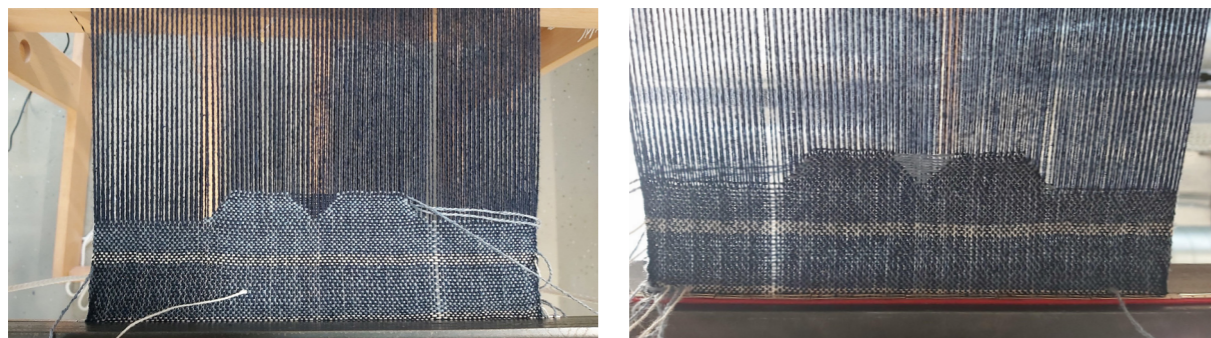


Figure 177: Top view of the weft rows (left) and the bottom view (right), showing how the weft floats between the two shapes

Experiment 12: Dome in plain weave

In Experiment 5 a dome was woven using all the warp threads in the fabric strip. Experiment 12 was conducted to explore how a dome can be embedded within a fabric and how the surrounding flat fabric is affected.

Weaving plan

The weaving plan in Figure 178 shows that the extra material needed to create the dome is only added in the middle of the fabric.

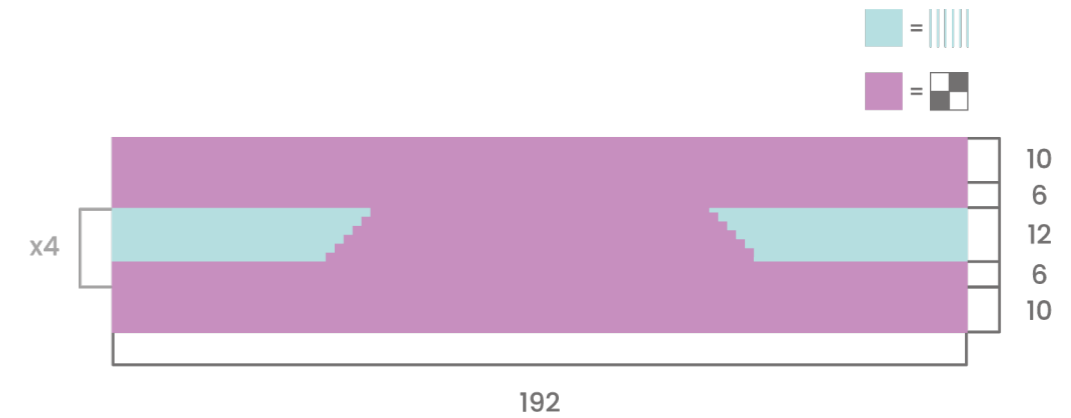


Figure 178: Weaving plan for a dome embedded in a plain weave fabric

Results

The resulting fabric can be seen in Figure 179.

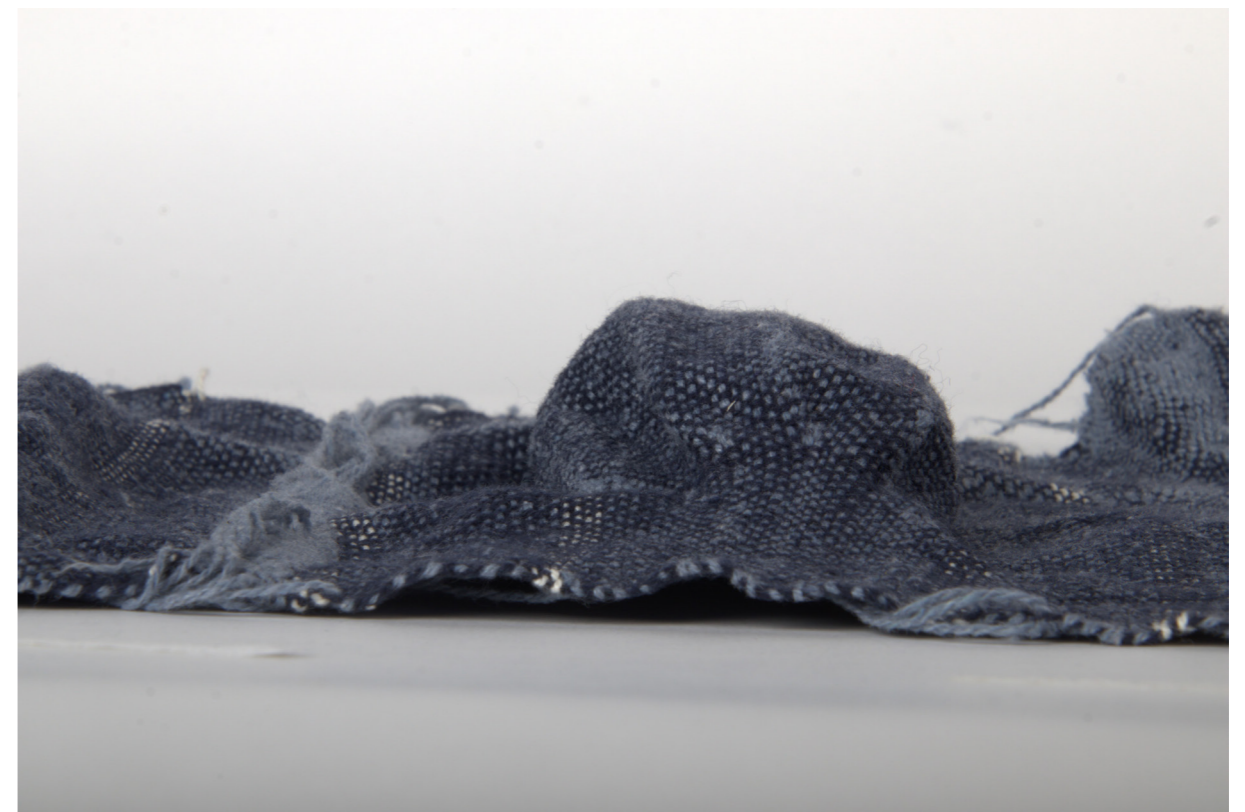


Figure 179: Resulting fabric with embedded dome

Experiment 13: Dome in plain weave surrounded by twill weave

In all the previous experiments the focus lay on adjusting the number of weft threads each warp thread intersects with in order to manipulate the warp threads to curve or rise up out of the fabric plane. The interlaced weft threads were pulled along by the moving warp threads. However, the length of the weft threads and the placement of the warp threads along a weft thread were not consciously adjusted to the envisioned fabric form. Ways of stimulating weft threads to rise up out of the fabric plane were introduced in Chapter 5.2.1, but were not the focus of this research. Nevertheless, a quick experiment was conducted to see how using different weave structures would affect the distribution of the weft and warp threads.

Weaving plan

The weaving plan (Figure 180) is largely the same as the one used in Experiment 9. An important difference however, is that the center section, which is meant to rise up into a dome shape, is woven in plain weave while the surrounding fabric is woven in a twill. The warp threads in the plain weave are pushed apart by the high number of intersections. The lower amount of intersections in the twill weave on the other hand should allow the warp threads to move closer together. It was hypothesized that extra weft length would be pulled into the doming area due to the spacing between the warp threads being slightly greater than in the twill areas. Ideally, this extra weft length would allow the weft threads to better follow the curve of the dome.

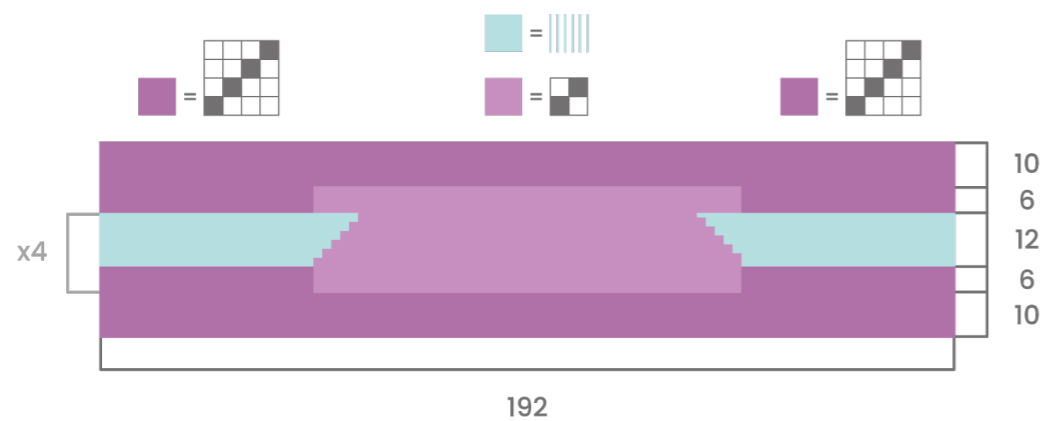


Figure 180: Weaving plan for a plain dome embedded in a twill fabric

Results

Figure 181 and 182 show the resulting fabric.



Figure 181: Top view of resulting fabric with embedded dome



Figure 182: Side view of resulting fabric with embedded dome

8.4 Observations made during weaving

During weaving observations were made on the use of the add-on within the weaving process. The most important observations are explained below.

8.4.1 Interaction between the reed and the clamp

First of all, the reed is supposed to move the fell until it lies in between the clamp halves. However, in the current prototype the reed cannot entirely meet the clamp because it gets blocked by one of the pulleys. This causes the fell to always lie slightly behind the clamp instead of in between (Figure 183). While not a problem for the weaving process, it did mean that this one cm wide strip of fabric remained under tension, which sometimes put strain on the threads.

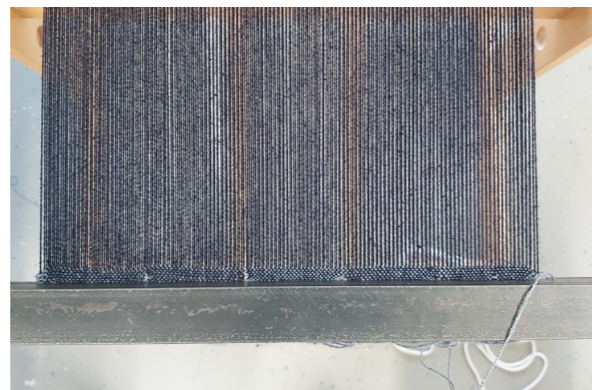


Figure 183: Picture showing how the fell lies slightly in front of the clamp

8.4.2 Required manual interventions

The clamp of the prototype add-on is not able to compensate for variations in fabric thickness. In order to keep the fabric in place, the clamp must thus press down onto a flat piece of fabric. This means the fabric cannot be doubled over or bunched up in the area under the clamp.

When the reed was pushed against the fell, the woven fabric tended to rise up against the reed (Figure 184). The clamp was intended to push the fabric down as it closes. However, the reed was restricted from moving completely against the clamp by one of the pulleys, this was not possible. Therefore some intervention was required from the weaver to push the fabric down and smooth out the bulges so that the fabric would lie flat from the fell to the edge of the area the clamp would press down on (Figure 185).



Figure 184: Picture showing how the fabric rises up against the reed



Figure 185: Picture showing how the weaver manually pushes the bulge down

8.4.3 Managing difficulties in fixating the straightened fell

There were instances in which straightening the fell required some warp threads to be moved considerably more than others. An example from Experiment 10 can be seen in Figure 186.



Figure 186: Picture showing a fell that has become strongly curved due to the interlacement of discontinuous weft threads

When the reed was used to align the fell, the woven fabric bunched up against it. It was very difficult to flatten an area of the fabric enough for the clamp to fall on (Figure 187). To lie completely flat, the fabric needed to be slightly stretched in some areas, but the woven structure and the warp and weft materials did not allow for this sufficiently.



Figure 187: Picture showing the fabric bunched up against the reed and the clamp falling onto double up fabric as a result

Due to the clamp falling onto bunched up fabric and thus not being able to press down properly along the whole width of the fabric, the middle of the fabric started sliding out of the clamp while the edges of the fabric got bunched up (Figure 188). The fixation of the fell was too unreliable and the spacing of the warp was affected by the bunching up of the fabric, making it difficult to continue weaving properly.



Figure 188: Picture showing a fell that has become strongly curved due to the interlacement of discontinuous weft threads

It was therefore decided to move the fabric back into the stable position it was in before alignment was attempted, continue weaving for another few rows, and try to straighten the fell at another point. According to the weaving plan, the weft rows had to become increasingly broader from that point. It was possible to weave in and beat up the broader rows because the fell was aligned during beat up, as long as the reed was moved forward far enough. When the clamp is not used to keep the straightened fell in place, it will return to its curved shape once the reed is moved away. This process can be seen in Figure 189.

