3D WOVEN DENIM JACKET

Exploration and development of 3d weaving as a more sustainable way to produce a denim jacket

Barbara Vroom
Integrated Product Design
Msc. Graduation Thesis

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Abstract

The clothing industry is one of the most polluting industries worldwide (Ellen MacArthur Foundation, 2017). The current industry for producing garments is built on the overproduction of cut-and-sewn textile products, which are produced as fast as possible for as little money as possible. The denim industry is a major contributor, producing over four billion denim garments every year (Toepel, 2018). Over the last 150 years, the aesthetics of a pair of jeans and a denim jacket has barely changed, which is a result of this cut-and-sew fast fashion industry that still exists. A way to reduce the global impact of denim garment manufacturing would be to reduce the number of production steps.

This research aimed to investigate 3D weaving to rethink the production process for a denim jacket. 3D weaving combines woven textile design and garment design in multi-layer textile forms. With 3D weaving, the number of production steps after weaving and the resulting cutting waste can be reduced by weaving parts of the garment as already connected pieces.

This project is executed in a sustainable context of limiting pre-consumer waste and reducing the number of parts to assemble the denim jacket. A change in the manufacturing process of a denim jacket will raise the question if the 3D woven denim jacket can and also has to look the same as a denim jacket produced with the regular cut-and-sew method. The 3D woven denim jacket versions in this report show how and to what extent this is possible. These concepts also show how this new production method affects the aesthetic outcome of denim jackets.

This report starts with setting the context of denim jackets, the industry and its polluting side. After introducing 3D weaving and setting the criteria the process of experiments is explained and visualised. Research through design has been the basis of this research. This iterative research led to three 3D woven versions of a chosen concept. These prototypes were developed at Diamond Denim during a visit to their factory in Pakistan through many weave cycles. One of the outcomes is a zero-waste 3D woven jacket.
The aesthetic of the 3D woven jackets was found to fit the description of a denim jacket but was different due to the fabric density, texture and raw fraying seams.
Change is inevitable. Let's wear the change!

Acknowledgements

I did it!
After just over seven years, I have woven an end to my time as a student at TU Delft's Faculty of Industrial Design Engineering.
From the age of 15, I started taking sewing classes and learned about the process of making clothes. Sewing allowed me to create shapes by sewing flat pieces with a sewing machine, which immediately got me excited. A few years later, I saw an episode of Project Runway where they had to use materials from junkyards to make an outfit. So there I was, asking our local junkyard if they had seatbelts to take home. I made a dress from seatbelts and later a three-piece collection from various car scraps. It is a fascinating exercise to use what is already there in a different way and show its beauty.

In the bachelor and the first year of the master Integrated Product Design, I learned how we can design products that matter, how we can design for the user and ultimately how we can design for change. But the interest in garment design remained an aspiration and when I heard Lidewij Edelkoort mention the need for Industrial Fashion Designers in the process of making the fashion industry more sustainable, that was like a role for me.
In my master's, I used the free space to learn more about the field of fashion and garment design with an internship at the denim design team of G-Star Raw and following Design for the Fashion System courses at the Politecnico di Milano. And then I met Holly McQuillan, who introduced me to 3D weaving as a new way of producing clothes. I was sold. In this project, I looked at garment manufacturing from a product design approach to discover the possibilities of a new way of producing garments. With this graduation project, I feel I will not just graduate as an Industrial product designer but also as an Industrial Fashion designer. Designing the most intimate products we own, our clothes.
Let's take on the change and wear it. By wearing the story, we can spread it.
A denim jacket in a new format but still as a means of rebelliousness, like through the past nearly 150 years of denim jackets.

I would like to express my gratitude to several people that mean a lot to me and have been of great support during this project.
Holly, my chair, thank you for introducing me to 3D weaving and your research. Meeting you was meant to be a step in my career which introduced me to a field I always hoped to find at the faculty of Industrial Design engineering. Thank you for the interesting meetings and your supervision of the direction of my project.
Eleni, my mentor, thank you for listening to all my rattling about my thoughts and for helping me create structure in these thoughts. I am very happy you wanted to get on board with this project. Our common history at G-Star Raw and your Industrial design engineering background made for a great connection and a feeling of trust.
Mohsin, thank you for sharing your knowledge and having me come over to your studio in London. Your denim passion is contagious and we hope we meet again soon.
A very big thank you to the guys of Diamond Denim. Ali Abdullah thank you for your generous support and for having me come over to visit Diamond Denim. Maurizio, Farhan and Omar thank you for all your help to make all my weaving dreams come true in this project. An unforgettable contribution to my project for which I will always be grateful.
Milou, my travel companion to Diamond Denim. Thank you for all your help to transform my ideas into woven concepts, without your weaving help they wouldn't have looked so beautiful. It was great working with you and I had great fun together in Pakistan.

To my family <3. Mom and dad, who are the loveliest people on the planet. Thank you for your endless trust and support all these years. You were always there for me and our conversations and hugs helped me to continue. Nik, love you.
To Koen, thank you for your trust in me and your support to keep me going.
To my dearest roomies in Rotterdam, Huug Kris Mau Suus Jolien Died.
To Amy, love you, we will get there!
To my fellow industrial designers and all the other dear people who have listened to me, supported or helped me. My thanks are great, I feel rich having you in my life.

Contents

Introduction

The clothing industry is one of the most polluting industries worldwide (Ellen MacArthur Foundation, 2017). From a global lifecycle perspective, textile consumption in Europe accounts for the fourth highest environmental and climate change impact on average in 2020. Textile consumption also accounts on average for the third highest impact on water and land use and the fifth highest in terms of resource use and greenhouse gas emissions (EEA, 2022). The denim industry is a major contributor, with the production of four billion denim garments every year (Toepel, 2018). In 2020, the Netherlands consumed around €124 million worth of denim apparel, corresponding to approximately 10 million units of clothing (CBI, 2021). The profit-driven fast fashion industry is built around the overproduction of cut and sewn textile products. During the last decades, the industry has built towards a system in which textile products are produced as fast as possible for as little money as possible. Garments look the way they are because of this fast fashion industry.

In the denim industry development towards a circular economy is mostly happening in the areas of alternative yarns, less polluting finishing techniques and recycling of cotton denim garments. But since the first pair of jeans was developed in 1873, a denim garment has always been made using the cut-and-sew manufacturing process. The denim fabric is woven on a shaft loom, often transported from the mill to the production factory. There the fabric is cut using pattern pieces after which the pattern pieces are sewn and finished into the final denim garment. Due to the same fabrication methods all these years, the look and feel of denim garments nowadays are still very similar to those of years ago.

A way to reduce the global impact of denim garment manufacturing would be to reduce the number of production steps, which could potentially reduce the polluting and wasteful impact of these manufacturing steps. Other ways could be to limit the amount of sewing or cutting steps needed for a garment. Whole garment weaving or 3D weaving, mentioned by McQuillan (2020), has the potential to tackle the exploitative, time-consuming and wasteful practice of the cut & sew construction method of how garments are made now by combining textile and garment manufacturing. Jacquard looms already offer the possibility of weaving in multiple layers at the same time.
This research will focus on using 3D weaving on a jacquard loom as the manufacturing method to rethink the garment manufacturing process of a denim jacket. This research is executed in a sustainable context of limiting pre-consumer waste and reducing the number of sewing stepsrequired to assemble the denim jacket. A change in the manufacturing process of a denim jacket will raise the question if the 3D woven denim jacket can and has to look the same as a denim jacket produced with the regular cut-and-sew method.

Reading guide

This report is divided into multiple chapters that guide you through the process of this graduation project. The report starts with an outline of the context of this project. The denim jacket is analysed first by looking into denim, its industry and its meaning. The meaning of a denim jacket is analysed by user interviews. Then onto the history and meaning of a denim jacket before analysing the manufacturing process of a denim garment.

From the context of the denim jacket and its industry, the next chapter showcases the polluting side of the denim industry. After introducing the circular economy proposed by the Ellen MacArthur Foundation the chapter continues into sustainable developments for the denim industry. This chapter ends by introducing the technology of 3D weaving which will be fully explained in the follow-up chapter. After the introduction to 3D weaving, the context part is concluded with a chapter gathering all the set criteria. Before going into the concept development first insight is given into related work and the methodology.

The chapter on concept development starts with design methods used for the executed experiments. From these experiments, three concepts were developed which will be displayed using illustrations of the upleading design iterations. The chapter about concept development is concluded with a concept choice using a weighted decision matrix.

The next chapter discusses the first made weave experiment and the tensile test that has been executed on these samples. The last part of this report discusses the three developed 3D woven denim jacket versions developed during a visit to Diamond Weave in Lahore, Pakistan.
The report is concluded with a small user study on one of the 3D woven denim jackets, an in-depth discussion of all the results and a conclusion with recommendations for further research.

If you are interested in viewing the physical prototypes or sparring about your project please contact me!

Stakeholders

This project could not have been to this extent without the supervision, support and help of some important stakeholders.

Holly McQuillan - chair supervisor

Dr Holly McQuillan is an Assistant Professor in Materialising futures in the Industrial Design Engineering department of the TU Delft. She obtained her PhD title with her thesis called 'Zero Waste System Thinking: Multimorphic Textile-Forms'. Which explores the theoretical, aesthetic and technical development of systems and methods for zero-waste textile forms. In her thesis, she undertook a series of experiments which aimed to expand the form-design methods available for whole garment weaving in the context of zero-waste system design (McQuillan, 2020). My graduation project will follow up on her developed methods.

Mohsin Sajid of Endrime

Mohsin Sajid is a denim design specialist and denim historian based in Londen. Together with his wife Sadia Rafique he runs Endrime. Mohsin is consulting and working together with multiple stakeholders in the denim industry including many projects working towards a more sustainable denim industry. In this project, Mohsin shared his knowledge and expertise on denim. I had the pleasure of visiting him twice at his studio near London. During these visits, Mohsin educated me on denim and its history, showed me many samples and he demonstrated the construction of a type 3 denim jacket. Next to this, he connected me to Ali Abdullah of Diamond Denim.

Diamond Denim by Sapphire

Diamond Denim is one of the branches of the Sapphire Group located near Lahore, Pakistan. They are a vertically integrated manufacturer that has the production facilities to manufacture yarn, denim, non-denim, corduroy, jacquard denim, and garments. Their focus is on innovation, creativity and transparency. I was introduced to Ali Abdullah, Managing Director of Diamond Denim, by Mohsin Sajid. Ali greatly supported my project by enabling multiple weaving cycles, visiting Diamond Denim and the help of its staff. The staff members that were of great help during my project are Maurizio Baldi, Farhan Afzal and Omar Daraz.

Milou Voorwinden

Milou is a woven textile designer & researcher. During this project, she worked as a research assistant for Holly McQuillan. Milou helped me during this project by transforming my designs and visions into weaving structures and files that could be woven on the jacquard looms at Diamond Denim. Together we had the great opportunity to visit Diamond Denim.

Context

There is no denim jacket without denim fabric therefore in this chapter firstly a dive into denim and the denim industry is made. According to Miller and Woodward (2011), nearly half of the world's population is wearing denim on any given day, making denim one of the most worn fabrics in the world. The first denim garments were made over 350 years ago. Even though denim has evolved over its long history, denim jeans will celebrate their 150 anniversary next year, marking the key role denim garments play in fashion history and our daily lives.

Denim

First, this chapter about denim discusses what denim is, which includes a short history of denim, and the cultural significance of denim throughout the last decades. This is followed by a spread visualising a breakdown of the denim industry as it is now.

What is denim

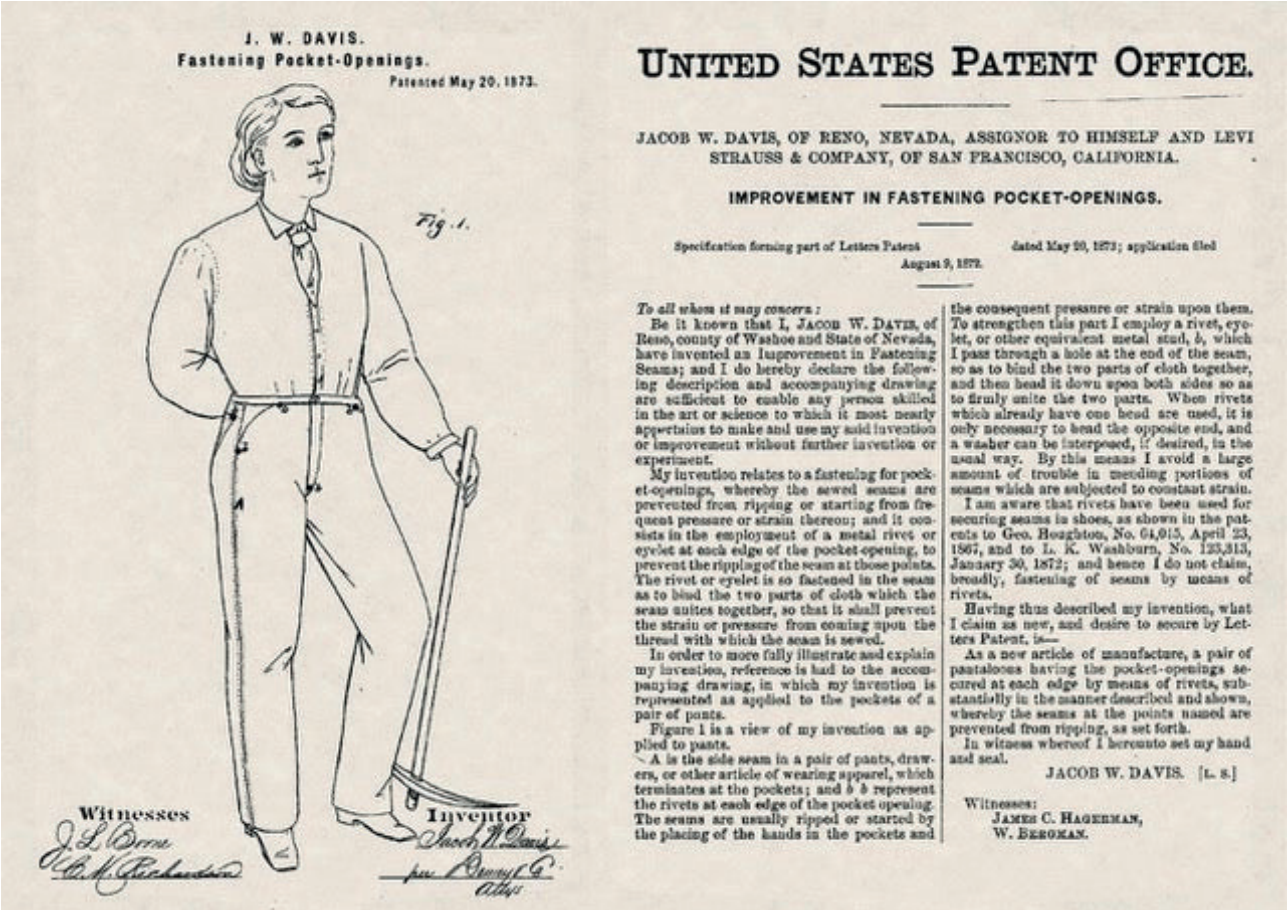
The information in this chapter is heavily based on a lecture by Mohsin Sajid (15-06-2022) in combination with the following literature: A short history of denim by Lynn Downey (2014) and Denim: Fashion's Frontier by McClendon, E. & Fashion Institute of Technology (New York, N.Y.) (2016). For readability reasons, these main sources are not cited in the text. Other sources will be cited in between the text.

Originally denim is made of 100% cotton, woven in a sturdy twill structure with indigo-dyed warp yarns and uncoloured weft yarns, see chapter 7 for a more in-depth explanation of this weave structure. Denim was originally used in workwear around the late 19th century because of the durable quality gained from the cotton twill combined with the aesthetical and financial advantages of the indigo colour.
The twill structure in denim fabric is warp-faced, meaning that the indigo-dyed warp yarns are mostly visible at the surface of the fabric, whereas the white weft yarns are mostly visible at the underside of the denim fabric, giving the denim its characteristic look. The denim twill brings the financial advantage that while the surface of the fabric shows 70% blue-dyed warp yarns and 30% uncoloured weft yarns the denim fabric still looks blue. Why the warp yarns are dyed and not the weft yarns remains a mystery. A twill structure is much stronger than a plain weave because the yarns can be packed together more tightly. This is possible because the warp yarns do not interlace as much in a twill weave as they do in a plain weave (Akou, 2017). This makes a twill weave stronger, thicker and also more capable of hiding dirt, these qualities together with the blue colour of the indigo dye, gives denim the unique quality to look neat even when dirty (Akou, 2017)(Mohsin Sajid, personal communication, 15-06-2022). The indigo dye is unique because of its property to stick to the cotton yarns without needing chemicals. In the dying

process, the warp yarns only go through baths of indigo dye mutliple times. This way, the indigo colour only penetrates the dyed yarn partially, which makes the yarn still look blue, but leaves the core of the dyed yarn uncoloured. When denim is worn and scratched the blue top layer of the yarn gets distressed and the undyed core becomes more visible. This gives denim its worn look and makes denim a product where patina is appreciated.

History of denim

The history of denim fabric started with two kinds of twill fabrics emerging in the 17th century: Serge de Nimes, made of silk and wool from France, and Jean, a fusion of cotton, linen and/or wool from Genoa, Italy. Both are durable and comfortable fabrics. Two Jewish immigrants in west America, Levi Strauss and Jacob Davids can be seen as the godfathers of denim. Levi Strauss had a dry good selling business and Jacob Davids was a tailor. Together they came up with rivets to enforce garments, patented on May 20, 1873 (see figure 1). They produced waist overalls and other workwear like jackets and shirts. From 1911 on, the overalls were made only out of denim.



J. W. DAVIS.
Fastening Pocket-Openings.
Patented May 20, 1873.

Fig. 1.

Witnesses
Inventor

UNITED STATES PATENT OFFICE.

JACOB W. DAVIS, OF RENO, NEVADA, ASSIGNOR TO HIMSELF AND LEVI STRAUSS & COMPANY, OF SAN FRANCISCO, CALIFORNIA.

IMPROVEMENT IN FASTENING POCKET-OPENINGS.

Specification forming part of Letters Patent dated May 20, 1873; application filed August 9, 1872.

To all whom it may concern:

Be it known that I, JACOB W. DAVIS, of Reno, county of Washoe and State of Nevada, have invented an Improvement in Fastening Seams; and I do hereby declare the following description and accompanying drawing are sufficient to enable any person skilled in the art or science to which it most nearly appertains to make and use my said invention or improvement without further invention or experiment.

My invention relates to a fastening for pocket-openings, whereby the sewed seams are prevented from ripping or starting from frequent pressure or strain thereon; and it consists in the employment of a metal rivet or eyelet at each edge of the pocket-opening, to prevent the ripping of the seam at those points. The rivet or eyelet is so fastened in the seam as to bind the two parts of cloth which the seam unites together, so that it shall prevent the strain or pressure from coming upon the thread with which the seam is sewed.

In order to more fully illustrate and explain my invention, reference is had to the accompanying drawing, in which my invention is represented as applied to the pockets of a pair of pants.

Figure 1 is a view of my invention as applied to pants.

A is the side seam in a pair of pants, drawers, or other article of wearing apparel, which terminates at the pockets; and *b b* represent the rivets at each edge of the pocket opening. The seams are usually ripped or started by the placing of the hands in the pockets and the consequent pressure or strain upon them. To strengthen this part I employ a rivet, eyelet, or other equivalent metal stud, *b*, which I pass through a hole at the end of the seam, so as to bind the two parts of cloth together, and then head it down upon both sides so as to firmly unite the two parts. When rivets which already have one head are used, it is only necessary to head the opposite end, and a washer can be interposed, if desired, in the usual way. By this means I avoid a large amount of trouble in mending portions of seams which are subjected to constant strain.

I am aware that rivets have been used for securing seams in shoes, as shown in the patents to Geo. Houghton, No. 64,015, April 23, 1867, and to L. K. Washburn, No. 123,313, January 30, 1872; and hence I do not claim, broadly, fastening of seams by means of rivets.

Having thus described my invention, what I claim as new, and desire to secure by Letters Patent, is—

As a new article of manufacture, a pair of pantaloons having the pocket-openings secured at each edge by means of rivets, substantially in the manner described and shown, whereby the seams at the points named are prevented from ripping, as set forth.

In witness whereof I hereunto set my hand and seal.

JACOB W. DAVIS. [L. S.]

Witnesses:
JAMES C. HAGERMAN,
W. BEROMAN.

Figure 1. The patent for the improvement in fastening pocket openings using rivets.

Around the 1900s the competition for look-alike pants for Levi's pants grew in America, but without the rivets. During the Second World War American soldiers brought their jeans with them to Europe and some were traded. American women, working in factories wore denim jumpsuits. After the war, the retired soldiers took to the streets riding motorcycles and wearing denim jeans and leather jackets. In the following decades, more famous people began to wear denim in their leisure time. The rebellious and cool style was adopted by young people, to a point that schools banned denim out of fear for the teenagers to rebel against any form of authority.

From 1950 on Levi's was selling nationally in America and the name for denim pants changed from

"overalls" to "jeans". In the 60s denim was connected to the "hippie" movement. They turned (second hand) denim in a matter to protest against "the growing materialism of postwar American culture" (McClendon, 2016). Here the trend started to wear pre-softened denim in the coming decades. Jeans and denim were now fashionable, global and mainstream and the focus shifted to European-designed denim.

Evolution of denim production

From the 1980s onwards denim became artificially treated to soften and recreate natural wear patterns. The quality of denim deteriorated due to an industrial conversion to a cheaper variant of spinning yarn. Around the same time stretch denim was introduced for women for better fit and comfort.

Industrial spinning and weaving machines introduced already by the end of the 18th century accelerated the production process of textiles. Together with the introduction of synthetic dyes and synthetic yarns in later years, rapid growth in the textile industry was seen. Textile products became more abundant and became affordable for all classes of people. Consumerism was born. The growing consumption of textiles is related to the fast-fashion business model of the fashion industry, built for recurring consumption of low-priced on-trend products. Those have to be produced as fast as possible for as cheap as possible to be used only for a short time by the consumer, to be thrown away soon after and buy new on-trend products (Niinimäki et al., 2020). To illustrate the extent of fast fashion in the denim industry; in 2006 around 2.7 billion metres of denim were produced annually (Muthu,2017). The size of the global denim industry is around $56.2 billion and each person owns around 6-7 pairs of jeans, of which each jeans has a lifetime of 1 year (FashionUnited, 2016).

We are now entering the denim renaissance where interesting developments are happening to make the clothing and denim industry more environmentally friendly. With its symbolic and cultural nature, denim has the possibility to express this changing world and educate consumers.

Meaning of denim

Miller & Woodward (2011) wrote that "Jeans seem to have taken on the role of expressing something about the changing world that no other clothing could achieve." Denim, as described in the history of the denim section previously, became an expression of freedom, rebellion and individualism (Paul, 2015). This individuality was expressed through embellishing the denim garments as well as the quality of raw denim to fade a bit with every wear. Through this quality, the denim garment moulds itself around its wearer and this way personalises the garment to become the most intimate and reflective garment people have (Solomon, 1986)(Candy, 2005). This unisex medium on the other hand also became the fabric accessible to everyone and worn by the most percentage of the world's population (Solomon, 1986). So denim garments both express global uniformity as personal expression. This global attitude makes denim a careless wardrobe staple that you can wear with almost everything, to almost every occasion and without the anxiety of others' opinions (Solomon, 1986). What makes denim so careless can be the quality of the fabric which does not show dirt or damage that easily and does not require much care (Candy, 2005). Or is it its natural toned blue colour that does not clash with other wardrobe pieces or its comfortable and easy fit (Candy, 2005)? Denim can also be thought of as 'anti-fashion' because it offers the opposite of contemporary fast fashion garments, which are characterised by novelty, social acceptance and where ageing is a bad thing. Denim offers the consumer tradition, and personalisation and is appreciated more with age (Solomon, 1986). It is quite incredible that while denim garments were originally designed to be durable and used for heavy physical work, denim garments now, almost 150 years later, still have the same intrinsic appearance (Candy, 2005). What has changed is the work we do while wearing denim. Another characteristic of denim that changed is the wearer's perception of comfort. When jeans became popular they were bought by the consumer in a "raw" state, meaning only the necessary steps were taken to prepare the fabric for sale. These raw jeans were not particularly comfortable, but by washing, soaking and most of all wearing them they became more and more comfortable and specially moulded

to the wearer. After the hippies and when denim became commercialised the consumer preferred “pre-worn” denim because it is already soft and comfortable. So companies then started washing and treating the denim garments to look like they were worn. This way we now buy jeans with a worn-in story that we did not give ourselves and therefore deny denim’s original durable quality.

Denim jacket

This project focuses on the denim jacket as a denim-specific garment. To design a denim jacket research has been done into what a denim jacket characterises, how a denim jacket is constructed and how a denim jacket interacts with its wearer. This way the origin and its function nowadays can be taken into account in the design development of this project.

What is a denim jacket

According to the Cambridge Dictionary the meaning of a denim jacket is “a short coat made of denim (= a thick, strong cotton cloth, often blue, used especially for making jeans)”. It also states that a denim jacket never goes out of style and that it will work with every outfit. The denim jacket started as part of a workwear uniform slowly transforming into an informal uniform worn for leisure and pleasure. The denim jacket is both worn by women and men making it one of the first genderless pieces of clothing (Museum of Youth Culture, n.d.). “What could be more equal than a jacket that both genders could comfortably wear without judgement or restriction?” (Museum of Youth Culture, n.d.). The denim jacket came to represent the rejection of all inequality, division and bigotry, for those who do not care about what was expected of them (Museum of Youth Culture, n.d.). It is a medium of self-expression where the jacket through its denim fabrics, as can be read in the chapter about denim, functions as a canvas (Borrelli-Persson, 2014). The jacket’s embodiment can both carry and represent experiences and memories, a symbol of individualism (Hutchison, 2011) (Museum of Youth Culture, n.d.). So, the denim jacket has both the status of a very ordinary item and that of rebelliousness aka an item that connects people as it is a sign of individualism (Borrelli-Persson, 2014) (Selfridges, n.d.).

Figure 2. Reconstruction of a triple pleated blouse. Copyright Mohsin Sajid.

History and types of denim jackets

History of the denim jacket

The history of the denim jacket in this report will be discussed on the basis of the most distinctive variations in the history of the denim jacket.

The denim jacket begins with this triple pleated blouse dating from around 1874 (Mohsin), figure 2, named after the three pleats on the front. These pleats could be opened up to give some extra room to the wearer (Mohsin). The blouse was made to fit as a shirt but from a jacket-weight fabric. The blouse, short and boxy, was designed to wear together with jeans (Trotman, n.d.). The front of the blouse was longer than the back and the blouse featured two rounded front pockets. On the back, the blouse is fitted with more pleats and a buckle cinch at the lower back (Trotman, n.d.). The blouse has exposed rivets and sewn-on buttons.

The Levi's Type 1 trucker jacket was based on the triple pleated blouse and was first made in 1936, figure 3. The type 1 jacket looks very similar to the triple-pleated blouse. A difference is the single raised squared front pocket with flap, different back pleats and the waistband construction. Also, the sleeve construction was changed to a two-panel sleeve. (Sajid, 2022)

Figure 3. Levi's type 1 trucker jacket. Copyright Mohsin Sajid.

In 1953 Levi's released the Type 2 trucker jacket as a follow-up of the type 1 trucker jacket. The jacket is made a bit longer and less boxy, see figure 4. Type 2 got an additional front breast pocket. The buckle cinch was changed to adjuster tabs on the waistband, to tighten the waist of the jacket. The rivets on the jacket were replaced by bartacks. (Sajid, 2022)

Figure 4. Levi's type 2 trucker jacket. Copyright Mohsin Sajid.

Lee introduced the rider jacket in 1931, a slim-fit jacket for cowboys, figure 5. The zig-zag on the front placket, slanted front yokes and the seams in the middle of the front panels make it stand out from Levi's jackets (Muzquiz, 2019).

Figure 5. Lee rider jacket. Copyright bronsonshop.

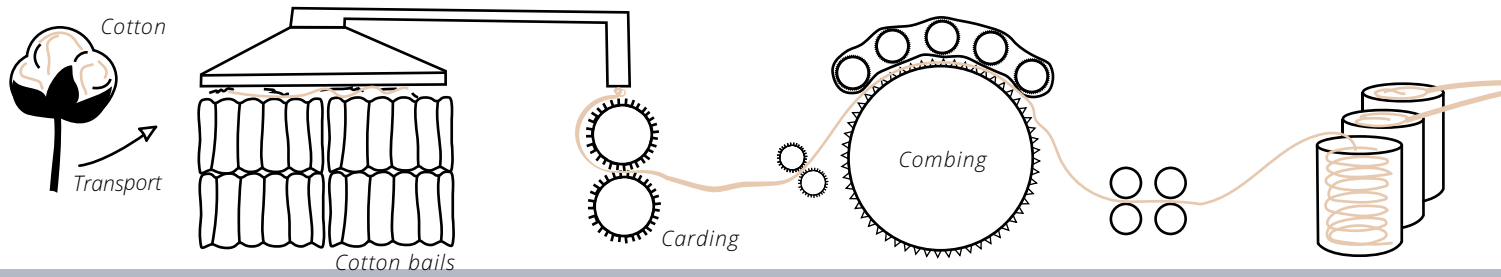
Figure 6. Levi's type 3 denim jacket. Copyright stridewise.

The third classic jacket of Levi's is the type 3 trucker jacket launched in 1967, figure 6. The design was made slimmer and eliminates details such as the front and back pleats. Type 3 is characterised by the v-shaped seams on the front body panels. The pleats in the back were replaced by two seams. The front breast pockets are made smaller and placed higher, up against the front yoke (Mohsin). In the 1980s, hand pockets were added to the front panels (Trotman, n.d.).
Denim at this time became more popular with the public with blue jeans around together with the launch of the Type 3 denim jacket. Although it was popular with many people, it caught on fastest with the counterculture youth of the 1960s, who donned it in defiance of their parents' professional button-down clothing (Gohl, n.d.).

