# DESIGN FOR SUSTAINABLE FASHION:
## 3D weaving for denim jeans production

Integrated Product Design Msc. Graduation Thesis by Jordan Groskamp

| 0% | 25% | 12 OZ | 0% | 40% | 100% |
| --- | --- | --- | --- | --- | --- |
| WASTE | LESS WATER | CO/HEMP 30% | PLASTIC | LESS SEWING | RECYCLABLE |

This project developed 3D woven 5 pocket denim jeans to showcase the potential benefits of this holistic approach to fashion design. 3D Weaving can minimize waste, maximise efficiency and provide unique opportunities for the industry

*These claims are estimations based on project results, for further explaination please find the full report in the TUDelft Repository

DIAMONDENIM ENDRIME STUDIO GROSKAMP TUDelft

TUDELFT MSC GRADUATION PROJECT BY JORDAN GROSKAMP, UNDER SUPERVISION OF HOLLY MCQUILLAN AND MILOU VOORWINDEN.

# Abstract (TL/DR)

The fashion industry is facing complex environmental challenges, and a need for change is prevalent for the industry to move towards circular economies. 3D weaving emerges as an innovative approach to garment design and production, allowing for novel processes that capture the opportunities missed by current linear systems. 3D weaving of integrated multilayer Jacquard fabrics for denim garments shows potential for increased efficiency, reduced environmental impact, new design avenues and unprecedented levels of automation in future processes.

This project sets out to research the practical application of 3D weaving for the sustainable design and production of denim garments. It explores the opportunities, limitations and execution of 3D weaving for creating a pair of 5-pocket denim jeans in existing supply chains. This report of the process acts as a practical guide for further adoption of 3D woven denim in academia and the industry. A production prototype is developed to showcase the benefits of 3D weaving for denim design and production, while also evaluating the implications of this particular zero waste design for 3D weaving and the industry as a whole.

Evaluation of the design results suggests that this application of 3D weaving could potentially: Reduce stitch length by 40%, reduce pre-consumer waste by 20%, reduce water usage by 25%, eliminate the use of microplastics and become 100% recyclable. Further improvements are expected when the technology finds further adoption in the industry. A majority of industry respondents (n16) expressed interest in the technology, estimating that commercial application is feasible within the next 3-5 years with a production price increase that does not exceed 25% compared to conventional denim jeans. Further potential lies in tackling online returns, overstockage, made-on-demand systems, user customization and further optimization of the technology for increased efficiency and reduced cost.

Overall, 3D weaving presents itself as a new fundamental tool in sustainable fashion design, requiring new levels of expertise and industry alignment. Further, while future research and development help to overcome limitations in the process of 3D weaving, the proof of concept presented in this report concludes that this process can already be done with existing machinery.

Innovations such as 3D weaving may find resistance while gaining wider adoption as their implications require a major shift in current processes, often straying away from common practices that feel safer from an economic perspective. Mitigating some of the risks through development in academic settings may help to persuade businesses to adopt pivotal methods like 3D weaving sooner, as the groundwork has already been done. This underscores the need for academic research through projects focussing on sustainable design and innovation.

*Design for sustainable fashion: 3D weaving for denim jeans production.*
*by Jordan Groskamp*

MSC. INTEGRATED PRODUCT DESIGN | TECHNICAL UNIVERSITY OF DELFT
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# Preface

Although I've gained so much expertise throughout this project, it could not have been done without the incredible help and support from the team involved. I want to thank you all for the amazing experience and I am eternally grateful for working on this topic with you. Challenging the industry with innovative new perspectives on sustainable practices is no joke, yet with you it became so much more enjoyable than I would've imagined. If anything, I'm more motivated than ever to drive innovative and sustainable change.

Holly McQuillan, if it weren't for you I wouldn't have been introduced to the world of sustainable fashion design and 3D weaving. Let alone dare to tackle the problems the industry faces these days. It was through your research and expertise that I was inspired to explore the potential of 3D woven denim jeans for my graduation project. I could not have wished for a better chair.

Milou Voorwinden, your expertise in weaving technology and continuous support as a mentor has been invaluable throughout this project. This project could not have been done without your extensive knowledge of Jacquard weaving. Your knowledge and guidance have helped shape and refine my ideas, pushing me to explore new possibilities in sustainable fashion design.

Diamond Denim, it was an honour to work with you on this project. Your commitment to innovation and pushing the boundaries of denim production has been truly inspiring. I am grateful for the opportunity to collaborate with your team, as it has allowed this project to showcase production-ready 3D woven denim jeans as a driver for sustainable change in the fashion industry.

Mohsin, your endless knowledge and expertise in denim design have been integral to the success of this project. Your input has driven this project to new heights, ensuring that the 3D woven denim jeans created are not only sustainable but also stylish and marketable.

Barbara & Sterre, your previous projects have provided a solid foundation to build upon, and I am grateful for your insights and efforts on the topic of 3D weaving.

# Glossary

***Words** - definition in this project*

**3D Weaving** - The process of creating multi-layered Jacquard woven fabrics. (This term is used for brevity throughout the project, although it's not an entirely correct term according to technical weaving literature).

**Circular economy** - An economy where product life cycles are without waste streams.

**CLO3D** - Digital garment design software.

**Cut & Sew** - Production model that utilises conventional cutting and sewing for garment assembly.

**Design for disassembly** - Designing a product in such a way that it can be easily disassembled for recycling or repair.

**Dope dye** - Dyeing fibres before extrusion.

**MOB** - Map of bindings, comparable to “artwork” in conventional weave design.

**Illustrator** - Graphic design software from Adobe.

**Industry 4.0** - Integration of intelligent digital technologies into manufacturing and industrial processes.

**Iterative design** - The process of gradually advancing a design concept through cycles of development, testing, evaluation and refinement.

**Jacquard** - Category of industrial looms with individually programmable picks.

**Kingpins** - Global denim trade show.

**LCA** - Life cycle assessment.

**List of layer bindings (LOB)** - Documents that match weave structures and their assigned colours for MOB.

**Localised production** - Production model where material, product and sales originate from closeby geographical locations.

**Made-on-demand** - Production model where products are created after ordering.

**NedGraphics** - Software for programming Jacquard looms.

**Over-stockage** - Retail inventory that is not sold.

**Parallel Prototyping** - Simultaneously developing variations of the same prototype.

**Parametric design** - Algorithmic manipulation of variables in a design.

**Picks** - Individual hooks in a Jacquard loom that hold and manipulate warp threads.

**Reed** - Part of the loom that spaces warp threads, guides shuttle motion and pushes weft threads into place.

**Repeat** - The width of the fabric on a Jacquard loom that can be individually programmed.

**RtD** - Research through design, a research method that gathers new knowledge through the development of artefacts.

**Tech Pack** - Combined file of technical drawings specifying design dimensions and details for the manufacturer.

**Triple bottom line** - Evaluation of business through economic, social and environmental perspectives.

**User-customization** - Production model that allows consumers to alter products to their specific needs.

**Warp count** - Number of vertical warp yarns in picks/cm.

**Weft count** - Number of horizontal weft yarns in ends/cm.

**Yarn thickness** - Diameter of yarns (expressed in Ne).

**Zero waste (ZW) design** - Garment design method aiming to remove pre-consumer production waste.

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# 1. Introduction

To gain an awareness of the challenges that can be tackled by 3D woven design, an understanding of the complex nature of the fashion industry is needed first. This section sets up the context, scope and objectives for this project. A big-picture view is provided of the problems that the industry faces as a whole, after which the scope gradually zooms in on denim jeans in particular.

## A. Background

Although the fashion industry's main focus is to make people look good while meeting fundamental needs of warmth and social acceptability, how this is done doesn't always make the industry itself look good. It's needless to say this industry is not positively impacting the environment, but just to put things into perspective, here are several key numbers.

For every second that passes, about the volume of one garbage truck of textile waste is dumped into landfills (The Roundup, 2022). This number is unfortunately not surprising, considering that the fashion industry created 109 million tonnes of textiles in 2020 (Statista, 2023b). To worsen the situation, 80% of all clothing sold in the EU ends up in landfills (The Business of Fashion, 2018). 30% of clothes produced each season are never even sold according to the World Cleanup Day Organisation (2022).

Clothing is also massively underutilised, with clothing utilisation halving between 2000 and 2015 (Fig. 1), while the number of garment purchases by the average consumer increased by 60% (Remy et al., 2016). A consequence of fast fashion is quickly alternating styles, an increasing number of collection 'drops' every season  and cost-related optimization devalues the clothing consumers buy (Pérez et al., 2021), driving consumerism at the expense of people and the planet. This makes the relevance of a triple bottom line perspective in this industry especially interesting, where the impact of business should be considered in parallel with the social and environmental impact.