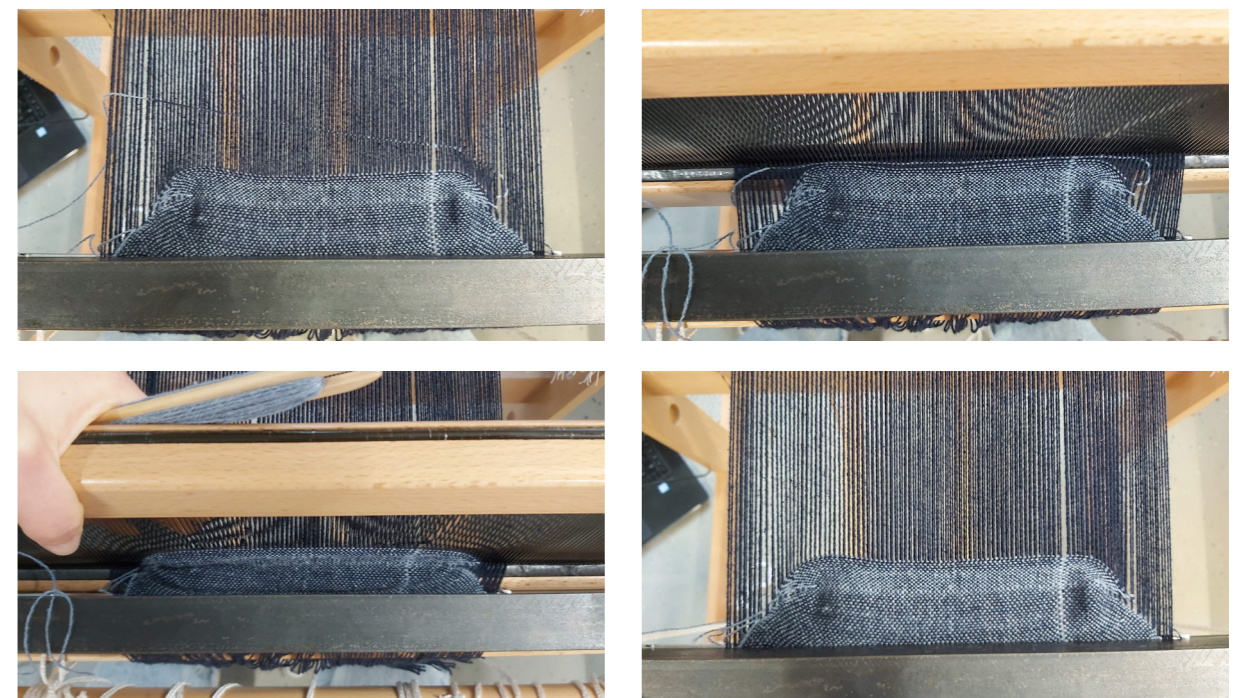


Figure 189: The process of weaving in and beating up broader weft rows by straightening the fell during beat up

These steps were continued while gradually increasing the width of the weft row. As the width of the weft became greater, it needed to be beaten up against a larger portion of the fell. This required more material to be moved forward during beat up in order to straighten a large enough portion of the fell. This became increasingly more difficult. In addition, the curve the weft was pulled into once the reed was moved away became more extreme. As can be seen in Figure 190, the curving weft threads pulled the warp threads together at the sides.



Figure 190: Picture showing how the curving weft threads pulled the warp threads in at the sides

The width of the weft was increased until two full weft rows were woven in. At that point another attempt was made to align the fell. Due to the full weft rows running through all the warp threads, these rows could easily be pressed flat. The fabric could start bulging behind these rows. Two full weft rows was enough to provide the space required for the clamp to press down on (Figure 191).



Figure 191: Picture showing how two full weft rows allowed the fabric to be flattened enough for the clamp to press down on

In more experiments it was sometimes beneficial to first weave in broader or even full weft rows before trying to fixate the straightened fell with the clamp. For example in Experiment 11, as seen in Figure 192.

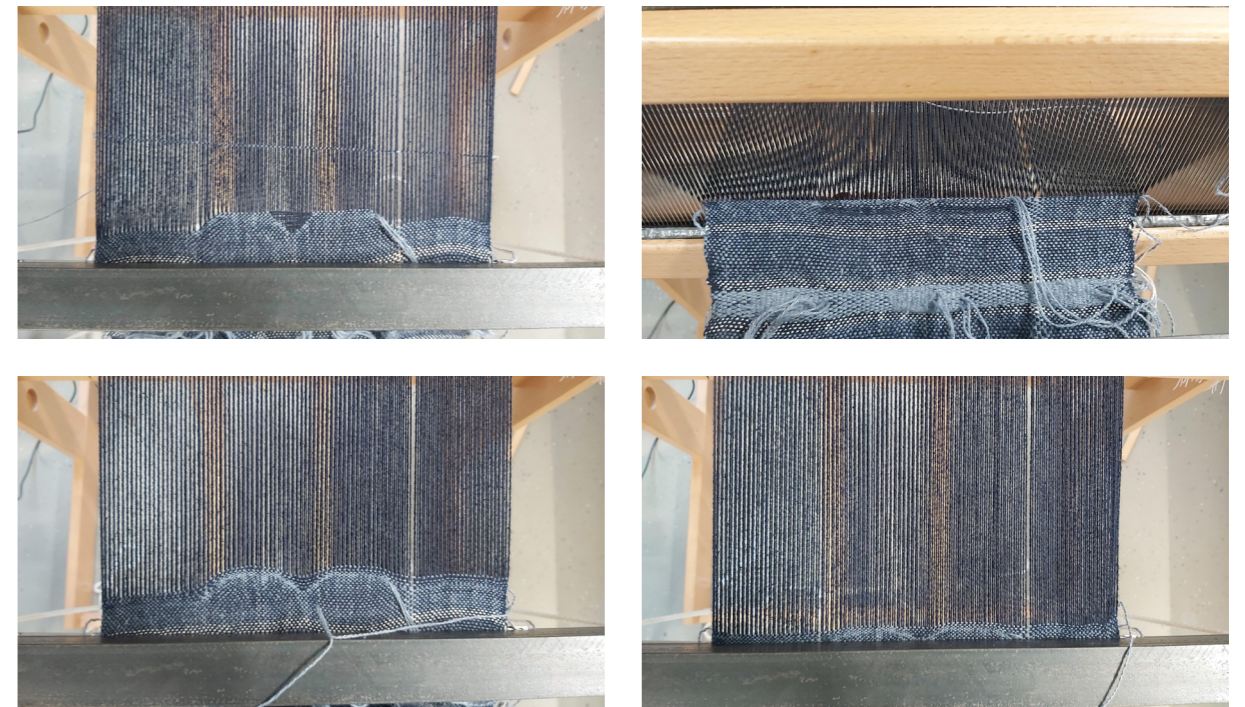


Figure 192: The process of weaving in full weft rows before trying to straighten and fixate the fell

8.5 Findings on shaping

The experiments provided insights into how the fabric can be shaped. The explored possibilities and the insights gained are described in the following section.

8.5.1 Approach to shaping

In each of the experiments a shape was made by interlacing more weft threads with some of the warp threads than others. Looking at the weaving plans, different approaches to building up the shape can be identified. To create fabrics that bulge out of the fabric plane, such as in Experiment 1, 5, 9, 12 and 13, additional weft material was added to specific warp threads in increments. The same was done to curve the fabric in Experiment 2, 4 and 8. In comparison, fabric was pushed out of the fabric plane to create a ridge that stands upright by pulling two sections of fabric towards each other during weaving. This can be seen in Experiment 6, 10 and 11. A similar approach was taken in Experiment 7 to push the separately woven fabric strip up. If sections of fabric are pulled together during weaving, they can also be split up again after the fabric is taken off the loom, as was done in Experiment 3.

8.5.2 Possibilities for 2D and 3D shaping

By changing the way the additional weft rows were placed, a variety of 3D and non-rectangular 2D shapes were created. A 3D fabric was created when warp threads were forced to bulge up due to previously woven in weft threads not being able to move or curve enough to make room on the XY plane for the additional weft rows. A fabric can be curved and shaped while staying flat on the XY plane if the additional weft rows are placed in such a way that previous weft rows can move out of the way while staying straight, for example in Experiment 4.

8.5.3 Effect of adjusting the weft length to the shape

While experimenting with creating 3D fabrics, the focus was placed on manipulating the warp threads to bulge out of the fabric plane. The weft threads were pulled into shape by the bulging warp threads, but their length was not specifically adjusted to the desired shape in most of the experiments. In Experiment 13 an attempt was made to increase the length of the weft thread in the doming area of the fabric. The doming area was woven in plain weave, while the surrounding areas were woven in a twill. This was done with the assumption that the warp spacing would be greater in the plain weave than in the twill and more weft length would therefore be pulled into the bulging area. The resulting fabric of Experiment 13 was

compared to that of Experiment 12, in which the dome and surrounding fabric were both woven in a plain weave.

The domes were created by weaving in a number of full weft rows followed by discontinuous weft rows decreasing in width. This process was repeated four times. In the sample of Experiment 12 the discontinuous weft rows are able to follow the curve of the dome nicely, but the full weft rows pull the dome down, giving the dome an uneven surface (Figure 193). The length of the full weft rows in the doming area is not sufficient to travel the additional distance along the curve of the dome.

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Figure 193: Close up of domed fabric from Experiment 12

Changing the weave structure in Experiment 13 seems to have helped solve this problem somewhat. Measuring the sample (Figure 194) shows that the plain weave section of a full weft row, which spans 92 warp threads, measures 11cm. This corresponds to a warp density of 8,4 ends per cm. The twill section, spanning 48 warp threads, measures 5cm, which corresponds to a higher warp density of 9,6 ends per cm.



Figure 194: Picture showing how the plain weave and twill areas were measured

This confirms the assumption that the warp spacing is greater in the plain weave section than in the twill. As a result, the length of the weft thread in the plain weave section is longer per warp thread than in the twill section. This longer length allows the weft thread to follow the curve of the dome better, resulting in a smoother surface (Figure 195).



Figure 195: Close up of domed fabric from Experiment 13

8.5.4 Option to float the weft

In most of the experiments discontinuous weft rows were used to build up weft material on specific warp threads. In Experiment 11 the possibility to float the weft behind the warp threads that are not engaged in that row was explored. These floating weft threads could be compressed and did not restrict the reed from straightening the fell, allowing the material to be pushed out of the fabric plane similarly to the other experiments.



9. Discussion

Textiles are essential to our daily lives, yet the current state of the textile industry imposes significant stress on both people and the environment. McQuillan (2020) proposes the development of textile-forms, of which the fabric and shape are created simultaneously, to support the transition toward a local, on-demand, and zero-waste textile system. The ability to create textile-forms in weaving, one of the two most common textile production methods, is unfortunately limited. Most looms are designed to weave flat, rectangular sheets of fabric and lack the capability to weave 3D forms, offering few possibilities for shaping.

This project was motivated by a desire to make the weaving of 3D fabrics accessible to textile researchers in order to uncover its potential for a more sustainable textile industry. The aim of this research was to find methods for weaving 3D fabrics and validate them by building an add-on prototype for a Magic Dobby shaft loom.



9.1 Findings and possibilities

This research has resulted in a number of interesting findings that have opened up new possibilities in weaving. This is elaborated below.

9.1.1 Weaving taxonomy

A weaving taxonomy was created to provide an overview of the variables that can be changed within the weaving process, which was previously lacking. The taxonomy was developed by focusing on the interlacement of the warp and weft threads, instead of the functions of certain existing looms. This allowed assumptions about weaving to be challenged and new options to be found. For example, on the majority of looms the warp threads are tensioned between the warp beam and the cloth beam and can only be moved along the y-axis as a whole. Questioning this typical loom set up was vital for discovering new ways to weave 3D fabrics.

The way the taxonomy enabled a systematic approach to considering different possibilities and conducting experiments in this research shows the potential of the taxonomy to be a valuable tool in other weaving research as well. It can help weavers break free from assumptions about what can or should be done in weaving. Weavers can use the taxonomy to first consider how they want to manipulate the warp and weft threads during the weaving process and subsequently consider how that can be achieved on their loom. This can lead to completely new ideas that might not have come up if the weaver approached the weaving process from the functionalities of the loom available to them. Even though weaving is an ancient technique, that does not mean there is no more room for innovation. On the contrary, given the problematic state of the current textile industry, innovation is needed. The comprehensive and visual taxonomy can aid weavers, researchers and industry players to find, communicate and discuss alternatives to the current wasteful production methods.

9.1.2 Methods for weaving 3D fabrics

A method for weaving 3D fabrics on a standard loom was found in this research that is more accessible, flexible and opens up more possibilities for fabric shaping than the existing methods and tools.

In order to create a 3D fabric, the placement of the warp and weft threads needs to be manipulated during weaving. The biggest barrier to creating 3D fabrics is the inability of warp threads to bulge up while on the loom. This research therefore focused on the way the weaving process and the loom had to change to create this possibility.

In the proposed method, additional length of specific warp threads is pulled forward as a result of the fell being straightened after additional weft threads were interlaced with the warp threads or the spacing between the weft threads along the warp threads was changed. This requires the warp threads to be able to move forward individually. In addition, it was found that the warp threads should be tensioned only up to the fell. This allows the

additional warp length that was moved forward to bulge up, pulling along the interlaced weft threads to create a 3D fabric on the loom. This method offers a way to weave 3D fabrics without being limited by the ability of the material to stretch and jump back into shape once taken off the loom. An extra benefit of shaping the fabric by interlacing additional weft threads is that a fabric with a constant density is created. By providing a flexible way to weave a variety of 3D fabrics without negatively impacting the integrity of the fabric, the method has potential to be used for creating functional textile-forms.

9.1.3 Loom add-on

A prototype of a loom add-on was built for the Magic Dobby shaft loom with which the theorized method for creating 3D fabrics could be put into practice. The add-on consists of a clamp and a let-off frame. The clamp keeps the fell in place at the front of the loom to enable the unwoven warp threads to be tensioned while allowing the woven fabric to bulge and curve. The let-off frame provides space to hang weights onto the warp threads to enable individual movement along the Y-axis. Through experimentation it was confirmed that the add-on could be used in combination with interlacing discontinuous weft rows to shape the fabric. The experiments resulted in an assortment of both 3D and non-rectangular 2D fabrics.

The add-on can be added to the loom without requiring any permanent alterations. This makes the weaving of 3D fabrics significantly more accessible in comparison to weaving 3D fabrics on a specialized loom. In addition, the add-on prototype is simple, robust, requires no electronics and could be built by hand at a low cost. This shows the potential of the add-on to be developed into an accessible product that can be made suitable for a variety of looms, to be used in crafting and research as well as larger scale textile production.