The manufacturing process of a denim jacket

Making a denim jacket involves many processes. The general outline of most of these processes has been the same for many years, although processes are modernised. The process can be divided into three categories; the making of the yarns, weaving and finishing of the denim fabric and construction and finishing of the denim garment. This chapter will review the production of denim garments, when made entirely from cotton yarn, from spinning cotton to finishing the garment. Nowadays, conventional cotton yarns are more often replaced by organic cotton or mixed with cotton alternatives such as hemp or Tencel. These developments are highlighted in Chapter x but not discussed in this chapter.
This visual on denim garment production, figure 7, was made using the following sources; Denim: Manufacture, Finishing and Applications (Paul, 2015), Sustainability in Denim (Muthu, 2017), visit Diamond Denim by Sapphire in Lahore, Pakistan and information from visits to Mohsin Sajid.
>> *see following pages*

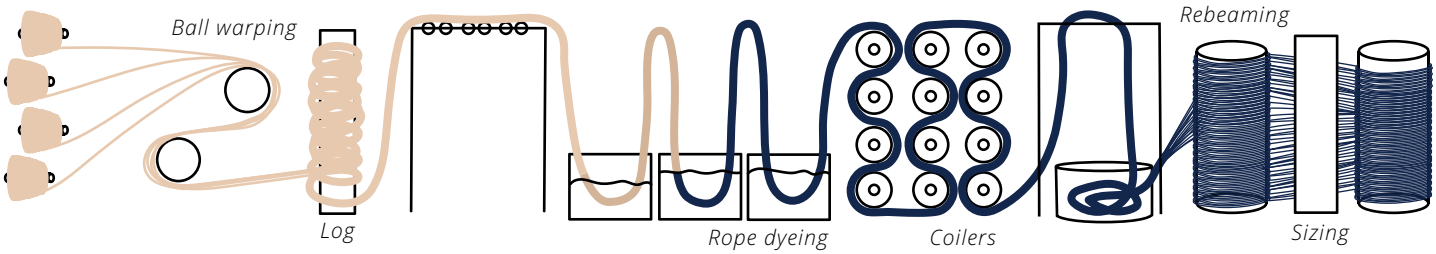
The denim industry from yarn to garment (figure 7)



Cotton
Cotton needs lots of sunlight, low humidity, good soil quality and plenty of water. To support cotton production, farmers use many chemicals. Of global cotton production, 79% takes place in China, India, the United States, Brazil and Pakistan (Impact Institute, 2019). Cotton is shipped in bails to weaving mills around the world.

Carding
Cotton is stored in warehouses. The main production factories for denim textiles are in China, Pakistan, Turkey, India and Japan (Impact Institute, 2019). In the blowing chamber, cotton is opened, cleaned, mixed. The cotton is transferred to the carding machine where the cotton Þbres are further cleaned, untangled, blended and aligned into a long bundle of Þbres.

Combing
These long bundles of Þbres are then passed through the combing machine to make the Þbres smoother, cleaner and more regular. Combing and carding together determine the Þnal properties of the yarn.

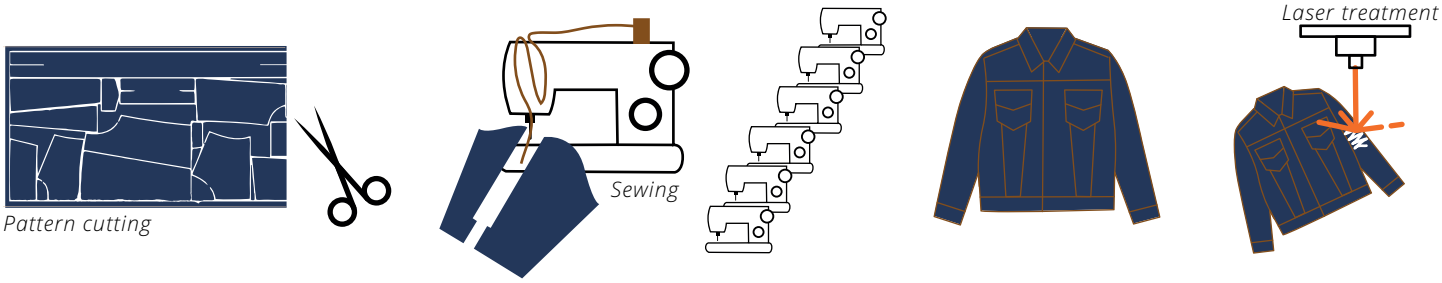


Ball warping
Between 250-400 yarns are put through a funnel process to gather the yarns together into a rope, wound on a log.

Rope dyeing
These logs are then taken to the creels of the rope dyeing machine. The ropes are pulled into the air, to oxidise the yarns, and transported to the baths. The ropes go through several baths, Þrst pretreatment, rinsing, several indigo baths and then rinsing. The ropes are transported through dry cans and transferred to baskets via coilers.

Rebeaming
Dyed clusters of warp threads are spun into warp threads and laid on warp beams.

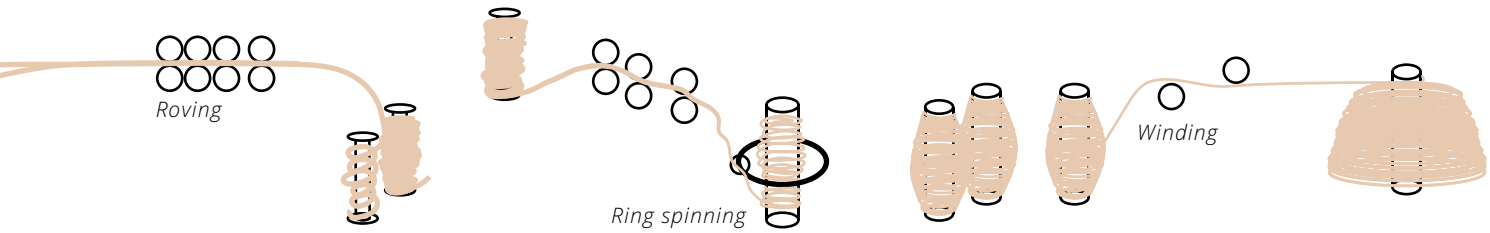
Sizing
Warp threads are sized to prepare them for weaving. The warp yarns, which are very close together, are subjected to stresses and strains during weaving (Cotton Incorporated, 2010). During sizing, the yarns are coated with a protective layer to improve the smoothness and quality of the warp yarns (Cotton Incorporated, 2010).



Production of denim garments
Fabric is transferred to the garment de-partment, as may be the case with Diamond Denim by Sapphire, or shipped to garment manufacturers around the world. According to Impact Institute (2019), most jeans manufacturers are based in ÔBangladesh,Turkey, Pakistan, China and Tunisia.
Garment construction is the most manually labour-intensive process and, after fabric costs, one of the most expensive parts of the garment production process, accounting for about 35-40% of the total garment cost (Khan, 2022).

Pattern cutting
The pattern pieces of the garment are cut from the denim fabric, several layers at a time. The pattern pieces are laid out efficiently to minimise waste of pre-cut pieces.

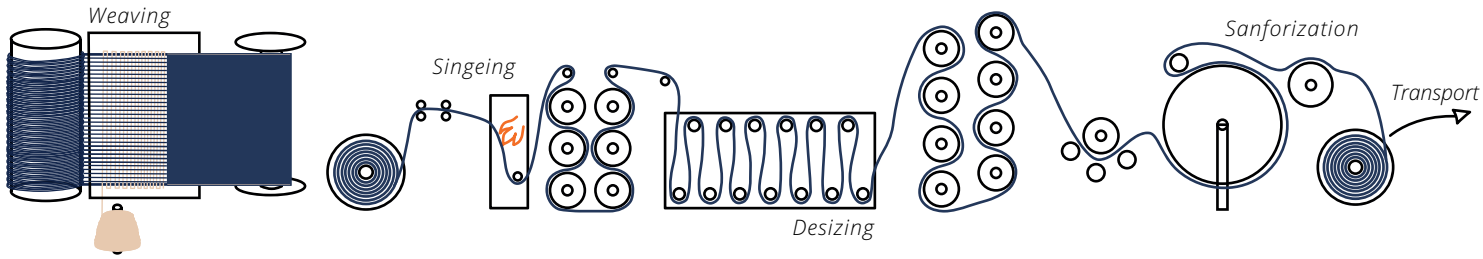
Joining - sewing
The most common way to join the cut pattern pieces is to sew them together, using several different machines like flat sewing, overlock and automatic thread cutting machines (Cheng & Liang, 2021).



Roving
The bundle of Þbres is passed through the roving machine to achieve the desired yarn Þneness to be spun on cones.

Ring spinning
The cones of roving are inputs for spinning. In ring spinning, the cotton yarns are drawn Þner and spun on another cone. At this stage it is possible to add Þllers such as polyester stretch yarn. In this illustration, ring spinning is highlighted because this is the spinning method used at Diamond Denim. Alternatives are compact spinning and rotor spinning.

Winding
Small bobbins of ring-spun yarn are wound and connected to other cones to obtain longer bundles of yarn.



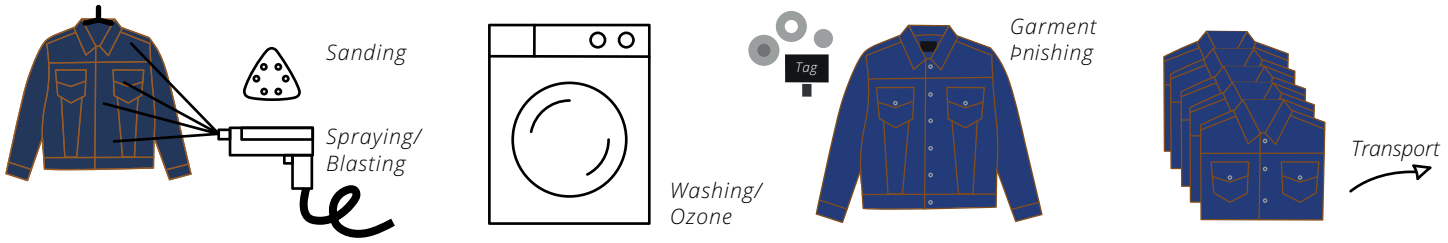
Weaving
Denim is a woven fabric made of a twill weave structure. The warp yarns lie in the length of the fabric, often spun on a loom. The weft yarns are laid in the width of the warp, one length at a time (Lord & Mohamed, 1982).

After weaving the denim goes through three steps to make it ready for shipping and/or garment manufacturing.

Singeing
Singeing removes any unevenness from the surface of the denim fabric, which is done by transporting the fabric through brushes and past burning ßames.

Desizing
After singeing the denim fabric is being desized, a wet process in which among others starch is removed from the fabric.

Sanforization
The last step to Þnish the denim fabric is sanforization in which the fabric is preshrunk. The shrinkage of the denim fabric is between around 11% and 15%.



Denim garment washing
Denim garments are treated to achieve a worn-in look, that has a softer hand feel and has a characteristic aesthetic. Different results can be achieved by making use of multiple treatments and a combination of dry and wet treatments. These Þnishing steps also preshrink the denim garments to be able to deliver a dimensional stable garment to the consumer.

Washing
Washing methods can be divided into dry and wet washing treatments.
Dry washing treatments like: sand blasting, monkey wash, brushing and grinding, 2D and 3D whisker creation, ozone fading or laser treatment.
Wet washing treatments like: desizing, regular washing, bleach washing, stone washing, enzyme washing or acid washing.

Finishing
After washing denim garments are Þnished with trims, like buttons and rivets, and labels. Before the denim garments are ready to be packed and shipped the items are ironed, checked and measured.

After garment manufacturing the garments are shipped to distribution centres and retailers all over the world.

Construction type 3 denim jacket by Mohsin

This chapter zooms into the garment construction section of the denim garment process on page 27. A Type 3 Levi's denim jacket will be replicated as this version of a denim jacket is the most know and worn denim jacket nowadays.

Introduction

For a live demonstration of how a type 3 denim jacket is made, a visit to Mohsin Sajid, denim designer, historian and consultant at Endrime based in London, was made. Mohsin prepared the pattern pieces based on a historic type 3 denim jacket from his archive. This section takes you through the construction of this denim jacket by Mohsin and will conclude with a short reflection on this cut-and-sew production method. Note that this is how Mohsin would construct the jacket, the construction of a denim jacket in a garment manufacturer may look different or involve other steps. Also, machines available at those manufacturers are different from the ones used in this demonstration.

Anatomy of a type 3 denim jacket

The figure below names the parts of a type 3 denim jacket.

Construction of a type 3 denim jacket

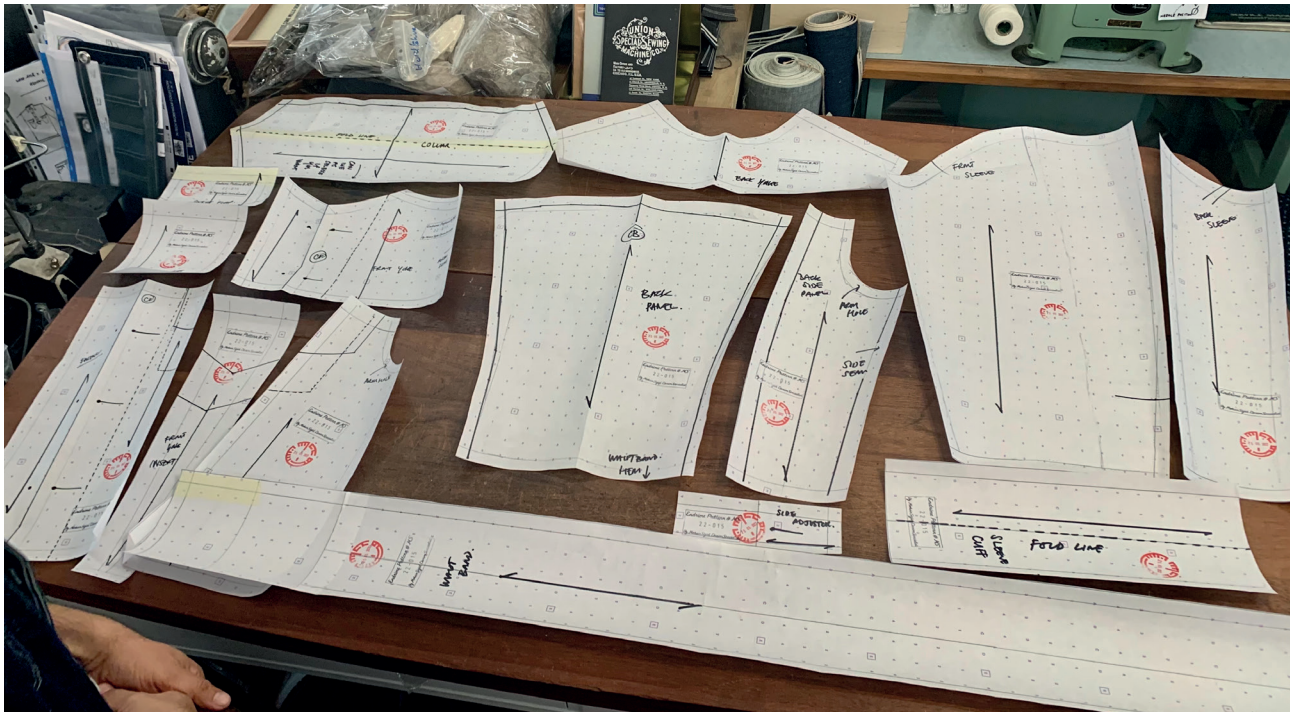
On the following two pages, a visual overview is shown of the steps involved in the construction of a historical type 3 denim jacket. For a more detailed explanation of the steps is referred to Appendix B.

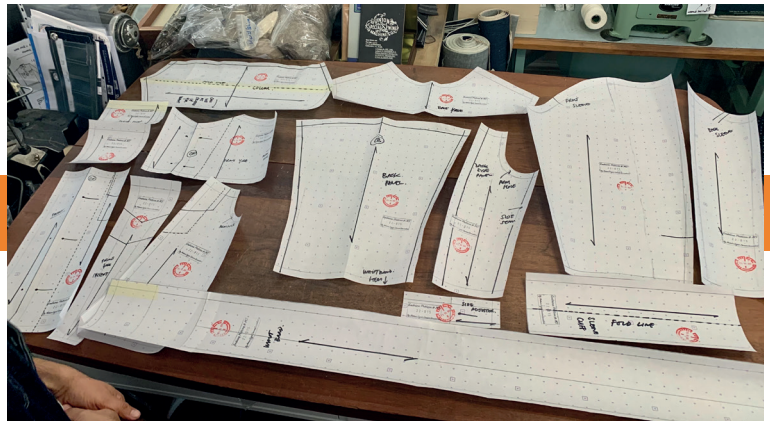
>> next pages 26 & 27

Observations

It takes 18 sewing steps, mentioned in white on the pictures in the next pages, to make the general shape of the type 3 denim jacket, a body with sleeves and a collar. Of this calculation 17 sewing steps are felt seams and 1 sewing step is for the construction of the collar which actually involves multiple steps. Not included in this calculation are the sewing steps needed for the construction of the two breast pockets, the waistband, the two side adjusters, the two cuffs and front plackets. The V-shaped seams to connect the front panels are classic for the type 3 denim jacket, as also the two V-shaped seams to connect the back panels. These seams are decorative rather than essential to make a fitted body for a denim jacket. By leaving these seams out of the calculation mentioned before, and by cutting the front and back pattern pieces as one piece, it will takes 11 felt seams to sew the basis of this denim jacket together.

Another observation about a denim jacket construction is that there are no unfinished fabric edges. The edge of the sleeve is finished with a double layer cuff. The bottom edge of the jacket is finished by a double layer waistband. Most of the neckline is finished with the two layer collar. And the rest of the neck line and the centre front are finished with an extra layer for the front placket. The cuff, waistband and collar are separate cut pattern pieces that when connected to the main shape of the jacket sandwich the raw hem of the jacket enclosed.






Seam [1],[2],[3],[4]


Seam [5],[6]


Seam [9]


Seam [10],[11]


Seam [13],[14]


Seam [15],[16]

Seam [7],[8]


Seam [12]


Seam [17],[18]

Type 3 denim jacket

Meaning of a denim jacket

Experiment

Interviews were held to find out what a denim jacket means for its wearer and what function and characteristics are key to a denim jacket. In addition, questions will be asked about what needs their denim jacket fulfils for them and what future needs they imagine for a denim jacket. Conducting interviews was considered the most appropriate way for these research questions, since it provides the possibility to gain a better understanding about the interviewee's opinions and feelings. And it provides the possibility to ask in-depth questions about their answers and to explain and discuss emerging topics.

Hypothesis

It was predicted that the main characteristics would be the use of a blueish denim fabric, the collar and the fit. It was also predicted that most interviewees use their denim jacket as an outdoor jacket.
Interviewees. The interviews were focused on people who own one or multiple denim jackets. No other requirements were taken into account with the selection of the interviewees.

Procedure

Before the interview started, the participants were told a short introduction about the purpose of the interview. Then the participants were asked to sign a consent form (Appendix C), to inform them about the interview procedure, data processing and to ask their permission to take a picture and record the interview. After the participants signed the consent form, the interview started and the audio recording was activated. At the end of the interview, participants were thanked for their participation and the audio recording was stopped. After the interviews the audio recordings were converted into written words.

Questions asked during the interview

- How many denim jackets do you own and can you briefly describe them?
- When (in what situations) do you wear your denim jacket?
- What is your reason for wearing your denim jacket?
- What kind of activities do you do when wearing your denim jacket?
- What function does the denim jacket have in your wardrobe?
- How do you feel when wearing a denim jacket?
- How do you want to appear to others when wearing a denim jacket?
- What do you like about your denim jacket?
- What do you dislike about your denim jacket?
- So what needs would you say your denim jacket fulfils for you?
- What characterises a denim jacket?

Findings

All of the participants used their denim jackets as outdoor jackets when they were on the road. For some, it is one of their only jackets, whereas for others it is a jacket out of many more. They use their denim jackets mostly during in-between weather, mostly during spring, summer and autumn, which can be worn in combination with a sweater or scarf. Participants related this to the denim fabric, which is not too hot or too cold and does not make you sweat. The fabric is liked because of its thicker heavier quality that feels strong and sturdy. On the contrary, the fabric is not popular in rainy weather as denim is not waterproof and does not have a hood, which would make you and the jacket get soaked.

The interviewees gave many different reasons for wearing their denim jackets. Some of the answers were that the jacket is comfortable, is a wardrobe staple, is versatile and has pockets, which make it a very practical jacket. All the interviewees stressed the importance of the pockets on their denim jacket, to

hold all their belongings, making the jacket also function like a bag. The inside pocket is especially a big crowd-pleaser among the participants, which feels secure and can carry rather big things without being bothered by it.

While some interviewees see it simply as a jacket for when they go outside, some participants see the denim jacket as a part of their wardrobe. In such a way that when composing their outfits they take their denim jacket into account as part of their outfit. The jacket has the possibility to toughen up a cute outfit. It can add something to their outfit.

Only one interviewee mentioned the long life span of the denim jacket making it a jacket she can trust and a statement for her sustainable wardrobe. Also interesting that this participant mentions the capability of the denim jacket to be a product which fulfils it all and does not make you crave another (denim) jacket. This was also noted in conversations with other participants; some may have 2 denim jackets, yet most had their jackets for a long time and have no intention of getting rid of them or replacing them. A denim jacket is timeless, the vintage and worn out look is also something that is liked.

Some participants just answer “fine” to the question of how they feel when they wear their denim jacket. This maybe is related to a participant mentioning that, when wearing the denim jacket, they just feel like themselves. Other answers were that participants feel cool, badass, pleasant or conscious. One participant mentioned that it makes her feel more like a creative person due to the vintage look of her denim jacket. Another participant mentioned that it makes her feel like she feels ready to face the world; everything fits in it and she is ready for anything.

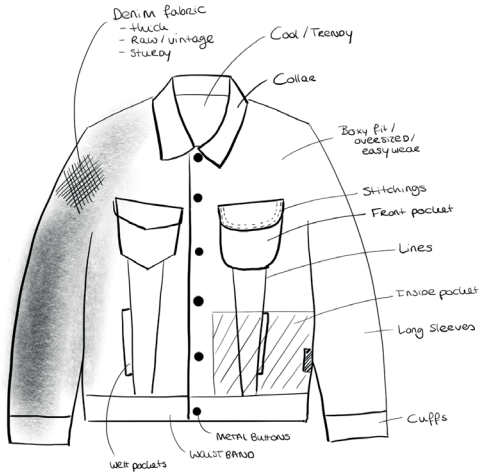
The jacket has something careless about it, one participant mentions the balance between it being an item that is both thoughtful and fashionable as well as something you don’t care about because it fits with everything. Some participants answer that they do not care how they appear to others, which can be related to the denim jacket also being careless. In other words, a denim jacket is such a standard, well-known and popular item, that there is not so much to argue about.

An element that was listed by interviewees that they like about their denim jacket is its versatility. Because of its blue colour which is found very neutral the denim jacket can be combined with many outfits. It was mentioned by a participant that she found the colour of her denim jacket something she disliked, because it has the same appearance as her denim jeans which are a staple in her wardrobe. Another element to the blue denim of the jacket that wearers do not feel the need to be careful with or when wearing the jacket. The fabric is not easily damaged and when dirty still looks neat. And when the denim fabric wears or gets dirty with for example paint, this only adds to the story of the denim jacket.

There are not many things disliked about the denim jacket by the interviewees. As mentioned earlier the jacket is not made for rainy weather. Some dislike the fit when the jacket is closed, done when the weather is cold or when it is raining, while the boxy fit is liked because it is comfortable but still charming. Some also mention that the buttons are not the easiest closure and a denim jacket is not easily stored or put away when on the road.

The needs it fulfils come down to it being a jacket that keeps you warm and protected, except when it rains. But it also has the purpose of storage and it makes you look nice.

The illustration in figure 8 shows all characteristics of a denim jacket mentioned by the interviewees. The denim fabric and its appearance were mentioned several times, as well as the collar, the oversized fit, the inside pocket, being cool and trendy and that a denim jacket needs at least one element that contrasts, such as metal buttons or a leather patch. But the aspects as chest pockets, lineation, cuffs, waistband,



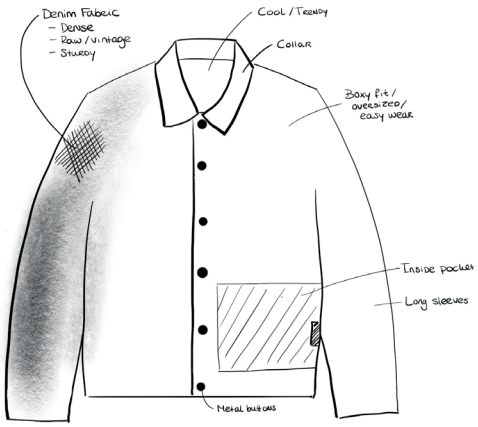


Figure 8. Illustration of all characteristics of a denim jacket mentioned by the interviewees.
Figure 9. Illustration of only the characterisics mentioned multiple times.

welt pockets were only mentioned ones. So with those elements limited out, a denim jacket would be defined as in the illustration in figure 9.

Conclusion

Both in resources and in the interviews a denim jacket is described as a timeless jacket that makes you feel cool, being both a styling piece as well as a careless garment, that you can wear with anything and in which you don't have to think about what people think of you. Literature illustrates a denim jacket as a canvas for expression both a symbol of individualism as well as a symbol of rebelliousness, which kind of makes the wearer belong to a group. The interviewees describe the denim jacket as versatile, careless and comfortable. Where the denim fabric plays an important role in these qualities. The jacket keeps them warm and protected, where the jacket historically was designed for, and is very practical mostly due to its pockets. A denim jacket is a common garment that you keep in your possession and can wear year after year. So the denim jacket means much more than just another jacket. These values are important to keep in mind and convert into the development of the 3D woven denim jacket concept. The denim jacket is defined by a slightly oversized boxy jacket made of denim fabric. A denim jacket has a collar, an inside pocket and a contrasting element like metal buttons. These elements are taken along to the 3D woven concept of this research project.

Conclusion

Denim and jeans have a long history and have been a middle of protest in many different forms. Although the quality of denim changed over the years, the general perception of denim stayed the same: warp faced twill fabric that is blue on the surface and a fabric that is strong and durable. The criteria that will be taken from this chapter related to denim are the following.

Denim requirements

- **Denim twill:** Must be made of a warp faced twill weave structure, where the surface of the garment should look blue and the underside mostly white.
- **Stiff:** The fabric feel of the jacket must be strong and stiff.
- **Durability:**
  - The seams of the final concept must have equal (+/- 10%) of tensile strength resistance compared to a cut & sew type 3 denim jacket seam construction.

- The fabric of the final concept must have equal (+/- 10%) of tensile strength resistance compared to a regular denim fabric cut & sew type 3 denim jacket.

A timeless denim short jacket that has been evaluated over time, but whose overall shape, like jeans, has remained very similar over the years. The genderless denim jacket is one that makes you stand out as well as ordinary, that brings a sense of belonging. The jacket makes you feel cool but is also a careless garment that goes with almost everything. For requirements, we will look at a type 3 Levi's denim jacket. The criteria that will be taken from this chapter related to a denim jacket are the following.

Denim jacket requirements

- The concept should contain the following **characteristics of a type 3 denim jacket**:
  - **Boxy fit:** The concept should contain a boxy fit around the body, so not to tight around the body;
  - **Sleeve connection:** The concept should contain an angled and shaping connection of sleeves o body, characterised by the sleeve curving into the armpit;
  - **A collar**;
  - **Front placket** that is dense to carry the metal buttons;
  - **Front of the body** is longer than the back.

Denim jacket wishes

- **Denim jacket construction:** The concept has an appearance in terms of construction like a cut and sew denim jacket. This could include the placement of seams on the bodice and sleeves. It is beneficial if the concept contains or can contain the following characteristics of a type 3 denim jacket:
  - **Front and back yoke** lines;
  - An **inside pocket** in (one of) the front body panels;
  - **Breast pocket**(s) like the Levi's type 3;
  - Distinctive visual difference between the body panels and the waistband;
  - Distinctive visuals difference between the sleeves and the cuffs;
  - Distinctive visual difference between the body panels and the front placket;
  - Decorative v shaped lines of front and back (characteristic for the type 3 denim jacket).

Tackling the polluting denim industry

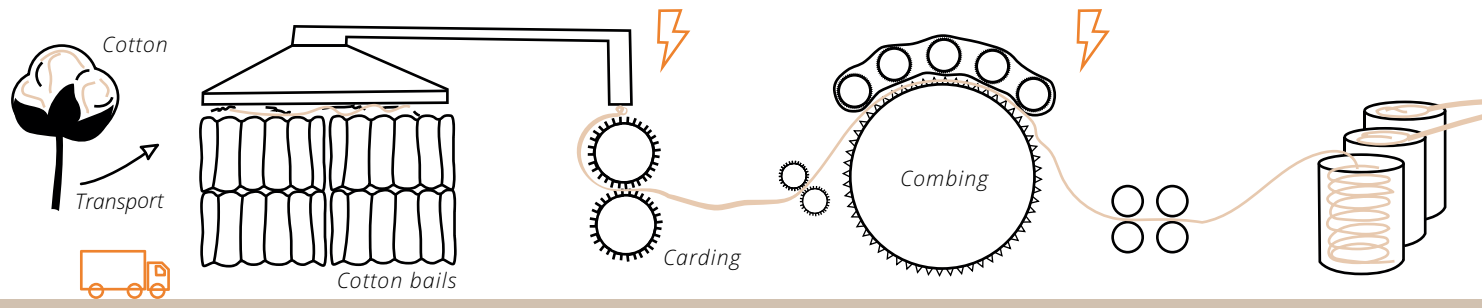
Introduction

The last chapter visualised and discussed the meaning, history and process of making denim garments. The process of making a denim garment involves many steps that can be divided into yarn manufacturing, fabric manufacturing and garment manufacturing. All processes have evolved over the past 100 years to become the industry it is today. This chapter looks at the unsustainable aspects of the denim garment industry. Using the same illustration as for denim garment production in the previous chapter, this chapter will highlight the polluting aspects of the denim industry. From the conclusion of this illustration, this chapter will lead to possible solutions. The circular economy proposed by the Ellen MacArthur Foundation is introduced and a project focus is indicated. From the circular economy, this chapter examines existing sustainable practices in the waste and pollution categories. The conclusion of this chapter highlights the criteria based on this chapter on tackling the polluting aspects of the denim industry.