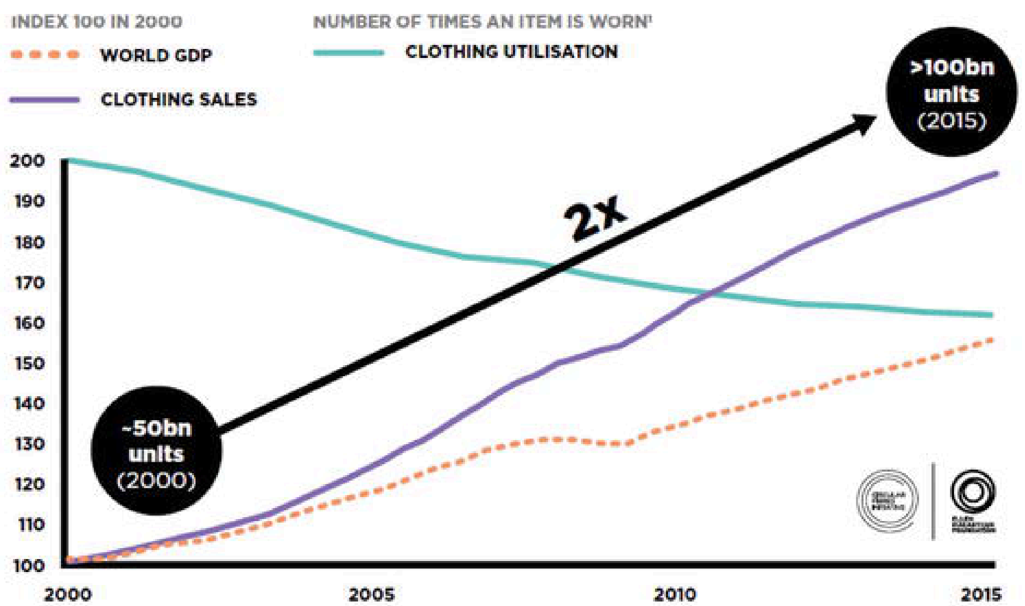



*Figure 1: Graph on clothing utilisation and consumer behaviour  (Ellen MacArthur Foundation, 2017)*

Even though the environmental impact per garment has decreased, the overall negative impact of the industry has increased as a consequence of these fast fashion practices (WRAP, 2023) (ref). This indicates that just making garments more sustainable isn't a net benefit, as it does not address the underlying issues of overconsumption and excessive waste generation (Wu & Li, 2020). The fashion industry is facing significant environmental challenges, including high levels of textile waste, underutilization of clothing, and the excessive use of resources and harmful production processes. To overcome these challenges, innovative solutions are needed in the fashion industry (Bick et al., 2018). Peters et al. (2021) highlight the importance of strategies that reduce impacts in the materials and production phase. The non-linear relationship between profit and sales is also mentioned, suggesting higher prices are justified when the quality and durability of garments return to pre-fast-fashion states.

To address the complex nature of the above-mentioned environmental issues, this project focuses on showcasing the potential of 3D weaving as a driver for sustainable change in the fashion industry. This innovative means of production re-evaluates the development of woven garments, navigating new approaches to design and production. A circular textile economy requires elevated levels of industry alignment according to the Ellen MacArthur Foundation (2017), achieving this demands a novel system-level approach which captures the opportunities missed by current linear systems.


Circular design is an important enabler of the transition towards sustainable production and consumption of textiles. The design phase plays a critical role in achieving a circular textile economy in all four quadrants: Longevity and durability, Optimised resource use, collection and reuse, recycling and material use (European Environment Agency, 2022).

3D weaving proposes a systematic restructuring to reduce waste and promote circularity in the fashion industry. It also evaluates increased production automation within current supply chains and the future potential for made-to-order garments. This is why 3D weaving is especially promising to drive change in the design and production phase of circular economies as can be seen in figure 2.

*Figure 2: The circular economy model (European Parliament Research Service, 2023)*

By utilising 3D woven design and production, this project sustainably redesigns a pair of 5-pocket denim jeans. The global denim jeans market value in 2023 was 66.5 billion US Dollars (Statista, 2023a), which highlights its role as both an iconic fashion staple, and a major contributor to environmental pollution. 3D woven design and production offers an alternative view on garment production processes and creates jeans that are not only fashionable and durable, but also sustainable and innovative. This report documents the potential, limitations, methodology and results of production-optimised 3D weaving within existing supply chains.

This project aims to address the alarming statistics surrounding textile waste through novel 3D woven design methods that utilise multi-layered integrated fabrics in parallel with zero waste practices and sustainable industrial design engineering.

## B. Research Objectives and Scope

3D weaving is an innovative production process that interweaves multiple layers of fabrics in a single blanket, enabling cost-effective production with better-quality materials. The main goal of this project is to showcase sustainable fashion design through the use of 3D woven denim jeans and examine their potential for reducing the environmental impact of traditional denim manufacturing. This will be achieved through the following objectives:

**1. Research challenges and opportunities for 3D weaving to drive sustainable change.**
Conducting a comprehensive literature review on the environmental impact of traditional denim manufacturing, including the use of harmful chemicals, water consumption, and waste generation.

**2. Define the impact of traditional jeans and points for improvement**
Analysing the life cycle of denim products to identify key areas for reducing environmental impact. An LCA comparison of common jeans (Levi Strauss & Co, 2015) will be used to assess the environmental impact post-design and guide decisions during the design of the new garment.

**3. 3D woven 5-pocket denim jeans design and showcase**
Investigating the potential of 3D weaving technology in reducing the environmental impact of jeans by using sustainable materials, reducing waste, and improving production efficiency in a final production-ready design. 3D woven jeans will be designed in such a way that reduces labour and waste (Estimated goal of 20% of manufacturing cost and 15-25% waste reduction).

**4. Benefits and limitations of 3D weaving for denim jeans production**
Evaluating the environmental benefits and limitations of 3D woven denim jeans compared to traditional denim manufacturing.

**5. Industry evaluation**
Assessing the perception and interest of 3D woven denim jeans by industry professionals. Define opportunities for improvement and better alignment of the industry.

**6. Practical design guidelines**
Offer practical guidance on design for 3D woven denim, presenting a point of reference for future designers.

This project aims to showcase how the design of 3D woven denim jeans can significantly reduce the environmental impact of traditional denim manufacturing. 3D weaving shows potential for reduced environmental impact when its practical application facilitates minimised waste, maximised efficiency and integration of sustainable materials. By demonstrating this ecological application of 3D weaving for denim, the project aims to raise awareness about the potential of 3D weaving technology in the fashion industry and inspire designers and manufacturers to adopt more sustainable practices.

By doing so, this project tackles important ambitions for a circular fashion economy as described by the Ellen McArthur Foundation (2021).

1. Phase out hazardous substances and minimise microfibre release, ensuring safe material cycles.
2. Transform clothing design, sales, and usage patterns to encourage longevity and reduce disposability.
3. Improve recycling processes, with clothing designed for this purpose and more efficient collection and reprocessing systems.
4. Utilise resources wisely, moving towards renewable inputs wherever possible.

This project has partnered with Diamond Denim, a vertically integrated Pakistan-based denim manufacturer that facilitates Jacquard woven production and has supported the research for multiple years now.

# 2. Context Review

This chapter dives into the insights gained from literature related to sustainable fashion, 3D weaving, zero waste design, and other relevant topics. Current practices of the Denim industry are also examined, after which distinct opportunities for the implementation for 3D woven denim are articulated. Finally, the relevance of life cycle data is discussed for steering design decisions.

## A. Sustainable Practises in the Denim Industry

Conveying the value of sustainability to consumers remains a challenge for many companies committed to eco-friendly practices. Despite these efforts, the fashion industry stands as the second-largest polluter globally. Fast fashion amplifies the problem by encouraging excessive consumerism, leading to the devaluation of clothing and generating vast amounts of fashion waste.

A staggering 80% of textiles end up in incinerators or landfills (The Business of Fashion, 2018), highlighting the urgency for change. From the small percentage that is recycled, large parts have to be manually disassembled in order to separate the viable materials for mechanical recycling. For denim jeans, the removal of rivets, zippers, buttons and even patches can be very labour-intensive (Åslund Hedman, 2018). Communications with recycling representatives at Kingpins suggest that this often results in the removal of the whole top section of the jeans, using just the legs recycling. Waste also occurs during the garment production process, and about 20% of denim textiles are commonly wasted pre-consumer (Make Fashion Better, 2023). This highlights the importance of reflecting on all environmental inputs and output of a garment when applying waste reducing techniques (Fig. 3), particularly with innovative methods like 3D weaving.