9.1.4 Fabric shaping

In the weaving experiments carried out with the add-on on the Magic Dobby loom, all the samples were created by interlacing discontinuous weft rows. However, two different approaches were taken to shaping. In some samples the shape was built up by adding discontinuous weft rows in increments. For other samples, the weaving process was more comparable to pulling two sections of fabric against each other.

Adding discontinuous weft rows in increments is very comparable to short row knitting, in which only a selection of the stitches are knit in some rows to build up extra material (Underwood, 2009). In the weaving process, the warp threads can be compared with the stitches. Engaging some warp threads with the weft thread and leaving others unwoven is similar to only knitting certain stitches.

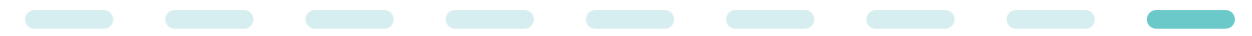
The other approach, in which two sections of fabric are pulled together, is similar to creating darts or connecting two pieces of fabric together in sewing. To create a dart a triangular or diamond shaped piece of fabric is folded or cut away and the edges of the triangle or diamond are pulled together. The removal of material in one area causes material in other areas to be pushed up (Colgrove, 2020). Equivalent of darts can be embedded in the weaving process by straightening the fell so that two areas of fabric are immediately woven against each other. This can also be compared to a seam. Weaving in darts and seams eliminates fabric waste and cuts down on the steps required to shape the fabric once it is off the loom. In addition, an interesting finding from the experiments was that areas of fabric can be woven against each other with the intention of cutting them loose and flattening the fabric later. This could be seen as reversing a dart to create a fabric with a cut out, but without requiring any material to be removed and wasted.

Short row knitting and sewing are established methods for shaping fabric. Therefore there is a large amount of available knowledge and tools that could possibly be used to create weaving plans. Besides, the large variety of shapes that can be accomplished with short row knitting and the creation of darts and seams show the potential of the proposed method and add-on for shaping woven fabric.

9.1.5 Potential for the textile industry

The ability to shape the fabric on the loom would offer new possibilities for creating woven textile-forms, which could contribute to the development of a local, on-demand and zero-waste textile system. The experiments conducted in this research show how 3D shapes can be embedded into the fabric during weaving and non-rectangular 2D fabrics can be created. For the creation of textile-forms, the presented methods could be used to weave pieces of a textile product in the desired shape, to be sewn together after being taken off the loom. This is similar to fully fashioned knitting. The multi-layer samples also show potential for creating a whole textile product directly on the loom, similar to whole garment knitting.

If the methods for shaping the fabric are applied on an industrial loom, it could change the way textile products are produced and consumed. Creating the form simultaneously with the fabric reduces the amount of post processing steps required to create the final textile product, and eliminates waste by only using the material required for the final form in the creation of the fabric. The textile products could be produced on-demand in local micro factories, shaped to the consumer's wishes. Local production enables designers, manufactures and consumers to collaborate, making the way the clothing is produced, where the clothing ends up, and what will happen at the end of its life more transparent and controllable. In addition, only producing a product when it is needed curbs overproduction, and personalizing the product stimulates longer use. This method of textile production and consumption has potential to be a more sustainable and ethical alternative to the globalized fast fashion industry.



9.2 Limitations

The limitations of this research will be described in the following section.

9.2.1 Weaving taxonomy

The weaving taxonomy presented in this research should be considered a first version. It was created to the best of the ability of the researcher, who had a limited knowledge of weaving prior to this research. The lack of weaving background may have aided the development of the taxonomy by reducing any preconceptions about weaving, but may also have resulted in gaps in the taxonomy.

Furthermore, the possibility to change the material and the weave structure is currently briefly mentioned in the taxonomy, but the available options are not described. A weaver can use the taxonomy to determine whether to change the material or weave structure, but must consult other sources to decide how.

The rest of the taxonomy also only describes what aspects of the weaving process can be changed, but does not describe how the weaver can go about changing a specific variable on their loom. This was done on purpose to not limit weavers to one method. The downside of this is that some weavers may not know how to put the possibilities they identified in the taxonomy into practice. Besides, some of the options in the taxonomy are currently only hypotheses that have not yet been explored.

9.2.2 Methods for weaving 3D fabrics

Methods for manipulating a weft thread and warp thread to rise up out of the fabric plane were analyzed separately. It was determined that adjusting the weaving process and loom to enable warp threads to bulge up was most vital to the weaving of 3D fabrics, because the interlaced weft threads would consequently be pulled up. The described methods for specifically manipulating a weft thread to rise up could be applied in tandem with the methods for raising up the warp threads to ensure the length of the weft matches the curve of the desired shape. However, how combining methods would work in practice and the effect on the resulting fabric was explored to a very minimal degree in this research.

Furthermore, there are some concerns related to the theorized methods for making adjustments so that a weft thread follows the desired curve. Ideally, extra warp threads would be added to a bulging weft thread in the same manner as additional weft threads are interlaced with bulging warp threads, as this would result in a fabric with constant density. However, this is difficult because all the warp threads on the loom are put in place prior to weaving. This means that if warp threads need to be inserted into a row during the weaving process they already need to be stored somewhere on the loom. This is easy to do if warp threads only need to be added at the sides of the fabric. It is more complicated if warp threads need to be added in the middle of a row. This requires the warp threads to be divided into at least two layers: one used for the fabric and one functioning as a storage

of warp threads that can be transferred to the fabric layer when needed. Dividing the warp into multiple layers decreases the warp density in the fabric. In addition, transferring threads from one layer to another would likely require a jacquard loom. Instead of inserting extra warp threads, the weft length can also be adjusted by increasing the spacing between the threads using weave structures or an adjustable reed, which can be done on a shaft loom. Although, this will impact the look, feel and integrity of the fabric.

9.2.3 Loom add-on

During experimentation some limitations of the add-on prototype were observed. First of all, the clamp was not able to fixate fabrics with a varying thickness reliably. This restricted the ability to use the clamp while changing the weave structure or varying the number of layers within a weft row, leaving these requirements of the add-on unfulfilled and the potential of these methods for fabric shaping unconfirmed.

Secondly, in order to properly fixate the fabric, the area onto which the clamp presses must lie flat. An attempt was made to minimize this area by using a corner profile with a thickness of 3mm. Despite the small area, the threads still needed to be stretched in order to flatten the fabric at times, which was not always possible. The problem was worsened by the fact that the reed was blocked by one of the pulleys from bringing the fell all the way between the clamp halves. To keep the fell straight, this strip of fabric also needed to lie flat, increasing the area in which the threads had to stretch. The weaving process was adjusted in some of the experiments to enable enough fabric at the fell to lie flat.

Thirdly, for the experiments the warp threads were divided over three warp beams. The amount of excess length let off the warp beams and tensioned with weights determined how much each warp thread could be moved forward. This put constraints on how much each individual warp thread could move without affecting the other warp threads.

Lastly, some of the requirements of the add-on were not yet tested in this research, such as the ability to use the add-on in combination with a fan reed or rail reed, leaving the ability of the add-on to fulfill these requirements unconfirmed.

9.2.4 Fabric shaping

Although knitting and sewing can be used as inspiration for how the fabric can be shaped during weaving, there are obstacles in weaving not experienced in these methods.

Knitting patterns in which stitches are added or removed to shape the fabric cannot be directly copied in weaving in the same manner as short row knitting patterns can be translated to a weaving plan. While in knitting extra stitches can be created anywhere in a row at any point during knitting, adding in warp material is more difficult due to the warp being put in place prior to weaving, as explained in Chapter 9.2.2. Instead of adding warp threads, the spacing between the threads can be adjusted. In order to use existing knitting patterns, the increase or decrease in the number of stitches would need to be translated to a change in warp spacing.

In comparison to sewing, less flexibility will likely be experienced in weaving. One can cut a sheet of fabric into any shape desired, create darts at any place and angle, and attach pieces of fabric as desired. In the experiments in this research on the other hand, only the simplest shapes were explored.

More insight into shaping is required to understand how tools and knowledge from knitting and sewing could be applied or whether alternative approaches should be sought.

9.3 Further research and development

This research has shown that it is possible to weave 3D and non-rectangular 2D fabrics, and it was hypothesized that this could be beneficial to creating woven textile-forms. Nonetheless, it is important to note that this research has only set the first steps. The add-on prototype provides a proof of concept of both the tool and the methods for shaping the fabric. However, more research and development is needed to firstly make fabric shaping accessible to textile researchers to further understand the possibilities, and at a later point explore its application in the textile industry.

Recommendations for further research in different areas are given below.

9.3.1 Weaving taxonomy

1. Develop the taxonomy further and fill any current gaps. through co-creation sessions with people with different textile backgrounds, such as hobby weavers, textile designers, researchers and loom manufacturers and operators.
2. Research, brainstorm and experiment to understand if and how all the options in the taxonomy could be put into practice. This knowledge can be used to develop new tools and create a guide for weavers.

9.3.2 Methods for weaving 3D fabrics

1. Experiment with combining different methods for changing the placement of warp and weft threads in order to create a 3D form. Analyze the effect of the methods on the look, feel and integrity of the resulting fabric, and determine the possibilities and limitations for shaping of the methods.
2. Research if the weaving process and loom could be adjusted to create more flexibility for adding additional warp material along a weft thread while keeping the warp spacing equal.

9.3.3 Loom add-on

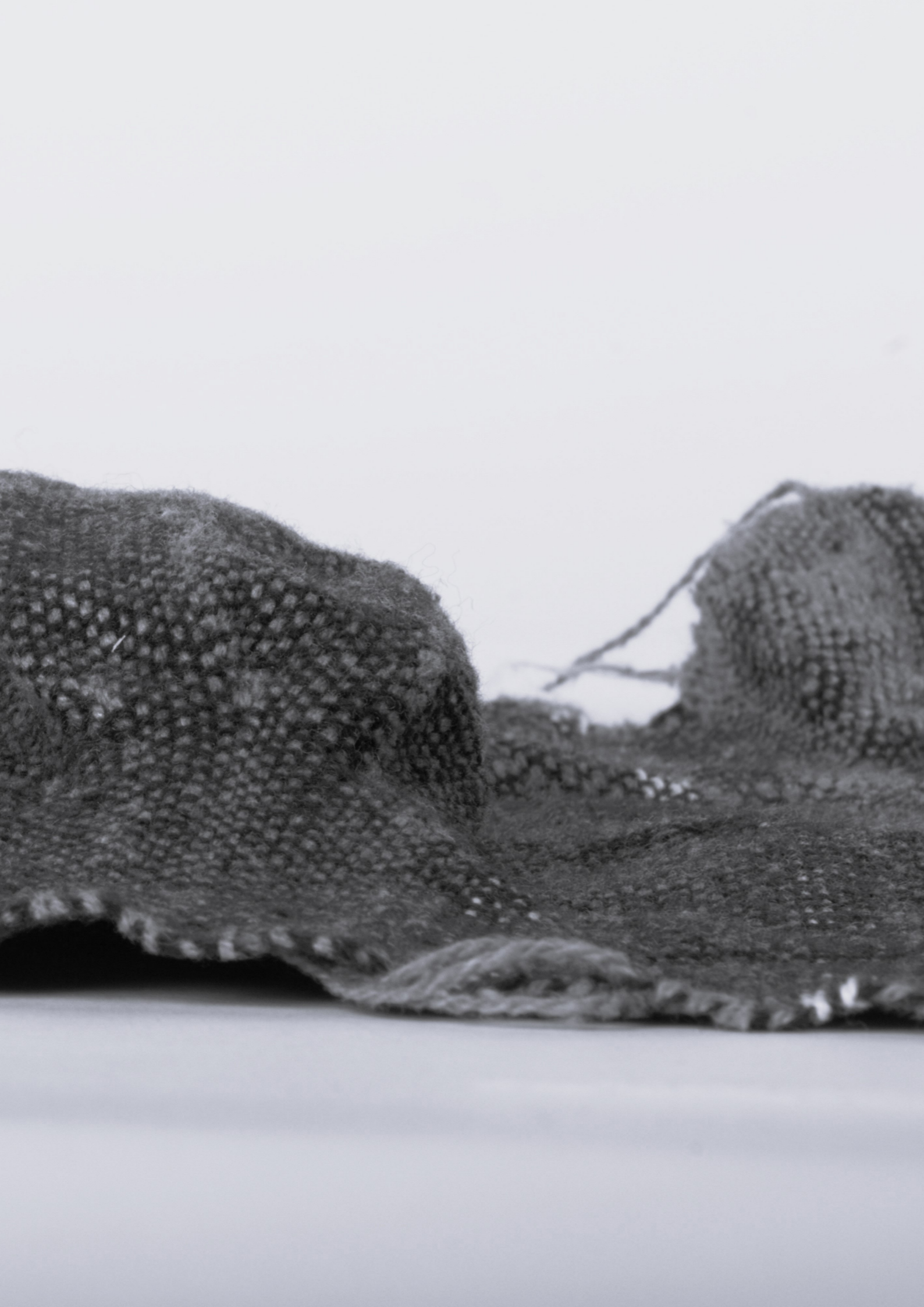
1. Develop the add-on to be able to reliably fixate fabric with a varying thickness.
 - A. Use springs to allow the magnets on the bottom clamp half to rise up to meet the top clamp half the required amount to clasp the fabric in between. By using separate magnets with individual springs, some magnets could rise up more than others to clamp thinner areas.
 - B. Change the way the clamp is closed and force is applied on the fabric. For example, by using mechanical fasteners, such as nuts and bolts. Rubber or foam could be placed in between the fabric and the clamp halves. The force with which the clamp is shut would force the rubber or foam to conform to the fabric, compensating for thickness variations.
2. Develop the add-on to be able to straighten and fixate the fell in any situation without putting strain on the threads.
 - A. Minimize the thickness of the clamp to reduce the area that needs to be flattened.
 - B. Consider if it is possible to fixate the fabric without clamping any part of it. For example, investigate whether the clamp could be placed on the unwoven warp threads behind the fell, or revisit the idea of a comb that is inserted in between the warp threads to block the fell.
3. Explore the use of a creel system to supply the warp threads to increase flexibility. However, whether a creel system is worth the added complexity and required space should be carefully considered. Alternatively, the let-off frame could be expanded to increase the amount of excess length that can be let off the warp beams.
4. Iterate on the add-on and conduct user studies to create a reliable and user-friendly product.
5. Develop the add-on in such a way that it is suitable or adjustable to different types of prototyping looms. This can include floor looms, such as the Magic Dobby, but also smaller scale table looms to make the add-on more accessible. To utilize the capabilities of a jacquard loom for experimentation, it would also be interesting to develop the add-on for the TC2 loom.