The denim industry is polluting

The denim industry is part of the fashion industry which is one of the most polluting industries globally (Ellen MacArthur Foundation, 2017). From a global lifecycle perspective, textile consumption in Europe accounts for the fourth highest environmental and climate change impact on average in 2020. Textile consumption also accounts on average for the third highest impact on water and land use and the fifth highest in terms of resource use and greenhouse gas emissions (EEA, 2022). The profit-driven fast fashion industry is built around the overproduction of cut and sewn textile products. Overproduction means producing more products than will be sold. The causes of overproduction may lie in estimated production quantities and fast fashion-buying consumers. In both cases, brands decide to overproduce and handle the excess later, which can be logistically easier and cheaper (López, 2021). This ever-growing system of overproducing cut-and-sew fast fashion comes with high environmental and ethical costs, “including water, air and soil pollution, climate impact, shortage of arable land, harmful and unsafe working conditions, poor workers’ rights’, fatal factory accidents, etc.” (Goldsworthy et al., 2018).
The illustration on the following pages, figure 10, points out the polluting aspects of water usage and pollution, greenhouse gas emission, chemical usage and waste created.

Polluting aspects of the denim industry (figure 10)

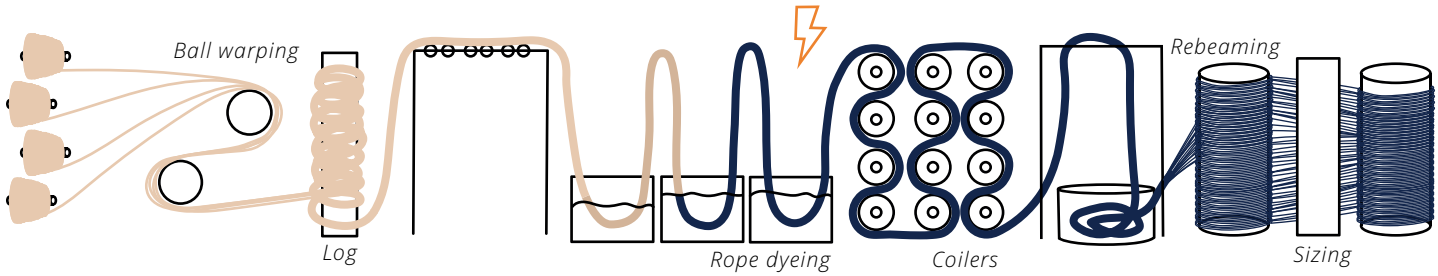


Cotton requires huge amounts of water and pesticides and fertilisers to grow well, 25% of all insecticides and 12% of all pesticides in the world are used on cotton (Muthu, 2017). Producing 1 kg of cotton, roughly a t-shirt and a pair of jeans, requires about 20,000 litres of water (Paul, 2015). This amount of water accounts for 68% of the water consumption of a pair of jeans (Muthu, 2017). So while cotton is biodegradable, making it partly sustainable, growing cotton is not so environmentally friendly. The chemicals pollute water and come with health risks to nature and humans (Muthu, 2017).

Transportation of the cotton to the spinning mills is another impactful aspect of the denim production.

The production of cotton consumes large amounts of energy in the form of fossil fuel or electricity (Levi Strauss & CO., 2015).

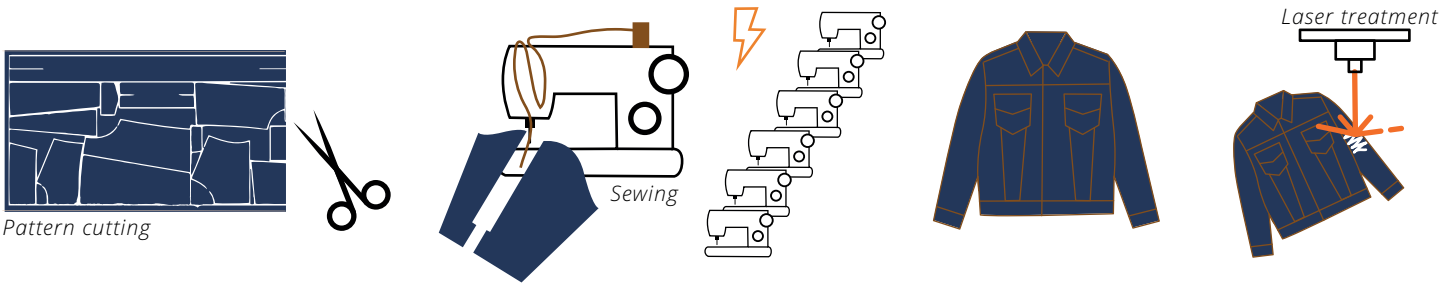
Alongside these processes dust, Þbres and yarn waste is produced which is eliminated and could harm the lungs of labourers.



The warping process consumes high levels of energy use and water (Levi Strauss & CO., 2015).

The baths used for dyeing and sizing the warp yarns consist of various chemical dyes, cleaning agents and reduction agents. The polluted water, when spilled into nature, can cause issues for nature and humans.

There are three kinds of indigo on the market, natural indigo, synthetic indigo and microbial indigo. The most commonly used dye is synthetic indigo, which is full of bad chemicals and uses lots of water which both come with major environmental impacts.



Environmental harming aspects of garment construction are the high level of energy consumption of mostly man operated machines and the amount of pre-consumer waste created (Levi Strauss & CO., 2015) (Cheng & Liang, 2021).

This step of cutting patterns from the fabric is estimated to create between 10 and 15% cut-off waste (Niinimäki et al., 2020). The amount of off-cut waste is inßuenced by the garment design and how well the ßat pattern pieces are designed to fit on the fabric efficiently (NiinimŠki et al., 2020).

Only looking at the garment production segment (cutting, sewing and Þnishing), the climate change impact is the largest at sewing and smallest at Þnishing (Cheng and Liang, 2021). At the sewing stage the carbon emission is two times larger (54.4%) than of the cutting stage (26.7%). The largest impact at sewing is created by the materials used (cotton, buttons and sewing thread) and equipment usage (Cheng and Liang, 2021). A pair of jeans requires around 180 meters of thread (Coats, n.d.).

Green house gas emission

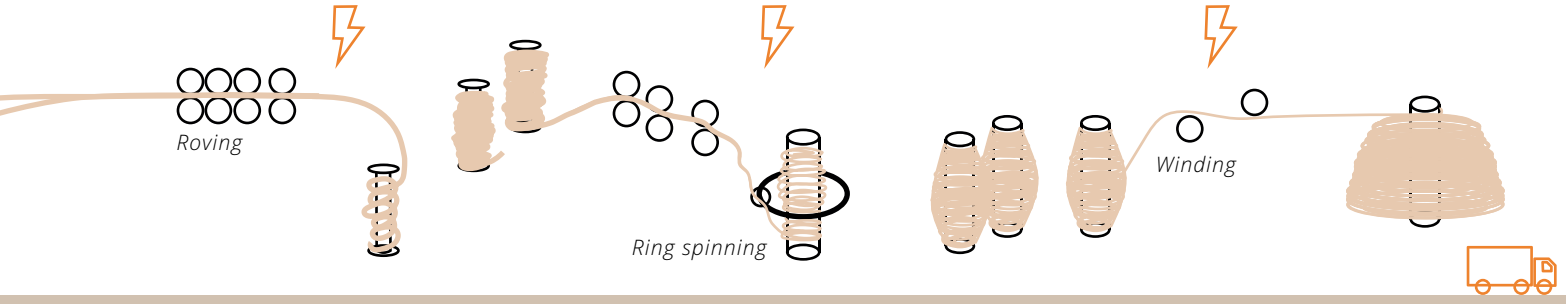
Water usage and pollution

Chemical usage

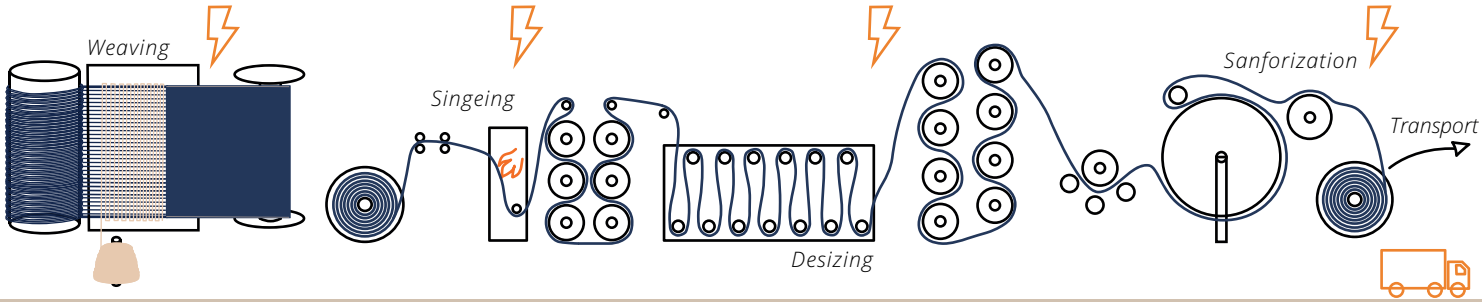
Waste created

Energy usage

Transport emission



The use of synthetic polymers, such as polyester, in yarns has a negative impact on the environment. They are not biodegradable and therefore pose an environmental threat. Although synthetic yarns require less water and land to produce than cotton, they are produced from non-renewable resources. This causes greenhouse gas emissions by using large amounts of energy.

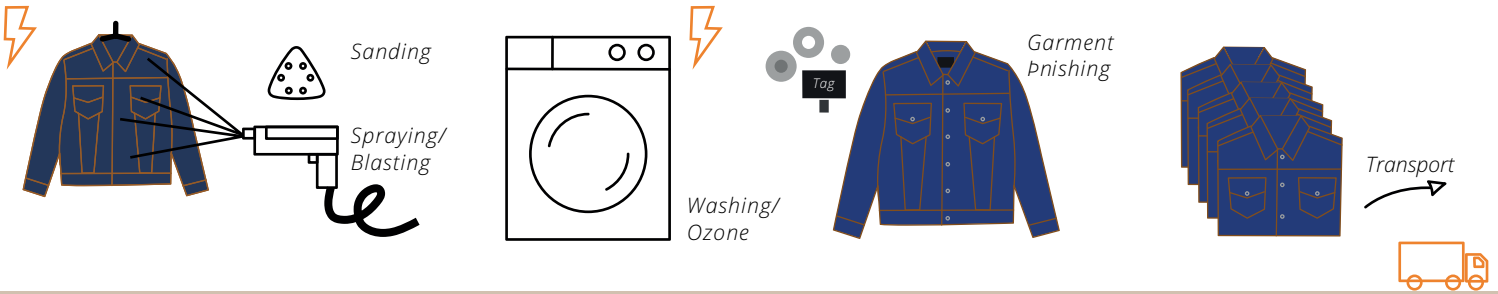


Fabric production, from yarn spinning to fabric Þnishing, has the second highest impact on climate change with 27% in the production of one pair denim jeans (Levi Strauss & CO., 2015). All processes involve great use of energy to keep the machines running (Levi Strauss & CO., 2015).

The Þnishing of denim contributes to around 40% of GHG emissions of the whole denim garment making process (Muthu, 2017).

Next to that the water waste of desizing can commit to up to 50 % of the total millÕs water pollution load.

Regarding water consumption, the fabric production of denim accounts for only 6% of the total LCA done by LeviÕs on a single pair of jeans (Muthu, 2017).



Garment washing includes the use of many chemicals and other liquids that can pollute water. Many of the washing treatments involve great risk for the health of the labourer who executes the treatment. For example potassium permanganate and Ozone can potentially be health hazardous if used incorrectly and unsafe. But also sandblasting, hand grinding, scraping and more of the processes come with great health risks. A lot of these washing treatments involve high manual labour, e.g. most of the whisker making and brushing and grinding is still done by hand one garment at a time.

Transport and retail have the third biggest impact, 11%, on global warming in the production of one pair denim jeans (Muthu, 2017).

Consumer care accounts for the second largest consumption (23%) of water for a single pair of denim pants (Muthu 2017).

Conclusion from illustration

As described in illustration 10 the production of denim garments involves large quantities of greenhouse gas emission (by energy use and transport), water and chemical usage to produce an overproduction of fast fashion garments, with a short life span. Whilst taking into consideration that energy usage is most harmful if relying on non-renewable resources. The production of denim garments also involves large quantities of waste created throughout the whole process. Pre-consumer waste consists of cotton waste in denim manufacturing and off-cut waste, yarn waste, samples and rejected garments from garment construction. Of the denim garment production process, garment construction involves the most manual labour, but all production steps involve risks for workers.

In terms of water consumption for the production of a pair of jeans the major gain can be achieved at changes in consumer care or alternatives to conventional cotton (Levi Strauss & CO., 2015). The climate change impact on the production of a pair of jeans is mostly caused by 'consumer care' (37%) and 'fabric production' (27%) (Levi Strauss & CO., 2015). After those two major influencers on climate change follow 'transport, logistics, retail' (11%), 'fibre' (9%) and 'cut, sew, finish' (8%) with an almost equal contribution (Levi Strauss & CO., 2015). A denim jacket is on the other side not washed regularly but rather yearly. This will reduce the impact of consumer care in the calculation of the impacts of water consumption and climate change. The impact of consumer care will therefore be out of the scope of this project.

Only looking at the garment production segment of a denim jacket (including cutting, sewing and finishing), the climate change impact is the largest at sewing (also including buttons) and smallest at finishing (which includes ironing and packaging and does not include washing) (Cheng and Liang, 2021). At the sewing stage, the carbon emission is two times larger (54.4%) than that of the cutting stage (26.7%). The largest impact of sewing is created by the used material (cotton, buttons and sewing thread) and equipment usage. For example, the production of a pair of jeans requires around 180 metres of sewing thread (Coats, n.d.), of which most contain a kind of polyester.

Circular economy

As previously visualised the denim industry contributes to many unsustainable practices. The industry is now still mostly a linear system, which means that the fashion industry is now built to take resources, make them into products and then dispose of the resources. In order to change this the fashion and denim industry must be reinvented to change the way garments are made and used. The Ellen MacArthur Foundation proposes to change this linear fashion system into a circular fashion economy.

The Ellen MacArthur Foundation describes a circular economy, figure 11, as 'A systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution. It is based on three principles, driven by design: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature (Ellen MacArthur Foundation, nd. A). For fashion, the Ellen MacArthur Foundation (2020) suggests that this means 'ensuring that products are used more, are made to be made again, and are made from safe and recycled or renewable inputs.'

'Used more' includes emotional and physical durability, reuse and repair. 'Made to be made again' includes composting, design for disassembly, recycling and remaking. 'Made from safe and recycled or renewable inputs' includes hazardous substances, microfibres, recycled material, regenerative production practices, renewable material and waste. (Ellen MacArthur Foundation, 2020)

Looking at the goals of the Ellen MacArthur Foundation the focus in this project is to eliminate the waste & pollution aspect of a denim garment, while retaining the existing emotional and physical durability and respecting the 'made to be made again' aspect of a denim jacket.

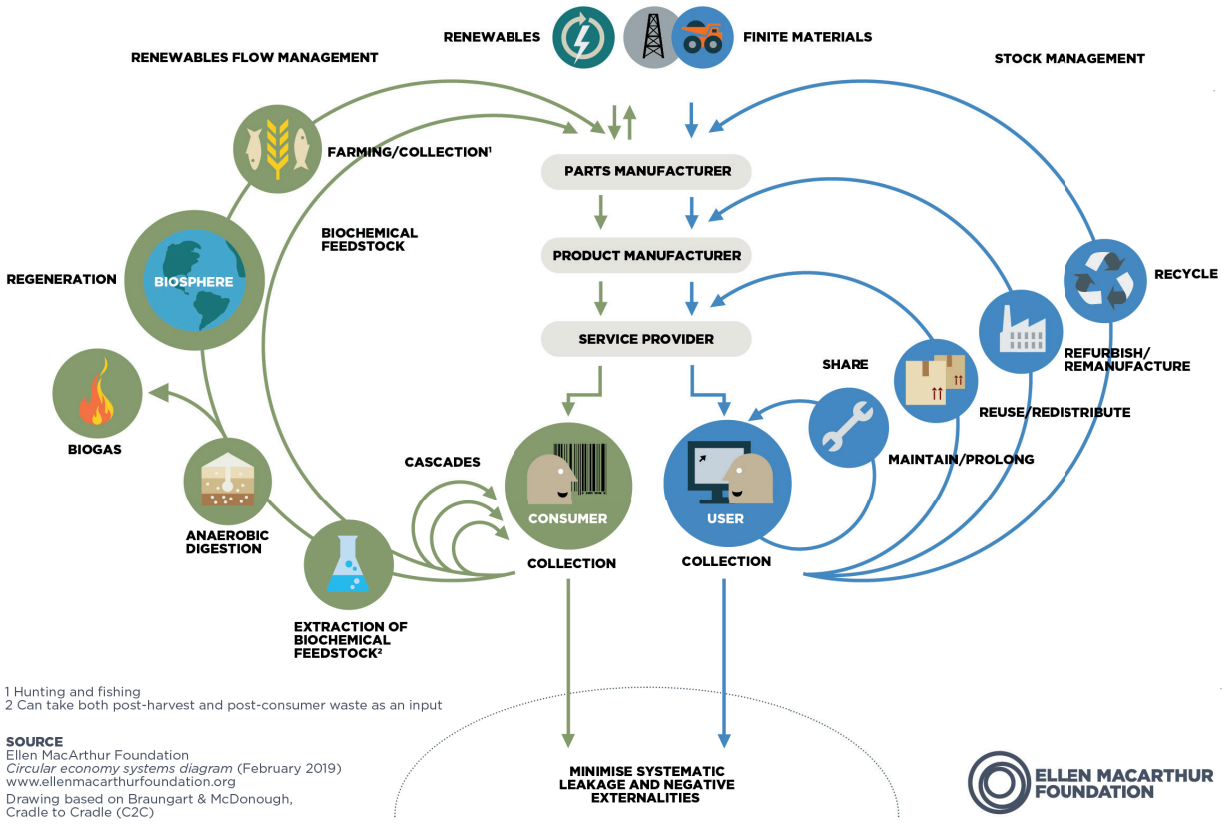


Figure 11. Circular economy systems diagram by Ellen MacArthur Foundation (2019).

Sustainable practices

Related to the focus mentioned above this subchapter will first discuss a summary of what developments are currently on the market that work on making the (denim) garment industry more sustainable in the categories of reducing waste and pollution, where less waste ultimately also means less pollution. Note that this is not a complete overview. The developments that are focused on design for disassembly and recyclability are listed under the heading waste or pollution as there is overlap between the topics.

Pollution

Alternatives to cotton to limit water, energy and chemical use

Organic cotton is maybe the most well known alternative to conventional cotton. Organic cotton meets organic agriculture certification standards and therefore is produced without synthetic chemicals and in a healthy ecosystem. But organic cotton still consumes tons of water and does not mean fair labour conditions. So organic cotton is a good step forward but to limit conventional cotton use it is good to look for alternatives. A great alternative to cotton is hemp. Hemp has a shorter growth cycle, consumes less water and does not need pesticides to grow almost everywhere. Another upcoming alternative is fibres made from cellulose material like yarns from Tencel or Spinnova that are made from wood pulp or fibres from Agra Loop that are made of agricultural crop leftovers. Yarns made from recycled textile waste are another great alternative to cotton, from companies like InfiniteFibre and Circ.

Alternatives to polluting finishing processes

One way to limit the use of finishing processes would be for more brands and consumers to adopt raw denim. Raw denim is not or barely finished and is characterised by the dark indigo colour. The raw denim will fade over time by wearing them. There are multiple alternative and more sustainable denim garment finishing technologies.

Laser technology by Jeanologia limits the use of chemicals and hazardous practices like sanding and sandblasting. Other alternative technologies are the use of ozone or enzymes to create bleaching effects. To limit the amount of water used and water polluted companies like Tonello designed more sustainable washing machines that can replace stone washing and can recycle water in a closed loop.

An alternative to dyeing the warp yarns with synthetic indigo would be to use more natural indigo, bacterial indigo or synthetic indigo but without the polluting chemicals.

Reduce production stepsA way to reduce the global impact of denim garment manufacturing would be to reduce the amount of production steps. This could be combining processing steps into a single process like desizing, sanding and bleaching (Fletcher, 2014). Other ways could be to limit the amount of sewing or cutting steps needed for a garment. See also the point about ‘whole garment production’.

More local production

To limit the amount of transportation involved in the production of denim garments, the industry could look at making production localised. This could involve transferring production more into Europe but also for manufacturers to use local sources for their fibre and other input.

Reduce microfibers

Synthetic yarns used to make denim garments stretchy release microfibers and are hard to recycle. Sustainable alternatives are plastic free alternatives like Coreva, made from natural rubber.

Waste

The sustainable practises to reduce waste in the production of denim garments are divided into pre-consumer waste and post-consumer waste.

Figure 12. 'Nothing goes to waste' collection by Mohsin Sajid and Cone Denim. Image from Instargam @mohsinsajid_

Pre-consumer waste

To reduce the off cut waste produced during the garment manufacturing stage designers should design garments more with the fabric in mind, or ideally design them together.

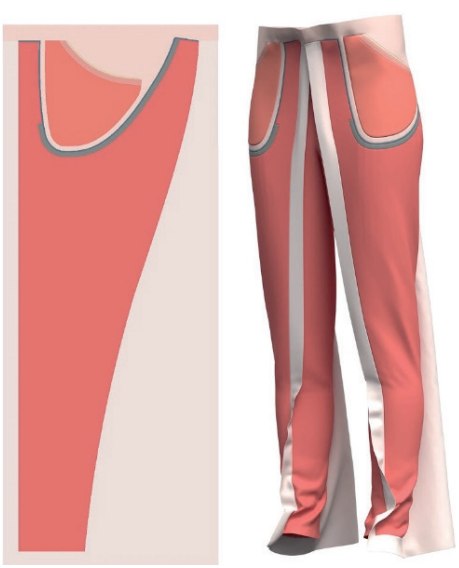
Zero waste design

Zero waste design, like the name suggests, is a way of designing pattern pieces in such a way that no off cut waste is included. This is done with the use of creative pattern cutting to enable a puzzle like placement of the pattern pieces (McQuillan, 2020). Mohsin Sajid designed in collaboration with Cone Denim and Jeanologia a Zero Waste Philosophy collection called 'Nothing goes to waste', figure 12. In this collection Mohsin redesigned the patterns of jeans and jackets in order to create as little off cut waste as possible.

Whole garment manufacturing

Another way to reduce pre-consumer waste is the development of whole garment production, where fabric and garment are designed and created simultaneously. This method already exists in knitting, called 3D knitting, where knitwear garments are knitted in one entire piece directly on the knitting machine. Sort of like 3D printing but then with a knitting machine, figure 14.

Dr. Holly McQuillan in her Phd thesis called 'Zero Waste System Thinking: Multimorphic Textile-Forms', undertook a series of experiments which aimed to expand the form-design methods available for whole garment weaving in the context of zero waste system design (McQuillan, 2020). This resulted in a production method called whole garment weaving or 3D weaving. These methods of whole garment manufacturing tackle the exploitative, time-consuming and wasteful practice of the cut & sew construction method of how garments are made now by integrating the construction of pattern pieces already into the weaving, figure 13. This can also bring the possibility to produce on demand and for the production of garment to become more localised.



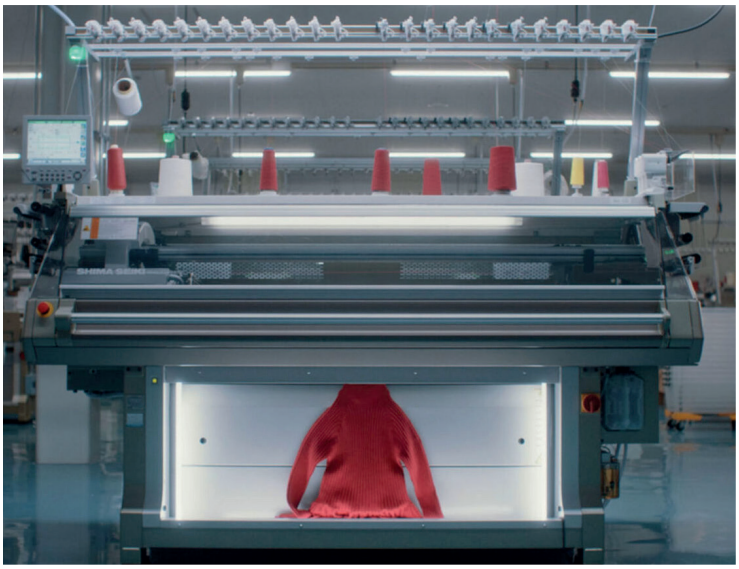


Figure 13. Digital model of a 3D woven jeans by Holly McQuillan and Milou Voorwinden (McQuillan, 2020).
Figure 14. 3D knitted garment by Uniqlo.

Digital design

Digitally designing garments and pattern pieces can reduce the amount or fabric used in the designing stage. By using for example a computer program like Clo3D it is possible to directly see how your design fits and what changes to your pattern look like in the constructed garment.

Post consumer waste

An important development needed to reduce the large amounts of post consumer waste is by changing the fast fashion perspective of most consumers.

On demand

A solution to overproduction can be to produce garments on demand or based on pre orders. On demand production can also include buying the garment made to your personal fit and taste. For example Unspun produces jeans that do not have fixed sizes but can be ordered to custom-fit by means of a 3D scan of your body.

Recycling

To limit the amount of garment ending up in landfills recycling is important. Many designers are creating collections made from pre worn garments. Some brands are offering return services where you can exchange the garment you no longer want for a discount, like at Nudie Jeans. Mudjeans is another example of a brand looking for a way to limit post-consumer waste by not selling jeans but leasing them. Consumers can swap their jeans or send their jeans back and Mudjeans will recycle them.

Reusable hardware

A difficulty when recycling denim garments is the metal hardware that is attached on them, like the buttons, rivets and zippers. Unscrewable buttons and embroidered rivets are developments that try to make recycling of denim garments easier.

Conclusion/Project focus

As stated above the sustainable focus based on the theory of the Ellen MacArthur foundation in this project was to reduce the waste & pollution aspect of a denim garment, while enabling the 'made to be made again' aspect and retain the existing emotional and physical durability.

Looking back at the conclusion on the polluting phases of the denim garment industry some assumptions can be made. The phase of consumer care is neglected in this project about a denim jacket. The phases of packaging, transport, logistics, retail and end of life are out of scope for this project. The impact of fibre is outside the scope of this project but will be tackled by setting up a criteria point of using yarns for weaving that have a lower environmental impact than conventional cotton. So for the elimination of waste and pollution in a denim jacket production this project will focus on the fibre production and garment construction and finishing phases. Concluding from the research Cheng and Liang (2021) and the impact energy usage has on climate change, reducing the amount of production steps required will reduce the impact.

Combined with the overview of current and potential developments for reducing waste and pollution it can be seen that there are already many developments working on making the denim garment industry more sustainable. The potential for this project is seen in whole garment production of 3D weaving, that by designing fabric and garment together, can reduce production and limit pre-consumer waste.

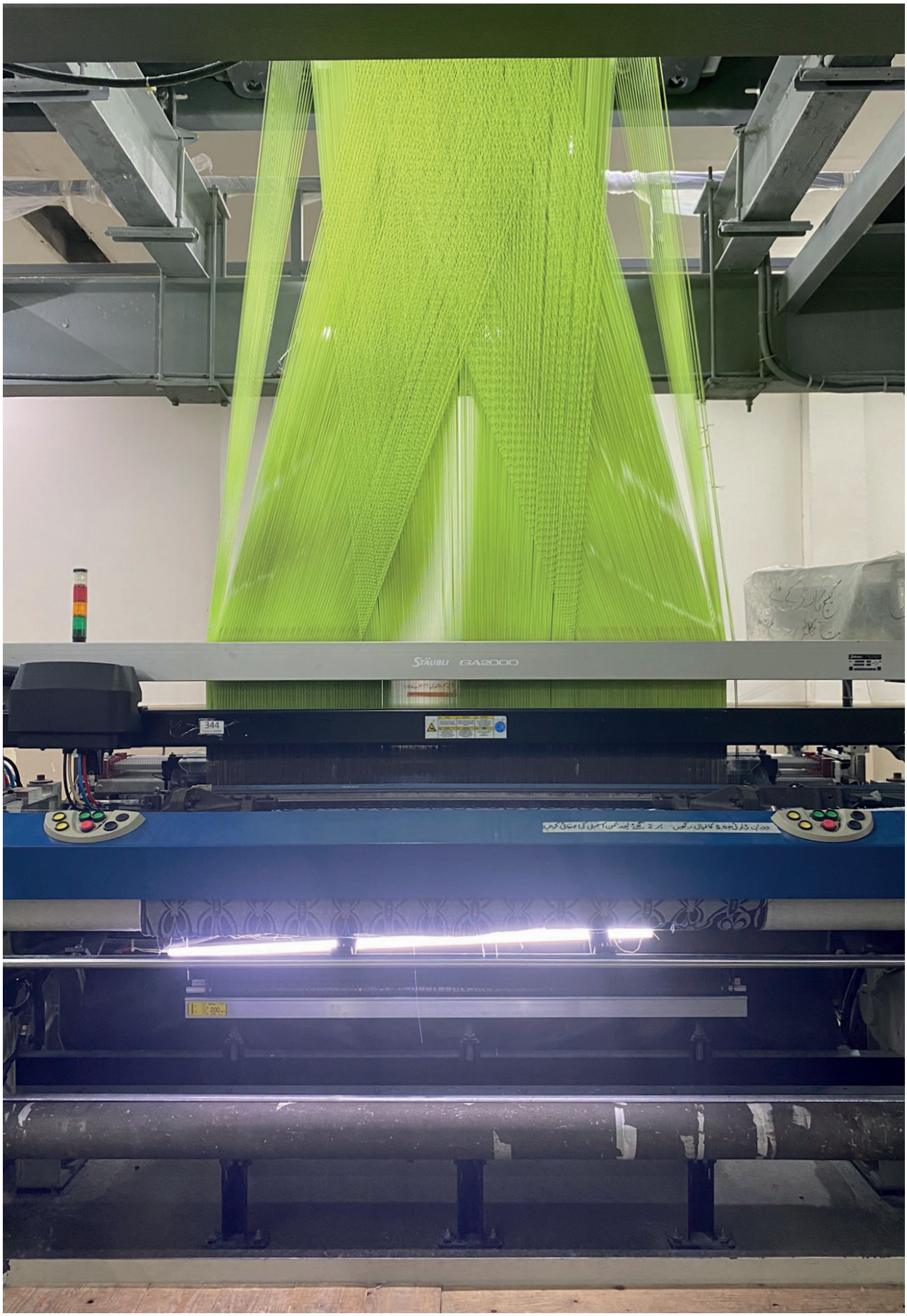
The following criteria will be taken from this chapter related to improving the polluting aspects of the denim garment industry.