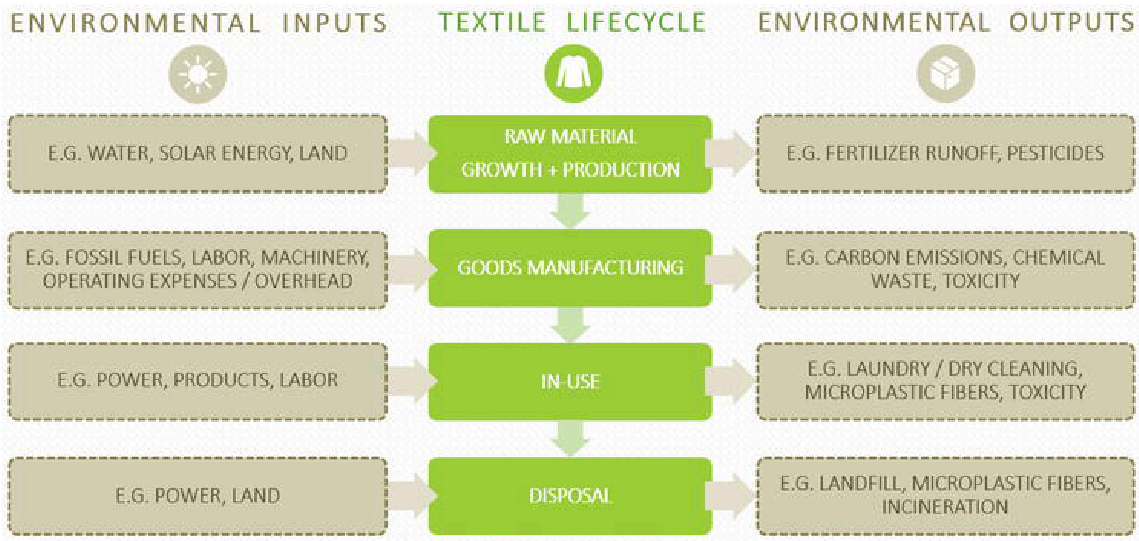



*Figure 3: Environmental inputs and outputs a textile's lifecycle. (Wu & Li, 2020)*

Though a small percentage of textiles is recycled, the majority undergoes a cascaded circular economy process, resulting in degradation into lower-quality products. Just 1% of clothing is recycled into new clothing. Synthetic fabrics, increasingly more commonly found in jeans, reduce their potential for recycling and contribute to microplastic pollution. This poses unforeseen risks to ecosystems with a reported 1900 plastic fibres shedded with each garment's wash (Browne et al., 2011). Renewable, biodegradable and recyclable materials should be prioritised for the industry to mitigate its environmental impact and promote a circular economy.

Blended fibres present challenges in recycling due to difficulty in separation, making mono-material compositions preferable. Companies like Renewocell and Spinnova are exploring methods to address this issue, initially focusing on cotton, the industry's predominant material. These innovative approaches not only enhance recyclability but also contribute to the development of sustainable alternatives in the textile industry. (Periyasamy & Periyasami, 2023)

Despite cotton's recyclability and biodegradability, it poses environmental challenges, requiring significant water, land, and fertiliser for cultivation. In contrast, hemp emerges as a promising alternative with considerably lower environmental impacts if processed correctly. Hemp requires minimal water and land, exhibits antimicrobial properties, and boasts high durability (Alverink, 2015). Employing biomimicry in the degumming process reduces environmental harm even further, utilising natural saltwater osmosis to separate fibres without harmful chemicals.

Additionally, regenerated cellulose-based fibres from brands such as Tencel offer sustainable alternatives with unique properties. Future potential awaits in the further implementation of industry 4.0 like automated laser cutting of patterns, parametric design for made-to-order jeans and customised low-impact fabric dyeing and washing techniques (Periyasamy & Periyasami, 2023). These advancements not only reduce environmental impact but also offer opportunities for customization and efficiency in garment production.

## B. Opportunities and Limitations of 3D Weaving

The term 3D weaving is used throughout this report to refer to the creation of multi-layered woven fabrics, but the more accurate terminology would be Jacquard woven textile-form (McQuillan, 2020). Not all 3D weaving results in 3D textile-forms (E.g. El-Dessouky & Saleh, 2018), and not all textile-forms are 3D woven on Jacquard looms (McQuillan & Karana, 2023). For the sake of brevity, this report refers to the process of multilayered woven fabric design and production of textile-forms as 3D weaving.

Industrial jacquard looms are advanced weaving machines that can create complex weave structures through the use of multiple sets of individually controlled yarns, which can be applied to embed three-dimensionality in woven fabrics in a variety of ways (Walters, 2021). Manipulating the program in these looms allows for the creation of multi-layer woven fabrics with unique textures, composites and forms (Piper, 2019). These fabrics can provide innovative solutions in terms of design, production, and sustainability in the fashion industry. They can be used to interweave pattern pieces of a garment without the need to manually sew them, for example by weaving the entire pant leg as displayed by the left example in figure 4.

The use of 3D weaving technology in sustainable fashion design has the potential to revolutionise the industry by integrating unique fabric structures that minimise waste, maximise efficiency and promote sustainable production. Related work by Vroom (2022) provides proof of concept that 3D weaving can be applied to create denim jackets, providing an excellent foundation for the further embodiment design of consumer-ready denim jeans. The trouser experiment from zero waste systems thinking: Multimorhpic Textile-forms between Voorwinden and McQuillan (2020) also provides a reference for the application of 3D weaving for zero waste trouser design, inspiring novel approaches to pattern design for 3D weaving. Further implementation of digital 3D design methods as a tool for augmenting zero waste practises (McQuillan, 2020b) allows for an iterative approach to sustainable garment design. These researchers have explored the use of 3D weaving to create garment concepts with minimal waste. Their insights provide a solid foundation for this project to further develop and refine the application of 3D weaving into a commercially viable design solution for sustainable denim jeans production.

*Figure 4: 3D woven trouser experiment 2 by McQuillan (2020) and Voorwinden, 3D Woven Denim Jacket by Barbara Vroom (2022)*

Key concepts that are relevant for the sustainable implementation 3D weaving are considered here:

**1. Circular economy:** This concept focuses on designing out waste and pollution, keeping products and materials in use for as long as possible, and regenerating natural systems to create a sustainable and circular textile economy (Ellen McArthur Foundation, 2017). This urges the industry to move away from linear models as simplified in figure 5. Here, the advancements of 3D weaving in production efficiency can be leveraged for reduced waste and more sustainable material selection. Besides this, the design implementation of 3D woven denim jeans considers the end of life from the beginning, limiting constructions that negatively impact recyclability.

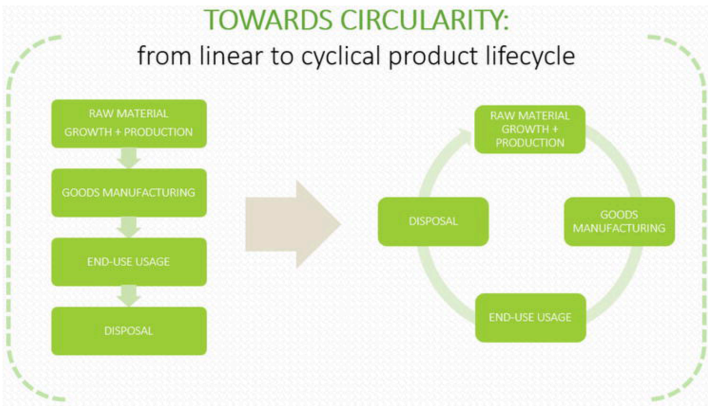



*Figure 5: linear to cyclical product lifecycle (Wu & Li, 2020)*

**2. Systems thinking:** This approach considers the interconnectedness and interdependencies of various elements within a system, such as the fashion industry, and seeks to understand the complex interactions and impacts of these elements on sustainability. Through systems thinking, we can analyse how 3D weaving technologies can disrupt the linear and wasteful textile system by reducing waste, and minimising resource consumption. Related work by Sterre De Jager (2023) highlights how analysis through such system-oriented strategies can unlock the future potential of 3D weaving. A systematic evaluation of each aspect of the jeans design and production process allows to guide possible improvements for 3D weaving as a system.

**3. Sustainable materials:** The use of sustainable and eco-friendly materials in the fashion industry, such as hemp, organic cotton, or recycled fibres, is crucial for reducing the environmental footprint of clothing production. Incorporating sustainable materials (Figure 6) into 3D woven denim jeans can help minimise the impacts associated with its production. Organic hemp compared to cotton requires no pesticides, uses 1/20th of the water and 1/4th of the land according to hemp-copenhagen (n.d.). Hemp is also up to 4 times softer, 3-8 times stronger, more durable, flame retardant and unaffected by UV rays according to Alverink, J. (2015). It has antimicrobial properties, excellent thermal and moisture-absorbing properties, potentially reducing the need to wash the jeans frequently and conserving water. Using low-impact cellulose-based yarns, be it organic hemp, recycled cotton or regenerated fibres, allows for a significant decrease in resources for fibre production. Since this implementation of 3D weaving happens in a vertically integrated supply chain, there is room for experimentation with such sustainable materials to optimise fabric quality.

**MADE-BY** ENVIRONMENTAL BENCHMARK FOR FIBRES

www.made-by.org

| CLASS A | CLASS B | CLASS C | CLASS D | CLASS E | UNCLASSIFIED |
|---|---|---|---|---|---|
| Mechanically Recycled Nylon | Chemically Recycled Nylon | Conventional Flax (Linen) | Modal® (Lenzing Viscose Product) | Bamboo Viscose | Acetate |
| Mechanically Recycled Polyester | Chemically Recycled Polyester | Conventional Hemp | Poly-acrylic | Conventional Cotton | Alpaca Wool |
| Organic Flax (Linen) | CRAILAR® Flax | PLA | Virgin Polyester | Generic Viscose | Cashmere Wool |
| Organic Hemp | In Conversion Cotton | Ramie | | Rayon | Leather |
| Recycled Cotton | Monocel® (Bamboo Lyocell Product) | | | Spandex (Elastane) | Mohair Wool |
| Recycled Wool | Organic Cotton | | | Virgin Nylon | Natural Bamboo |
| | TENCEL® (Lenzing Lyocell Product) | | | Wool | Organic Wool |
| | | | | | Silk |

More Sustainable — Less Sustainable


bwe This Benchmark was made in cooperation with Brown and Wilmanns Environmental, LLC. For further information on this Benchmark see www.made-by.org/benchmarks

*Figure 6: Environmental benchmark for fibres (Made-by, 2015)*

**4. Life cycle assessment:** LCA is a method used to assess the environmental impacts of a product throughout its entire life cycle, from raw material extraction to end-of-life disposal. Knowledge about life cycle assessment could accelerate the transformation towards a more sustainable fashion production system (Van der Velden, 2016). By examining LCA data from a standard pair of jeans (LEVI STRAUSS & CO, 2015), the 3D woven jeans can be designed in a way that limits the environmental impacts associated with its production. This includes factors such as embodied energy, water consumption, eutrophication, and land occupation (Peters et al., 2021).