9.3.4 Fabric shaping

1. Continue research into and experimentation with shaping the fabric into different types of forms. Knitting and sewing can be used as inspiration.
2. Create guidelines and tools for creating weaving plans for a specific shape.

9.3.5 Application in the textile industry

1. Explore how the shaping possibilities the proposed methods and add-on offer can be applied to the creation of a textile product.
2. Explore how the possibility to create 3D forms could be utilized in other techniques for creating woven textile-forms, such as multi-layer weaving.
3. Investigate how the add-on could be developed for automated industrial looms and consider what existing tools, such as creel systems, could be used.
4. Analyze the capabilities of different types of looms to determine if and how different weaving methods could be applied on an industrial loom to shape the fabric, such as weaving in discontinuous weft rows or changing the weave structure.
5. Research how the creation of textile-forms directly on the loom would change the way textile products are produced and consumed. Consider how this will impact people along the value chain.



Final remarks

It baffles me how textiles can be such an integral part of all our lives and simultaneously so overlooked. Textiles have been around as long as humanity, and the methods for turning yarn into fabric, namely knitting or weaving, have stayed the same for tens of thousands of years. Today, we are supplied with an endless stream of products that, besides a new style or print, seem to barely change. One could jump to the conclusion that in all that time textiles have been around we must have fully explored and perfected the tools and methods used for production, and that room for innovation is limited. This project has shown me that nothing is less true and new possibilities are still to be found, specifically in weaving, if one only decides to look.

Before starting this project I think I touched a loom a grand total of three times, which may make me seem completely unsuitable to conducting weaving research. However, I think my skills as a designer made up for it. The value of design is to gather all the available knowledge in such a way that it creates a starting point for the discovery of new ideas. Taking a design approach to this research provided a fresh look into the weaving process and enabled ideas to quickly be made tangible through sketching and prototyping. It was an absolute joy to work on this project and I hope it sets the tone for my future as a designer.

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I could never have imagined that I would be able to combine all the things I love doing most in my graduation project: drawing, building prototypes and playing around with yarn. There are so many people without whom I never would have reached this point.

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Furthermore, I want to thank my parents, brother and sister. I am so happy I was born into this family and was taught to find joy and humor in everything. Thank you for supporting me in everything I do, no matter how big or small, with love, encouragement and food.

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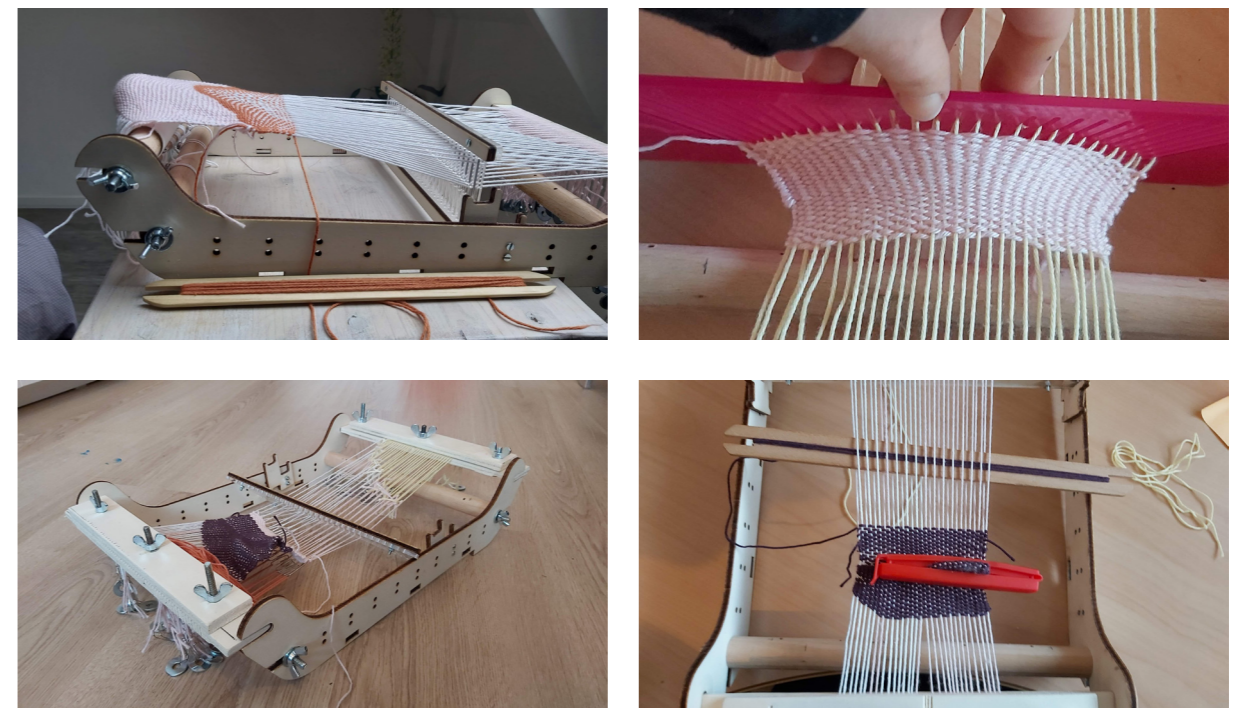
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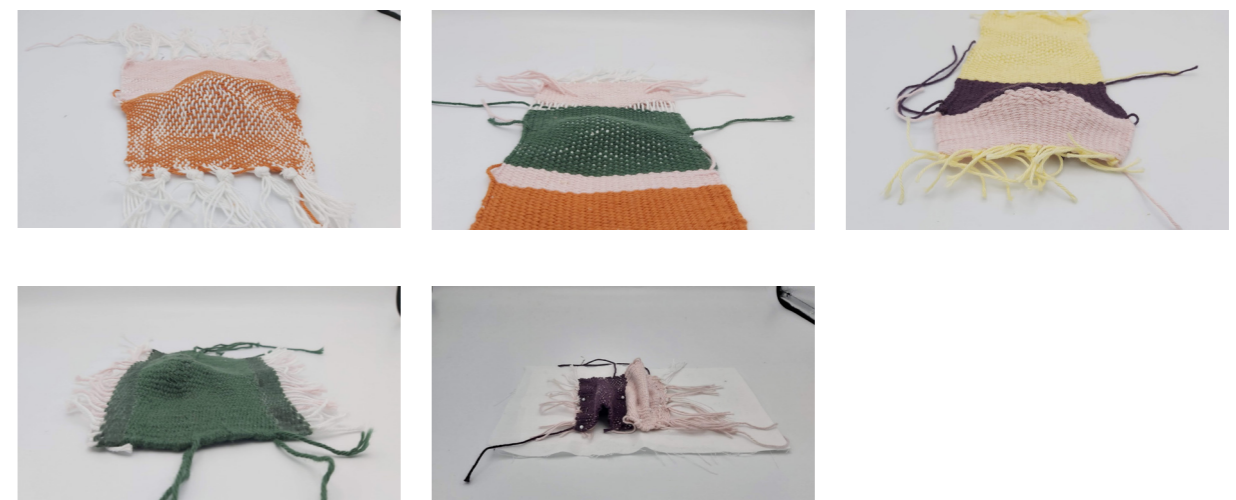
Appendix

A. Weaving experiments

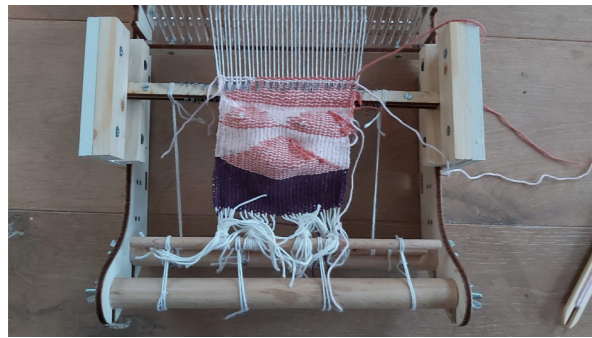
Loom adjustments



Samples



B. Testing comb prototype



Two full weft rows (pink) and two discontinuous rows (orange) were woven in above the comb. The reed was used to beat up the threads to lie against the comb. The two discontinuous rows caused the fell to no longer be straight.



The comb was removed from the fabric. Without the comb the warp threads lost tension.

The comb was placed behind the fell. The teeth were inserted in between the warp threads.



The clamp at the back of the loom was opened so that the warp threads can be moved.

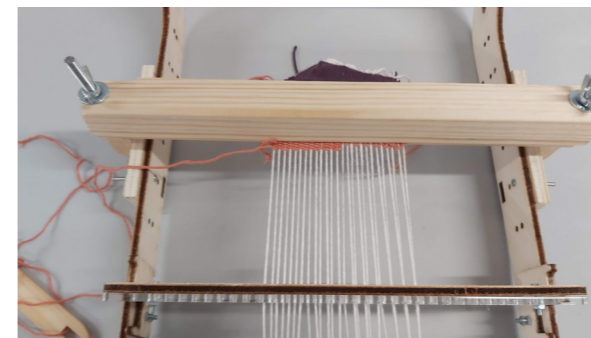
The comb was pulled forward by rotating the beam to which it was attached with threads. While moving forward, the comb pressed against the weft threads. The comb first encountered the discontinuous weft rows. These weft rows and their interlaced warp threads were moved forward until the fell was realigned.



Once the warp threads were all in their new position, the clamp at the back of the loom was once again closed, locking the warp in place.

The warp threads were tensioned up to the fell due to the comb pressing against the interlaced weft and the warp threads being restricted from moving forward at the back of the loom. The woven fabric was not tensioned and could bulge up.

C. Testing clamp prototype



Four rows of discontinuous weft were woven in on half of the warp.



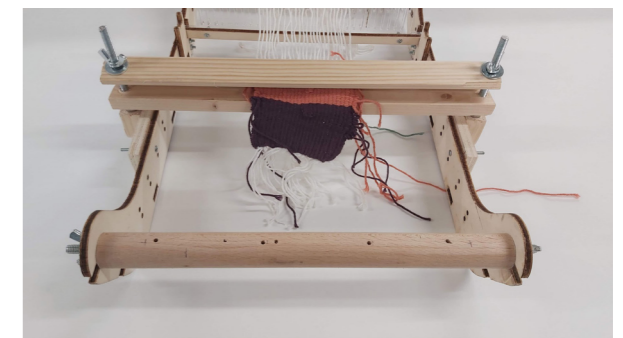
The clamp was opened by unscrewing the nuts and manually lifting the top half up. The reed was pressed against the fell while the clamp was opened.

The fell aligned due to the reed being pressed against the weft while the weights pulled the warp threads back.

The reed was used to push the aligned fell in between the two clamp halves.



The clamp was closed on the new fell and the nuts were tightened to keep the fell in place.



The warp threads are tensioned up to the clamp while the woven fabric is left untensioned, free to bulge and curve.

D. Comparison of concepts

The concepts were compared based on their potential to meet the requirements. Below, the requirements and wishes on which the concepts vary the most are reflected upon.

Requirements

Requirement	Comb	Clamp
Moving weft and warp threads to restore a straight fell	<p>The teeth of the comb must push against the weft to move it and pull the warp threads along.</p> <p>Ideally a comb tooth would be inserted in between every warp thread. Fewer teeth can be used, but that puts limitations on the width of the weft thread. The width of the weft must be more than the distance between two teeth in order to be moved by the comb.</p>	<p>The reed is used to push against the weft in order to move it forward. Any weft thread that can be beaten up by the reed can also be moved forward by the reed to align the fell.</p>
Fixating the fell while tensioning the warp threads	<p>The comb effectively fixates the fell by blocking the weft, and thus the interlaced warp threads, from moving. The comb must be secured in place to withstand the movement of the weft due to the tension placed on the warp threads.</p> <p>The warp threads must not slip out from in between the teeth of the comb. The difficulty lies in keeping the warp threads in place in the comb when desired, while enabling the comb to be removed from the warp when it needs to be moved to the next weft row.</p>	<p>The clamp presses down on the fabric and thus relies on friction to keep the fell in place.</p> <p>The challenge is to ensure every part of the fell experiences enough friction to resist the tension placed on the warp threads in that area. There is a risk of the fell slipping out from between the clamp halves.</p>
Varying the weave structure	<p>The comb falls in between the warp threads to press against the weft. How the weft is interlaced with the warp does not influence the functionality of the comb.</p>	<p>Different weave structures can impact the thickness of the fabric.</p> <p>If multiple weave structures are used within a weft row a way must be found to compensate for thickness differences and ensure every section of the fell is clamped sufficiently to keep it in place.</p>

Requirement	Comb	Clamp
Varying the number of layers	<p>The comb falls in between the warp threads and can press against multiple layers of weft threads in the same manner as it would press against a single layer.</p>	<p>Weaving multiple layers increases the thickness of the fabric.</p> <p>If the number of layers varies along the length of the fell a way must be found to compensate for thickness differences and ensure every section of the fell is clamped sufficiently to keep it in place.</p>
Use in combination with a fan reed or rail reed	<p>A fan reed or rail reed can be used to adjust the spacing between the warp threads during weft insertion and beating the weft up to the comb.</p> <p>The teeth of the comb have a fixed spacing. If the warp spacing is constant, the teeth spacing can be adjusted to ensure each comb tooth falls neatly in between two warp threads. However, if the spacing is varied by a specialized reed, the comb teeth spacing will no longer match the warp spacing. It is not a problem if a tooth falls in between different warp threads than before. However, some comb teeth might need to nudge a few of the warp threads aside when the comb is inserted into the warp, which could damage the threads and affect the warp spacing in the final fabric.</p>	<p>The clamp presses down on the woven fabric at the fell. The spacing of the warp threads does not influence the functionality of the clamp.</p>