Towards a more sustainable industry requirements

- **Yield waste:** The concept design, in the desired loom formation, where the loom has no repetition and no specified width, produces equal or less than 10% of the fabric yield of the overall layout of the concept.
- **Less production steps:** The concept must contain equal or less production steps of a current type 3 denim jacket, without losing the characteristics (see x) of a type 3 denim jacket.
  - To limit the required total cutting length from the woven fabric;
  - To limit garment finishing where possible;
- **Sewing complexity**: The sewing construction of the jacket should not be more complicated than a current cut & sew denim jacket (this costs time and time is money).

Towards a more sustainable industry wishes

- **More sustainable yarn:** The yarn used in the prototypes have a lower environmental impact than a full conventional cotton yarn, so use options that contain organic cotton or alternatives like hemp or tencel.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7

3D WEAVING

Introduction

The last chapter concluded with 3D weaving as a method to reduce pollution in the denim garment industry. In this chapter 3D weaving and its potential will be explained. To explain what 3D weaving is, this chapter will start with an explanation of weaving.

Weaving

Weaving is done on a loom with a warp and weft whose interconnections form a weaving structure (Lord & Mohamed, 1982). The warp beam consists of a multitude of individual yarns spun on the loom. The warp yarns, therefore, lie along the length of the weave, while the weft yarns lie across the width of the weave. To weave the weft yarns into the warp yarns, a selection of the warp yarns is raised, so that the weft yarns can be placed between the flat and raised warp yarns, see figure 15. This interweaving of warp and weft yarns can be done in very many different ways and determines the structure of the fabric. The properties of the fabric are determined by the weave structure and the yarn properties (Lord & Mohamed, 1982).

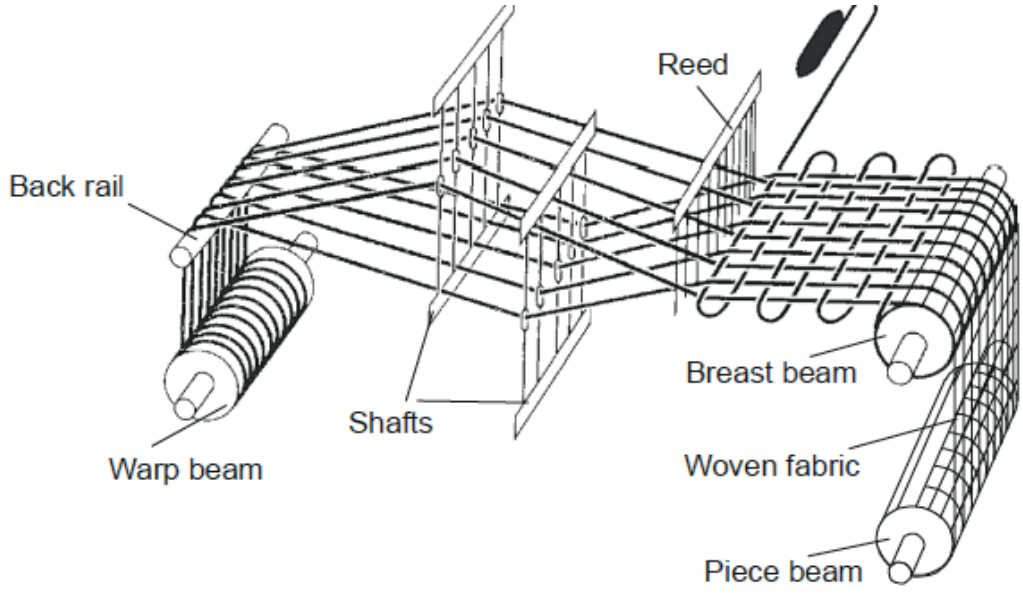


Figure 15. Principle of weaving (Paul, 2015)

Shaft and jacquard looms

Weaving is done on a weaving machine called a loom (Paul, 2015). Some looms use a shuttle to bring the weft yarn through the warp yarns and shuttleless looms, for example, rapier or air jet looms. Using air jet shuttles makes it possible to weave at very high speed and therefore this is used in parts of mass textile manufacturing. There are multiple types of looms, in light of this project two kinds of looms are discussed, the shaft loom and the jacquard loom. Normally, denim fabric is woven on a shaft loom, where it is only possible to control the warp yarns in groups, moved by harnesses (Lord & Mohamed, 1982). When a harness goes up or down, all the warp yarns attached to it move up or down (Guilford of Maine, 2015). In the jacquard loom, all warp yarns can be controlled individually, which makes a lot of possibilities for creativity. Jacquard looms are not often available for denim but some mills like Diamond Denim by Sapphire have a small number of them. Jacquard looms often come with a repeat in their width, this means that one part has design freedom and that section is repeated in the rest of the loom width. Shaft and jacquard looms come in all kinds of widths.

Notation

When a warp thread is raised and thus the weft thread passes under the warp thread, this is considered the “up” position of the warp thread, assigned with the color black (Kyosev & Boussu, 2022). The warp yarn will then become visible on the surface. When a warp thread is not raised and so the weft thread passes over the warp thread, this is considered the “down” position of the warp thread assigned with the color black. The weft yarn becomes visible on the surface. The notation in weaving structures for the upward position is a white box and for the downward position a black/filled box.

Twill weave

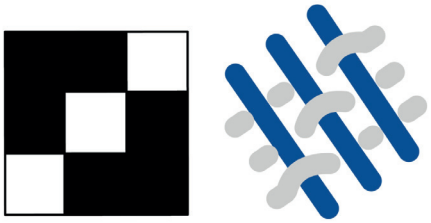


Figure 16. Denim twill notation

Denim is characterised by a warp-faced twill weave (Paul, 2015). A twill weave is a type of weave structure whose pattern is characterised by diagonal parallel ribs, figure 17. Twill weave structures are made by the weft thread passing under two or more warp yarns and then over one or more warp yarns (Kyosev & Boussu, 2022). This pattern is repeated with a step to the left or right to create the diagonal parallel ribs. In figure 16, a scheme of a common 3/1 warp-faced twill is visualised.

Factors that influence the outcome of the weave:

= Type of machine
= Shaft or jacquard loom
= Kind of shuttle
= Width of the loom
= Width and kind of repeat on a jacquard loom
= The density of the warp yarns on the machine, indicated in ends/cm
= The type of yarn used for the warp: material and thickness
= The type of yarn used for the weft: material and thickness
= The weave structure(s)
= The density of the weft yarns, indicated in picks/cm
= The map of construction: 2D plan of the weave structures

Figure 17. Close-up photo

3D weaving

How does it work

The dimension that 3D weaving adds to weaving is the possibility to weave multiple layers on top of each other. In an ordinary single-layer structure, all the warp and weft yarns are woven together to form a full-density textile. In a structure with two or more layers, the warp and weft yarns are distributed among the layers, creating individual layers, each with a distribution of the density of a single-layer structure. For a two-layer weave structure alternately one weft line per layer is woven. For the top layer, only the warp yarns that will be visible in that line are raised. For the bottom layer, all the warp yarns of the first layer are raised plus the warp yarns that will be visible in that line on layer two are raised.

Fractional density

This distribution of density is called fractional density. A warp with a density of 40 ends/cm combined with a four-layer structure will result in a layer density of 10 ends/cm in the areas where all four layers are used. The fractional density is important to consider when designing as it directly affects the appearance of the fabric. Layer density also depends on the density of the weft yarns and the thickness of the warp and weft yarns used. To create a section of 2 layers in a textile, at least two weft yarns per weft insertion are needed. To create 3 layers you need at least 3 weft yarns per insertion and so on. Weaves with 4 weft yarns per insertion can be divided into multiple layers in different distributions, see figure 18. For more layers, the same idea applies. The distribution of the warp yarns is indicated by numbers, starting from 1, 2, 3 and so on. The distribution of the weft yarns is indicated by letters following the alphabet, starting from A, B, C and so on.

The freedom that the jacquard loom brings to control each warp thread individually makes it possible to design a complex map of bindings where different kinds of weave bindings, with different kinds of layer distribution, are combined.

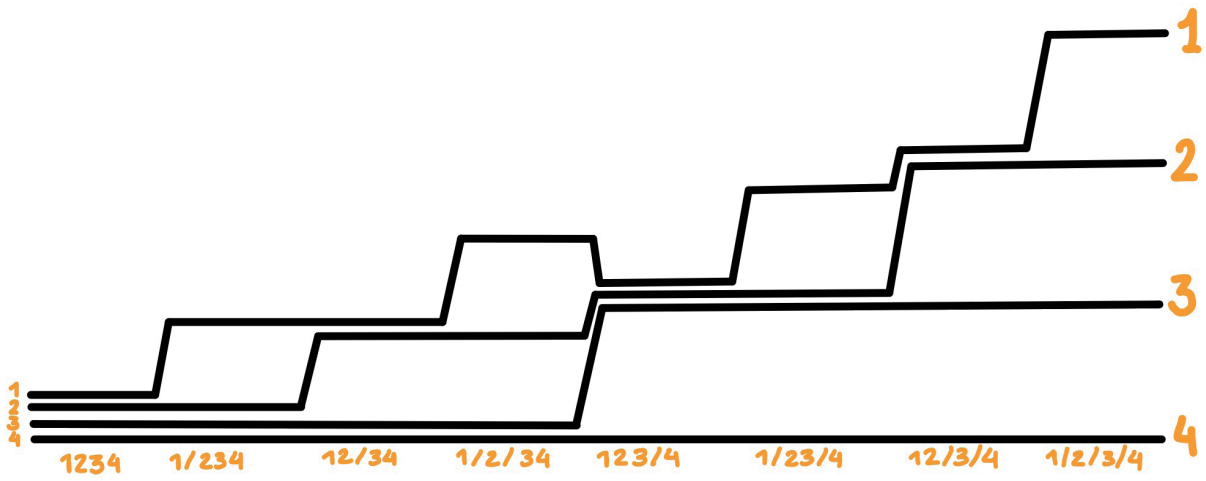


Figure 18. Possible diviation of layers when 3D weaving with four weft yarns.

3d weaving for garment construction

When creating those layers it is important to consider how the different kinds of layers distributions are connected to each other. Each transition from a layer distribution to another layer distribution takes place using a seam that weaves together the warp and weft of the layers distributions to be connected. These connected and unconnected multiple layer structures create textile forms, which can be released or unfolded from each other. The following sample by McQuillan in figure 19 visualises this layer's constructions.

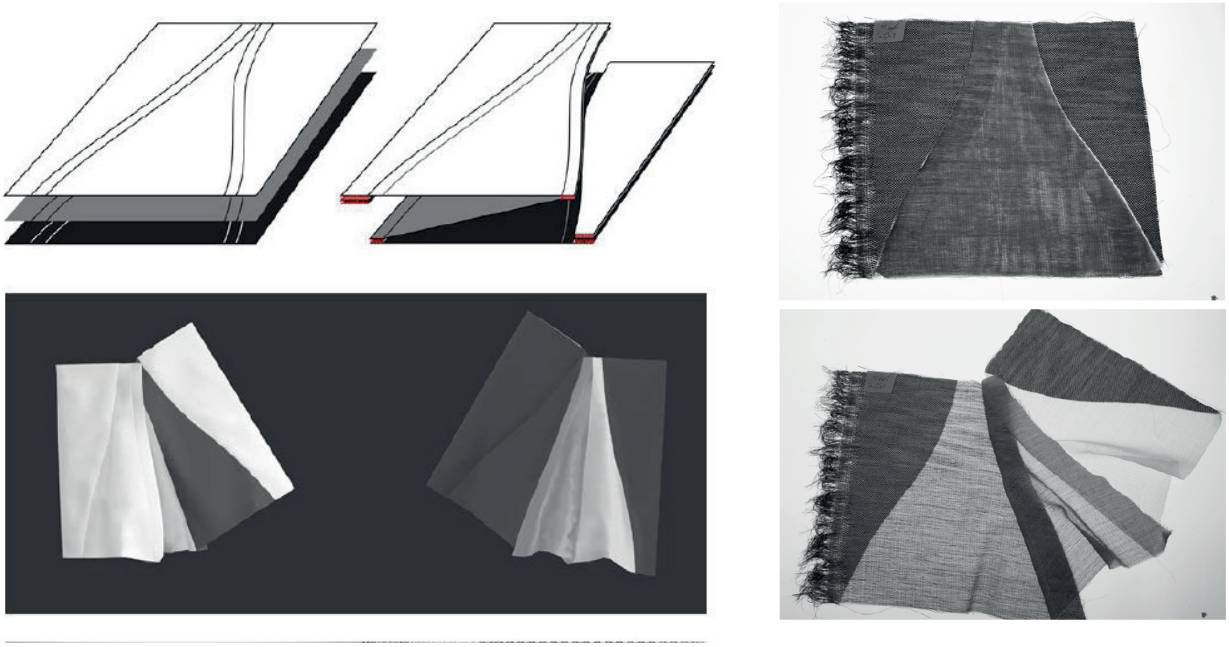


Figure 19. Images by McQuillan (2020) showing the relation in a woven textile form with three layers in a digital and woven

3D weaving, unlike 3D printing, creates the 3D shape in a 2D flat construction, which then can fold open into a 3D construction. 3D weaving is done on existing looms from which the result is a 2D fabric plane. So the garment is still made from a flat pattern but with 3d weaving the pattern can consist of multiple layers on top of each other. The process of making a 3D garment construction into a 2D formation is called flattening. The visual process, figure 20, of a 3D woven pants by McQuillan shows the transition of a pants like we know it to a flattened 3D woven textile form. The 3D woven pants in figure x are made in one piece where the red parts form the leg panels that are woven together by the pink areas. The colored drawing is the so-called Map of Bindings (MoB). In the map of bindings every section with different weave bindings (weave structures, amount of layers, warp and weft distribution between the layers) is indicated with a different colour. As can be seen in the example of a 3D woven garment in figure x, this technique will have an influence on the appearance of the garment.

Added factors that influence the outcome of the 3D weave:

= Fractional density of layers
= Map of bindings
= Connection of layers
= The distribution between the layers of the warp and the weft yarns.

Potentials of 3D weaving

As mentioned shortly in the last chapter the potential of 3D weaving is promising for the reduction of pollution in the garment industry. By designing fabric and form together lies the potential to reduce production steps and the amount of off-cut waste, ideally to create a zero-waste garment. Reducing the number of production steps in the garment construction phase can result in fewer manual labour hours

needed to produce the garment. If less manual labour is needed it may become compelling to move the production to more local locations near the places where the clothes are bought. The potential of more local production and weaving whole garments at once makes it also more compelling to produce garments on demand. On-demand, production could tackle the fast fashion industry based on overproduction. Replacing complex sewing construction for 3D woven construction may also allow production to be automated, using for example CNC cutters to cut out and open the 3D woven textile form.

Figure 20. Images by McQuillan (2020) shows the development of a 3D woven pants from a regular pants to a flattened 3D woven textile form by Holly McQuillan and Milou Voorwinden.

Challenges of 3D weaving

The current garment manufacturing industry, for denim garments but also for most other garments, is based on decades of developments to make the most cut and sew textile products for the least amount of time and money possible. These developments created a polluting and wasteful industry that is set up in a certain way. Implementing new technologies and or strategies can therefore cause complications. 3D weaving is a very new technology that now is executed on machines that are not specially built for it. The development of 3D woven textile forms is therefore still limited to the machines available.

Another aspect of 3D weaving is the certain appearance that is a result of the technology. Just like the industry is built to produce fast fashion products, consumers are also used to the appearance of these textile products. The acceptance and implementation of technology like 3D weaving also require consumer adoption of this new appearance.

Tools for designing a 3D woven textile form

For designing for 3D weaving several prototyping tools are described by Holly McQuillan (2020). McQuillan mentions that using existing flat patterns of constructed jackets can lead to outcomes that are closely related to the starting point.

= Flat garment patterns
= Multi-layered paper models
= Digital prototyping in Clo3D
= Existing 3D garment forms
= Cut and sew prototypes

Conclusion

3D weaving is done on a jacquard loom that makes it possible to weave multiple layers on top of each other. The created layers are a fraction of the total density. A textile form can be made up of different weave structures and different layers and warp and weft distribution. The weave structures make when folded open and or cut open at some places form like for example a garment. This new technology will bring challenges when integrating it into the existing industry, e.g. machines and infrastructures that are not built for or around this technology. 3D weaving defines a new appearance that will challenge the designing of products for consumers that are used to the appearance of the fast fashion industry now. By integrating the textile and form the structure of the industry will change, see figure 21. Instead of ordering fabric before designing, fabric and design are designed together.

The following criteria will be taken from this chapter related to 3D weaving.

3D weaving wishes

= To keep in mind the influence of the fractional density on the design to achieve a fabric look and feel resembling denim fabric. The wish is to, with a warp density of 40 ends/cm at the sampling machine at DD, make the maximum layers for the essential part of the denim jacket, like body and sleeves, a maximum of 2 layers.
= Loom repeat at DD: The concept fits in the repeat from the loom at Diamond Denim without having to segment the concept design in multiple parts that were not designed in.

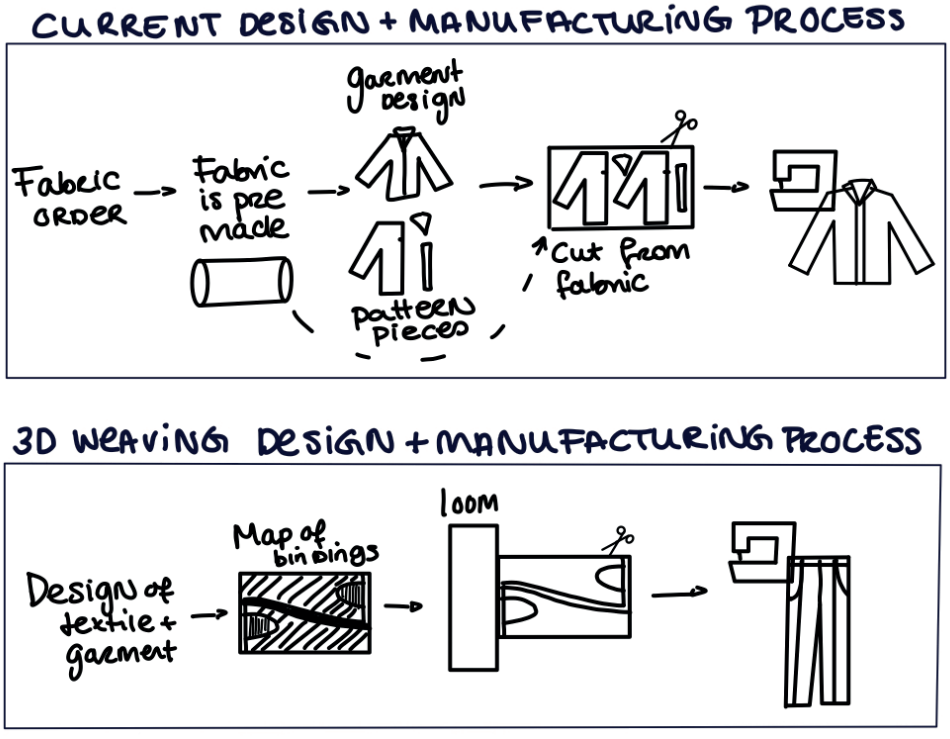


Figure 21.

Weaving parameters

Chosen loom at Diamond Denim to work with

Diamond denim has two kinds of jacquard looms at their disposal, see the table below. The loom named CONFIG-1 has a total fabric width of 144.27 cm and the loom named CONFIG-2 has a total width of 186 cm. Both machines have a different repeat size and setup. CONFIG-1 has one main repeat of 59.5 cm in the middle of the fabric and two partial repeats on left and right. CONFIG-2 has a setup of five complete repeats of 36.6 cm. Another worth mentioning difference between the two machines is their density of the warp, expressed in ends/cm. CONFIG-1 has a warp density of 40.31 ends/cm and CONFIG-2 has a warp density of 70.2 ends/cm. Both machines can have four weft colours inserted per weft insertion (who do not have to be a different colour). This does mean that the maximum layers possible would be four layers. Most of the other data in table x was used by Milou Voorwinden to program the weaving files in NetGraphics.
For this project the ideal jacquard loom would have no repeat, it was decided to work with the machine with the largest length without a repeat, CONFIG-1, to give as much design freedom as possible.

Information table provided by Diamond Denim about their jacquard looms	CONFIG-1	CONFIG-2
Total design hooks	2400	2560
Ends/cm	40.31	70.2
Total fabric width in cm	144.27 (42.385-59.5-42.385)	186 (36.6-36.6-36.6-36.6-36.6)
Repeat	2400 Ends	2560 Ends
Repeat in cm	59.5	36.6
Kind of repeat	One main repeat in the centre and two partial repeats on left and right	Five complete repeats
Warp count	From Ne 10 to Ne 80	From Ne 10 to Ne 80

Weft and warp density

CONFIG-1, from now referred to as just ‘loom’, has a warp density of 40.31 ends/cm. This means that if a weave structure is divided into four separate layers each layer has a fractional warp density of only around 10 ends/cm. The weft density was set in consultation with Diamond Denim and Milou on 50 picks/cm. The same calculation applies here, so if a part of the weave structure is divided into four separate layers, each layer then has a fractional weft density of around 12.5 picks/cm.
Because a layer that has 10 ends/cm in the warp and 12.5 picks/cm in the weft is quite low in density this is not desirable for the main parts of the denim jacket. So the premise for this project was to design the main structure of the denim jacket in no more than 2 layers. Each layer then has around 20 ends/cm in the warp and 25 picks/cm in the weft.

Weft and warp yarn

As discussed in chapter 2 the production of cotton is quite harmful for our environment. Therefore a weft yarn with a more sustainable composition was decided on. The preference would be to use a yarn made partially of hemp and or has recycled cotton yarns incorporated. Diamond denim was asked what yarns concerning these wishes they could provide for the project. For the weft yarns it was decided to use a Ne 8 60%HA 40%CO yarn. For the warp yarn it was decided to make use of the indigo cotton warp they have available for the loom used for this project.

Criteria

Looking back at the last chapters it can be concluded that the rich history and a distinctive appearance of a denim jacket are shadowed by the negative aspects of production. The established criteria in this project make sure the good characteristics of a denim jacket are maintained while improving the polluting aspect of the production side of a denim jacket. This chapter brings together the criteria from the chapters above.

Requirements

- **Yield waste**:
  - The concept design, in the desired loom formation, where the loom has no repetition and no specified width, produces equal or less than 10% of the fabric yield of the overall layout of the concept;
  - The concept must contain equal or less sewing production steps of a current type 3 denim jacket, without losing too much of the characteristics (see other criteria) of a type 3 denim jacket;

- **Sewing steps:**
  - To limit the required garment sewing steps after cutting the garment;
  - To limit garment finishing;

- **Sewing complexity:**
  - The sewing construction of the jacket should not be more complicated than a current cut & sew denim jacket (this costs time and time is money);

- **Durability:**
  - The seams of the final concept must have an around equal tensile strength resistance compared to a cut & sew type 3 denim jacket seam construction;
  - The fabric of the final concept must have an around equal tensile strength resistance compared to a regular denim fabric cut & sew type 3 denim jacket;
  - Must be made of a warp faced twill weave structure, where the surface of the garment should look blue and the underside mostly white;

- The concept should contain the following **characteristics of a type 3 denim jacket**:
  - Boxy fit: The concept should contain a boxy fit around the body, so not to tight around the body;

- Sleeve connection: The concept should contain an angled and shaping connection of sleeves to body, characterised by the sleeve curving into the armpit;
- A collar;
- An inside pocket in (one of) the front body panels;
- Front placket that is dense to carry the metal buttons;
- Front of the body is longer than the back panel.

Wishes

- **Denim jacket construction:** The concept has an appearance in terms of construction like a cut and sew denim jacket. This could include the placement of seams on the bodice and sleeves. It is beneficial if the concept contains or can contain the following characteristics of a type 3 denim jacket:
  - Distinctive visuals difference between the sleeves and the cuffs;
  - Distinctive visual difference between the body panels and the waistband;
  - Distinctive visual difference between the body panels and the front placket
  - Front and back yoke lines;
  - Decorative v shaped lines of front and back (characteristic for the type 3 denim jacket);

- **Yarn:** The yarn used in the prototypes have a lower impact to the environment than a full conventional cotton yarn, so use organic cotton or alternatives like hemp or tencel;

- **Fractional density:** To keep in mind the influence of the fractional density on the design to achieve a fabric look and feel resembling denim fabric. The wish is to, with a warp density of 40 ends/cm at the sampling machine at DD, make the maximum layers for the essential part of the denim jacket, like body and sleeves, a maximum of 2 layers;

- **Loom repeat at DD:** The concept fits in the repeat from the loom at Diamond Denim without having to segment the concept design in multiple parts that were not designed in;

- **Future design freedom:** Potential for future design freedom of the 3D woven denim jacket for future design work involving the concept created in this graduation project.

Figure 22. Garment woven jeans in indigo cotton by Kelly Konings.

9

Related work

Jacquard weaving is on the rise and many developments use these looms to combine the design of textile and form. Weffan developed 3D woven trousers made in one piece on a jacquard loom, turned inside out after being cut from the loom. Unspun developed, as a follow-up of their jeans that is produced on demand and based on a body scan, a topographical weaving machine that can 3D weave yarns into seamless woven pants tailored to individual buyers. Kelly Konings uses jacquard weaving to research new ways of designing and making denim garments and redefining the aesthetics and form of such garments. Jacqueline Lefferts and Linda Dekhla use jacquard weaving of the double-layered fabric, creating tubes, with synthetic yarns and or different weave structures to create a form in a fabric cloth. Stem uses jacquard weaving to weave the pattern pieces already on the loom. They eliminate off-cut waste by optimising the placement of the pattern pieces and a specific cutting technique. Leonie Buckhardt uses jacquard weaving to develop flat woven textile forms that can be folded into geometric shapes. Margiela and Andrew Bell designed garments that when laid flat fold into a two-dimensional shape. Issey Miyake in the A-POC collection developed a knitted tube of fabric that contains an entire outfit when cut loose by the wearer.

The examples shown in this chapter display a variety of approaches on how to look differently to the production of garments as we do now. Multiple usages of jacquard weaving and optimised machinery show great potential for a textile and form integrated industry that eliminates waste and pollution. The projects differ in their aim to either reproduce a familiar aesthetic with a different production technique or use these production techniques to research new aesthetics. What they have in common is that a change in production technique will influence the process and outcome.

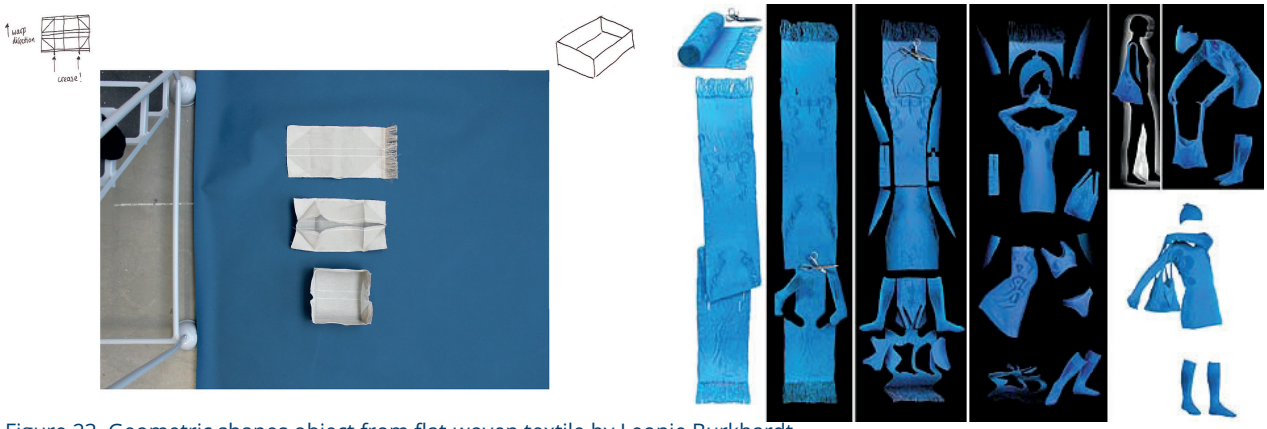


Figure 23. Geometric shapes object from flat-woven textile by Leonie Burkhardt.
Figure 24. Flat knitted tube from A-POC collection by Issey Miyake

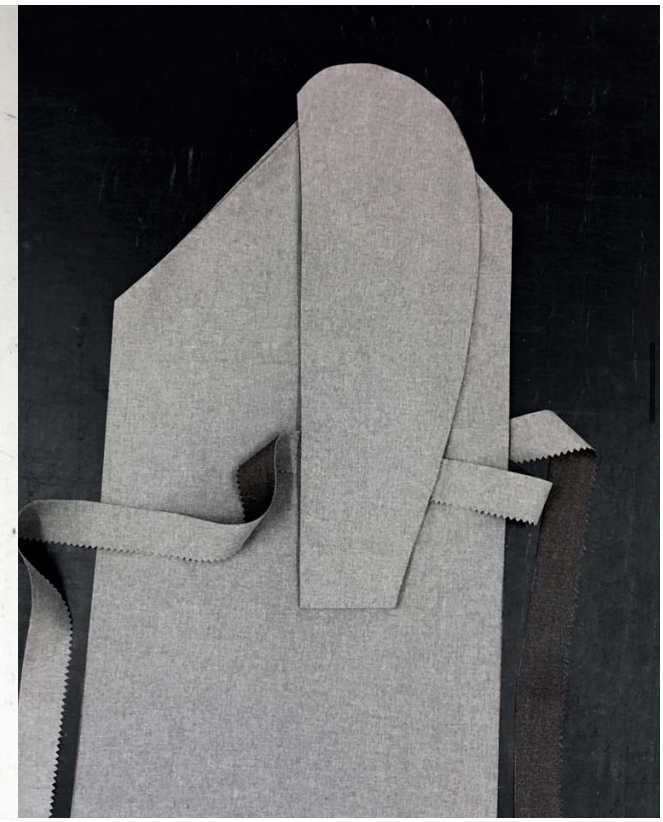



Figure 25. Maison Martin Margiela Blue Flat Jacket
Figure 26. Heat sealed coat by Andrew Bell . (Instagram @adrew_bell___)



Figure 27. and 28. Gestalt Process by Jacqueline Lefferts.
Figure 29. Dress by Linda Dekhla.