**5. Design for disassembly:** This concept focuses on designing products in a way that allows for easy disassembly and recycling at the end of their life cycle, which is relevant to consider during the redesign process for 3D woven jeans and their hardware. Design for disassembly ties in with circular economies for fashion (Ellen McArthur Foundation, 2017) as it aims to prevent cascaded recycling by promoting the separation of materials at the end of life. This can be applied during garment design by avoiding composite materials and parts that are difficult to recycle or separate, ensuring material qualities can remain adequate when recycling.

**6. Zero waste design:** This design approach aims to minimise waste by utilising every piece of fabric and eliminating excess materials during the production process. Zero Waste Fashion Design (Rissanen & McQuillan, 2023) provides foundational knowledge on zero waste history and principles for garment design. 3D weaving provides a new frontier for integrated zero waste pattern design, which propels the potential environmental benefits of 3D weaving even further. The t-shirt experiments for zero waste design and 3D weaving, or composite garment weaving, by McQuillan (2019) illustrate potential applications of multi-layer weaving for waste reduction. The discipline of zero waste design has been implemented from the start of this project, and while it might not completely eradicate pre-consumer waste, it should provide a significant reduction.

**7. On-demand manufacturing and consumer customisation:** This approach involves producing garments only when there is a demand for them, reducing overproduction and waste. It also allows consumers to customise their garments, increasing their experience and appreciation, leading to longer garment lifespans and reduced waste. VEGA (Unspun, n.d.) applies proprietary 3D weaving techniques for this purpose, showcasing how new systems allow for further automation of processes.

**8. Localised automated production and sourcing:** By producing garments closer to the consumer and sourcing materials locally, the fashion industry can reduce carbon emissions associated with transportation and support local economies. Besides this, other source materials such as hemp can be grown in more versatile regions, depleting fewer water resources, further decreasing stress for local environments. (Averink, 2015). The combination of locally source-able materials with 3D weaving's potential for automated production provides a new perspective from which to consider existing supply chains.

**9. Industry collaboration and partnerships:** Encouraging collaboration between fashion brands, manufacturers, suppliers, and other stakeholders can facilitate knowledge sharing, resource pooling, and the implementation of sustainable practices throughout the fashion supply chain (Niinimäki et al., 2020). As this project is also a collaboration between academic research, practical design and industrial production, it should allow for 3D weaving to be implemented with insights from all three perspectives. This report aims to promote further collaboration with 3D weaving and the industry, so that this fundamental new approach to garment design and production gains wider adoption.

By incorporating these key concepts into the production of 3D woven denim jeans, a truly sustainable and innovative garment can be created that promotes production efficiency, user desirability and minimal environmental impact. Navigating these concepts during a design process can be quite a balancing game, the implementation of these concepts is further documented in Chapter 4: Design and Innovation.

# C. Environmental Impact of Jeans

This review will assess the environmental impact of conventional denim production and compare it to the potential environmental benefits of 3D woven denim jeans. This process uses a comparative life cycle assessment to identify missed opportunities in conventional production. This comparison will consider factors such as energy consumption, water usage, greenhouse gas emissions, chemical usage, and waste generation associated with conventional garment production.

Analysing the Life Cycle Assessment (LCA) of a typical pair of jeans (Levi Strauss & Co, 2015) reveals areas for improvement. Metrics such as embodied energy (33.4kg CO2-e), water consumption (3,781 litres), eutrophication (48,p g PO4-e), and land occupation (12m2/year) provide insights into the environmental impact of denim production, informing strategies for sustainable innovation in the industry. Looking at the carbon emissions per stage also informs critical contributors to a garment's environmental impact, suggesting source material has the biggest contribution as can be seen in figure 7. The production life cycle of jeans consists of three main processes: Cutting, sewing and finishing. (Åslund Hedman, 2018).


*Figure 7: The carbon footprint of clothing in the UK (WRAP, 2017)*

It is important to consider that the fashion industry is plagued with untransparent sustainable practices, making it fairly difficult to acquire objective data on the environmental impact of new processes. In this instance, the quality of data is highly dependent on the supplier's calculations. Public sources, or databases such as CES Edupack, can indicate material impacts. However, due to the complex nature of fashion supply chains, these sources lack sufficient tracking and give just a mere indication.

**3D weaving could address and mitigate environmental issues in several ways**:

- By using sustainable and eco-friendly materials, such as hemp or organic cotton, in the 3D weaving process, the environmental impact of material production can be significantly reduced. This also minimises the use of harmful chemicals and pesticides that are commonly used in conventional denim production.

- By utilising the principles of circular economy, 3D weaving can optimise material usage and minimise waste during the production process. This potentially reduces the necessity of new material production and limits the amount of waste that ends up in landfills or pollutes waterways.

- By incorporating design for disassembly principles, 3D woven denim jeans can be constructed in a way that allows for easy disassembly and recycling at the end of their life cycle. This can be done by using recycling compatible or mono materials, and designing the jeans with detachable components and limiting their general use.

- Limit production steps and manual labour through integration and automation of production processes. This not only improves production efficiency but also reduces the potential for worker exploitation and poor working conditions. By implementing these strategies, 3D woven denim jeans can significantly reduce their environmental impact compared to conventional denim production. Made-on-demand customised garments also hold future potential for limiting overstockage and online returns. Both are large contributors to the environmental impact of a fashion garment, but often not considered in traditional LCA calculations. 30% of clothing gets thrown out without ever being sold, and just 60% of inventory is sold at full price (Coresight Research, 2019). It's important to reduce the environmental impact per garment, but it's even more valuable to reduce the environmental impact of the entire supply chain in a way that limits this unnecessary waste.

This review of the industry's problem context helps to inform design decisions while implementing 3D weaving for denim jeans production. Insights from sustainable design principles further help to position 3D weaving for emerging circular economies. The large impact of fibre sourcing merits practices that explore reduced pre-consumer waste, less environmentally stressful materials and overall retention of materials for as long as possible. This includes creating assemblies that are, recyclable, and in case of disposal, also biodegradable and renewable. Consequences of this are the elimination of polyester-based materials, as well as overall hardware reduction that also allows for end-of-life disassembly. Besides this, the resulting design should strive to utilise 3D weaving's benefits for increased production efficiency while promoting further adoption by (automated) circular supply chains.

# 3. Methodology

This chapter describes the design practices and research methods that were applied in this project, as well as the reasoning behind their selection.

## A. Research and Design

The design research methodology of this project is an iterative approach to research through design. As this project explores methods of research through design, the project aligns with RtD principles documented by the Interaction Design Foundation (n.d.) as follows:

- **Knowledge**: Principles, design techniques, opportunities and limitations of 3D weaving for (sustainable) garment manufacturing in existing supply chains.
- **Artefacts**: 3D woven 5-pocket denim jeans, prototypes, production samples.
- **Learning**: Design experiments (lab, field), expert interviews, and professional surveys.
- **Sharing**: Academic publications, exhibitions, presentations and portfolio.
- **Context**: MSc Integrated Product Design.

This allows for the execution of practical design and development of a potentially commercial product, while still innovating further on 3D weaving and contributing new knowledge to the field of 3D woven production. This project builds upon previous knowledge generated through the projects by Vroom (2022), Voorwinden and McQuillan (2020), providing a reference point for the current capabilities of 3D weaving. This work provides an excellent foundation for this project to push production techniques and embodiment design to new frontiers for 3D woven jeans. The physical 5-pocket denim jeans prototype is developed to examine the current opportunities and limitations of 3D weaving, and the iterative development of the design itself is an experiment to push the technology further towards commercial applications. The design will be evaluated through the innovation lenses of human-centred design; business viability, people desirability, and technological feasibility. The process will be evaluated by the addition of new findings to the body of knowledge that is 3D weaving. Finally, the overall project considers the pillars of sustainable design through every step.