Wishes

Wishes	Comb	Clamp
Robust	<p>The comb consists of a large number of teeth. The teeth must be thin enough to fit in between the warp threads. Preferably, the teeth are so thin that the warp threads are not pushed aside by the teeth.</p> <p>Depending on the material used, the thin teeth will likely be very fragile.</p>	<p>The clamp mainly consists of two large clamp halves, making the clamp simple and robust.</p>
Minimal extra actions from the weaver	<p>After the weft is beaten up, the comb needs to be placed in front of the fell. The comb then needs to be moved forward to align the fell. Moving the comb is an extra action that, in the current concept, cannot be carried out in tandem with other weaving steps.</p> <p>In addition, the comb is currently manually inserted into the warp. Ensuring the teeth fall neatly in between the right warp threads takes some fiddling.</p>	<p>The reed is used to beat up the weft as well as move the weft threads the extra bit to align the fell. The reed can be moved in a continuous movement while the clamp is opened and closed.</p>
Different warp densities	<p>It is not necessary for a comb tooth to be inserted in between every warp thread. If the warp density is increased or decreased, the number of threads in between two comb teeth can be changed.</p> <p>However, a higher warp density makes it more difficult to insert the comb without damaging the threads or affecting the warp spacing.</p>	<p>The clamp presses down on the woven fabric at the fell. The warp density does not influence the functionality of the clamp.</p>

Wishes	Comb	Clamp
Warp tension	<p>When the tension on the warp is increased, the weft threads are pulled against the comb. Different solutions can be found to keep the comb securely enough in place to resist movement under the pressure. The material and shape of the comb can be chosen to resist bending.</p>	<p>The clamp keeps the fell in place using friction. As the tension on the warp increases, the friction required to keep the fell in place also increases. The friction can be increased by pressing the clamp halves against each other with more force and/or using a material with a higher friction coefficient.</p> <p>The challenge lies in pressing the clamp halves together with enough force while ensuring the clamp can be operated in a user friendly manner. In addition, the clamp halves must be pressed together along their whole length to ensure the whole fell experiences the same friction.</p>
Damage to threads or woven fabric	<p>The comb must frequently be inserted and removed from the warp. Every time the comb is inserted there is a chance that a comb tooth hits a warp thread and causes damage.</p>	<p>The clamp presses down on the fell and therefore must not have a surface texture that damages the fabric. In addition, the clamp must truly fixate the fabric. The fabric should be kept from being dragged through the closed clamp to avoid the threads getting stretched or worn down.</p>
Effect on look, feel or integrity of the woven fabric	<p>If the teeth of the comb are thicker than the space between the threads, the threads will always be slightly pushed to the side, altering the spacing between warp threads. On top of that, every time the comb is inserted, there is a chance that teeth will fall in between slightly different warp threads. This might cause some threads to be pushed out of their natural path a bit.</p> <p>The warp threads may return to their natural spacing once the comb is removed, but there is a chance that due to friction between the warp and weft threads, the warp threads stay slightly curved.</p>	<p>The clamp does not affect the placement of the threads.</p>

E. Functionality tests

During the prototyping process, tests were carried out to see if the add-on prototype could fulfill the functions required to weave samples. How the last iteration of the add-on prototype, after being installed on the warped shaft loom, performed on the main tests is explained below.

Fixating the fell

The most important function of the clamp is to keep the fell in place while the next rows are woven. This requires the fell to experience enough friction to not move due to the weights pulling on the warp threads or due to the movement of the warp threads during shedding.

For these tests, the warp was split up into five groups, each weighed down with a 500gr weight as described above. To equalize the tension in all the threads, an equal small amount of excess length was let off all three of the warp beams. Letting off only a small amount resulted in the angle of the weighed down thread being minimal and the tension in the thread therefore being higher, as explained in Chapter 7.2.3. The tension in each individual thread was about 0.30N during the tests.

Plain weave

To test the clamp's ability to fixate a fell with no thickness variations, a section of plain weave was woven and clamped. No movement of the fell was observed due to the tension on the warp threads (Figure 1). The clamped section also stayed in place when the warp was repeatedly shed to weave a couple more weft rows.



Figure 1: Picture showing how the fell remained straight as the warp threads were tensioned and a few rows of weft were woven in

Varying weave structures

Another test was conducted to see if the clamp presses on the fabric enough to compensate for any thickness differences. The center section was woven in a plain weave, the middle two sections as a twill and the two outer sections as a compound weave. Due to weft threads being stacked on top of each other in a compound weave, it is twice as thick.

The fell with varying thickness was not sufficiently kept in place by the clamp, as can be seen in Figure 2. The clamp clamps down properly on the compound weave section, but the thickness of the compound weave keeps the clamp open enough that it can't press down on the section of plain weave or twill enough.

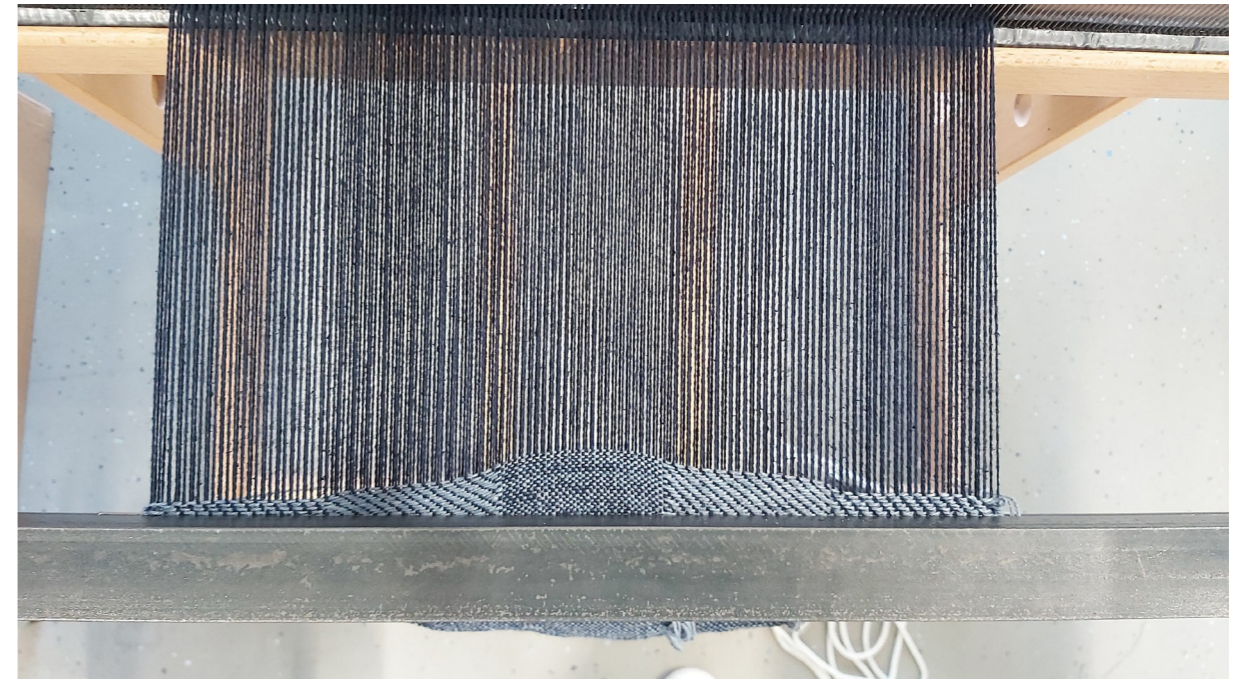


Figure 2: Picture showing how sections of a fabric with variations in thickness slipped out from under the clamp

Straightening the fell

The add-on is used in combination with the reed. As the reed is pushed against a curved fell, the weft threads must be able to move and pull the interlaced warp threads along until the fell aligns. Tests were conducted to judge whether the reed was able to make the necessary movement without getting blocked by the clamp, and whether the let-off frame and weights allowed warp threads to move relatively to each other. A separate 30gr weight was hung onto every warp thread to allow individual movement.

Figure 3 shows a fell that has become curved due to the use of discontinuous weft rows.

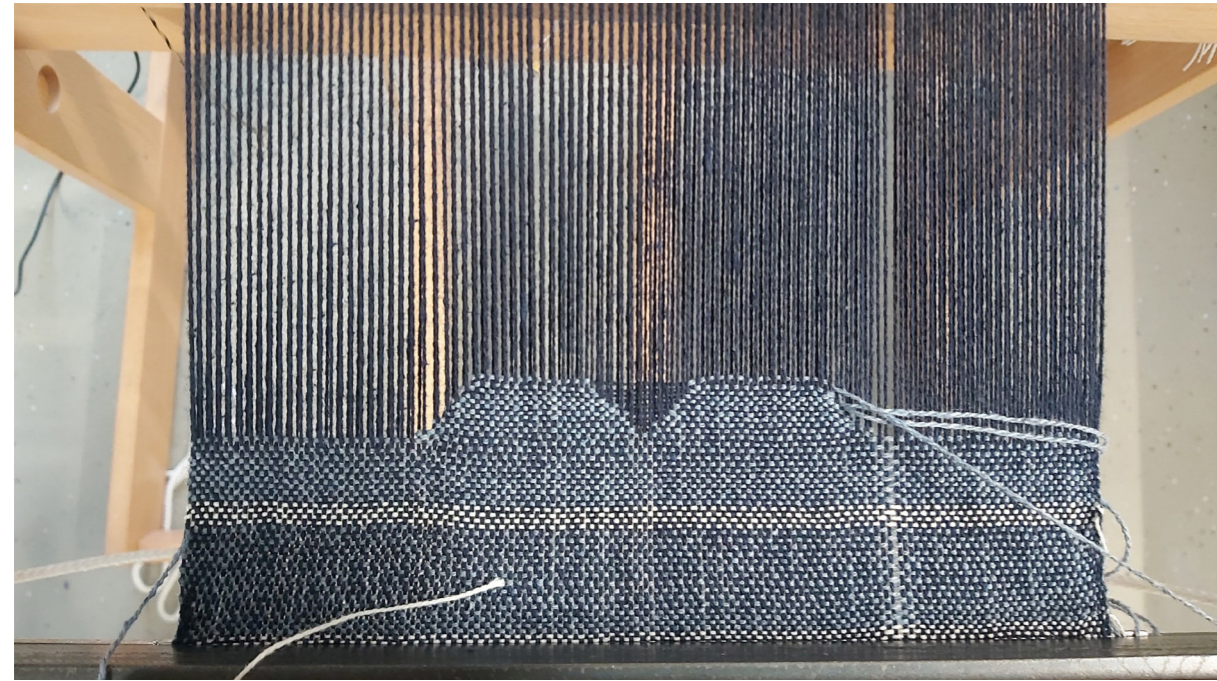


Figure 3: Picture of a section of fabric woven with discontinuous weft rows

Figure 4 shows how the fell is straightened by the reed, validating that the reed can be moved forward enough to straighten the fell, and that the warp threads are able to move along accordingly.



Figure 4: Picture showing how the fell is straightened by the reed

Maintaining and restoring tension

The weights on the threads must ensure that they can move, but stay tensioned at all times. A test was conducted to see if a thread, weighed down with a 30gr weight, would be drawn back and restored to tension after being pulled forward and released (Figure 5). The thread returned to its original position and maintained the same tension.

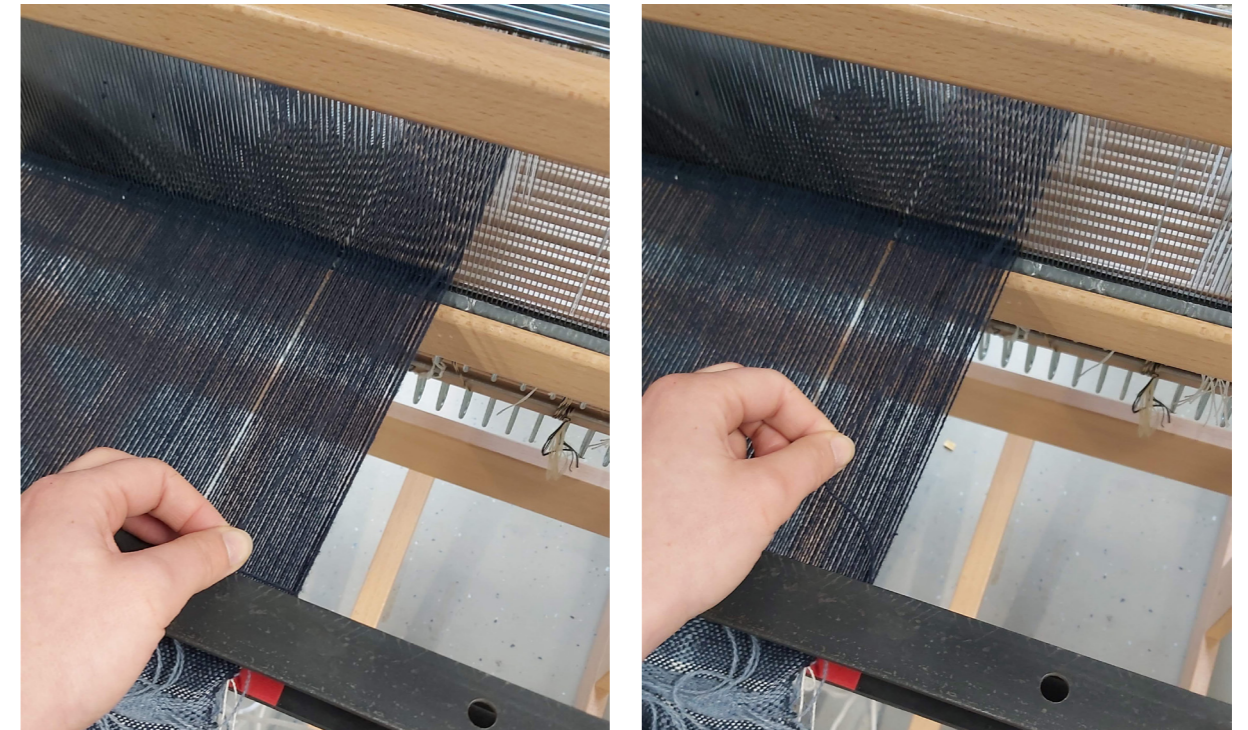


Figure 5: Pictures of a test conducted in which a thread was pulled forward (left) and released (right). Once released, the thread was retracted by the weight