Figure 30. Seamless 3D woven pants made by a machine that 3-D-weaves yarn by Unspun.
Figure 31. 3D woven trousers by Weffan.

Figure 32. Jacket by Stem using Stem's zero-waste textile system.
Figure 33. Stem x Ganni zero waste jacket.

10

Methodology

This chapter discusses the methods used in this project that structured the research. The general outline of this project is the Double Diamond method from the British Design Council (2019). The phase of 'discover' was to explore the context of this project related to the denim industry, denim jacket and 3D weaving. These insights were defined in a set of criteria. From three developed concepts one direction was chosen using a weighted decision matrix. The chosen concept was developed into three directions for 3D weaving. This project was an iterative integrating methods as reflection on action and design research.

3D weaving as highlighted in the last chapter requires an approach of both textile and product design, as they are mostly produced simultaneously. The outcome of this project is therefore a trade-off in a framework of circularity (the potential of 3D weaving) - form (the desired form of a denim jacket) - and fabric (the desired fabric aesthetics if denim), see figure 34. This framework exists in the framework of product design that is a combined approach of designing for the industry, the user and of technology. McQuillan (2020)described designing in these frameworks as a multimorphic design approach: 'The lens needed when designing Textile-forms. In this approach, the design process considers multiple scales, time-frames, perspectives and contexts at the same time in order to develop holistic outcomes.'

The Research through Design approach (Stappers and Giaccardi, 2017) describes the activities of research and design as intertwined. The activities will inform and influence each other during the process of the project. In this project many prototypes are made to help understand and interpret the new knowledge gained. During the process reflection on the made prototypes is used to create new knowledge and understanding. This is also called reflection-on-action which is part of 'reflective practice' by Schön (1953).

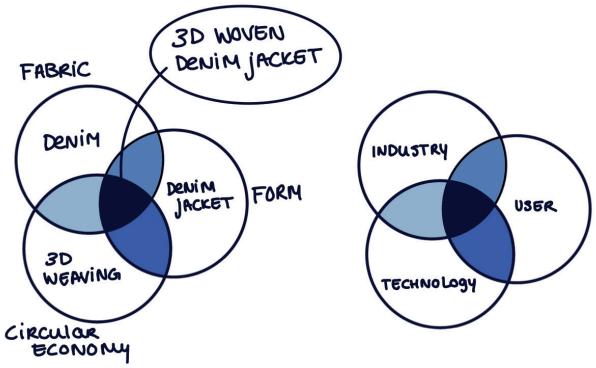


Figure 34. Frameworks to illustrate the trade-off approaches of this projcect.

11

Concept development

Introduction

This chapter guides the reader through the process towards three form development concepts for a 3D woven denim jacket. First, the design methods used for the executed experiments are explained. From these experiments, three concepts were developed which will be displayed using illustrations of the upleading design iterations. The chapter about concept development is concluded with a concept choice using a weighted decision matrix.
The size base used for the experiments in CLo3D can be found in Appendix D.

Design methods

Flattening of a constructed denim jacket

The first experiments aimed to explore how a constructed denim jacket could be flattened while keeping it (partly) fully constructed. By keeping it as much constructed as possible the shape would need fewer construction steps to manufacture the 3D woven denim jacket. Flattening means taking the 3D shape and flattening it into a 2D formation. These experiments were done to be inspired to create prototype ideas on how a 3D woven denim jacket could be constructed. These experiments also helped to understand the shaping and pattern construction of an exciting type 3 model denim jacket.

Flattening with a constructed denim jacket

By playing around with a constructed denim jacket, multiple ways of flattening the jacket were found. The jacket was flattened by laying it on a flat surface and trying out different ways to make a flat packet out of the whole jacket. Some experiments considered the jacket as a whole and other experiments took on half a jacket, of which the centre back seams would need sewing. Considering the jacket as two halves gave more freedom to the experiments in playing around with different formations. By flattening only half a jacket, fewer layers were also created as a result overall. During this process, the maximum amount of stacked layers that the formation created was taken into account. Therefore formations with a maximum of 4 layers were explored. These first explorations of flattening a denim jacket were done with the idea in mind that the jacket should be made up of as few components as possible, which correlates with fewer construction steps after weaving.
In most experiments, the collar was not taken into account because this made the process of flattening the jacket more complicated. The collar could be woven separately and make up for some extra construction steps. In the layout of the pieces, the collar was found to be a piece that could also fill up areas that would otherwise be wasted.

From some flattened shapes that looked potential, a paper model was made. To help understand the layer distribution of the folded construction, it helped to make a drawing overlay of the paper model, see the images above. The number in the drawing stands for how many layers that section is.

Flattening inspired by pattern-cutting inspiration

Pinterest and pattern-cutting books were used to gather inspiration about inspiring methods to pattern draw a jacket or similar garments. These methods brought inspiration on how to flatten the constructed denim jacket and/or on how from a pattern-cutting perspective the jacket could be constructed. Paper prototypes were created from this inspiration to understand and experiment with the folded concept. To create these paper models, a small version of a conventional Type 3 denim jacket pattern was printed. This pattern could then be traced and puzzled around into new patterns. While experimenting the loom repeat width was also taken already into account by trying out some layout puzzles with the paper prototypes.

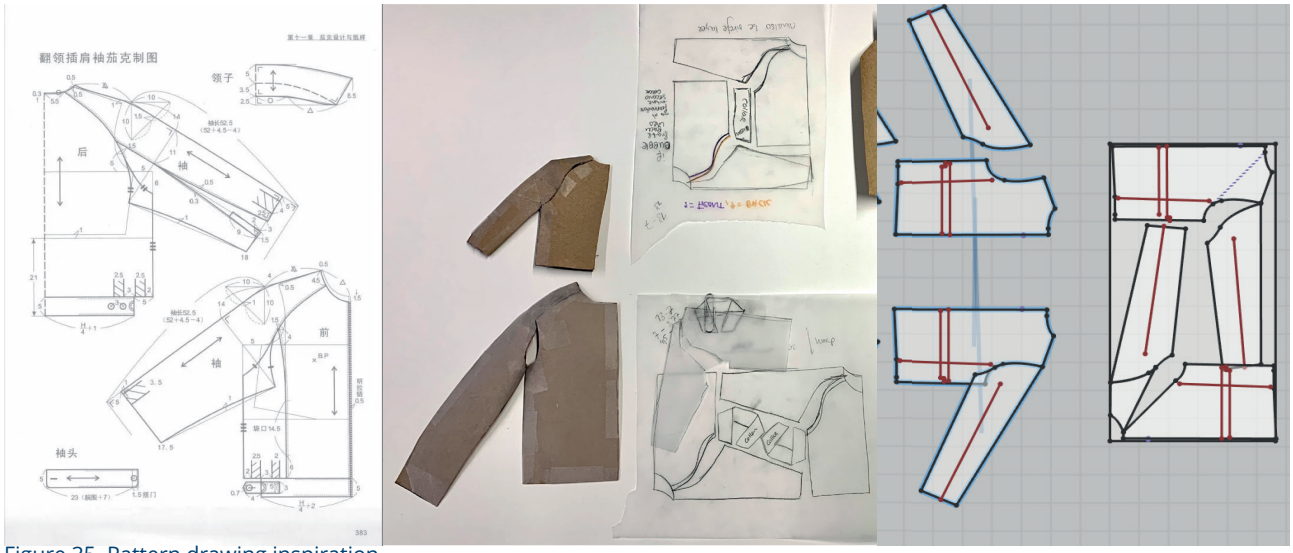


Figure 35. Pattern drawing inspiration found on Pinterest.

Insight: it is recommended to include seam allowance right away during prototyping.

Observations

From this way of experimenting with a constructed denim jacket and pattern drawings rose the understanding of the form of a denim jacket. One important observation for the progress of the project was about the construction of the armpit, the bottom of the armhole, where the tube of the sleeve is attached to the body tube. The armpit area could not be flattened without compromising the actual shape of that seam, which could translate into a less inward-curving arm seam that will affect the overall fit of the jacket.

Another observation that was important to the overall fit of a denim jacket was the angles of the shoulder and the sleeve. The shoulder seams in most denim jackets observed are drawn under a slight angle from the centre front, which gives a more fitted jacket at the shoulders because the shoulders of a human body are also slightly slanted. The sleeves in most denim jackets (patterns) observed are made under a slightly steeper angle down from the shoulder seam.
Looking deeper into the construction of sleeves to body panels, there are some variable aspects: the angles of the shoulders and sleeves and the curve of the seams of the armhole on the body and sleeve panels. Figure x gives an overview of these variables.
To achieve the desired fit of a denim jacket it was decided to take these shoulder and sleeve angles into account in further development of the 3d woven denim jacket design. It was also decided that the goal for the 3d woven denim jacket concept is to achieve a curved sleeve-to-body panel construction.

Development of the concepts

To further develop the concepts and be able to translate them into sewable concepts paper and/ or digital pattern pieces were developed. Sometimes working digitally in Clo3D gave more flexibility for playing around with changing and corresponding lines and their length. The developed digital prototype in the experiment was exported to Adobe Illustrator to make a printable pattern. The (printed) paper pattern pieces were cut from a denim (no stretch) cloth.

Development of the sewn prototypes

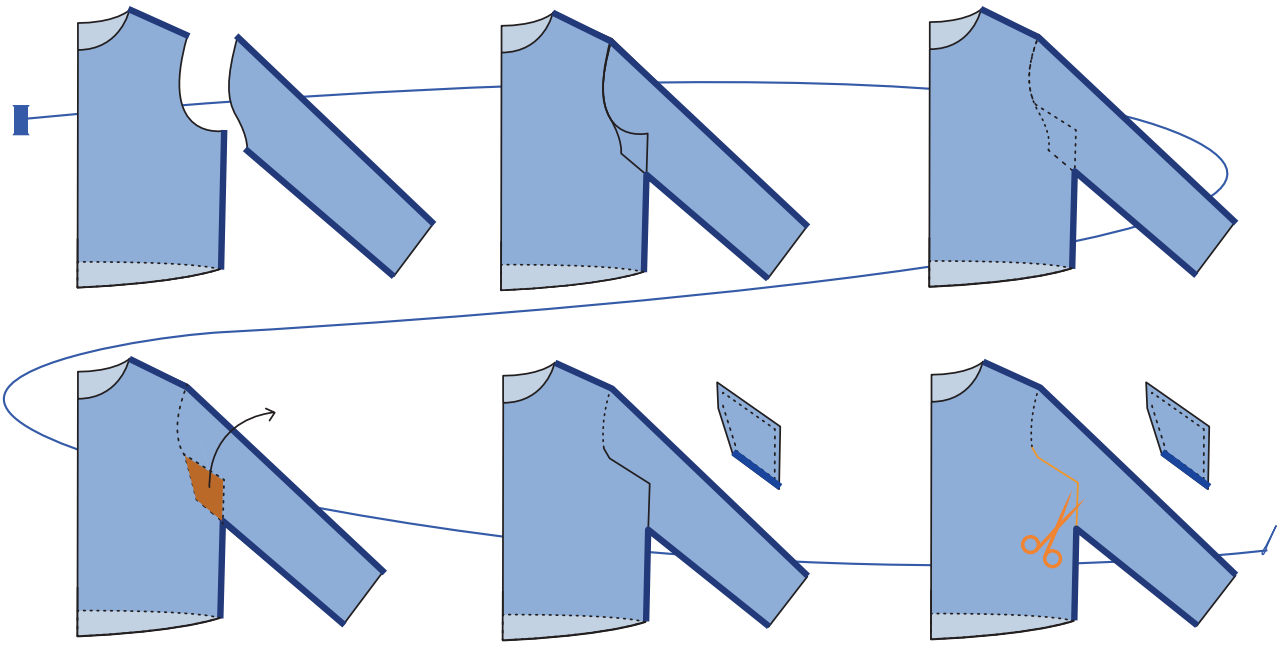
In prototyping, an attempt was made to construct the sewn prototypes of the three concepts in such a way as to mimic their woven structure as closely as possible. This was done by sewing the two-layer cut-out fabric pattern pieces together at the places where the fabric sample was supposed to represent a one-layer weave structure.

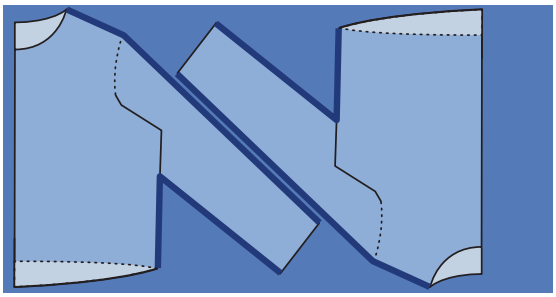
Insight: It was decided for all concepts to leave the woven seams, a result of 3d weaving, visible on the outside of the denim jacket prototypes. Having the seams on the outside embraces the 3D weaving technology which can help convey the message about the 3D woven denim jackets.

Concepts

Three concepts emerged from various experiments of figuring out a new flattened shape for the 3D woven denim jacket. The concepts were chosen based on their potential to match the set criteria. Each concept will first be discussed in terms of the concept idea and how the concept emerged from the experiments conducted. To test the fit and appearance of the concept a sewn prototype was created. Each concept is concluded with a reflection. This concept development chapter concludes with a concept selection based on a weighted decision matrix.
The complete overview of the experiments leading to the concepts can be found in Appendix E.

2 layers (1/2) | 1 layer (12) | 1 layer seam (12)





Concept 1

Concept idea

Concept 1 is a result of multiple experiments that can be viewed in Appendix E. The development behind this concept is visualised on page 64 The concept is based on the idea of keeping the full body and the sleeves connected while separating them into two parts. The pattern of this concept needs to be cut into to separate the sleeve a bit from the body in the armpit. The armhole area will be closed with a separate cut gusset. The two halves of the jacket make a rectangle by laying the upper arm seams alongside each other which fit in the width of the repeat of 59,5 cm at Diamond Denim.
Due to the shrinkage of the fabric after finishing this concept should be woven in multiple parts to achieve the set size or it can be decided to weave a smaller size sample.

Fabric sample

Pattern cutting

The pattern pieces, half jacket and the gusset, are cut out of the fabric two times. The part of the back neck where the two cut layers of fabric resemble one woven layer is cut loose from the front body and attached to the back by sewing all around.

Sewing steps

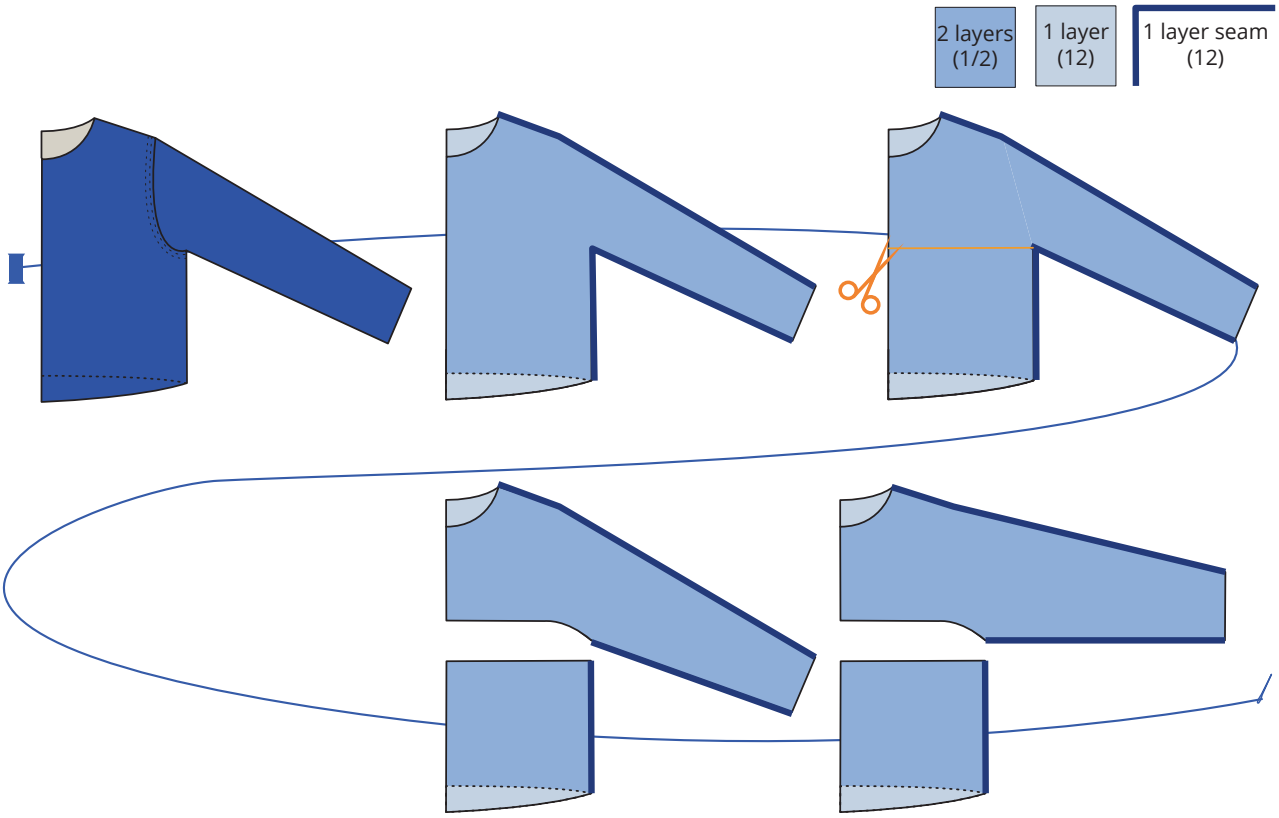
The first step is to sew the envisioned 3D woven seams that run on the side of the body panel, from the shoulder to the cuff opening, the underside of the sleeve and the underside of the gusset. In figure x these woven seams are indicated with a blue line. For the construction of the gusset into the body sewing started from the underarm seam, going up to the point. Then down to the armpit and to the back of the body. The gusset can be sewn in in one go all around following the gusset.

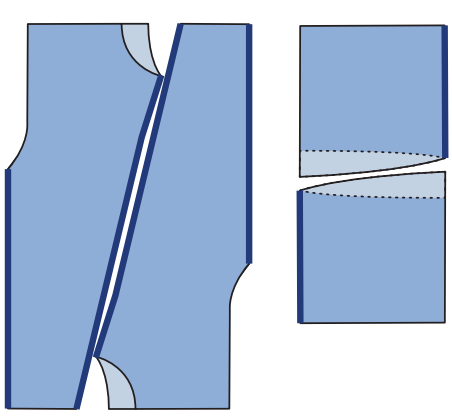
Result/reflection

The construction of the inserts presented some difficulties. The top corner was difficult to sew in due to the pointed angle and the small seam allowance in the corner on the main body. In the armpit area, the seams on the bodice and the inset edge gave difficulties with construction. The pattern of the gusset had a centimetre too long where it was supposed to match the sleeve hole, which is why the construction looks crazy there.
The fit of the sample was fine and the gusset did not create annoying seams. The gusset also does not disrupt the appearance in this fabric sample that much in the researchers opinion. The gusset does give an appearance that differs from the appearance of a conventional denim jacket. One could argue that the seams over the shoulder and upper arm look like a splitting of the body through the middle.
A downside to this concept is that to fit the loom at Diamond Denim and be the right size, the jacket would need to be cut into two pieces, probably on the sleeve. The two parts would need to be sewn together after weaving, which would influence the overall appearance.

This way of replicating the woven structure with a layered stitched version works well to test the fit and construction. The impact of fractional density on the appearance is less visual with a sewn sample, but an idea can be formed by the quilted sections

Insights: the woven seam will need to be sewn down when sewn to other pieces.


2 layers
(1/2)
1 layer
(12)
1 layer seam
(12)



Concept 2

Concept idea

Concept 2 is a result of multiple experiments that can be found in Appendix E. The development behind this concept is visualised on page 66. Concept 2 is based on cutting a constructed denim jacket open from armpit to armpit. The concept of separating the top of the body and sleeves from the bottom of the body from armpit to armpit, gave space for the arm seam to lay flat.

Fabric sample

Pattern cutting

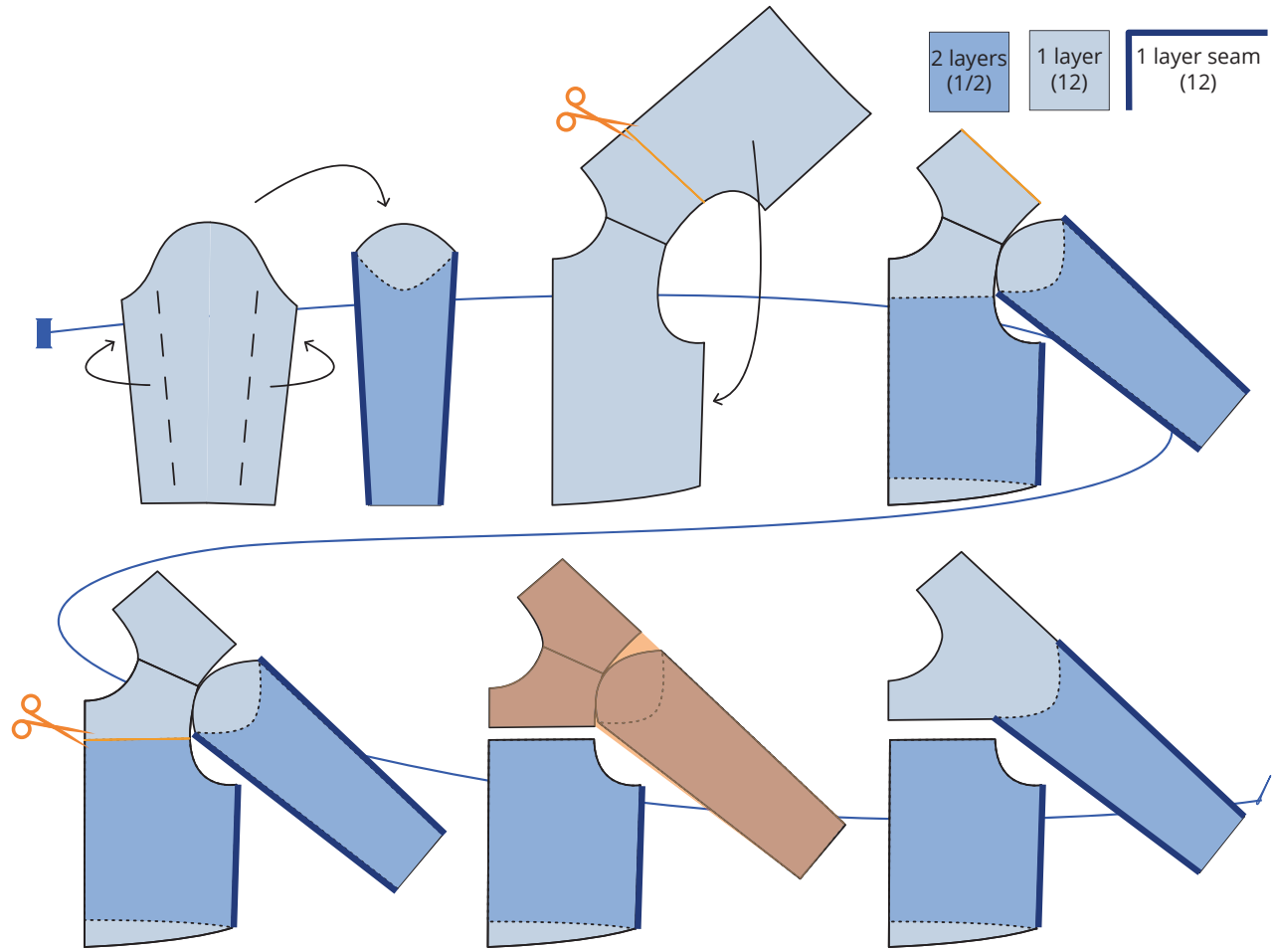
This pattern was constructed by copying parts of an existing denim jacket. Both the sleeve and shoulder part and the bottom body part are cut out two times from the fabric.

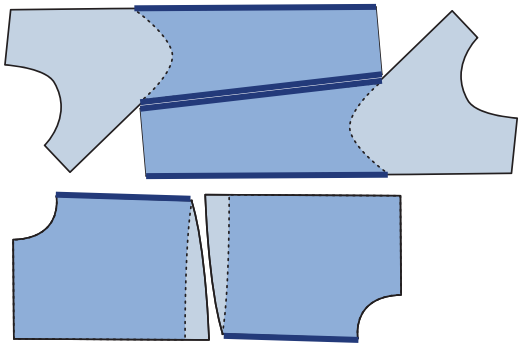
Sewing steps

The first step is to sew the envisioned 3d woven seams. These three seams are the shoulder and upper arm seam, the lower arm seam and the side seam of the body panels. For the construction the top and bottom of the jacket are pinned together connecting first the centre front, centre back and side seam of the body to the underarm seam. The seam is sewn starting from the centre front following the seam to the underarm and to the centre back.

Result/reflection

This construction gives less shaping in the armpit area than expected, probably due to the separation of the top and body in this way, part of the roundness of the armhole seam is lost. And as a result, this construction does not bring enough roundness to the armhole seam. As shown in the photos, the sample creates fabric folds in the transition from body to arm at the front and back. This could mean that there is too much fabric in that area because, in the pattern, the front and back yoke are joined to the sleeves by merging the pattern pieces together. This joining changes the original pattern shape, making the fit around the armhole less tight. The great aspect of this concept is that the sewing lines simultaneously create the front and back yoke lines in the body. In the pattern on which this fabric example is based, the shoulder and upper arm seams were flattened with the idea that the pattern piece would give a more efficient shape to create a layout with limited cutting waste. But this resulted in a jacket with a very straight sleeve-shoulder line, eliminating the visual difference between the shoulder seam and arm seam. One could argue, as in concept 1, that the seams over the shoulder and upper arm look like a splitting of the body through the middle.


2 layers
(1/2)
1 layer
(12)
1 layer seam
(12)



Concept 3

Concept idea

Concept 3 was created during experiment 10 that can be found in Appendix E. The development behind this concept is visualised on page 68. This concept consists of the sleeves with front and back yokes attached to it and the rest of the body panel, front and back woven together at the side seam.
The sleeve top and bottom are woven together at the sides that overflow in the front and back yoke edge. The layout of this concept could be the sleeve part fitting together and the body pieces laying in the length of those.

Fabric sample

Pattern cutting

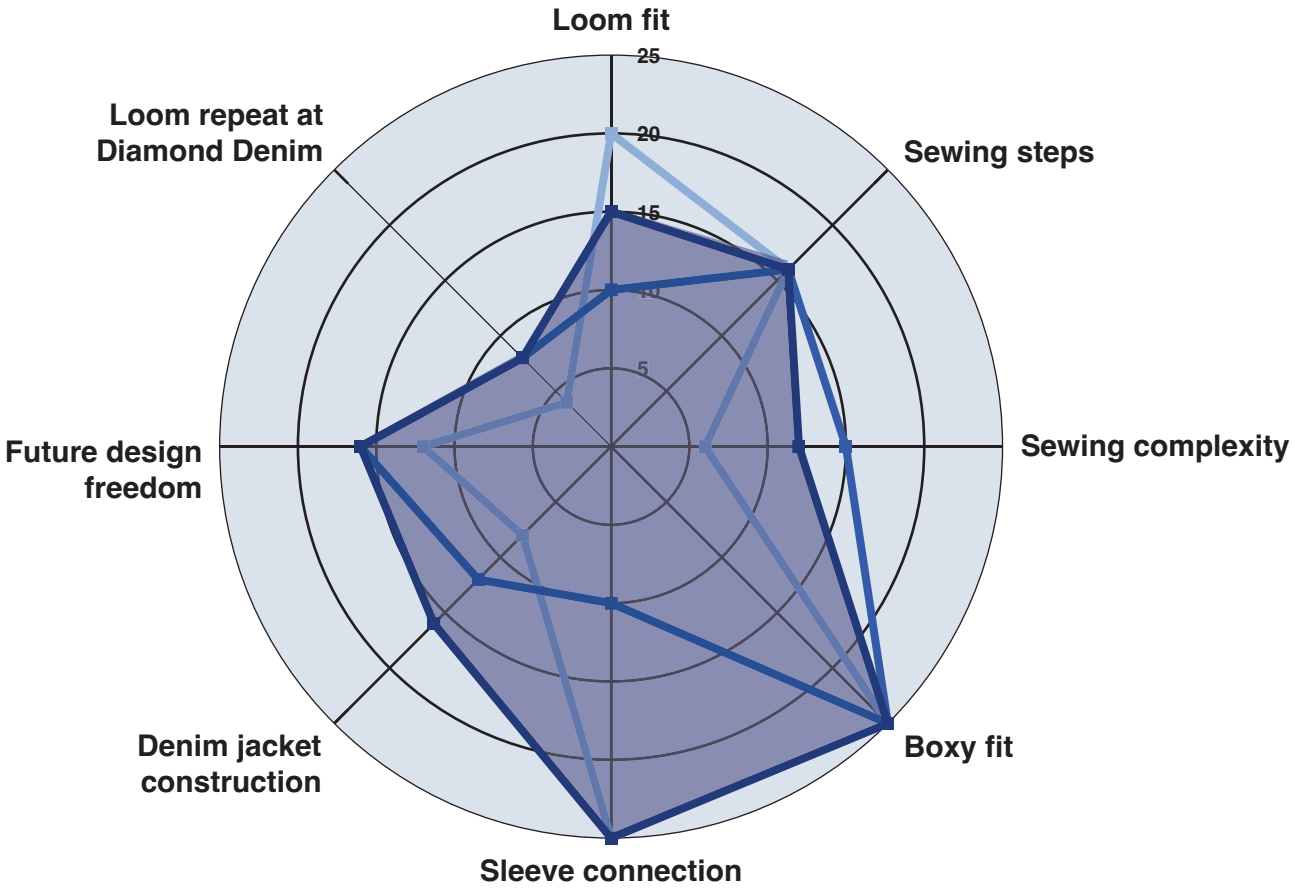
Both the pattern pieces were cut out double from the fabric. The back part of the sleeve pattern will be cut into two pieces along the line of the underarm seam. The front and back yoke part consist of one layer in the envisioned 3d woven sample, so the two layers of fabric are sewn together all the way around.