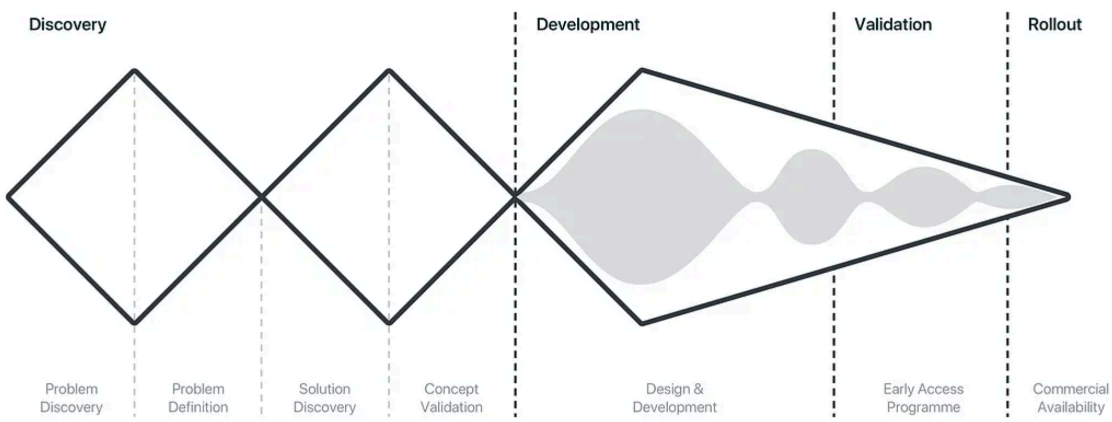



*Figure 8: Triple Diamond design process (Zendesk, 2021)*

The design development resembles the triple diamond development model, and uses 3 iterative stages of divergence and convergence marked by 3 levels of prototypes. The visualisation of these stages varies between projects, but for this project, the triple diamond process by Zendesk (2021) in figure 8 applies to a large extent. Key prototypes, as well as several other experiments, were executed in these stages to test the current technology. These key prototypes served the following purpose:

1. **Cut & sewn prototype:** Integrating design criteria through mimicking of 3D woven behaviour using 2D fabric. This prototype was used to test the dimensions and assembly of the jeans, as well as gather feedback from Holly McQuillan to optimise fit while maintaining the zero waste pattern. A design workshop was also held with denim expert Mohsin Sajid to gain insights into detail design using this prototype as a reference.
2. **3D woven concept:** This prototype embodies the first attempt to create 5-pocket denim jeans through 3D weaving. It was created by adapting the 2D pattern for integrated woven seams, as well as adjusting the pattern for fit and efficiency. It was used to test the design for manufacturability, ease of assembly and overall quality. The concept provided positive results, as well as key opportunities to further refine the jeans.
3. **3D woven iteration:** This prototype run adapts the design for better fit, improved level of quality, and fewer production steps. It also translates the design to different sizes, accounts for shrinkage due to fabric finishing, and tests several design elements using multi-layer jacquard denim patterns.
4. **Sample blankets and test files**: Several samples were created throughout all 3 stages to test further opportunities of 3D woven production techniques. These applications include testing 4-layer constructions, testing for shrinkage, design opportunities and further experimentation with weave structure settings.

The research and development of these prototypes are discussed in further detail in chapter 4. These prototypes were used to iteratively and simultaneously test various design possibilities, and narrow the concept down to its commercially plausible showcase. Please refer to chapter 5 and 7 for the final design and key insights.

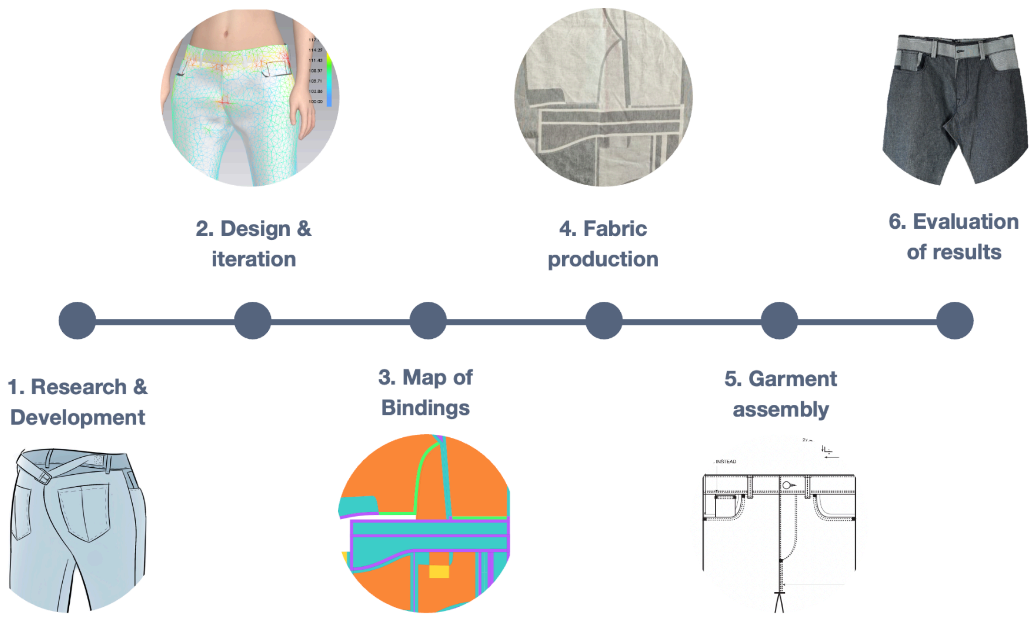
## B. Data Collection and Analysis

This section describes the data sources, data collection methods, and tools used for this research. The methodology for this project involved a combination of primary and secondary data sources. Primary data was collected through interviews and surveys with industry professionals, designers, and researchers to gather insights on current practices in the fashion industry, as well as the specific challenges and opportunities related to prototype design for 3D weaving. A detailed description of industry evaluation can be found in chapter 4. Stage 6: Evaluation.

Secondary data was collected through a comprehensive review of sources, which included academic papers, industry reports, and case studies on sustainable fashion design, 3D weaving technology, and the environmental impacts of conventional denim production. The primary data provides first-hand insights from key stakeholders in the fashion industry, ensuring the project's practical applicability. The secondary data provides a comprehensive understanding of the existing knowledge and practices in sustainable fashion design and 3D weaving. Additionally, this project employed tools such as design thinking, brainstorming and prototyping to iteratively develop and refine the concept of 3D woven denim jeans. These tools were chosen as they facilitate a collaborative and iterative approach to problem-solving, allowing for the exploration of different perspectives and ideas, as well as the evaluation and refinement of design concepts. Besides these data sources, techniques such as digital drawing (Procreate and Photoshop), graphic design (Illustrator), traditional pattern design and digital fashion design (Clo3D) were used to shape the design according to insights resulting from analysis.

# C. 3D Weaving Design Process

The design process for a 3D woven garment in this project consists of 6 consecutive stages, which are individually explained in this chapter. Their practical implementation of 3D woven design is discussed in the next chapter.




The process starts with identifying the possibilities and limitations of 3D weaving for denim jeans within the current supply chain. This is done through researching the available machines and testing variations in weave structures and materials. The result of which provides a set of design limitations, such as fabric repeat size and total width, warp picks/cm. Also, the desired weft yarn count, yarn thickness and fractional layer density should be tested for machine and material compatibility. In short, the first stage of the design process involves identifying the technical limitations and possibilities of 3D weaving for denim jeans within the existing supply chain through sample production, testing, and analysis. The result of this stage is a list of layer bindings (LOB) and characteristics which act as the colour palette for the map of bindings, which is retrieved from a produced sample blanket.

The second stage is the research inspiration stage, where the designer explores various sources of inspiration to inform the design concept. This may include studying trends in conventional fashion design, as well as zero waste pattern design and experimentation with translating conventional jeans with 3D woven folding structures. This phase considers the design legacy of denim jeans and iteratively develops a concept that balances familiar product characteristics with innovative design opportunities. This process manifests through sketches, digital pattern design using Clo3D, and cut-and-sew prototypes that mimic 3D weaving in their construction. The result of this stage is a garment design with an accompanying waste-optimised pattern, most commonly a PDF export of the simplified Clo3D file.

The third stage is focused on creating the map of bindings (MOB), which is an Adobe Illustrator file that combines the waste-optimised pattern design with the list of layer bindings. It acts as a guide to develop the NedGraphics file together with the weaving expert, the MOB indicates both pattern and weave structure in a single file which is used to program the jacquard loom.

The fourth stage is production and troubleshooting together with the manufacturer and involved stakeholders. Since this means of production has not yet had 150 years of optimization, this stage dedicated to optimising the design for production helps to reduce issues such as reed cuts, weft cracks, fragile layers etc. The result of this stage is a 3D woven roll of finished fabric that is about 25m, the minimum length to go through the fabric finishing process. This process increases the characteristics of the fabric, but does introduce shrinkage which has to be accounted for within the pattern design. The shrinkage varies tremendously between materials and structures, and although their behaviour could be estimated, the only way to determine average shrinkage over weft and warp respectively is to test it.

The fifth stage is garment assembly. The first garment is assembled by the designer, which yields insights on construction that are to be incorporated into the assembly guide. Depending on the development progress of previous iterations, this stage also defines the desired design details, dimensions and finishes in a tech pack. This tech pack acts as a reference for the assembly of the final garment. The result of this phase is the final garment, possibly including metal hardware and/or laser wash finishes.

The sixth and final stage of this project is the evaluation and presentation of results, which is not only done through this report. But also through presentations and surveys with industry stakeholders near the end of the project.

# 4. Design and Implementation

This is the heart of this research, where the execution of the practical aspect of this RtD project is documented, including visual representations, such as sketches, diagrams, and images of the design process. The concept, design process, and application of 3D weaving and zero waste principles to create the 5-pocket jeans are discussed. This chapter aims to provide a practical guide and reference point for 3D woven denim design.

## A. Stage 1: Research and Development

Without much knowledge currently available on 3D weaving, the beginning of this phase was used to dive into the details of working with jacquard looms, as well as inquiring practical insights on (sustainable) fashion design. Even though previous projects have yielded great concepts for 3D woven garments, there was much yet to discover for the creation of production-optimised 3D woven 5-pocket jeans.