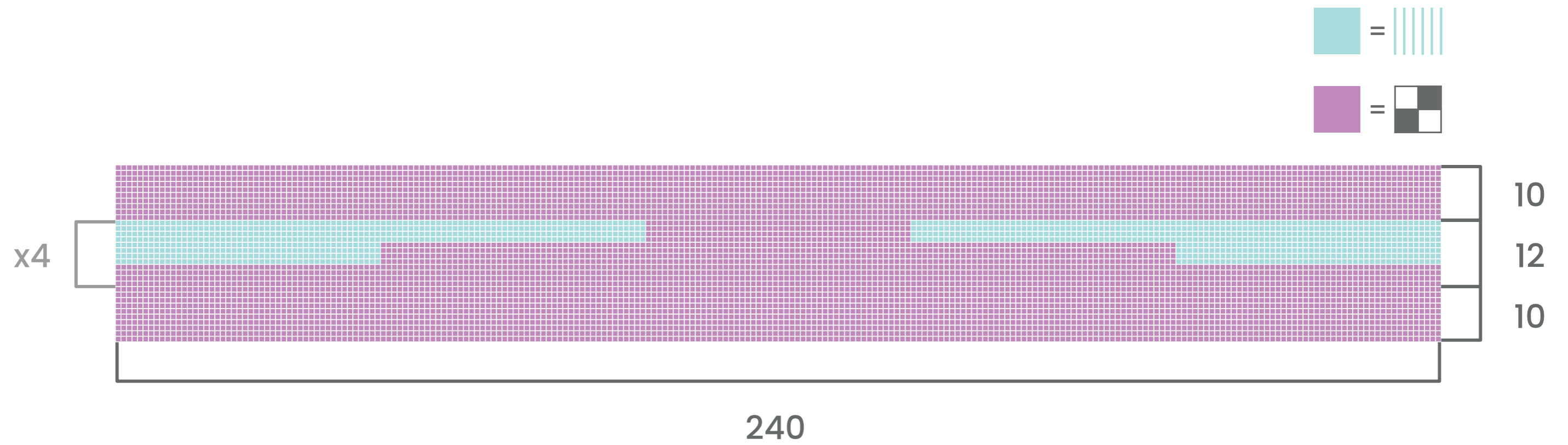
The test also allowed the ability of the grid to keep the threads separated to be tested (Figure 6). Multiple warp threads were pulled forward and released one by one and in groups. No entanglement of the threads was observed.



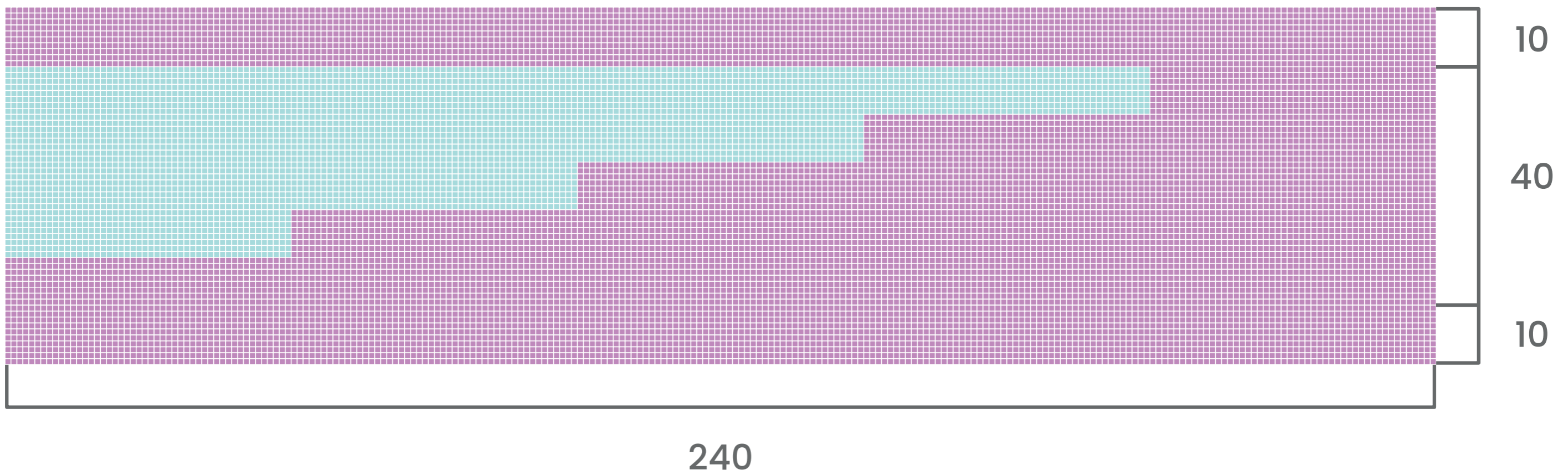
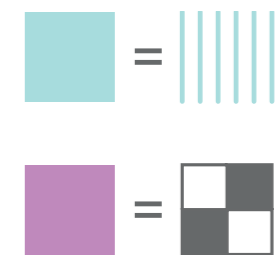
Figure 6: Picture showing how the fell is straightened by the reed

F. Weaving plans

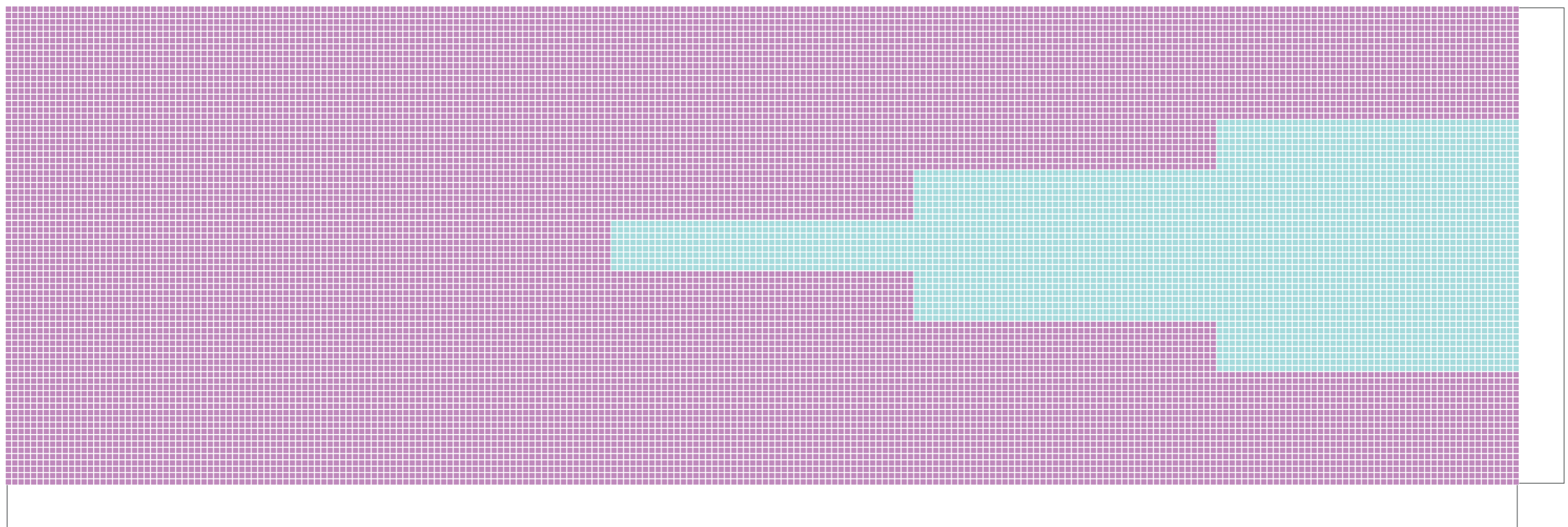
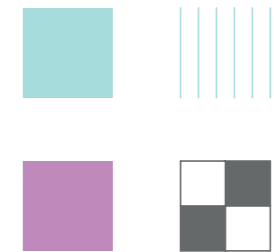
Experiment 1: Dome