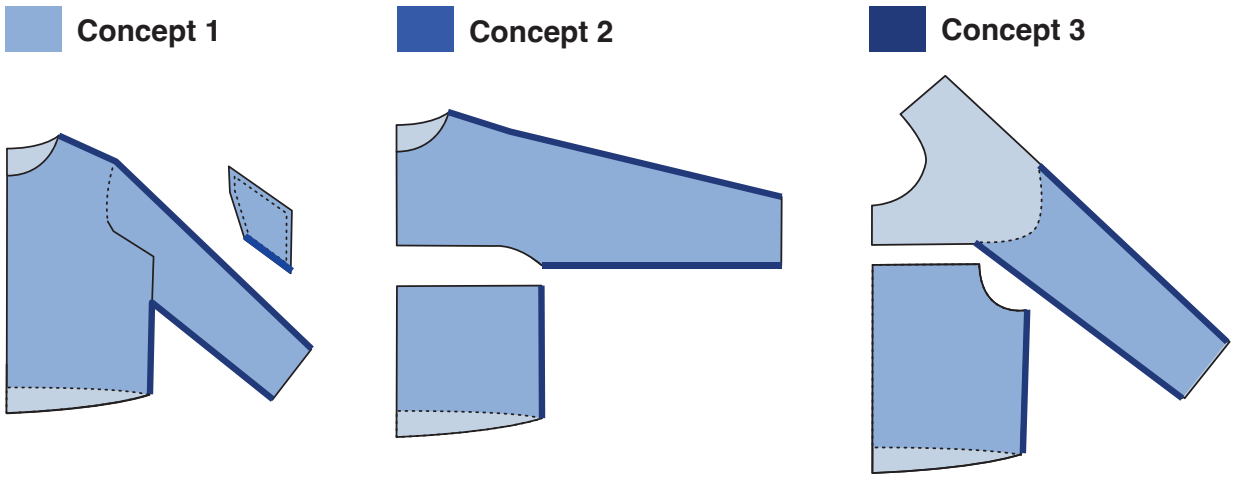
Sewing steps

The first step is to sew the envisioned 3d woven seams. The side seam of the body panels and the underarm seams to the top sleeve part. The construction of the body to the sleeve panel starts by pinning the centre front of the body and the sleeve panel good sides together. Following the pattern the whole front yoke can be pinned. At the part where the seam of the sleeve starts the underarm seam is folded open. To connect the underarm of the body to the underarm seam of the body it will be needed to fold down the side arm seam. Then you can pin the underarm parts together and at the back side seam the same principle needs to be applied. Then the back yokes can be pinned together. After pinning the two parts can be sewn together.

Result/reflection

In this sewn version of concept three the part where the front yoke turns into the armpit seam bulges. Some work on the pattern is needed in that place to make the construction in that area correct. The construction of the panels gives a good shape to the armhole and the sleeves angles down naturally as a result. The construction was not that difficult to sew after figuring out how to unfold the underarm edge separate from the rest of the top body. When sewing the bodice to the under arm edge the sleeve seams will need to be folded flat into the seam. The great aspect of this concept is that the sewing lines simultaneously create the front and back yoke lines in the body. Another great aspect relative to the other concepts is this concept does not divide the body in two over the shoulder and arm seam. The woven seam on the back of the sleeve even corresponds with the construction of a cut and sewn denim jacket.


Loom fit
25
20
15
10
5
Sewing steps
Sewing complexity
Boxy fit
Sleeve connection
Denim jacket construction
Future design freedom
Loom repeat at Diamond Denim


Concept 1
Concept 2
Concept 3

Concept choice

A weighted decision matrix was used to decide with which concept to continue. The following selection of criteria were used in the weighted decision matrix, which can be found in Appendix F. The criteria are weighted on importance on a scale of 1 (not so important) to 5 (very important). Note that some requirements were adjusted or left out to fit this step in the design process better. The concept will be assessed on the requirements and wishes on a scale from 1(not qualified) to 5 (very qualified).

Criteria

Requirements

- Yield waste: The concept design, in the desired loom formation, where the loom has no repetition and no specified width, has a potential to produce equal or less than 10% of the fabric yield of the overall layout of the concept.
- Sewing steps: The concept must contain equal or less sewing production steps of a current type 3 denim jacket. On a scale of 1 is equal sewing steps to 5 is one to no sewing lines.
- Sewing complexity: The sewing construction of the jacket should not be more complicated than a current cut & sew denim jacket (this costs time and time is money).
- Boxy fit: The concept should contain a boxy fit around the body, so not to tight around the body;
- Sleeve connection: The concept should contain an angled and shaping connection of sleeves to body, characterised by the sleeve curving into the armpit;

Wishes

- Denim jacket construction: The concept has an appearance in terms of construction like a cut and sew denim jacket. This could include the placement of seams on the bodice and sleeves.
- Future design freedom: Potential for future design freedom of the 3D woven denim jacket for future design work involving the concept created in this graduation project.
- Loom repeat at DD: The concept fits in the repeat from the loom at Diamond Denim without having to segment the concept design in multiple parts that were not designed in.

Results

Based on the total weighted rating of the concepts in the weighted decision matrix concept 3 is the best choice to continue the project with. Concerning the criteria of sewing steps and the boxy fit, the three concepts carry the same score. Concept 3 scored best overall in the weighted criteria matrix as can be seen from the colored overlay covering the largest surface. The difference was mainly made on criteria like sleeve connection and denim jacket construction. The pattern of concept 3 does need some adjustments to the pattern which will be discussed in the following subchapter. The aspects of loom fit and loom fit at Diamond Denim were still being estimated at this stage of the project. During further developments it will be explored how the pattern panels of concept 3 can best be fitted inside the looms and if these layouts create minimal off-cut waste.

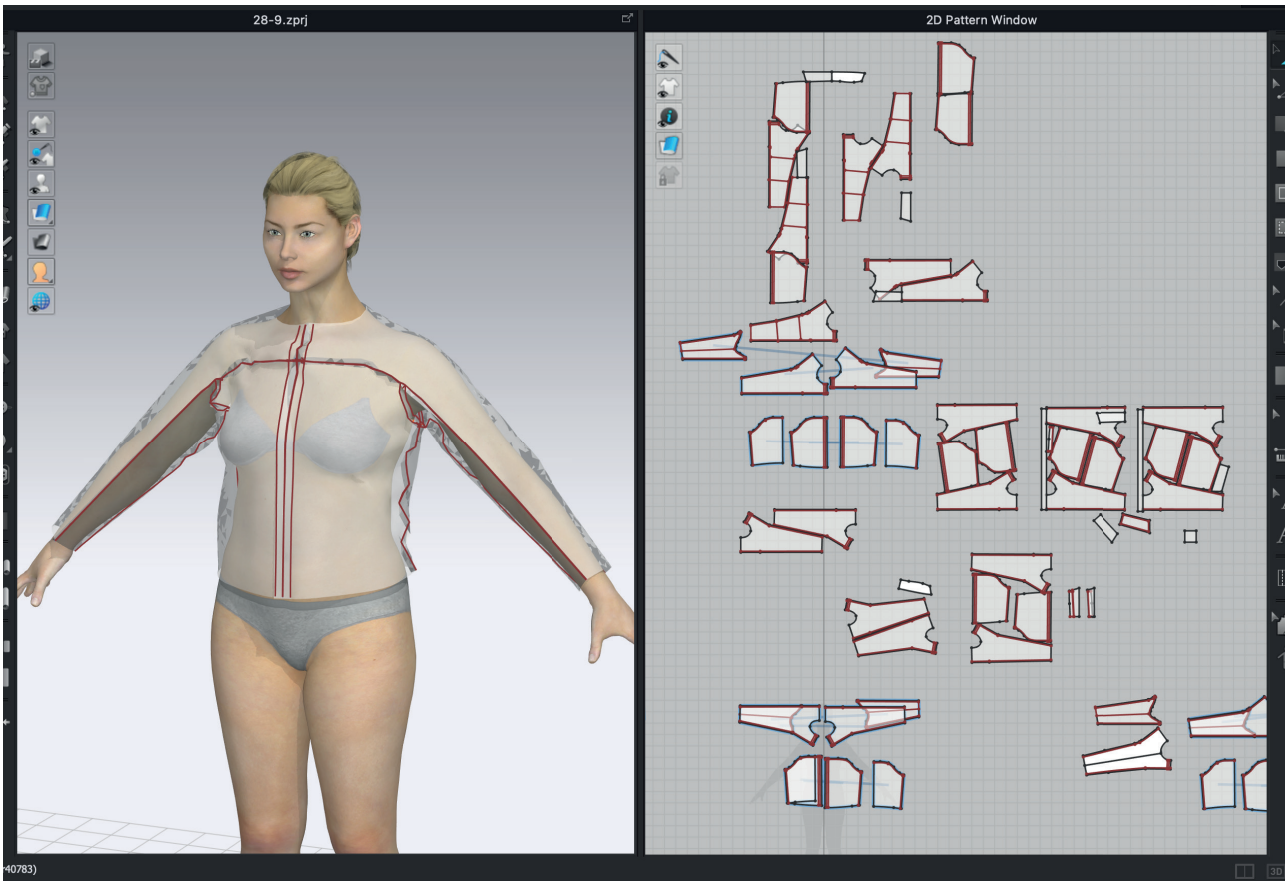
Shape optimization concept 3

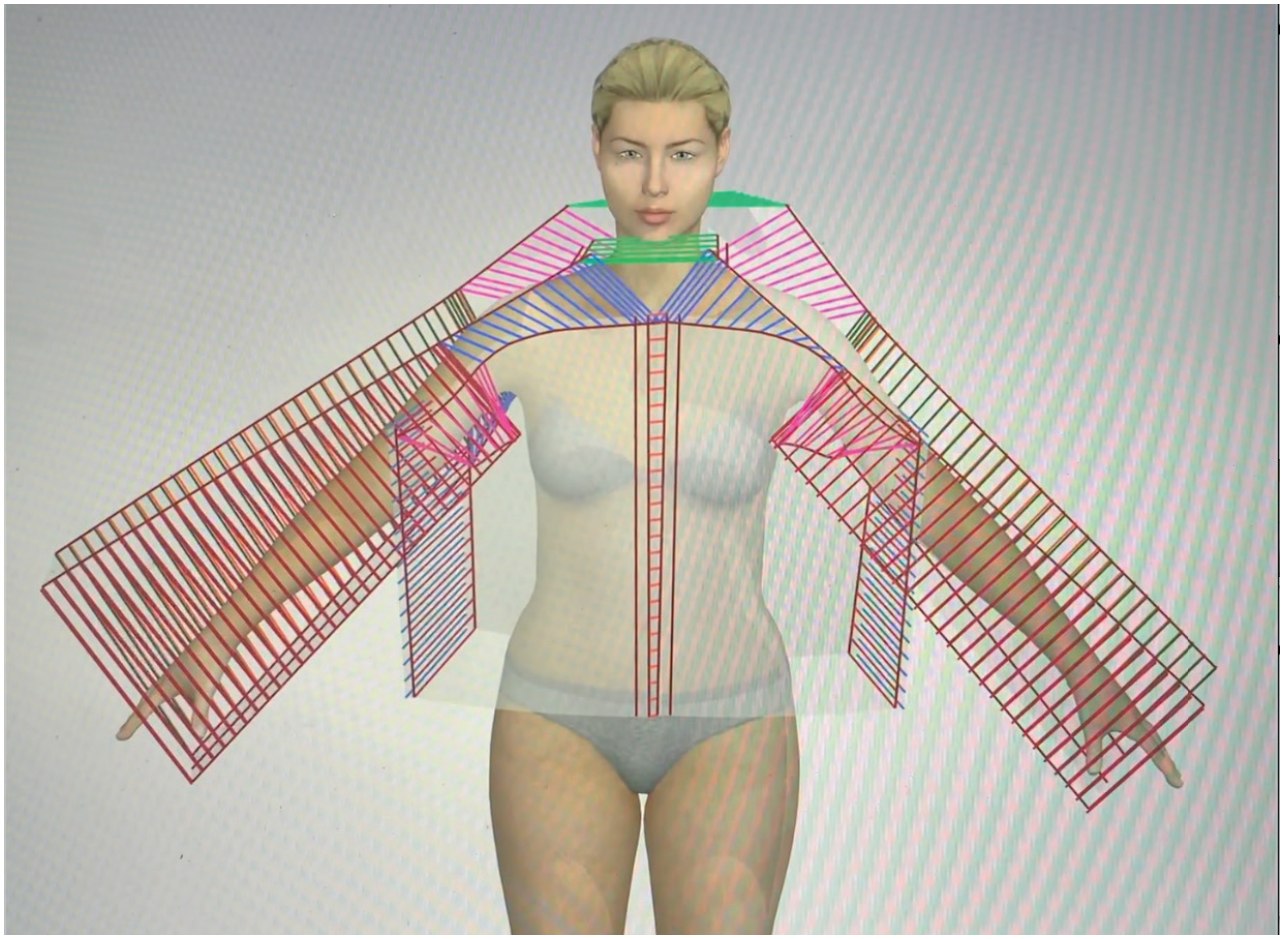
The development of the final pattern of the 3D denim jacket of concept 3 started with improving the paper pattern used for the sewn prototype. The pattern was improved in several iteration steps using paper models, sewn prototypes and digital prototypes.
The first step was to improve the connection between the body and shoulder and sleeve sections. It was a process that involved curving the top of the body part. The images in figure x show the highlights of the iterative steps of this prototyping to arrive at the correct pattern shape.

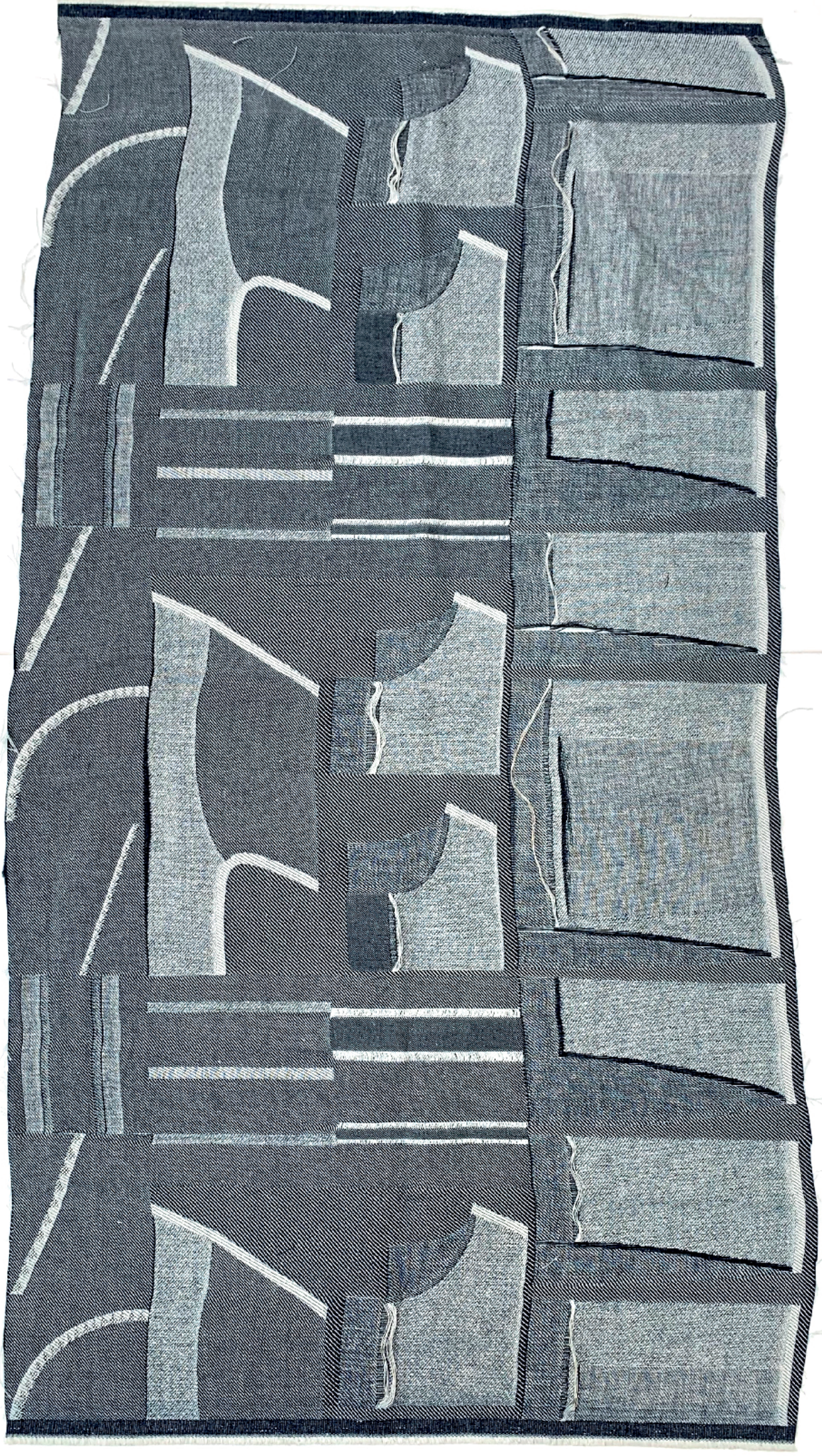
The modified pattern parts were translated into a digital prototype in Clo3D by tracing a photo of the pattern. Some fine-tuning was done in Clo3D to ensure, for example, that all sewing lines are the same length. To maximise the puzzle factor for the layout in the loom of this concept, one of the sides of the top body part was made straight. The back yoke and back arm sleeve are then in line with each other, see figure x.

Conclusion

To come to the three presented concepts was a process of experimentation using different methods. The basis of the experiments was the analysis of how a constructed denim jacket can be flattened while retaining the fit. Flattening was practised by folding and cutting into a constructed denim jacket and by looking at flat pattern drawing inspiration sources. Models were made using paper and Clo3D to understand the folding mechanism and the construction of the experiments. The development process of the three concepts was an iterative and intertwined experimental process that was guided by a few restrictive criteria, like the construction of the armhole, the size of the loom repeat and a maximum of two layers for the weaving structures.
The three concepts share the same amount of required sewing steps and all have a boxy fit. While the scores on the weighted decision matrix do not differ that much, concept 3 took the highest score with a difference of around 20 points. The difference was mainly made on criteria like sleeve connection and denim jacket construction. The pattern of concept 3 does need some adjustments to the pattern and the aspects of loom fit and loom fit at Diamond Denim will need further development.


28-9.zprj
2D Pattern Window





12

Weave experiments

Introduction

Before weaving the prototypes of the selected concept, Diamond denim provided the opportunity to first weave some trial samples. Two batches of samples were created in this first weaving opportunity. The first samples were used to experiment with multiple layer textile forms and how to achieve the right denim like aesthetic. The second samples were used to try out different weave and form construction related to the appearances of some ideas for the 3D woven denim jacket concepts.
The weave set up at the loom was an indigo cotton warp and four white hemp/cotton weft yarns.

Weave experiment 1

Aim

To weave samples of multiple layer construction to examine the fractional density. And to weave samples to explore how to recreate a denim look by weaving different weave structure compositions. These samples will also be used to test the elongation and tensile strength (N) of the different woven seam constructions.

Set up and observations

In the section in figure x 4 rows of samples can be seen. The first row, from the bottom up, holds three tests for four layer weave structures with two diagonal seams in the middle. The second row holds three tests for three layer weave structures with two diagonal seams in the middle. The third row holds three tests for two layer weave structures with two diagonal seams in the middle. The top row consists of a two layer structure with different one layer seam constructions. The three weave structures in the same row differ in the kind of weave structure.These weaeve experiments were set up together with Milou Voorwinden, weaving designer and technician.

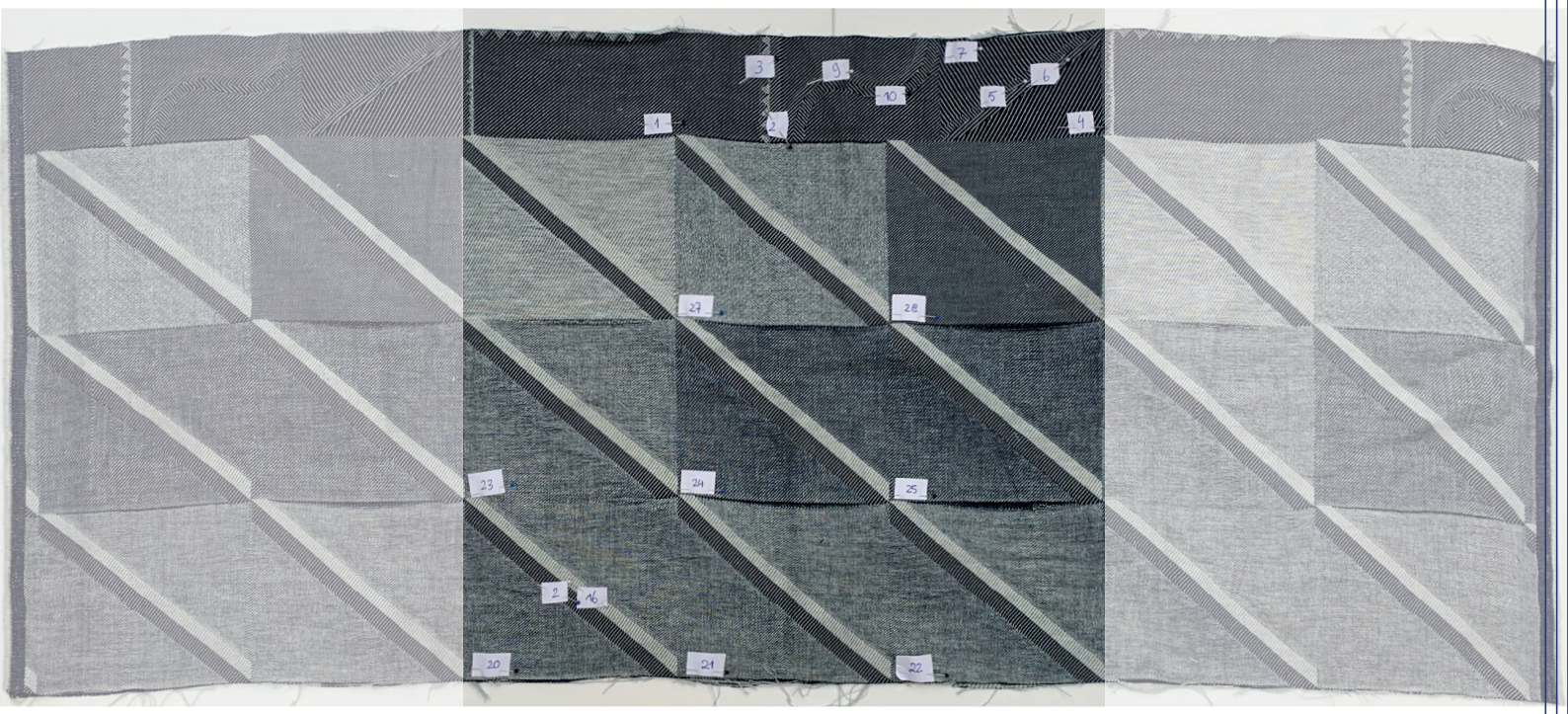
Fractional density

In this section, only the observations that were taken along in this project will be discussed. The extended version of this experiment can be found in appendix x.
The four-layer weave structures, structures 20, 21 and 22, were as expected very thin because the fractional density of the warp was only about 10 yarns/cm. This density was not preferable to continue with for the main construction of the denim jacket form because it would not match the desired fabric density.

The three-layer weave structures, structure 23, 24 and 25, were made as a four construction but the middle two layers are woven together. Therefore the outer layers were very thin because the fractional density of the warp was only about 10 yarns/cm. And the middle layer was, with a fractional density of about 20 yarns/cm, a fine density to work with. This deviation of the layers into three layers of which two are very thin was not a weave structure the project will continue working with.
The two-layer weave structures, structures 26, 27, 28 and a part of the top layer have a fractional density of the warp of about 20 yarns/cm. The jacket is expected to feel a bit lightweight. For the concept of this project and being able to make a 3D woven textile form this is the minimum needed.

Denim appearance

The different appearances programmed for these three four-layer weave structures were not visible. The appearance of the weave structure is very white and visually not a lot like denim.
In the second row with the three-layer weave structures more visible difference can be seen between the three samples. As can be seen in the detailed picture of those samples, figure x, the visual appearance differs between the layers. The top layers of samples 24 and 25 have a more blue appearance.
Between the two-layer weave structures, many visual differences between the samples can be seen. Sample 28 looks the most blue on the outside and has, just like conventional denim fabric, an underside that appears mostly white. But sample 28 also has a marine striped feel to it due to the visible white stripes. Sample 28 will be used as the start of the prototype weave samples.
That most samples look still very white is partly due to the ratio of the blue warp and the white weft yarns. In every cm, there are more white weft yarns relative to the blue warp yarns. In the prototyping samples, the four white yarns were changed into two white yarns and two blue-dyed yarns, to try to achieve a more denim appearance.



Weave experiment 2

Aim:

To try out different weaves and form construction related to the appearance of the 3D woven denim jacket.

Set up and observations

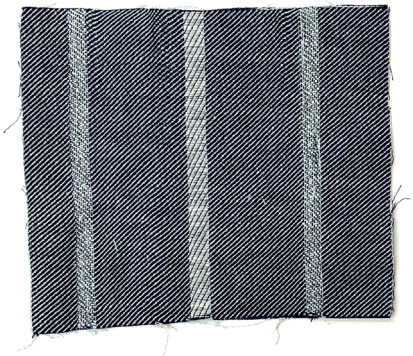
Weave experiment 2 is built up of many different samples testing out different weaves and form construction of some ideas for the 3D woven denim jacket.
The samples that represent a part of a denim jacket are woven under 90 degrees because at the moment of sending out these samples the prototypes were at the stage of experimentation with a 3D woven denim jacket form that would fit sideways in the width of the repeat, neckline to waistline.

Sample 3 tested the possibility to add decorative lines to mimic the felt seams on a conventional denim jacket. Samples 4 and 5 test two different ways to design a front placket that is denser than the two-layer structure of the front and back panels with a fractional density of 20 yarns/cm. Samples 7 and 8 use the front placket alterations from samples 4 and 5 and combine that with a test to make the front waistline longer than the back waistline. Sample 7 includes a trial for an inside waist pocket.

Idea

To try to create visual lines by applying an alternative weave structure. This effect could mimic the V-shaped lines on a Type 3 denim jacket. The idea was that one line would have a more angled twill weave, one line an s-twill (instead of the z-twill) and one line a weft twill weave that would appear white.

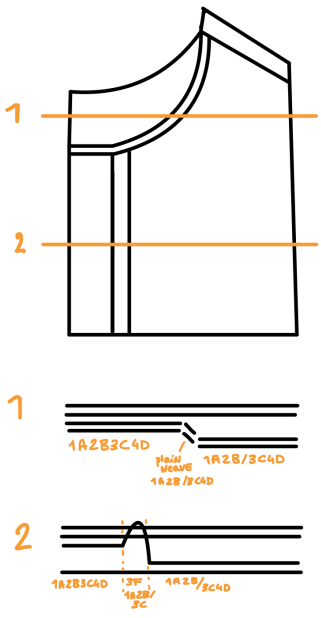
Sample 3



Reflection

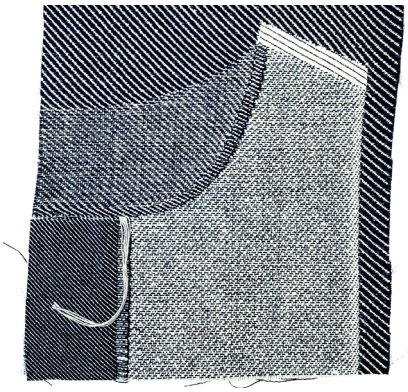
Due to some miscommunication the idea did not work as planned, so two lines were woven the same. But the idea of creating visual difference by switching the weave structure there works well.

Sample 4



Idea

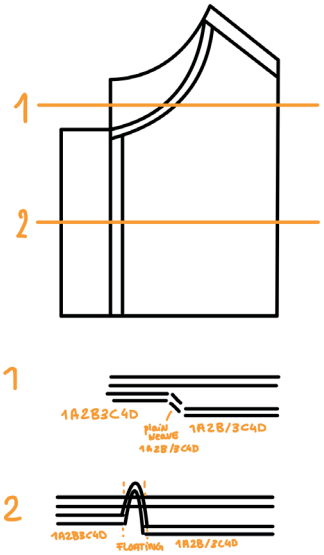
To try to make the front placket, the yellow-green part, denser than the bodice part (purple), which is a 2-layer weave structure. To make this work, one of the warp threads of the back piece will pass to the front layer to make it a three-layer structure and the centre back a one-layer weave structure. This example shows the neckline of a half jacket. The front neckline must be cut loose from the back to open up the bodice, held together by the blue seam of one layer. The yellow line is a plain weave to prevent the neckline from fraying after cutting.