**Yarn count and specifications**
First, basic knowledge of jacquard weaving and the desired requirements of the fabric were needed. To create an approximated [12 OZ] gauge fabric, the two-layer fabric should be a combined [24 OZ] fabric after finishing. To achieve this medium denim weight and feel, a twill structure was used over a 59.5 cm wide repeat (Fig. 9) with 40 picks/cm and Ne 10 ring spun indigo warp yarn, utilising a variety of weft yarn sizes, materials and ends/cm. Even though the resulting fabric has a denim look, it has distinct qualities such as its lighter tone, variable weave structures and raw denim behaviour on the unfinished insides of the multilayer fabrics. Further background information on yarn definitions is not included in this report, but Textile Yarns (Cottonworks, 2010) covers the above-used terminology.

| | |
|---|---|
| Total design hooks | 2400 |
| Ends/cm | 40.31 |
| Total fabric width in cm | 144.27 (42.385-59.5-42.385) |
| Repeat | 2400 Ends |
| Repeat in cm | 59.5 |
| Kind of repeat | One main repeat in the centre and two partial repeats on left and right |
| Warp count | From Ne 10 to Ne 80 |

*Figure 9: Jacquard specifications*

Further details of the garments were inspected by creating a sample blanket, housing these variations in yarn as well as various compositions for layered weave structures. The result is a roll of fabric consisting of unique squares, with each variation of structure, weft count and thickness included. Calculations were done as well in an attempt to predict the fabric weight, but due to non-uniform shrinkage between weave structures, this was a mere educated guess. Involvement from stakeholders, as well as the 3D woven denim jacket design (Barbara, 2023), provided a solid foundation for developing the samples. An example of the sample blanket can be seen in figure 10.

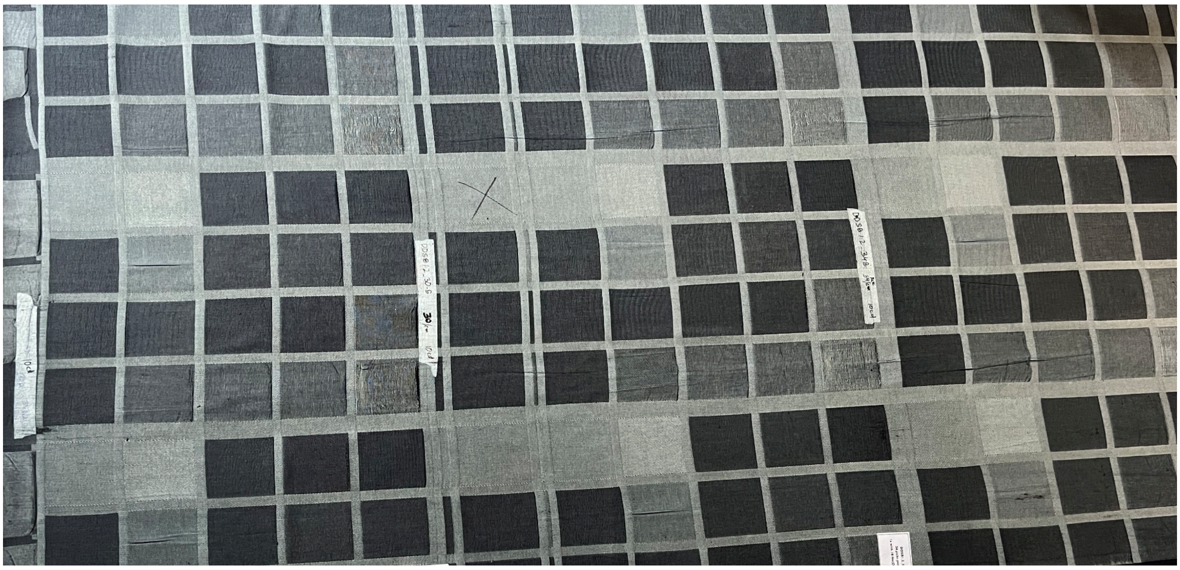


*Figure 10: Sample blanket variations*

**Material composition**

As indicated by previous research, the material sourcing, washing and processing have a tremendous impact on the environmental footprint of jeans. By introducing 60% hemp / 40 cotton blend weft yarns of Ne10, an approximate 30% organic hemp blend was achieved without any specialised tooling. This significantly reduces water, land, and chemical use at the fibre sourcing level with a slight increase in yarn spinning energy. No adverse consequence to the fabric feel or material behaviour was detected with this blend, but a higher percentage is currently not advised. A higher hemp percentage would require a new indigo-dyed warp, pose risks for the machinery and could result in a lack of structural integrity of the yarns. Further increase of sustainable fibre content can possibly be achieved by adding regenerated cellulose-based fibres from Tencel, and preferably dope dying these fibres to be used in the warp as well. These adjustments could considerably reduce the garment’s negative environmental impact further. Considering the majority of weft yarns are worn on the skin, both the antimicrobial and temperature-regulating properties of hemp are interesting to consider. This potentially decreases the need for frequent washing, but this is considered out of scope for the current project. Besides the pattern being of 100% renewable, recyclable cellulose -based fibres, it is important to account for material recyclability in the other jean parts. Often when jeans are recycled, removing hardware or trims is a manually intensive process. This leads to a majority of garments being cut into separate sections, if they’re being recycled at all.

After consultation with several professional representatives at the Kingpins denim trade show, the ability to recycle 60% hemp/cotton blended fibre in current cellulose-based fibre recycling processes could not be confirmed. However, there seems to be significant feasibility in future recycling techniques as processes exist that a) use agricultural waste streams, b) separate up to 5% of some foreign materials, and c) utilise other sources for regenerated cellulose-based fibre. Since 3D weaving expects adaptation over a longer timeframe, it was chosen to use the same weft yarn composition as proposed in Barbara’s project, as covered by McQuillan et al. (2023)

**End-of-life considerations**
To reduce negative end-of-life aspects, each detail of the jeans is reconsidered in the design phase. A full list of design criteria is presented in the next chapter, but key elements that must be obeyed are:

- Use the same material sewing yarn as the garment: Often, synthetic yarns are used during assembly. This negatively impacts recycling, as synthetic and cellulose-based fibres are difficult to separate leading to reduced material qualities of the recycled yarn. Even though some recycling processes claim to accept up to 5% of synthetic content, this is not industry-wide and negative material impact is up for debate.

- Insert same material woven labels: these decorative elements serve a purpose, but they are often made with synthetic materials.

- Remove zippers and leather patches: these elements are not desirable as they require manual disassembly, refer to options that are recycling compatible or easy to disassemble.

- Use screw-on metal hardware: these metal buttons are essentially the only other material incorporated in the design process. They can be easily removed by the user before washing or disposing of the garment, resulting in a 100% recyclable garment. Additional buttons or hardware, such as brand elements or buckles, should be considered with the same perspective.

- Use organic and low-impact dying solutions: several innovations to combat the negative impact of synthetic dyes are in development, such as dope dying regenerated fibres (Tencel modal), bacteria-based natural dyes (HUEE), jet printing, and many others. These innovations all try to reduce the water and chemical use involved with fabric dying, while maintaining adequate colour properties. Within this project’s 3D weaving focus, however, indigo was chosen as a natural dye.

- Use raw denim or low-impact fabric finishing and washing: processing of fabric post-weaving requires an elaborate process using different water and energy-consuming machines. Consider to which extent their use is necessary, and evaluate alternatives such as laser washing (Tonello), jacquard wash structures and other processes.

- Consider modular or adaptable design elements: These elements could for example enable the user to adapt the garment to their preference, potentially increasing the garment’s life cycle and fit.

- Use bar tacks instead of metal rivets: this reduces the need for disassembly, as this alternative to rivets utilises the same yarn and can be recycled without additional processing.

**3D woven layer composition**
With the material properties itself somewhat defined, it's also important to understand how 3D woven textile structures behave. The warp yarns run vertically across the fabric and the guiding picks can be individually manipulated, resulting in a set amount of yarns creating a flow of weaves. The weft (reminder: from right to left) yarns are inserted using a pressurised shuttle, with a flexible amount of yarn ends per centimetre. The jacquard loom is programmed to embed the variations in pattern layers in the woven fabric, resulting in a woven fabric with interwoven sub-assemblies. A cross-section of such a multilayer fabric simulated in NedGraphics can be seen in figure 11.