Experiment 2: Triangular fabric



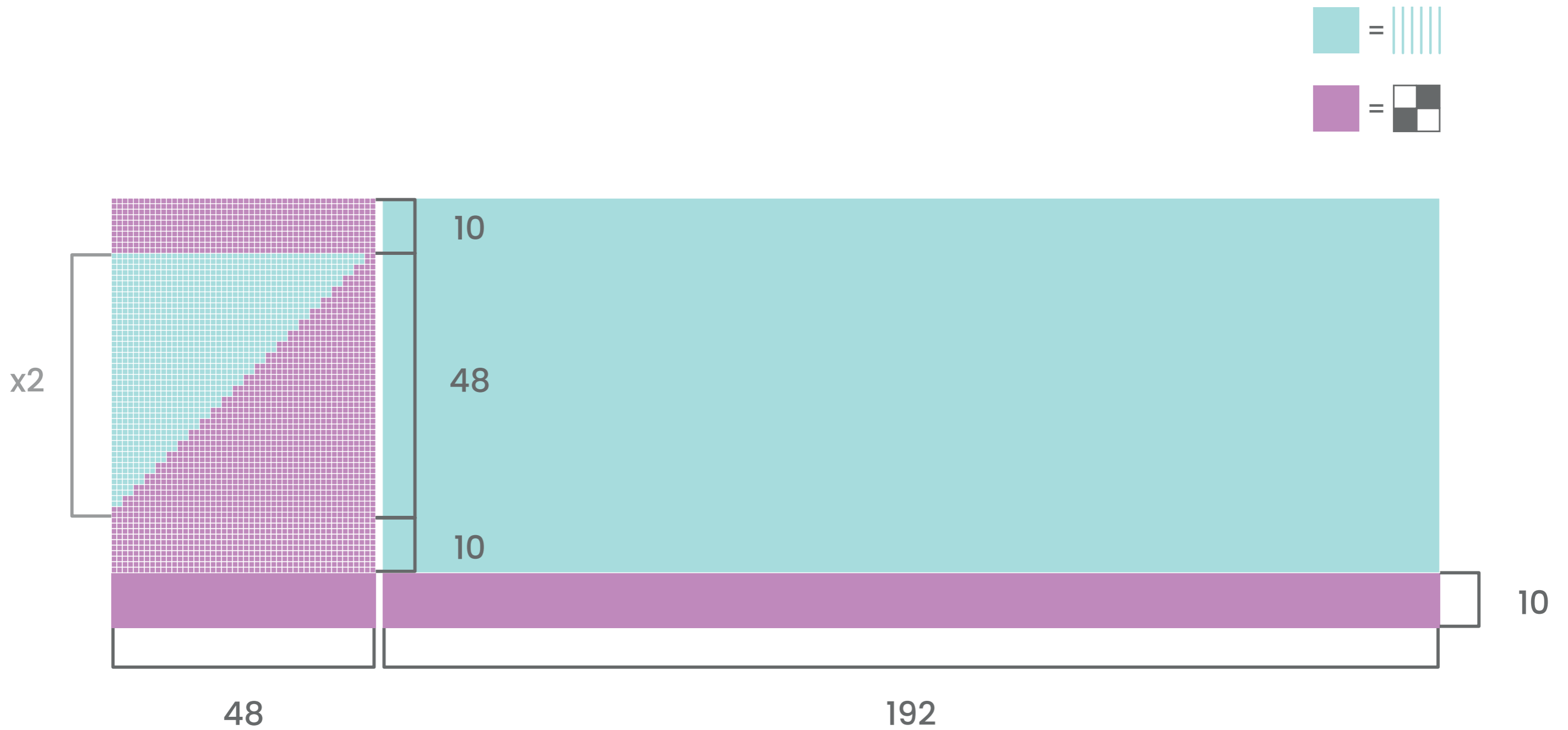
Experiment 3: Fabric with cut-out



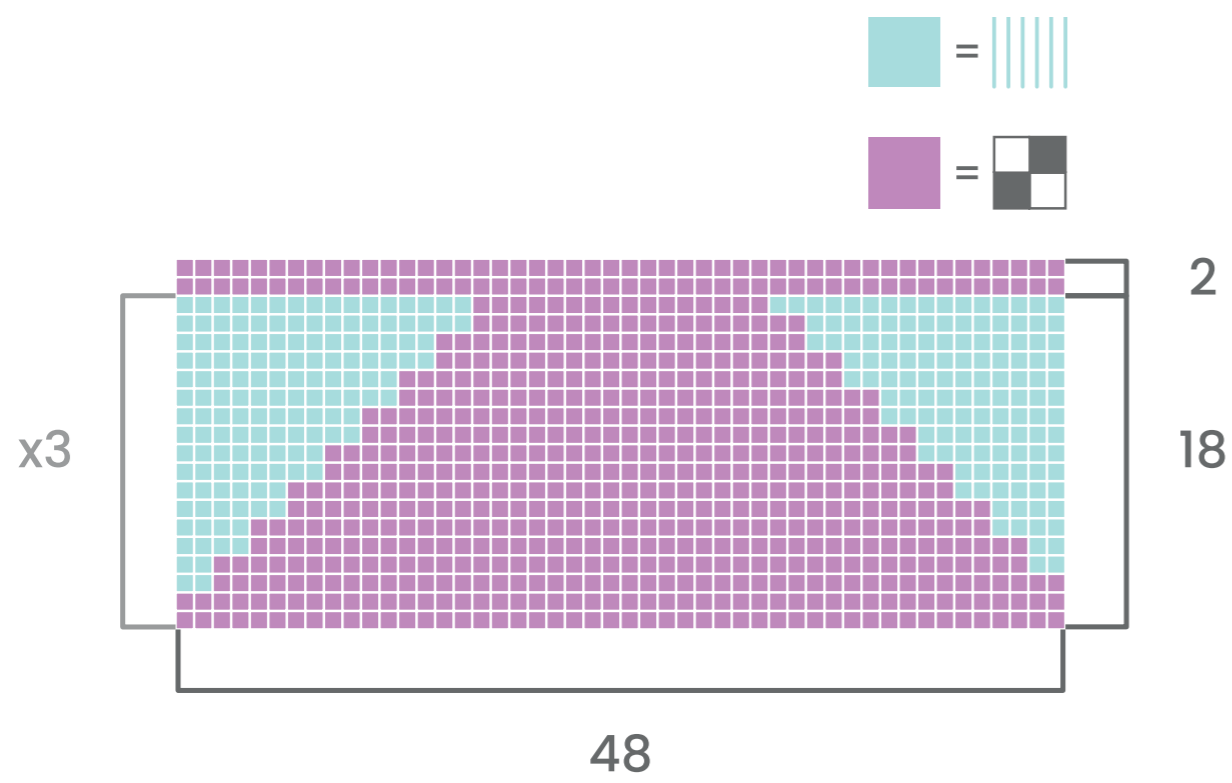
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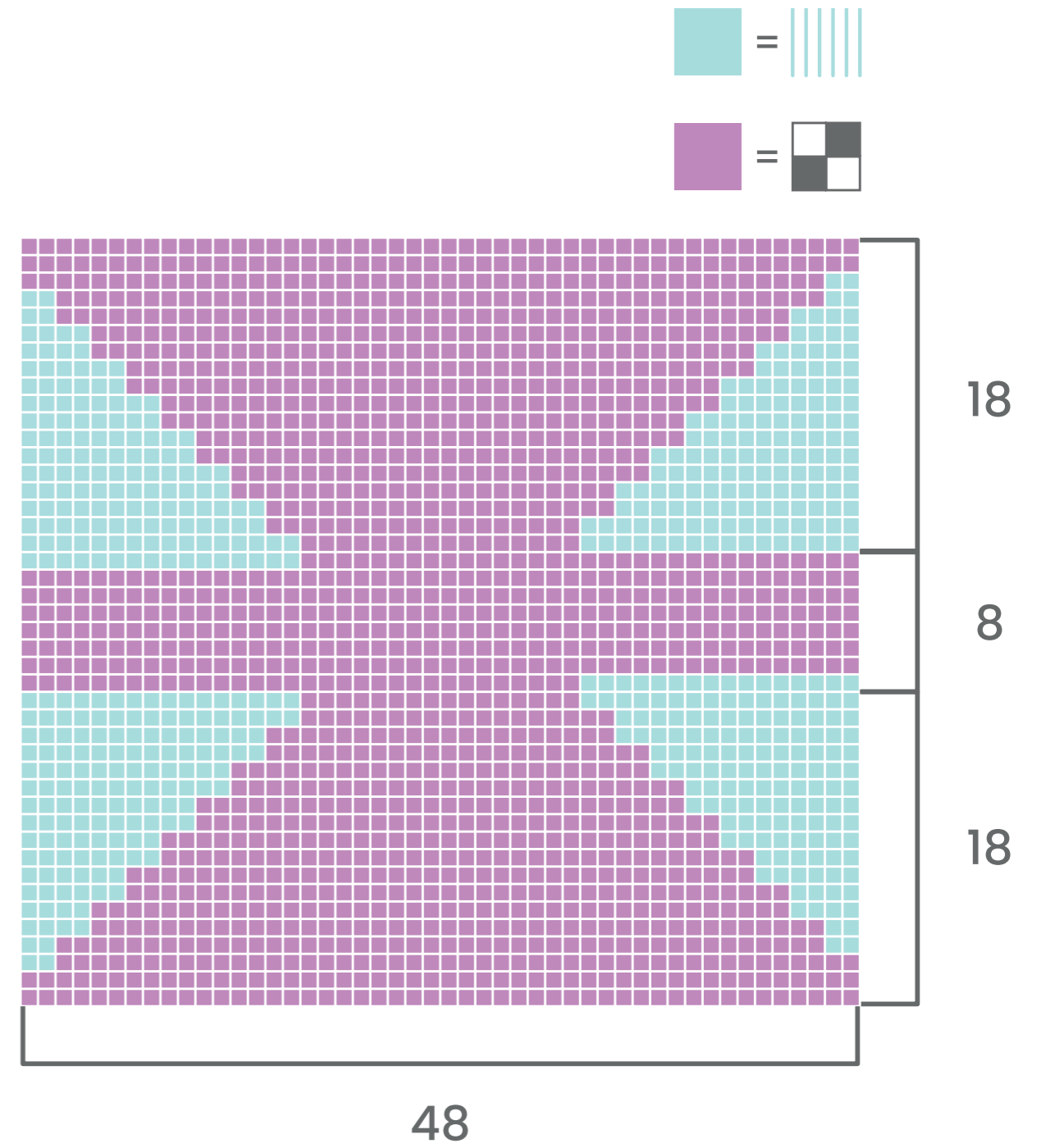
Experiment 4: Curving strip of fabric