Reflection

The change in fractional density for the front placket worked out. The float weave structure that should help to separate the front and back from each other did not work out, due to a wrong binding in that area.

Sample 5



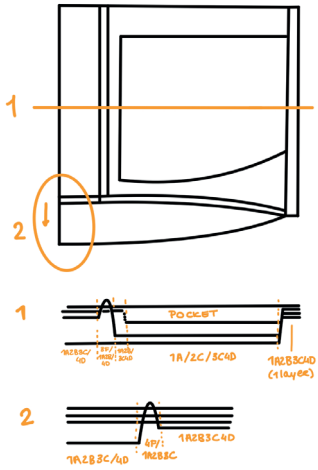
Idea

To try to make the front placket denser than the 2-layer fractional density of the bodice part (purple) by moving it separate from the back pattern. To help cut the front and back loose a float (black) was added. This example shows the neckline of a half jacket. The front neckline must be cut loose from the back to open up the bodice, held together by the blue seam of one layer. The yellow line is a twill weave, a heavier weave compared to a twill weave, to prevent the neckline from fraying after cutting.

Reflection

The float did not work and was also not so needed for the sample because the cutting area was accessible. ALthough the weave structure from the front placket is wrong (3 layers instead of 1) the idea has potential.

Sample 7

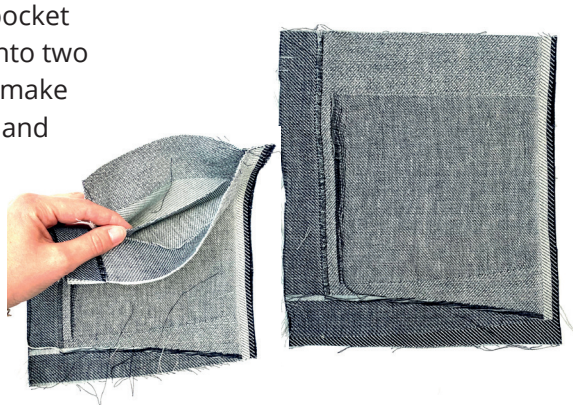


Idea

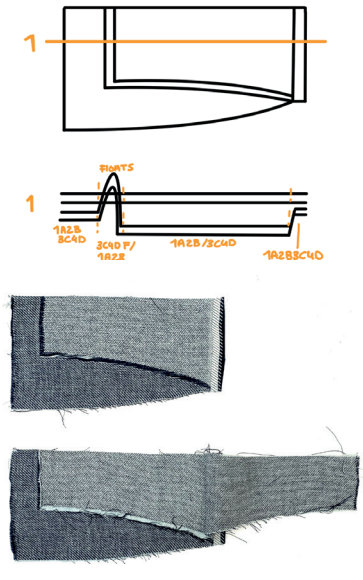
Test the idea of example 4 in combination with the idea of making the front waistline longer than the back waistline, see figure x. So the bottom of the front waistline will be denser than the rest of the front layer. In this sample a pocket is integrated in the front body panel, this pocket separates the front panel into two layers. Floats are added to make the separation of the front and back easier.

Reflection

In this sample, different warp and weft distributions were used for the different weave structures, making it unable to separate the layers. The inside pocket construction worked out well but the weave structure of 1 layer is very thin and fragile for a pocket.



Sample 8



Idea

Test the idea of example 5 in combination with the idea of making the front waistline longer than the back waistline. So the bottom of the front waistline will be denser than the rest of the front layer. Floats are added to make the separation of the front and back easier.

Reflection

Although the floats only worked in the line between the front placket and the body the sample demonstrated well the idea of cutting the back panel loose from the front body. The front placket is denser and the bottom of the front longer than the back.

Reflection
Due to time and communication problems, some weave structures turned out differently than planned. For example, some weave structures were intended to be a single-layer weave structure, but was woven as weave structure 24, which consists of three layers. Different warp and weft distributions were used for some weave structures in the same sample, so some samples could not be opened as intended. The weave structure in these samples also do not have the desired colour shade. The samples from weave experiment 1 focused on creating a blue looking twill and these insights will be taken along the following form weaving samples.
Apart from these flaws in the weave structures it was very educating to have these samples made. The front placket as a separate piece works great to achieve the desired density. Making the front of the body longer that the back is a feature that is integrated into the experiments and concept designs.

Insight: make sure connected weave structures use the same warp and weft distribution between layers.

Insight: distribution of yarns is done in the warp and weft yarns. Warp 1 and weft A do not have to be combined. It is possible to have 1B2A for example.

Seam strength test
Introduction
Some 3D woven samples are tested on their resistance against tensile strength. through this test, we can see whether the 3d woven samples show similar behaviour to samples of a regular denim jacket. By making this comparison, an assumption can be made about the durability of the 3d woven denim.

Parameters
Machine used: Zwick tensile tester
Setting: Tensile 500N load cell 1kN grips crosshead

Test parameters
Maximum extension: 3 mm. Test speed: 305 mm/min (ASTM D1683). Pre-load 0,1 N.

Test samples
Two different kinds of samples are tested in the tensile tester. First, the woven seams of two-layer weave structures, from samples 26, 27 and 28, are tested and these can be compared to the tests of two seams taken from a conventional denim jacket with a comparable fabric weight. The seams from the conventional denim jacket are both stitched through felt seams.
Secondly, fabric samples from samples 26, 27, 28 and 1, are tested and can be compared to the tests of denim fabric taken from a conventional denim jacket with a comparable fabric weight.
The 3D woven samples are indicated as WS and the samples from a conventional denim jacket are indicated as ES.

Seam samples
The samples that are used for the seam tests measure 150 mm by 43 mm, in the same ratio as the given measurement in ASTM D1683. For the seam test, the clamps are placed 75 mm apart, according to ASTM D1683. The samples are placed with the seam in the middle of the 75 mm gap between the clamps. A line was drawn in the middle perpendicular to the to-be-tested seam to align the sample in the centre of the clamps.

Fabric samples

The samples that are used for the fabric tests measure 75 mm by 43 mm. For the seam test, the clamps are placed 15 mm apart, sample size minus two times the height of the clamps. A line was drawn in the middle perpendicular to the to-be-tested seam to align the sample in the centre of the clamps.

More detailed information and images of each sample tested can be found in Appendix H.

Elongation (mm)

As can be seen in figures 36 and 38 the elongation of most 3D woven samples is longer than the conventional denim jacket samples, especially in the seam samples. In those cases, the samples deform already when put under a small force. This shows that these 3d woven samples are quite elastic. This can have multiple reasons e.g. the sort of fibre or the weave structure.

Tensile strength (N)

The tensile test shows how much force the samples can withstand before they “break”, or the strength of the sample under tensile force. A debatable point for this test is the question of when the substance is considered broken. This can be when a few threads break but do not make a visible hole or when the fabric is completely pulled apart, the broken samples showed different results. But of course, broken is broken.

Looking at the fabric sample comparison, figure 37, it can be seen that most 3D woven samples score below the conventional denim jacket fabric samples and two 3D woven fabric samples, WS8 and WS10, can resist more tensile force. It should be mentioned that the used tensile tester machine was set to a maximum of 500 N, those four samples achieve a tensile strength greater than that. The precision of these calculations can therefore be slightly off.

Looking at the seam sample comparison, figures 39, it can be seen that almost all of the 3D woven seam samples come near the tensile force of the conventional denim jacket seams.

Fabric samples

Samples WS1 to WS7 are taken from a two-layer 3D woven weave structure and have a fractional density of half the one-layer construction in the seams. Thereby, these samples have a warp in the diagonal direction. As can be seen in figure 39 the samples of WS1-7 perform all relatively equally. The ruptures between these samples do differ in terms of how much the sample is torn apart. WS9, with the warp laying in the vertical direction, performs only slightly better than the samples WS1-7. Both WS8 and WS10 are one-layer 3D woven fabric samples with the warp laying in the horizontal direction. If compared to WS9, where the warp lays in the vertical direction and thus the direction of the tensile test, it can be seen that the samples with the warp in the horizontal direction are stronger. This can be explained probably by the fact that there are more weft threads per cm in this weave construction and because the weft threads are also a bit thicker than the warp threads.

Looking at the fabric samples of the conventional denim jacket, ES3 (warp vertical) and ES4 (warp horizontally) it can be seen that the sample with the warp in the horizontal direction is stronger. Although the difference between the two samples is way smaller than between the 3d woven samples.

Seam samples

Looking at figure 39, the tensile strength of the tested seam construction lay in a range of around 200 N to 400 N. ES1, which is a seam taken from a conventional denim jacket with a warp in the vertical direction, performs the best in the test. In ES2 only the yarns from the seam construction have broken. In all 3D woven seam samples, except for WS7, the fabric ruptured before the seam ruptured. These fabric ruptures differ in placement from near the clamps of the machines or the 3D woven seam.

Seams from WS1 to WS7 perform sort of equally. WS1 and WS2 are both using weave structure 28 from

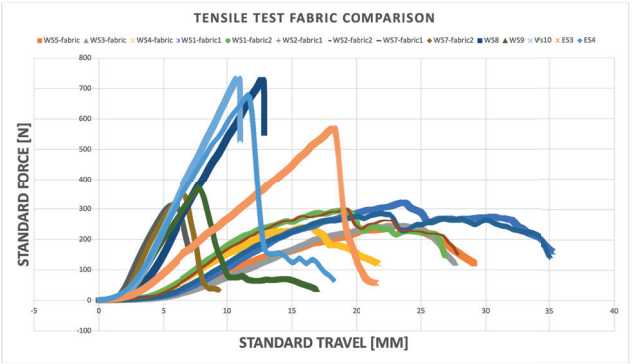
the weave experiment 1. As can be seen in the figure those samples together with WS7, which has a vertical warpw, perform slightly better than samples WS1-6. Although there is a difference in that in WS7 the 3D woven seam actually ripped, possibly due to the warp yarns laying in the directions of the force whereas the other tested 3D woven seams have yarns lying diagonally. This could be a coincidence or it could be explained possibly by a different weave structure that makes the fabric a bit stronger. These seams do perform relatively close in the test to ES2, which is a conventional denim jacket seam with the warp in the horizontal direction, where also the fabric ruptures before the seam does.

Conclusion

Looking back at the results from the tensile test it can be concluded that the 3D woven samples perform below but close to the conventional denim samples used. When comparing the fabric test results the 3D woven samples with the warp in the horizontal direction perform best. Overall in the seam test, the tested conventional denim seams perform slightly better than the 3D woven seams. When looking at the tensile seam test samples WS1, WS2 and WS7 come near the performance of ES2. In most 3D woven seam samples the fabric ruptured before the seam did. This can indicate that the 3D woven seams are possibly nearly as strong as the conventional denim jacket seam but the 3D woven fabric, as can also be seen in the test results, is weaker than the conventional denim jacket fabric.
For this test only a limited selection of 3D woven samples was available. The size of the tested samples was a ratio of the required dimension according to the ASTM test setups. And most samples were only tested ones. These three factors could have influenced the outcomes of the tests.

Takeaways:

The 3D woven fabric is the strongest in the direction of the weft.
In the diagonal direction, the 3D woven seams are strong but the two-layer fabric weave structure attached to it breaks before the seam does.



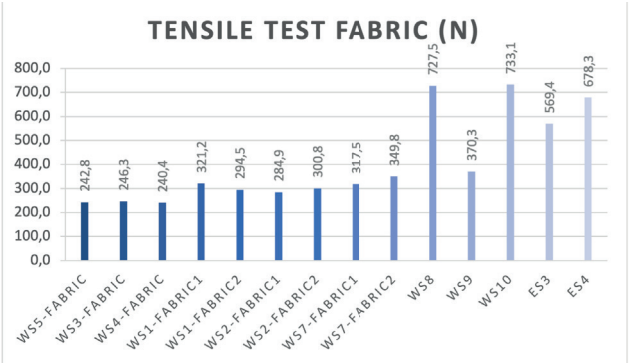
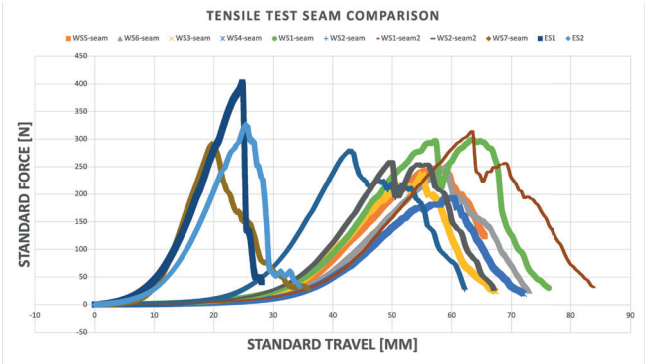


Figure 36 and 37. The results on tensile test for the fabric samples. Figure 36 shows the full graphs of the force (N) displayed over the elongation (mm). Figure 37 shows the maximum tensile force before considered broken.



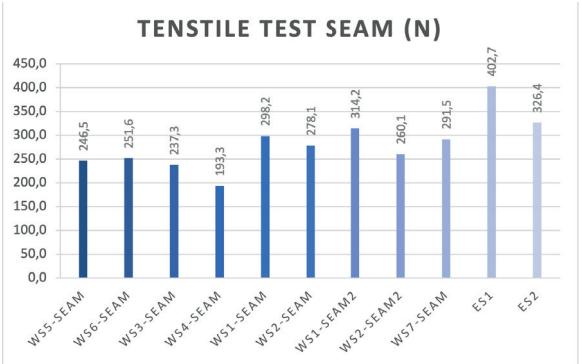


Figure 38 and 39. The results on tensile test for the seam samples. Figure 38 shows the full graphs of the force (N) displayed over the elongation (mm). Figure 39 shows the maximum tensile force before considered broken.

13

3D woven denim jackets

Introduction

Concept 3 was the basis of the three 3D woven denim jacket developments that will be discussed in this chapter. From the idea that the researcher wanted to leave open the discussion on how finished a 3d woven denim jacket should be, two versions of the same model of the jacket were developed. In the 'raw edge' jacket version, unlike how we know a denim jacket, all the edges are left unfinished. These edges are expected to fray but with this, the concept more fully embraces the potential of 3d weaving. In the 'finished edge' version, care has been taken to ensure that all edges (collar, front placket, waistband and cuffs) can be finished as they are in a conventional denim jacket. As both of these versions did not lend themselves to a layout in the loom that would save a lot in cut-off waste, a zero waste version of the 'raw edge' version was also developed, called 'zero waste raw edge'. This required several adjustments to the shape of the jacket and this way of weaving will also affect the appearance of the zero waste raw edge 3D woven denim jacket. All samples for these developments were created at Diamond Denim by Sapphire in Pakistan. It should be noted that these versions are still prototypes and are being developed as a basis for further development. All main structures are two-layer weave structures except for the integrated pockets which are ¼-layer weave structures. The idea of the chest and waist pocket is integrated into the 'raw edge' and 'finished edge' versions to test the visual appearance and capabilities of such a feature.

In Appendix I more information about the prototyping of the 3D woven samples at Diamond Denim can be found.

Waste calculation

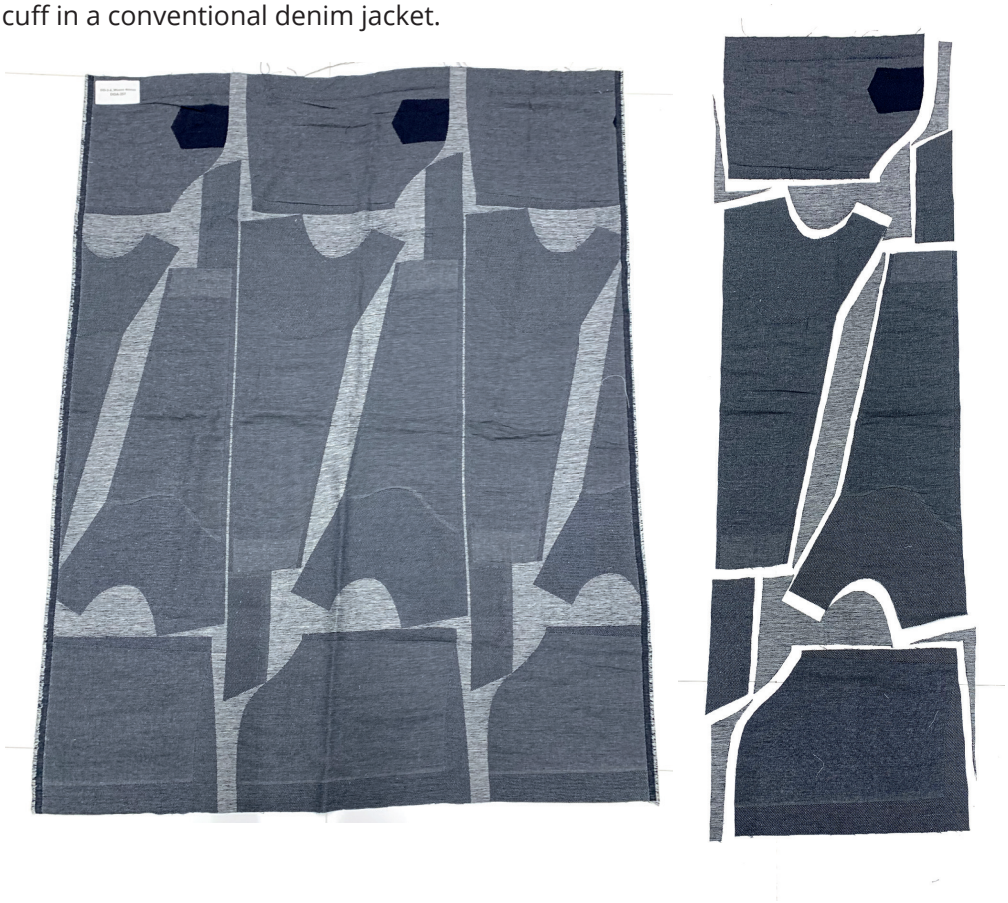
To evaluate the 3D woven versions on the requirement of the amount of off-cut yield waste, the waste percentage of the off cut panels must be calculated. For the 3D woven denim jackets, in which the panels consist of multiple pattern pieces (looking at a conventional denim jacket). This makes it impractical to calculate the waste percentage over the area (cm2) in the fabric. Therefore the waste percentage will be calculated according to the yield weight. Although the comparison of the 3D woven concepts to a conventional denim jacket is uneven both are designed as denim jackets and on that aspect they can be compared. The comparison is uneven because with 3D weaving pattern panels are integrated, less square metres of fabric is used when 3D weaving but those metres of fabric are used differently. Also the 3d woven concepts integrated seams already in the panels and the concept of 'raw edge' and 'zero waste raw edge' use less fabric by leaving the edges raw after cutting. A disadvantage with 3d weaving is that with the current method of weaving, your waste is always equal in weight to the heaviest thickness of the weave structures. To calculate the yield waste percentage of the off-cuts of the 3D woven samples the layout in the repeat is cut out and weighted. Then the pattern panels are cut out and the off cut and the jacket panels are weighted separately.

"RAW EDGES"

‘Raw edges’ 3D woven denim jacket

Concept explanation

This ‘raw edges’ 3D weave prototype is designed to embrace the full potential of 3D weaving. This prototype takes the developed concept 3 into a 3D woven denim jacket in which the edges are purposely left raw. Raw means that after cutting the panels from the fabric cloth the edges are left untreated and are expected to fray. The concept consists of five parts; two half-body panels, two shoulder and sleeve panels and two halves of a collar. The collar can be woven in one piece or in two parts that should be sewn together. Taken from concept 3 the front waistline is designed longer than the back waistline. On the design, a breast pocket and a waist pocket were added both on different front panels. Another feature that was added is the differentiating weave structure at the cuffs to visually try to mimic the visual look of the cuff in a conventional denim jacket.



Final prototype and embodiment

The ‘raw edges’ version took five weaving trials at Diamond Denim to come to the desired outcome. Of which the fourth trial was also sewn and finished by Diamond Denim. To make this happen the cutting and sewing process of the samples was explained to the head of the garment manufacturing department. The pattern pieces are cut out from the fabric. The second cutting step is to cut open the under arm seam and then cut the back body panel loose from the front body panel.

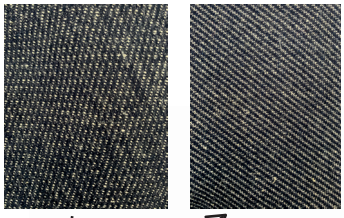
The ‘raw edges’ concept requires five sewing steps (four if the collar was in one piece); the two body panels are sewn to the shoulder and sleeve pieces, then the centre back seam is closed, the two parts of the collar need to be connected and lastly, the collar has to be sewn to the neckline of the jacket.

To finish the jacket it will be needed to add buttonholes and buttons to the front plackets.

The jacket has a boxy fit with a collar and shapes following sleeves. The jacket has front and back yoke lines, a sturdy differentiating front placket, a front waistline that is longer than the back waistline and a breast and a waist pocket.

Denim fabric

The weave structures for this sample were taken from the weave experiments in chapter x. But the four white weft yarns were changed into two white yarns and two blue yarns. This caused the weave structures in this sample to look different than envisioned. The weave structures were programmed into neat and denim-looking weave structures via multiple trials.



Pockets

The placement of the breast pocket after some trials was placed more to the centre front. It was decided to make the pockets appear blue on the outside of the jacket. To reinforce the thin four-layer weave structure of the pockets it was decided to change their weave structure to a plain weave.

Fit updates

The first trial of this jacket was pinned together to check the fit of the jacket, as visible in the figure below the shoulder panel on the back needed some extra fabric. For the rest of the jacket, the fit was good.

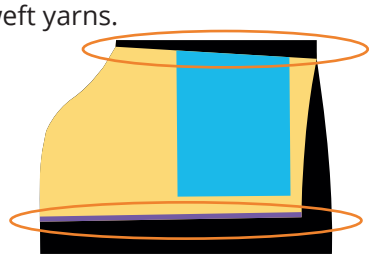
Side

Twill stripe line up

All weave structures can have a direction of the twill diagonal stripe appointed to them. To make the overall look of the denim fabric align on all panels it was made sure that the twill stripes went into the desired direction.

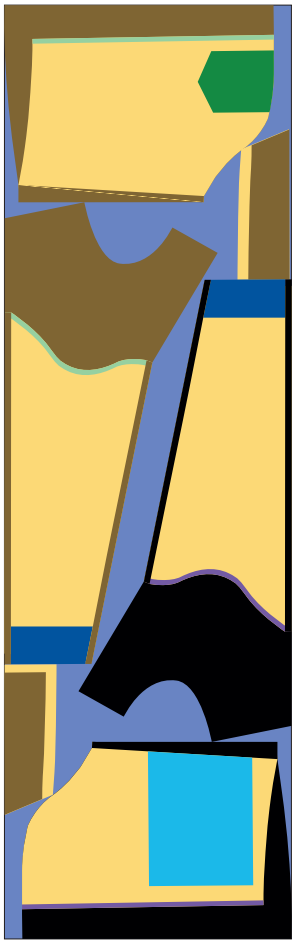
Front placket to body transition

Because the body panel was placed horizontally in the loom the transition of the front placket to the two-layer construction was fragile. This line was put under a slight angle to have the transition distributed over more weft yarns.



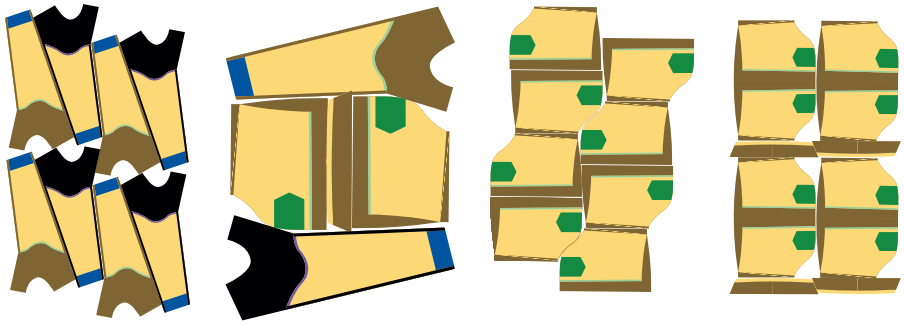
Fraying

Fraying of the raw edges in this sample was an issue. The one-layer weave structure needed some improvement to make it less likely to fray. Especially in the side seams, which were designed under a slight angle and horizontally placed in the loom, this was an issue. To prevent the side seam even more from fraying the seam was straightened. Also, the two-layer weave structure in the cuff was too loose and was changed into a tighter weave.



Loom layout

The amount of off-cut waste created by the garment design and the quality of some weave structures depends on their placement in the loom. The loom used for these samples had a repeat in the middle of the fabric. The repeat limited the layout possibilities of the pattern panels. The pattern pieces were fitted in the repeat to create as little off-cut waste during prototyping as possible, see the figure on the left.
If there were no limitations on the size of the loom or a repeat the pattern pieces could be arranged in ways that would possibly create less off-cut waste than the samples do in the current layout. Suggestions for these layout possibilities can be seen in the figure below.



Waste calculation

Total weight: 514 gram
Weight of the jacket panels: 442 gram
Weight of the off-cuts: 72 gram
Yield waste percentage of off-cuts: 14%

Reflection

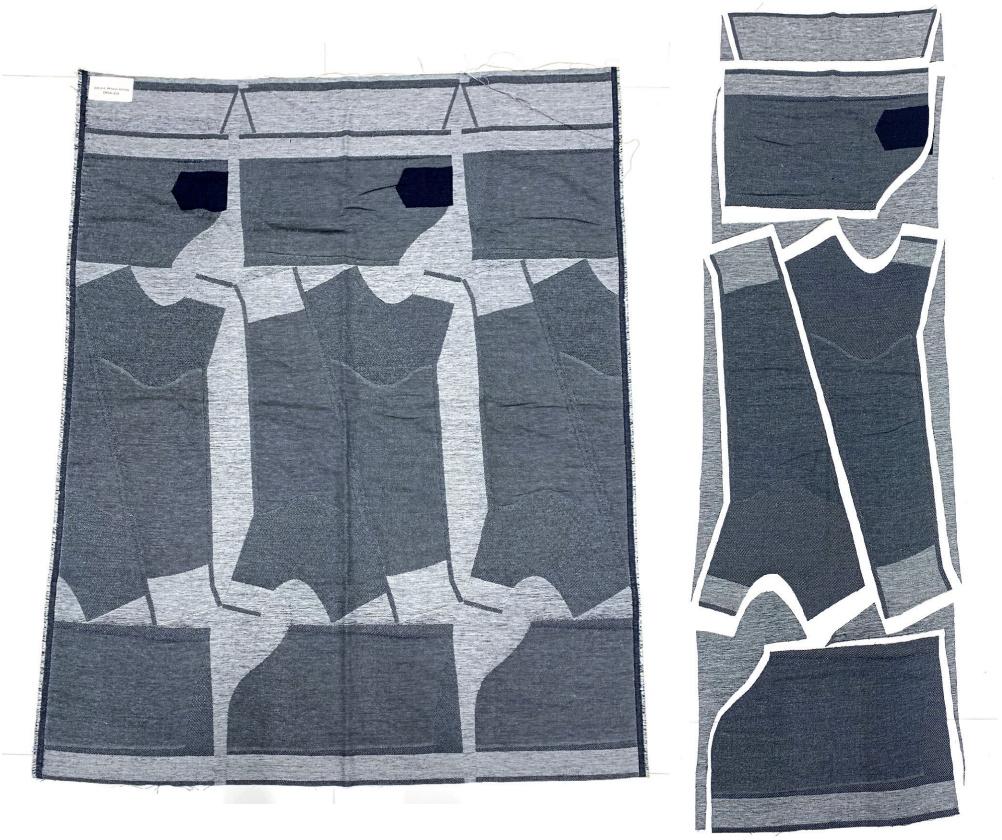
This 'raw edges' 3D woven denim jacket requires five sewing steps (four if the collar was in one piece). It does however create around the same or higher percentage of waste as a conventional denim jacket. A different jacquard loom with no repeat can resolve some of this off-cut waste problem because it would give more freedom to the layout of the pattern panels. But the off-cut waste with this concept will not get to zero per cent. Another solution to reduce the waste percentage would be by overlapping parts of the pattern panels. This way they could form a layout form with less off-cut waste. Another recommendation would be to optimise the design of the panels or the whole concept.
The fraying of the edges in the final concept is partly resolved but would need further research, like into weave structures that have less tendency to fray. Another solution against the fraying could be to research and pay attention to how to place the panels in the loom.
As can be seen in the picture from the 3D woven version of this concept the fractional density of the changing weave structures creates panels with different appearances in the jacket. For the front placket for example this feature is found beneficial because it visually highlights it. For the sleeve panels, it could be argued that it is less beneficial because the fabric change draws the shoulder line down.
The feature of 3D weaving to change weave structures anywhere in your design works also well for creating visual differences in the design like done with the cuffs. The same effect could be added on the front and back body panels to create the diagonal seam characteristic for the type 3 denim jacket
The placement of the breast pocket is a bit high because the choice was made to align the pocket with the front yoke seam. The seam can not be lowered because it is an extension of the sleeve panels but the pocket can be located elsewhere or left out.

"FINISHED EDGES"

‘Finished edges’ 3D woven denim jacket

Concept explanation

This ‘finished edges’ 3D weave prototype is designed as a hybrid between embracing the full potential of 3D weaving and a conventional denim jacket. This prototype takes the developed concept 3 into a 3D woven denim jacket with the edges finished to look like the edge finishes as in a conventional denim jacket, with sewn-on cuffs and a waistband and a double-layer front placket. The concept consists of four parts; two half-body panels, two shoulder and sleeve panels and a collar. Taken from concept 3 the front waistline is designed longer than the back waistline. On the design, a breast pocket and a waist pocket were added both on different front panels.