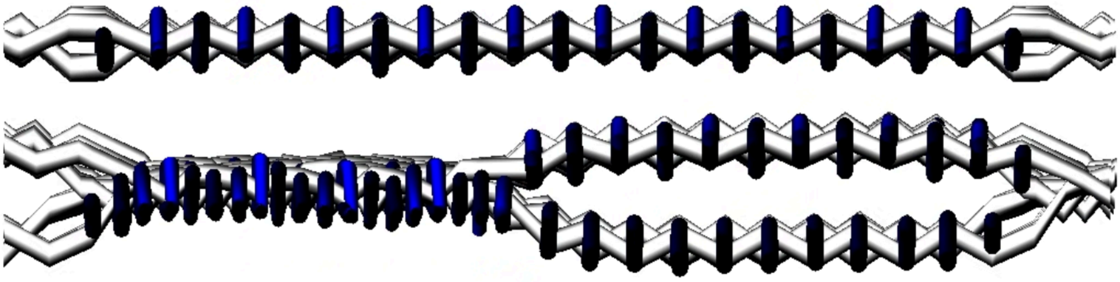


*Figure 11: Multi-layer fabric cross-section*

Most often layers behave with an almost linear distribution in fractional layer density, meaning that both warp and weft yarn density are half with every equal fabric layer split. Besides the main use cases of 1, 2 and 3-layer fabric constructions (figure 12), several other even and uneven distributions of layers were tested. It was found that 4 layer structures yield fairly thin fabrics, undesirable for long lifespan jeans but perhaps of value with summer wear trousers. 4 layer constructions cannot currently be done with each layer meeting denim fabric characteristics, future development of machinery can easily account for such structures. This yields further potential for integrated designs that exceed the limitations of current layers, such as further reduced production time and emissions. Considering public knowledge, denim up to 12.5 OZ gauge is usually a 2/1 twill and above 12.5 OZ gauge is a 3/1 twill. Besides this, it was found that 3D woven layers with a density of less than half of the total fabric, it's best to use a plain weave as these add strength in less dense fabrics. Several other weave structures and layer combinations were tested as well. These samples have all been created with the above-mentioned criteria, and serves as a basis to define the list of layer bindings. The list of layer bindings summarises the different types of layers applied in the design, a necessary process for conveying requirements between the design and weave department. During several iterations of the design, the layers have been selected for further refinement.

*Figure 12: Fractional behaviour of multi-layer fabrics by Barbara Vroom (2022)*

## B. Stage 1B: Rules of Thumb for Zero Waste 3D Woven Fashion

With the current basic fabric structure opportunities and limitations discovered, it is important to understand how to distribute them in a pattern across the entire width of the loom. Here, zero waste design practice comes into play. This way of design reduces pre-consumer production waste, creating patterns that house every inch of available fabric. A discipline that was learned through the continuous work and support of Holly McQuillan, and adapted within the design methodology of this project for sustainable 3D weaving. Here follows a set of design rules from practice that were defined throughout this project.

- **Fractional density:** The amount of warp yarns is constant and therefore has a negative relationship with the amount of layers created out of a single fabric. If 1 layer has 40 ends/cm, then 2 layers could be 20 ends/cm x 2 or any other combination that equals the original warp count.

- **Waste counts extra:** It is important to consider that the weight of a multilayer denim fabric is generally higher than conventional denim fabrics, this is because the Jacquard woven fabric roughly houses the equivalent of two medium-weight denim layers. When a pattern layout results in waste, consider that this could impact multiple layers of the fabric as opposed to one. Be aware of the relatively high weight of one Jacquard woven multilayer fabric and prevent waste across layers as much as possible.

- **A game of balance:** 3D weaving is an intricate balance between fit, waste reduction, aesthetics, production steps minimization and weave structure manipulation. One rarely can be changed without influencing the others, it is therefore important to maintain an integrative perspective during the design process.

- **Adapt zero waste techniques:** Valuable in general, but essential with 3D weaving. Start with large elements, and work towards smaller ones. A cut-out here becomes another part there. Corners and curves can be achieved to some extent by making the intersection of 2 parts identically curved/cornered. Mirroring and aligning patterns also helps.

- **Grading:** There are several ways to overcome grading patterns through the lens of zero waste design. One that helps limit material waste is to define sizes in predetermined measures such as S, M, L. The patterns of 2 L's can fit side by side, and a balance can be struck between the S and L. Ideally resulting in no waste in the weft direction due to grading.

- **Sizing:** The most common size indicators for jeans seem to be the inseam and waist. Parts that are influenced by this should ideally be oriented in the same direction. The waistband and leg width are both influenced by the waist, and makes grading easier to align them in the same direction. Ideally stretch material is avoided to accompany size deviations, as current recycle technology cannot separate the materials properly yet. Currently, Renewcell's recycling method can recycle cotton stretch blends up to 95/5 and this number hopefully increases.

- **Folding is your friend:** As the technology pushes forward, this discipline can be further strengthened. But when a certain part doesn't fit, it can create design freedom to fold it along the symmetry line.

- **Think in planes:** It's up to the designer (and jacquard engineer) where a pattern exists of 1 or multiple layers. In the case of multiple layers, it can be seen as 2 planes in which each plane can house its own pattern.

- **Seam assembly:** Create additional seam width for folded sewing of joined fabrics. This both strengthens the seams, and leaves some room in the pattern for consumer dimension-based tailoring.

- **Both additive and subtractive:** Normal pattern cutting is subtractive in nature, as volume is removed by cutting it away. With 3D weaving, certain folding weave structures can be used to add volume in a certain area. Keep in mind that fractional density and therefore reduced strength continue to play a role.

- **Automation:** The envisioned purpose of 3D weaving is to enable more sustainable design and materials without excessive increases in price. This can be done by reducing the amount of production steps required to assemble a garment, which usually accounts for the largest proportion of garment production cost. 3D weaving can be used to compensate for higher material & design costs with reduced labour cost, and potentially localised production reduces carbon emission and transportation costs even further.

- **Cutting edges:** The pattern of the design is ideally made in a way that enables automated CNC cutters to separate the majority of parts. This further improves the made-to-order potential.

- **Think inside out:** Clean seams are achieved by folding pre-assembled parts inside out, leaving the folded seam on the inside. This does not stop fraying but reduces its visibility.

- **Seams like trouble:** Besides the fact that woven seams can be reduced and placed in unconventional ways for the benefit of 3D weaving. Woven seams have one additional superpower: Because of their increased thickness they can withstand considerably more force than their layered cousins, placing them in wear-intensive locations such as the knees can increase the garment's durability without requiring more material.

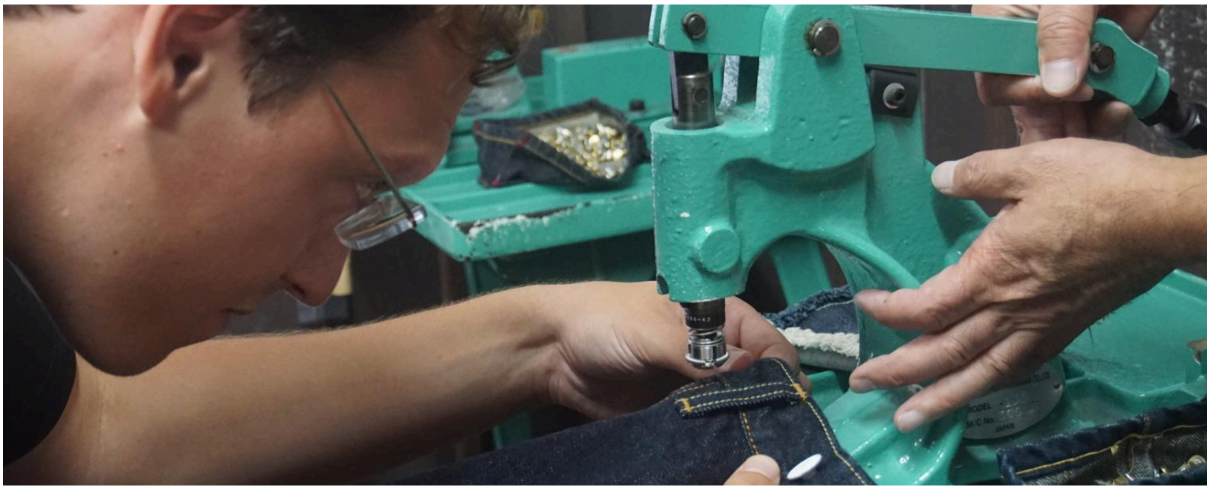
The struggle of finding balance between production efficiency, fit and waste is often prevalent during this project. These three inevitably influence each other, and it can often mean that one needs prioritisation based on the narrative of the design. The methods and tools used to develop this balance and navigate the design space are shared in the next chapter.