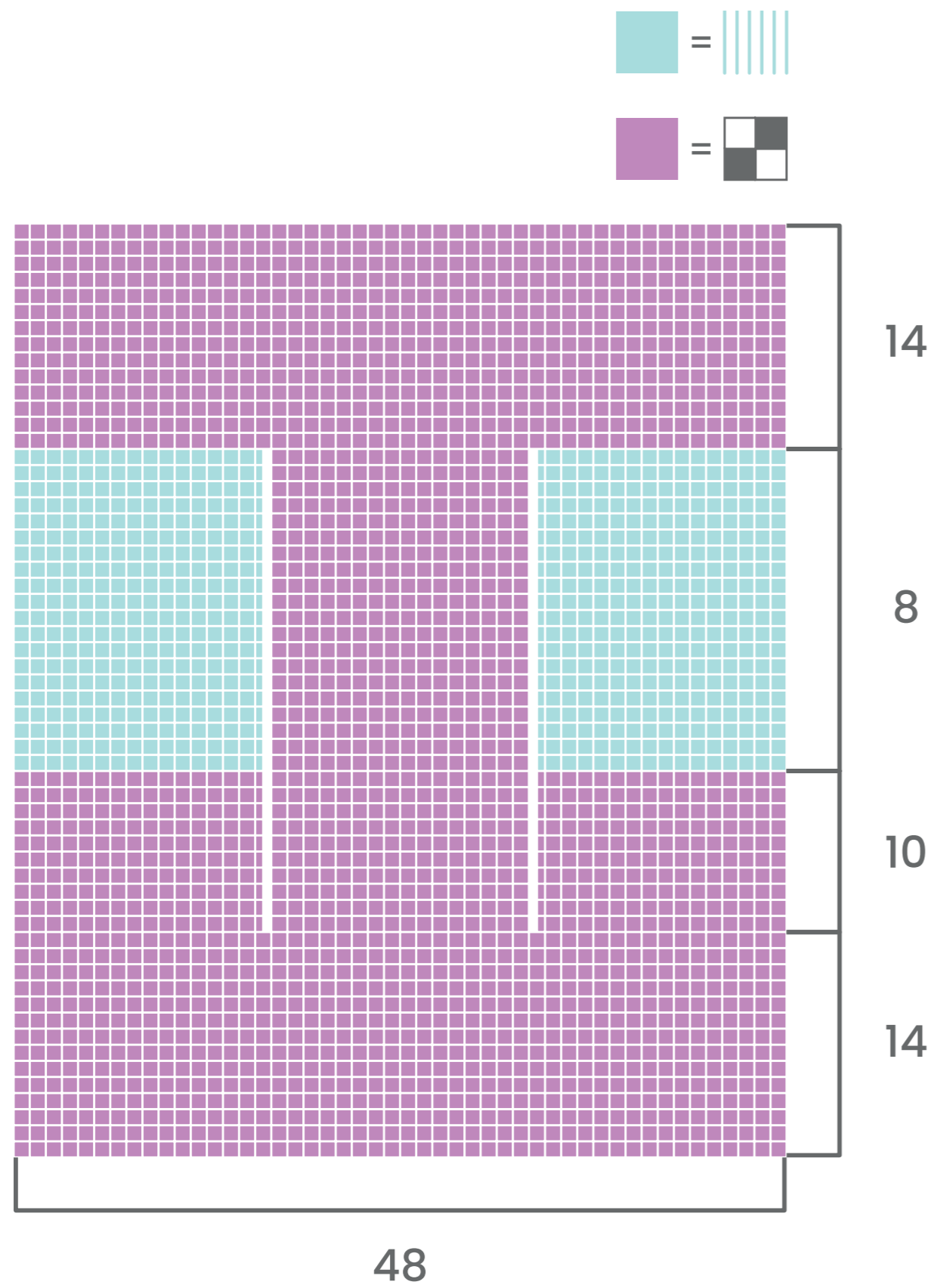
Experiment 5: Dome



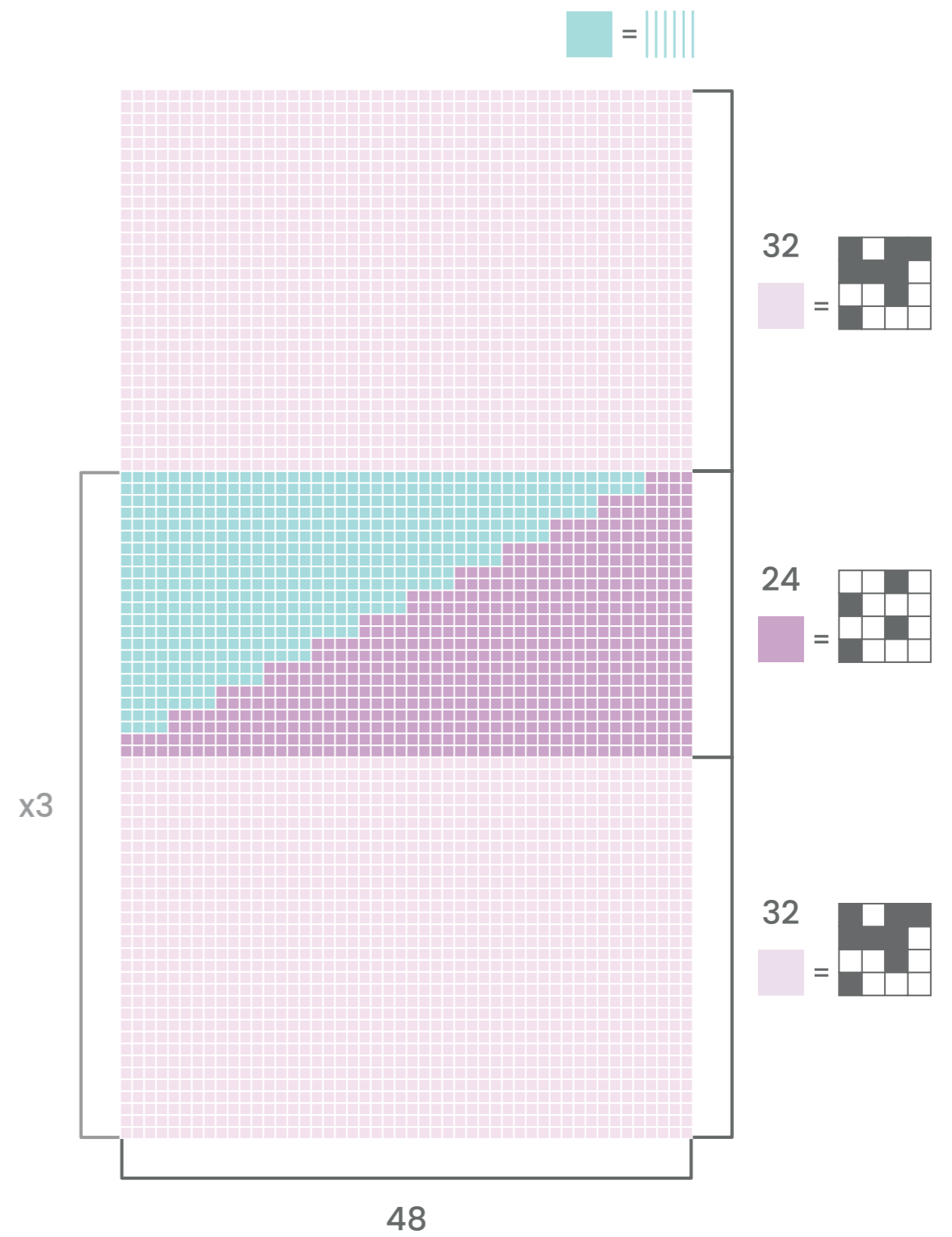
Experiment 6: Ridge



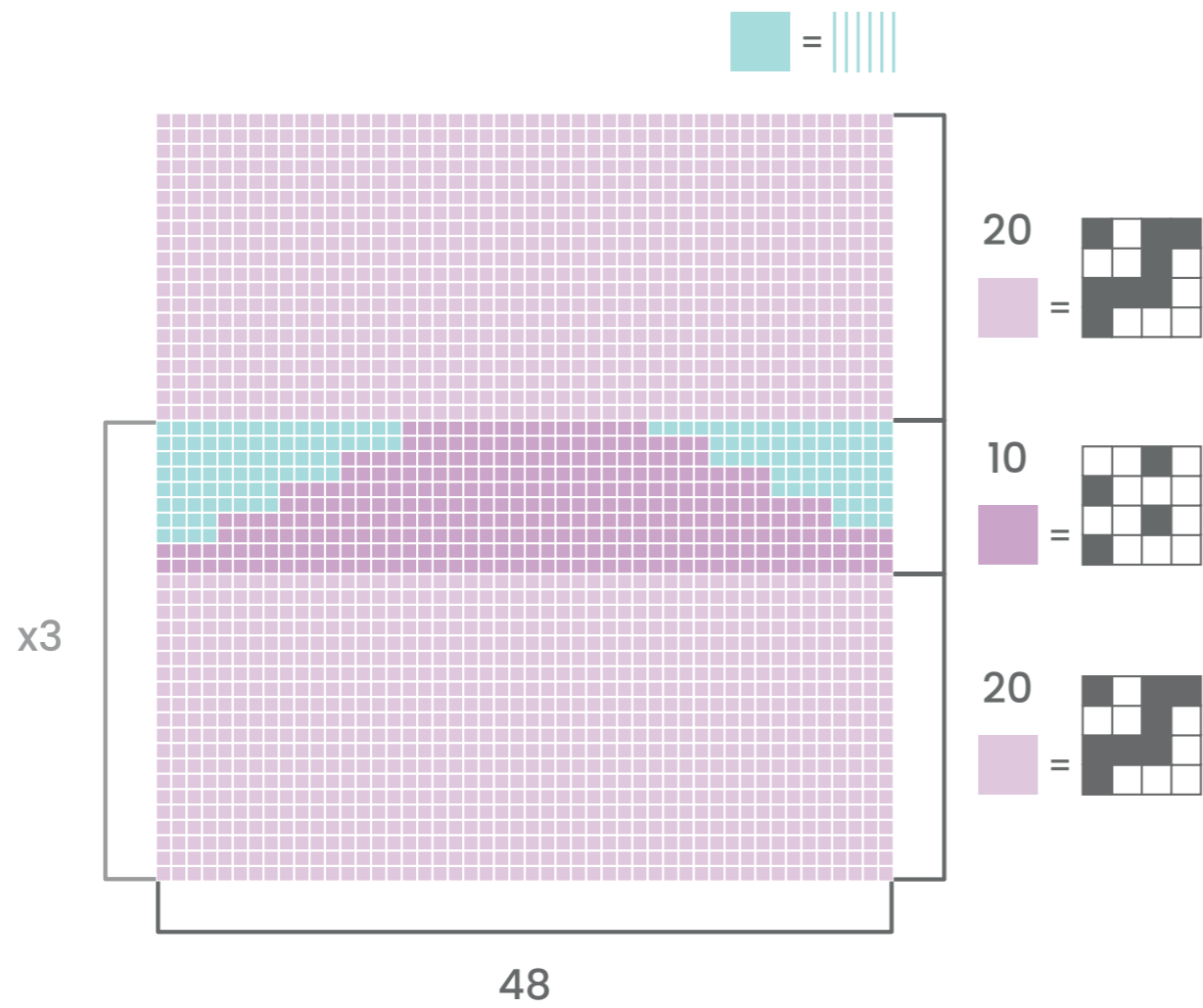
Experiment 7: Loop



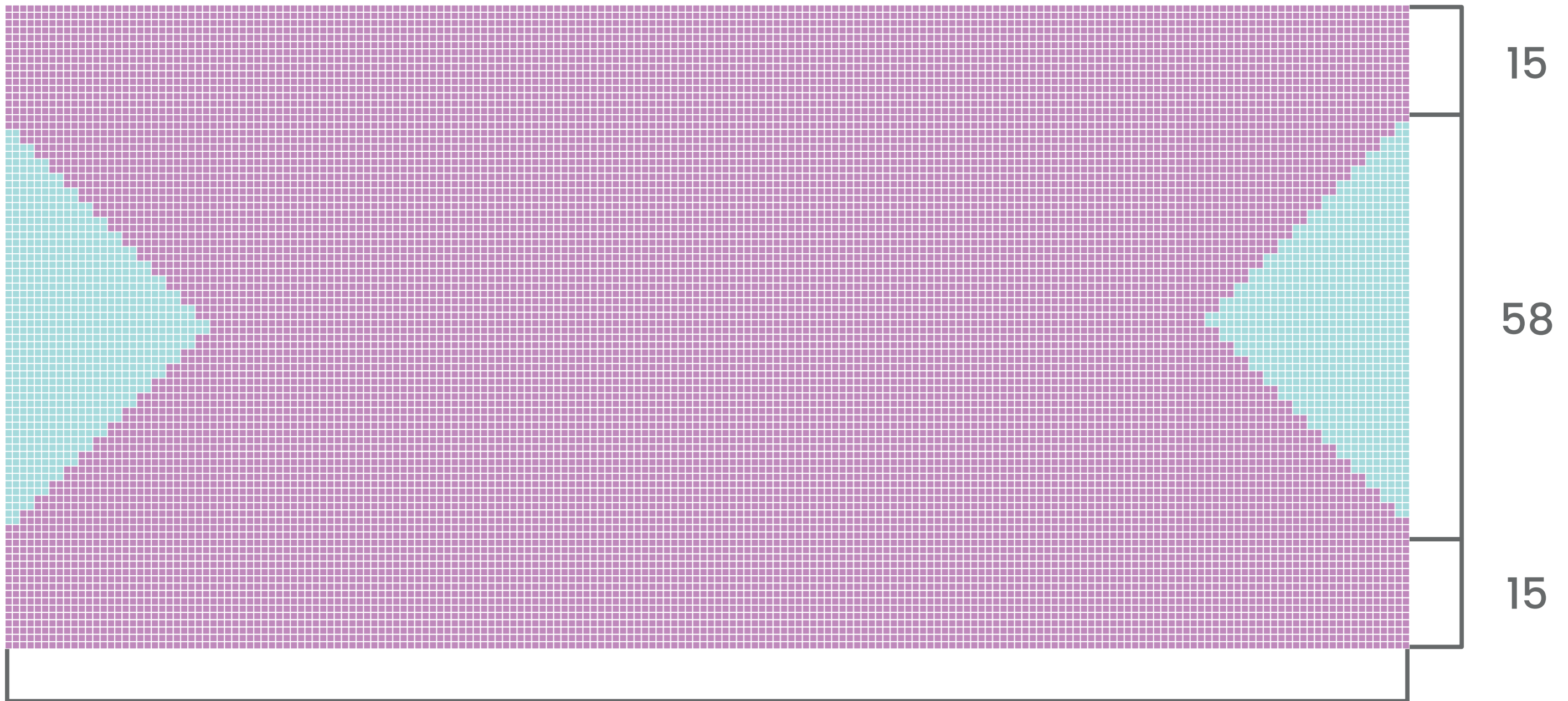
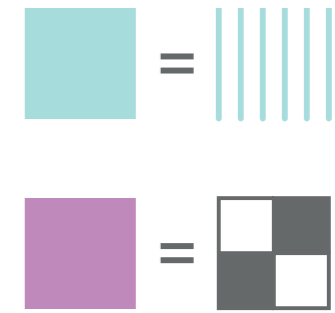
Experiment 8: Double layer pocket



Experiment 9: Double layer dome

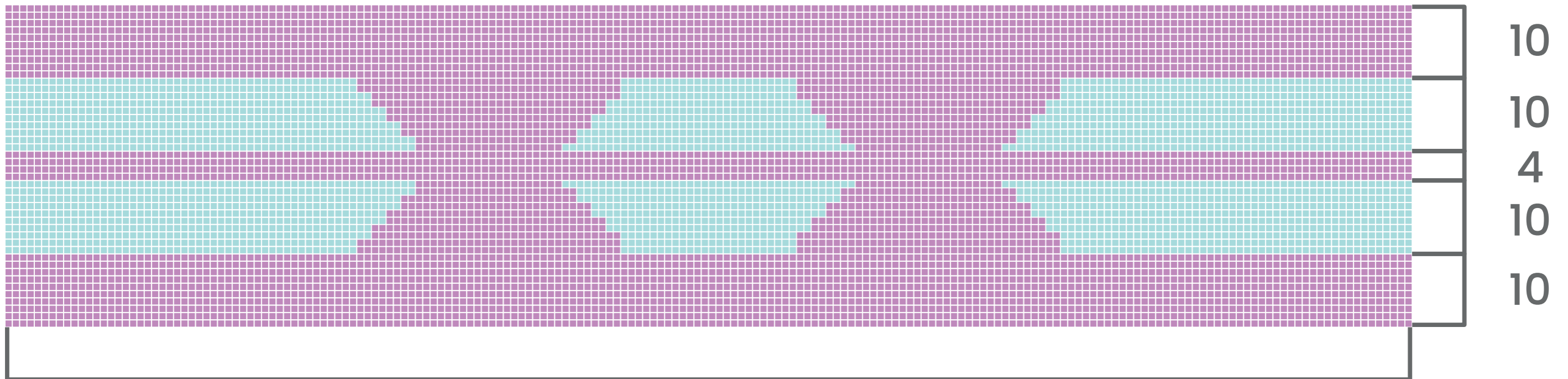


Experiment 10: Corners

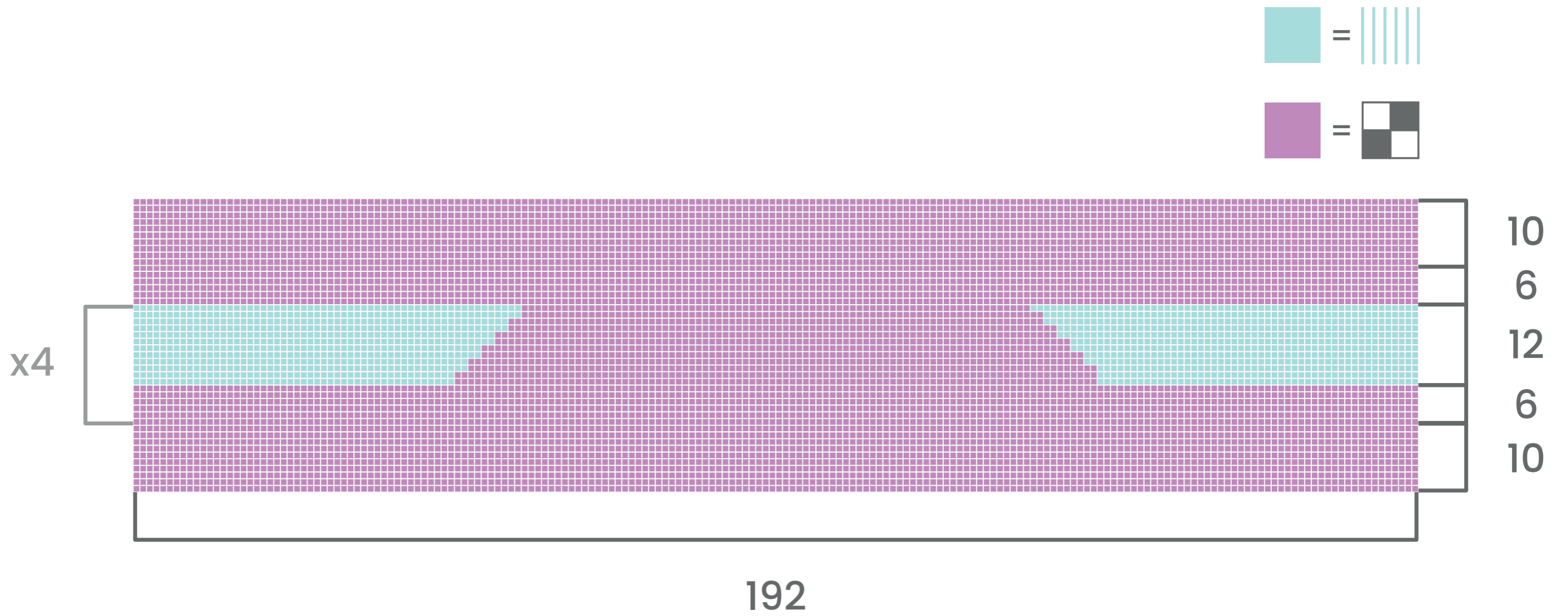


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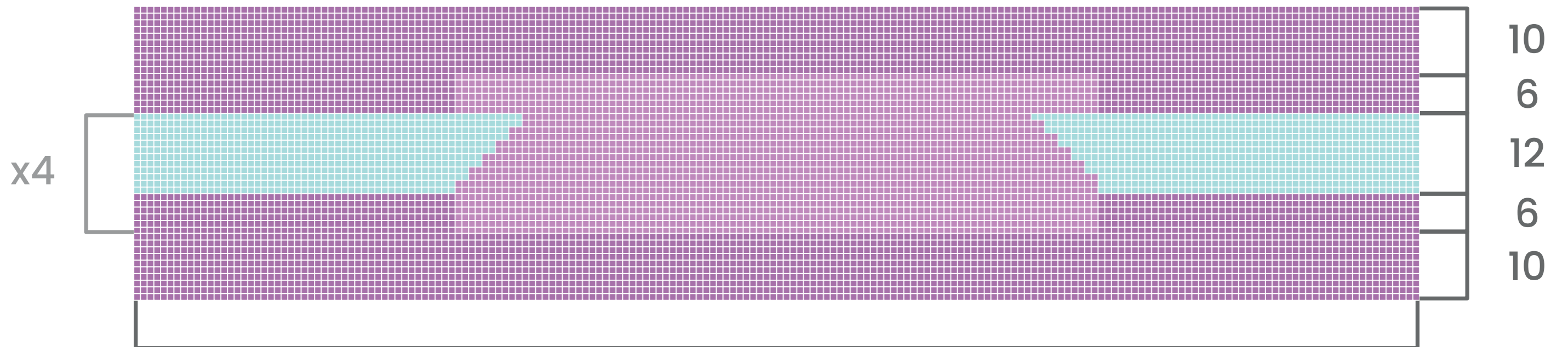
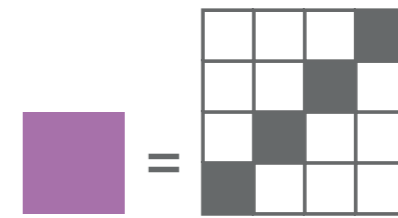
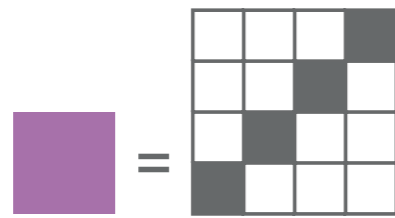
Experiment 11: Two ridges



Experiment 12: Dome in plain weave



Experiment 13: Dome in plain weave surrounded by twill weave



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