Final prototype and embodiment

The ‘finished edges’ version took only two weaving trials at Diamond Denim to come to the desired outcome. Fewer trials were required because much development could be taken from the ‘raw edges’ prototype. The pattern pieces are cut out from the fabric. The second cutting step is to cut open the under arm seam and then cut the back body panel loose from the front body panel.

The ‘finished edges’ concept requires nine sewing steps; the two body panels are sewn to the shoulder and sleeve pieces, then the centre back seam is closed, sewing both cuffs closed, sewing both front plackets closed, the collar to the neckline of the jacket and sewing the waistband double.

To finish the jacket it will be needed to add buttonholes and buttons to the front plackets.

The jacket has a boxy fit with a collar and shapes following sleeves. The jacket has front and back yoke lines, a sturdy differentiating front placket, a front waistline that is longer than the back waistline and a breast and a waist pocket.

Adjustment from 'raw edge'

This concept is the same as the 'raw edge' version. For the development of this concept the adjustment regarding fit, weave structure, fray and pocket carried out with the 'raw edge' sample have been included in this 'finished edge' concept.

Front placket

For the front placket, a different construction was made than for the cuffs and the waistband. The front placket is partly made into a two-layer weave structure. This two-layer weave structure can be cut open and folded onto itself. The front placket can then be sewn shut.

Collar

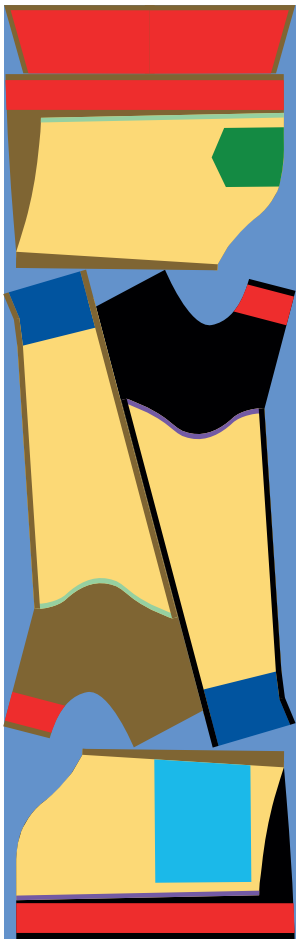
For this concept it was the collar was woven as a two-layer weave structure that could be turned inside out.

Waistband

For this concept the length of the waistline was elongated. This extra fabric when constructing the garment can be folded and stitched through to create finish the edge of the waistline. The waistband will differ in thickness over the waistline where some sections are a one-layer weave structure and other parts half of a two-layer weave structure.

Cuffs

For this concept the length of the sleeve ends was elongated. This extra fabric when constructing the garment can be folded over the sleeve and stitched through to create the idea of sewn-on cuffs.



Loom layout

The amount of off-cut waste created by the garment design and the quality of some weave structures depends on their placement in the loom. The loom used for these samples had a repeat in the middle of the fabric. The repeat limited the layout possibilities of the pattern panels. The pattern pieces were fitted in the repeat to create as little off-cut waste during prototyping as possible, see the figure left.
If there were no limitations on the size of the loom or a repeat the pattern pieces could be arranged in ways that would possibly create less off-cut waste than the samples do in the current layout. For suggestions about these layout is referred to the suggestion at the 'raw edge' version.

Waste calculation

Total weight: 490 gram
Weight of the jacket panels: 414 gram
Weight of the off-cuts: 76 gram
Yield waste percentage of off-cuts: 15,5%

Reflection

The construction of the 'finished edges' version requires five more seams than the 'raw edges' version. These are however fewer seams that are required for a conventional denim jacket with the same features of the double layer cuff, waistband and front placket.
Also, this version creates around the same or higher percentage of waste as a conventional denim jacket. A different jacquard loom with no repeat can resolve some of this off-cut waste problem because it would give more freedom to the layout of the pattern panels. But the off-cut waste with this concept will not get to zero per cent. Another solution to reduce the waste percentage would be by overlapping parts of the pattern panels. This way they could form a layout form with less off-cut waste. Another recommendation would be to optimise the design of the panels or the whole concept.
The appearance of the jacket gets busier from these added finishing edges. On other visual aspects, this version follows the reflection of the 'raw edges' version.
The construction of this jacket version with the finished edges needs some improvement. Because the extra fabric to finish the edges is woven on the panels the construction is hindered by the number of layers folding over each other.

"ZERO WASTE"

‘Zero waste raw edges’ 3D woven denim jacket

Concept explanation

The before-mentioned versions did not lend themselves to a layout in the loom that would potentially reduce the cut-off waste to zero. Therefore the ‘raw edges’ 3D woven jacket concept was developed into a zero waste version, called ‘zero-waste raw edge’. To achieve zero waste (or almost zero waste) the panels of the ‘raw edges’ version were fitted together into a rectangle. To make the panels into a compact zero-waste layout the parts of the panels which were a one-layer construction were overlapped. By overlapping these one-layer weave structures are made into two-layer weave structures of which each layer belongs to a different pattern panel. To make the pattern panels fit into a rectangle some adjustments were made to the pattern pieces. The creation of the rectangle started by laying the inside arm sleeves side by side. To fit the width of those panels the side seam of the body panel was moved more to the back. Other adjustments were made to the shoulder panels, the neckline and the sleeves. This construction will affect the appearance of the ‘zero-waste raw edges’ 3D woven denim jacket.

Final prototype and embodiment

The ‘zero-waste raw edges’ version took four weaving trials at Diamond Denim to come to the desired outcome. The cutting of this jacket is more complicated because in the overlapping parts the right seams have to be cut open.

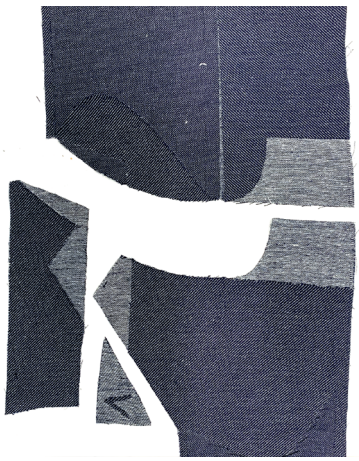
The ‘zero-waste raw edges’ concept requires four sewing steps, like the ‘raw edges’ version; the two body panels are sewn to the shoulder and sleeve pieces, then the centre back seam is closed, sewing both cuffs are closed, sewing both front plackets closed, the collar to the neckline of the jacket and sewing the waistband double.

To finish the jacket it will be needed to add buttonholes and buttons to the front plackets.

The jacket has a boxy fit with a collar and shapes following sleeves. The jacket has front and back yoke lines, a sturdy differentiating front placket, a front waistline that is longer than the back waistline and a breast and a waist pocket.

Align all the weave structures

The biggest challenge of this concept was to designate all surfaces that would become visible on the outside in the same colour and direction in the map or bindings.



Align the side seam and back arm seam

The first prototype showed that the back arm seam and the side seam of the body almost aligned with each other. Some adjustments were made to try to make these seams touch each other. Eventually, we managed to have the ends of the seams align with each other.

Denim fabric

The weave structures in this woven concept are the same as the other two woven concepts. The developments of these concepts were intermingled and so was also the development of finding the right weave structures for the one-layer and two-layer weave structures.

The fraying aspect is therefore in this concept the same as in the 'raw edges' concept.

One-layer weave structure too dense

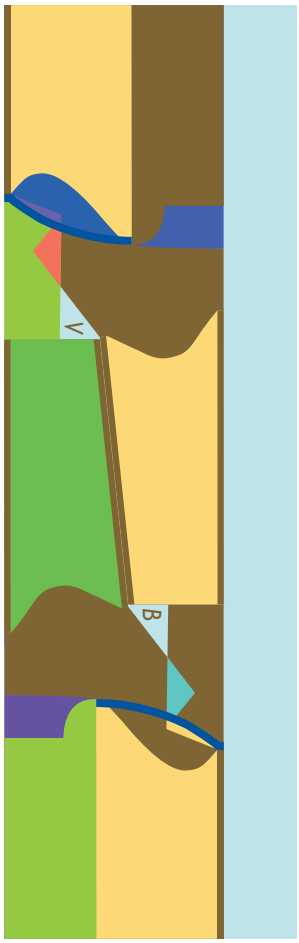
When weaving the second sample of this zero-waste version the weave structure of the one-layer parts was too dense for the loom. The one-layer weave structure was made lighter by changing the position of the binding points in the weave structure.

Front yoke

In the first prototype, the front yoke seam was drawn too straight which made the seam look unappealing compared to the rest and the curved back yoke. The front yoke line was drawn more curved, which in this layout had some influence on the shape of the neckline in the shoulder panel. But this was not visible in the end prototype.

Label

From the two "leftover" triangles a rectangle can be made that can be used as a label on the jacket. To try out this idea the initials of the author were woven inside the labels.

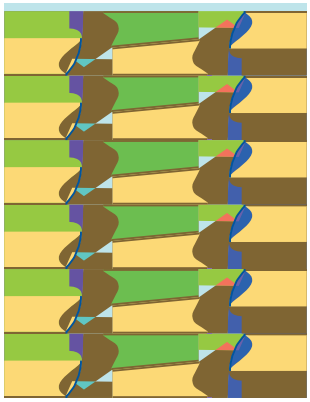


Loom layout

The loom layout for this concept differs from the other two presented 3D woven denim jacket concepts. By overlapping the panels of the denim jacket into a rectangle almost zero waste layout was created. This size of the rectangle is linked to the size of the denim jacket. The rectangle was woven at Diamond denim in the length of the loom, because of the repeat. In other looms the rectangles could be woven side to side or in the width of the loom side by side. For this layout, only one size has been considered. Potentially when designing a loom layout for multiple sizes and multiple jackets at a time the overlapping of the pattern panels could be done in different ways to fit the width of the loom best. For example, multiple sizes could be combined into rectangle(s) where different sizes overlap. This will influence the appearance of the 3D woven zero-waste denim jacket even in a different way.

Waste calculation

Total weight: 340 gram
Weight of the jacket panels: 336 gram
Weight of the off-cuts: 4 gram (the two triangles that can be turned into a label)
Yield waste percentage of off-cuts: 1,16 %



Reflection

This 'zero-waste raw edges' 3D woven denim jacket requires five sewing steps. The cutting of the panels separate from each other is somewhat complicated, mostly because the overlapping and the weave structures are not yet optimised to support cutting the layers separate from each other. Especially in the small panels on the collar, the cutting is difficult. Future research will be required to optimise the process of cutting overlapping panels.

The layout of this concept creates almost zero per cent off-cut waste, only two triangles are off-cuts. In this concept, the triangles are used as a label inside the jacket, which would turn the layout into a zero-off-cut waste layout.

The overlapping of the panels in these concepts is only done with one-layer weave structures. This effect of the overlapping is visible on the jacket and results in some places an unfamiliar appearance. The shapes are a bit odd in shape and placement. The appearance of these 'zero waste raw edges' is very much influenced by the layout and the overlapping happening due to the layout. As suggested in the part about loom layout this concept of overlapping pattern pieces can be taken also into a larger production of multiple sizes and jackets. Which will maybe create jackets that have a certain appearance based on the loom layout, which could be fascinating.

Finishing of the 3D woven denim jackets

As discussed in chapter x denim garments can be finished in many ways, but many of these treatments are not so sustainable. A relatively sustainable upcoming finishing technology is laser treatment, which consumes less water, energy and chemicals (. During the visit to Diamond Denim, there was the opportunity to have jackets undergo laser treatment, figure 40.

Jacquard weaving makes it possible to have many different weave structures combined in one fabric cloth. Normally wear patterns of denim garments are created by finishing treatments after the garment is constructed. But with jacquard weaving these wear patterns could already be woven into the fabric. Diamond Denim recently launched a pair of jeans that has this idea applied, see figure 41. These jeans were not 3D woven but constructed after cutting the panels from the jacquard fabric that had the wear patterns woven in. If this idea would be combined with a 3D woven garment, more production steps can be included in one process and fewer polluting finishing treatments would be required.

Figure 40. Laser and ozon treated 3D woven denim jacket developed by Barbara Vroom at Diamond Denim

Figure 41. Jacquard woven finished look by Diamond denim. Middle picture from instagram @diamond_denim_by_sapphire

Conclusion

The three concepts show that 3D weaving influences the appearance of the outcome. For the concepts, it was decided to keep the woven seams on the outside of the jacket to also embrace and show the manufacturing process of the jacket. This new production technology of 3D weaving will direct a different design outcome. The seam construction of the sleeve panel to the body panels creates a line similar to a front and back yoke line.

The development of these prototypes was characterised by several challenges.

Fraying: That cut fabric fray was no surprise but the extent to which it frayed was in some cases. Weave structures were optimised several times to limit the amount of fraying. Next to that, the side seam of the body panels was straightened in the version of 'raw edges' and 'finished edges' as another way to limit the fraying of that seam. In the 'zero waste raw edges', the side seams did not fray so much because of their vertical placement in the loom. When designing a 3D woven garment this is an aspect that is handy to take into account.

Look like denim: An important aspect of a denim jacket is the denim fabric, a twill fabric that is blue on the surface and white on the back achieved by combining a blue warp with white weft yarns. Achieving the same look was challenging in the 3D woven denim jackets, because of the layered weave structures and their fractional density. The first prototypes were made with four white weft yarns and a blue warp. Because the resulting weave structures turned too white, two white weft yarns were replaced by two blue weft yarns. For a weave structure of two layers, each layer was assigned one white and one blue weft yarn. Together with Milou Voorwinden the one and two-layer weave structures were designed to have them look blue on the surface and white on the underside. The four-layer weave structures could be made blue or marbled. The conclusion of this is that the number of weft yarns and their colour is another design aspect of a 3D woven textile form. Combined with jacquard weaving an almost endless combination of weave structures can be created. The weaving aspect of this project like designing the weave structures and programming them could not have been to this extent without the help of weave designer and technician Milou Voorwinden.

Fractional density: The density of the loom used in this project was about 40 ends/cm. This was found relatively low for designing a 3D woven denim garment. The maximum layers of the panels were kept at two layers because the density of 20 ends/cm was already found to be relatively thin for a denim jacket fabric. For future projects, it would be recommended to use a machine with a higher warp density. That would also make it possible to design a 3D woven garment consisting of more layered weave structures. A different density of the warp and or the weft will change the appearance of the fabric, so this would need further research and testing.

Weave structure placement: Especially for the 'zero waste raw edge' version it was a challenge to program every weave structure with the desired colour and binding direction on the surface. But when this finally works out the outcome does make the difference.

Repeat size: The size of the repeat of the loom used at Diamond Denim was a limitation in this project. The width of the repeat sometimes limited the placement of the pattern panels and layout which created more waste than desired. Not many denim mills have jacquard looms, so having the possibility to make use of this machine with a relatively workable width has been a great part of this project.

Fabric shrinkage: Denim fabric shrinks quite a lot. After weaving the fabric is finished and in this process, the denim fabric shrinks by about 14%. If you would also finish the constructed garment using a wet process the denim fabric will shrink an additional amount of percentage. This is an important factor to keep in mind when designing and deciding on the side of your designs.

Unfortunately, the designs of 'raw edges' and 'finished edges' create according to these calculations and this layout creates more cut-off waste than the set requirement. These concepts require more development to achieve less than 10% cut-off waste, like changing the shape, using a different machine or overlapping some panels like in the concept of 'zero-waste raw edges'.

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User evaluation

To conclude this research a small user study has been conducted to receive some first feedback on the sample of 'raw edge'. This sample was chosen because it was the most finished sample available with buttons and buttonholes.

After giving the sampel the following questions were asked to three participants (consent forms in Appendix J). The same sample was also discussed during an informal discussion with housemates who participated in the denim jacket user research in chapter 5. The explanation of how the sample was made was done during the end of the interview.

Questions:

- How would you characterise the given garment?
- As what kind of garment would you describe it?
- What do you like about it? What do you not like about it?
- Did something catch your eye?
- How similar or different do you think it is from a denim jacket that you know?

All interviewees think of the given sample as a summer jacket because they think the fabric is lightweight, flexible and thinner than denim as they know it. They do say it is a jacket as it is thicker than a blouse-like garment and it is clear that it can be worn open and closed.
The participants mentioned that the colour makes it recognizable as denim. But the structure on the fabric, mentioned as dots and stripes, is different from denim as they know it.
The structured appearance of the fabric and the difference in structures cause the jacket to be found a little busy. The pockets, described by some as patches, caught the attention.
The positive points mentioned are a nice design, nice colour, fun to see the different textures and the seams on the outside. The seams on the outside do make this 3D woven denim jacket different from denim jackets as familiar to the participants. The seams on the outside and the fraying make the 3D woven denim jacket look raw and handmade.
The participants describe the sample as a denim jacket due to its similar boxy fit, the colour and the raw/workwear aesthetics by the fabric and the seams.
They all concluded that it falls into the category of a denim jacket where it has some similarities but it's also different from a denim jacket as they know it. The sample being different is not mentioned as something bad but rather as something cool.
The researcher from these interviews got the idea that the interviewees are more familiar with washed, light blue denim rather than the dark blue colour of the used sample.

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Discussion

This project is about using 3D weaving, a new and potential production method, to redesign the construction of a denim jacket, a product whose aesthetic and production method has hardly changed over almost 150 years.

Towards a new fashion industry

Jeans and denim jackets are an indispensable part of our daily lives. Denim garments are comfortable and have an image of both carelessness and an expressive garment in our wardrobe. But the (denim) garment industry has gotten out of hand to an extent that in 2006 around 2.7 billion metres of denim was produced (Muthu,2017). The fashion industry has evolved over many years into a fast fashion industry focused on the overproduction of cheap and easy-to-produce textiles (López, 2021). Denim garments are made from a woven fabric that is cut into pattern pieces, which will be constructed into a garment using sewing machines. This production method (denim) garments and the industry in which they are produced in all factors determine the way the denim garments look. As visualised in chapter 6 this way of producing is very polluting and wasteful. It is time for the industry to change.
Looking at the goals of the Ellen MacArthur Foundation the focus of this project was to eliminate the waste & pollution aspect of a denim garment while retaining the existing emotional and physical durability and respecting the 'made to be made again' aspect of a denim jacket.
3D weaving integrates the design of fabric and form and integrates parts of the cut-and-sew process into the weaving construction. This integration of production steps can possibly reduce pollution and pre-consumer waste. 3D weaving is not a technology to be integrated into the current polluting industry, the current fashion industry is not built to produce less and some parts like cutting the 3D woven textile forms can not be done in layers at a time. 3D weaving was proposed in Dr Holly McQuillan her PhD as part of form design methods in the context of zero waste system design for whole garment weaving.

New aesthetics

This project demonstrates that a new production technology comes with a new aesthetic. Achieving the same aesthetics with a different production method is impossible. The goal of this project was to retain the qualities of a denim jacket like the fit, colour, and fabric quality while improving the polluting aspects of its current industry.
This goal was achieved in some aspects while others still need improvement and further research. The outcome of this project is three versions of a 3D woven denim jacket. Looking at the denim aspects of these 3D woven denim jackets the density and the look will need further development. The density of the

loom, 40 ends/cm, is too low for the two-layer 3D woven structures and makes the jacket feel lightweight. The separation of the warp to create multiple layered weave structures changed the ratio of warp to weft yarns. The outcome of the fabric is not a fabric that appears fully blue on the surface. Rather in both the one and two-layer weave structures, the white weft yarns are clearly visible in the form of stripes or dots. The small group of respondents also mentioned the lightweight and the different appearance as a differentiation from denim as they know it.
The durability of denim fabric is related to the weight and density of the woven fabric. The tensile tests showed that the 3D woven fabric is more likely to tear. The test also showed that the seams are strong enough but the fabric attached to it breaks relatively easily. To achieve the same durability a denser weave is needed, which will be achieved with a machine with a higher warp density and the possibility of a higher weft density. The durability and strength of the 3D woven fabric could also be improved by using thicker warp and weft yarns. Changing these factors will influence the outcome of the fabric and thus also that of the garment.

Criteria analysis

Looking back at the criteria regarding the pursued aesthetic qualities of a cut-and-sew type 3 denim jacket all of the requirements were met. The three 3D woven denim jacket versions have a boxy fit with sleeves that are connected under an angle and curved around the arm. The jackets have a collar, the front placket is dense enough to carry buttons, the front waistline is longer than the back waistline and a waist pocket was added. The jacket has a dynamic shape which after sewing will not lie entirely flat. The collar was not the main point of attention during the development and is a relatively simple design. Especially in the 'zero waste raw edges' version, the collar was a single-layer piece. The collar could use a bit more attention and when more layers could be used the collar could also maybe be implemented into the shoulder panel. Due to the low fractional density, the pockets are very thin and not very functional to use. The pockets do show another aesthetic difference because of the fully blue colour, which was a direct result of the weaving decisions made.

Respondents from the user evaluation also mentioned that the fraying of the seams and edges made the jacket look handmade. The respondents also mentioned that the appearance of the jacket was rather busy through all the surfaces with different appearances. The respondents did only see the 'raw edges' version, it would be interesting to discuss also the other two versions and to expand the study to include more participants.

Fraying

The fraying was embraced in two out of three versions to embrace the full potential of the 3D weaving technology. In this project, the fraying was minimised by exploring different weave structures and adjusting lines and seams. The size of the loom repeat was also a limiting factor in this process. The body panels were laid in the repeat horizontally but the fabric is more likely to fray in that direction and according to the performed tensile test also the only tested seam that ripped before the fabric did. Ideally, the pattern pieces are laid under an angle or at least with a critical seam in the vertical direction. The raw edges could also be hidden on the inside by designing the 3D woven garment inside out. Another approach could be to stitch the seams through. This would however add additional production steps which do not correspond with the original idea behind the implementation of this process. Future development that could minimise the fraying of the edges would be to finish the edges with a sustainable material like a bioplastic that could coat the raw edges. This step could potentially be combined with automated cutting options, like using a CNC cutter.

Waste

Comparing waste and production steps of the 3D woven denim jackets and a conventional type 3 denim

jacket will be for all these reasons difficult. But the 3D woven versions are designed as denim jackets and on that concept, they can be compared to the yield waste percentage of a conventional denim jacket. The yield waste percentage of a conventional denim jacket is estimated between 10 and 15 per cent. The versions of 'raw edges' and 'finished edges' unfortunately, in the loom layout as woven at Diamond Denim, have a yield waste percentage of respectively 14 and 15,5%. This is not in line with the set requirement of yield waste percentage of 10% or lower. On a different note, the designs are estimated to have a lower yield waste percentage. The version that does match the yield waste requirement is the 'zero waste raw edges' version. This version produced only 1,16% yield waste that could potentially be used as a label. The possibility of overlapping pattern pieces was only considered near the end of the project and from there the zero-waste version was created. The overlapping of the pattern pieces shows a potential that could be used also on the other two versions and their layout. The overlapping of the pattern pieces does make the cutting steps and the design of the weave structures more complicated which is something to take into account.

The last samples showed that the woven fabric changes shape in some places after weaving and finishing. Some pattern pieces, for example, when cut from the fabric, were slightly misshapen. For future research, this could be important as it would mean that there are irregularities in the woven outcomes and pieces may be unworkable.

Sewing steps

All three developed 3D woven denim jackets take fewer sewing steps than a conventional type 3 denim jacket. The 'raw edges' and the 'zero waste raw edges' even only need four seams. These minimal construction steps come with design restrictions such as raw seams and edges. The 'finished edges' shows that finishing all the edges takes at least another four sewing steps. The sewing steps are estimated to not be more complicated than the sewing steps of a conventional denim jacket.

Future design freedom

The 3D woven denim jacket versions show a range of outcomes of 3D weaving for the garment industry. There are many more variations and alternatives to discover. The versions and additional factors like the pockets are made to showcase a variety possible in the time frame of this project. 3D weaving where jacquard weaving and the weaving layers are combined opens a world full of possibilities. These versions are hopefully an inspiration for other designers to think differently about how they produce garments.

Researchers pre-knowledge

The outcome of this project is related to the researcher's knowledge and understanding of 3D weaving, weaving and garment constructions. 3D weaving was a completely new process to the researcher and a big part of this project was used to understand how it worked and especially how to design for it. Next to that, the researcher's knowledge of pattern cutting and garment construction was limited. When designing for 3D weaving the designer takes on multiple roles as a textile designer and garment designer. The design outcomes are wearable and fit a human body. But as a disclaimer, it should be mentioned that sizing is not taken into account and the shape still after many prototypes is a bit off. Maybe not being an expert pattern cutter was an advantage because it can not keep you from doing things differently than you are used to. This multidisciplinary designer for sure requires the education and training of many stakeholders in the garment design industry.

3D weaving is probably not the end but it for sure is a way forward towards a new fashion industry. This new fashion industry will change how products are made and as a result also the appearance and feel of textile products. The new fashion industry would also require consumers to accept these new aesthetics and to use and take care of textile products in a different way.

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Conclusion

This research aimed to investigate 3D weaving as a new production method for a denim jacket. 3D weaving combines woven textile design and garment design in multi-layer textile forms. With 3D weaving, the number of production steps after weaving and the resulting cutting waste can be reduced by weaving parts of the garment as already connected pieces. The 3D woven denim jacket versions in this report show how and to what extent this is possible. These concepts also show how this new production method affects the aesthetic outcome of denim jackets.
The fractional density resulting from layering in 3D weaving creates surfaces with varying appearances. This aesthetic of 3D woven denim jackets is found to give the jacket a busy look. In this project, it was decided to keep the woven-in raw seams, also a result of 3D weaving, visible on the outside of the samples. The fraying is a component of 3D weaving that requires further research to reduce fraying and ensure durability. Achieving a denim-like appearance for the 3D fabrics proved difficult because the ratio of warp and weft yarns differs in 3D weaving. The fabric in the concepts is still a little too light to represent denim, but this could be improved with a denser machine and future research.
Designing textile and garment/form together adds another level to garment design with many more possibilities to be discovered. 3D weaving is a new proposition that comes with new challenges as machinery and design tools. It would also require the education of designers, weavers, mills and other stakeholders in the production cycle.
The potential of 3d weaving to improve the denim and fashion industry grows when striving for zero waste, the use of sustainable inputs, and limited and less polluting finishings which could potentially be woven in. 3D weaving belongs to a new industry, part of a circular economy, where we produce and use less and production is more local and on-demand.

To become viable change in the industry is needed. As related work shows, jacquard weaving and combined textile and shape weaving are being adopted and new machines are being built to enable these new developments, such as the machine of Unspun.
Desirability is a subject that would require further research. I think people will start looking for a change. But we have to show it to them. 3D weaving can give the user the same qualities as a garment but with a reduced environmental impact. 3D weaving potentially can make on-demand garments produced to personal fit and liking. Further research can also be interesting to explore possibilities to reinforce places that normally would wear out easily to lengthen the life of your garments.
This research shows that with a new manufacturing method the aesthetic of garments will change. Let's wear the change!

Recommendations

Based on this research recommendations for future research are made.

= To research and explore the advantages and potentials that 3D weaving can bring to this denim jacket, its production and its users. In terms of advantages and potential for the denim jacket one can think of weaving in reinforcements of places that wear quickly or using different kinds of yarns to play with the shape and fit of the jacket. In terms of the user, one can think of improved user experience like better fit and sizing, personalization or longer durability. In terms of production, one can think of already weaving in the after-treatments or on-demand production.
= Experimenting with a jacquard loom with a higher warp density would also open up the possibility to experiment with more layered weave structures. To achieve a denser quality denim and to be able to explore the possibility of weaving a denim jacket out of fewer components even.
= To do a design project where the possibility of overlapping in the layout puzzle is considered earlier on in the process.
= Interesting to explore weaving denim with other yarn options like Tencel or yarn containing recycled cotton.
= Research and development of reducing/limiting the fraying of weave structures after cutting. This could be into different weave structures or methods to finish the cut edges, like using a bioplastic for example.
= Research into the automatization of processes like cutting out the (3D) woven fabrics.
= Research into the durability of the 3D woven seams and structures.
= Research if cutting into the 3D woven garments, like needed when overlapping as in the version of the developed zero waste version, affecats the quality of the fabric.
= Digital tools: Development of digital design tools that would support the design process of 3D textile forms and weaving files.
= Research into the desirability of new aesthetic
= An LCA comparison between a production cycle using 3D weaving and a conventional production cycle.

During this project in all the prototyping stages and due to the repeat in the loom many fabric metres were produced. I wanted to mention that the materials will come to good use. I will integrate them into other projects and maybe they will be used to teach others about 3D weaving.

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Figure 6. Levi's type 3 denim jacket. https://stridewise.com/type-1-vs-type-2-vs-type-3-denim-jackets/

Figure 11. Circular economy systems diagram by Ellen MacArthur Foundation (2019). https://ellenmacarthurfoundation.org/circular-economy-diagram

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Figure 22. Garment woven jeans in indigo cotton by Kelly Konings. https://kellykonings.com/textile-design-projects/

Figure 23. Geometric shapes object from flat-woven textile by Leonie Burkhardt. https://www.leonieburkhardt.com/geometrical-construction

Figure 24. Flat knitted tube from A-POC collection by Issey Miyake https://u1123683.wordpress.com/2012/03/15/150/

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Figure 26. Heat sealed coat by Andrew Bell. (Instagram @adrew_bell___)

Figure 27 & 28. Gestalt Process by Jacqueline Lefferts. http://www.jacquelinelefferts.com/#/gestaltprocess/

Figure 29. Dress by Linda Dekhla. https://www.notjustalabel.com/linda-dekhla

Figure 30. Seamless 3D woven pants made by a machine that 3-D-weaves yarn by Unspun. https://time.com/collection/best-inventions-2021/6114413/seamless-3d-woven-pants/

Figure 31. 3D woven trousers by Weffan. https://theweaveshed.org/3064/weave-designer-profile-graysha-audren-founder-weffan/weffan_jean-jacket_weaveshed/

Figure 32. Jacket by Stem using Stem's zero-waste textile system. https://www.stem.page/product/shirt-with-fringes-edition-1

Figure 33. Stem x Ganni zero waste jacket.
https://www.stem.page/collaborations/ganni-x-stem

Figure 35. Pattern drawing inspiration found on pinterest.
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