***Personal reflection on Stage 1: Research & Development***

*During the process of gaining contextual knowledge on 3D weaving, sustainable practices and garment design, it became obvious that my background in industrial design would be useful in this multifaceted process. Moreover, my initial lack of detailed knowledge of practical garment design proved a blessing in disguise. This was, strangely, because it allowed for such an unbiased new perspective on the challenges that it helped to prioritise sustainable decisions from the start. It must be said that surrounding yourself with industry experts helps to keep an eye on quality, as these perspectives help to optimise details of the design that you otherwise might not realise. It was comforting to know I could consult with these experts either as individual disciplines or group discussions (Weaving, sustainable fashion design, denim production and denim design). Sustainable design is in my background, and it helped the process a lot to know these rules by heart while balancing an efficient 3D woven denim garment design. I did come prepared for this project: I did some evening classes on basic pattern design, as well as some freelance CLO3D work to get acquainted with the software and company discussions before the project started (Decode, Kings of Indigo, G-star, Betty Smith, Momotaro). Before the start of the project, I had already discussed previous 3D woven projects with McQuillan, and the knowledge derived from these projects provided an excellent starting point for this project.*

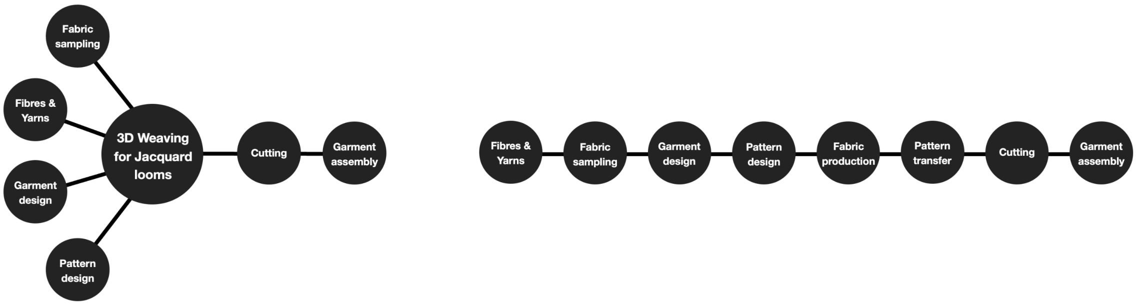
# C. Stage 2: Design and Iteration

Now that there is a sufficient grasp of the current state of technology, the design process can move towards applying the retrieved set of criteria within the context of jeans design. As previously mentioned, the balance between efficiency, fit and waste is complex to navigate. It's best to ensure proper awareness of the desired garment characteristics, which in this case requires close inspection of 5 pocket jeans and their history. The inspiration for this process was fueled, amongst other things, by the council from Mohsin Sajid, a field trip to the G-Star garment archive, desk research and a trip to the Kingpins denim trade show in Amsterdam. Before the official start of this project, a visit to the Betty Smith factory and traditional denim weaver of Momotaro (Kojima, Japan) also gave insights into the story and meaning of denim jeans.



The insights from these activities were incorporated into the virtual project tool Miro. Here, an accumulation of research, references, notes and visuals creates a backlog and design space. This tool offers the valuable benefit of always being able to zoom out, limiting the risk of overindulging a single design element at the cost of unbalanced results. Compiling and implementing a wide variety of design inspiration sources was done using multiple tools, but the flexibility of digital iterations in CLO3d and reflection in Miro played a key role in the practical design stage.

This design process used for 3D weaving integrates several disciplines of fashion design into one holistic approach. It combines the development of yarn, fabric, garment, pattern, jacquard programming and assembly. A simplified representation of this 3D weaving process can be seen on the left, the linear process on the right represents traditional design and manufacturing of denim jeans.




**Defining the standards of jeans**

Jeans are most often made of indigo-dyed cotton twill, traditionally originating from miners' workwear in the gold rush era. Duck-coloured or hemp blends also surrounded the many early variations of jeans. These sturdy garments needed to withstand harsh conditions, while also offering both comfort and functionality. One key development that propelled the popularity of jeans was the introduction of metal rivets, first used in Levi's jeans. This kicked off a widespread adaptation of jeans by American workers, because they created much stronger and long-lasting garments than before. The iconic garment came to life, and over 150 years have passed without ever going out of style. But, it was not only the rich origin story that made it iconic. American jeans have been improved for the last 150 years as well, optimising material sourcing, machinery and supply chain. This drove down the price and made jeans a popular casual garment. In the early Hollywood days, idols wearing blue denim filled the screens, sharing denim as a rebellious style to be seen across the world. Seen as a protest against authority, this icon of freedom became synonymous with liberty. And soon, both its use and production span across the globe. It wasn't until the early 70s that synthetic yarns were introduced, ushering in the era of designer denim.


*Figure 13: Moodboard material for 5-pocket denim jeans*

*Figure 14: Images at G-star Archive*

**Jeans concepts**

The traditional jeans concept is recognized by two back pockets, 2 inner front pockets and a 5th coin pocket in the wearer's front right pocket. Besides this, the jeans have a fly and 5 belt loops around the waistband. Earlier denim garments often had singes to adapt fit, which is a welcome addition for these long-lifecycle 3D woven jeans. The jeans have a fly stitch, safety stitch across the side, and a slightly thicker and darker-coloured top section. This section also houses the yoke, which is the triangular fabric below the back waistband that accommodates the body's curvature.

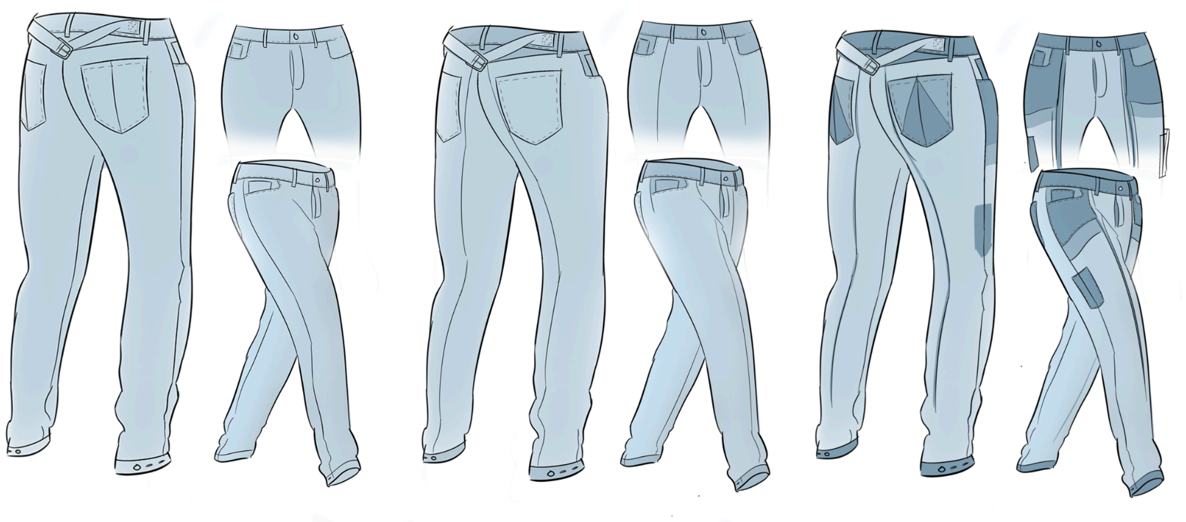


*Figure 15: Jeans concepts*

**Digital pattern design**

The process of pattern design and form design is executed using CLO3D, a digital fashion design tool allowing for 3D visualisations of their 2D pattern counterparts. This software allows for flexible changes in the garment, making it an invaluable partner for optimising fit and waste. First, several fits were created to explore zero waste opportunities. It has to be noted that the physical limitations of 3D weaving have to be imitated by the designer while using CLO3D. This requires a good understanding of the production technique, as well as some mental gymnastics while using single layers for multi-layer patterns.

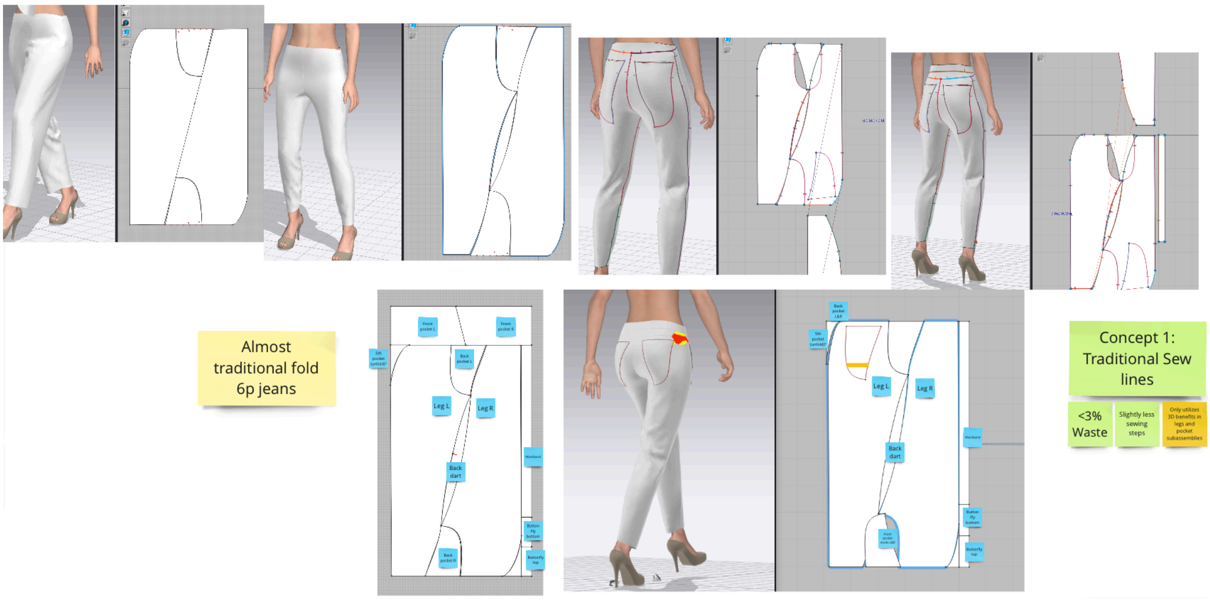



*Figure 16: Digital fit iterations*

Then, the remaining parts were designed from large to small, starting with the waistband. Since each element in the fabric directly influenced another, endless adjustments of variables were necessary to balance for both fit and waste. Besides the pattern looking good in 3D, it also needs to be assembled in a factory. Thinking about construction and (woven) seam allowance will pay off later. About 1 cm of allowance was added in clo3D.

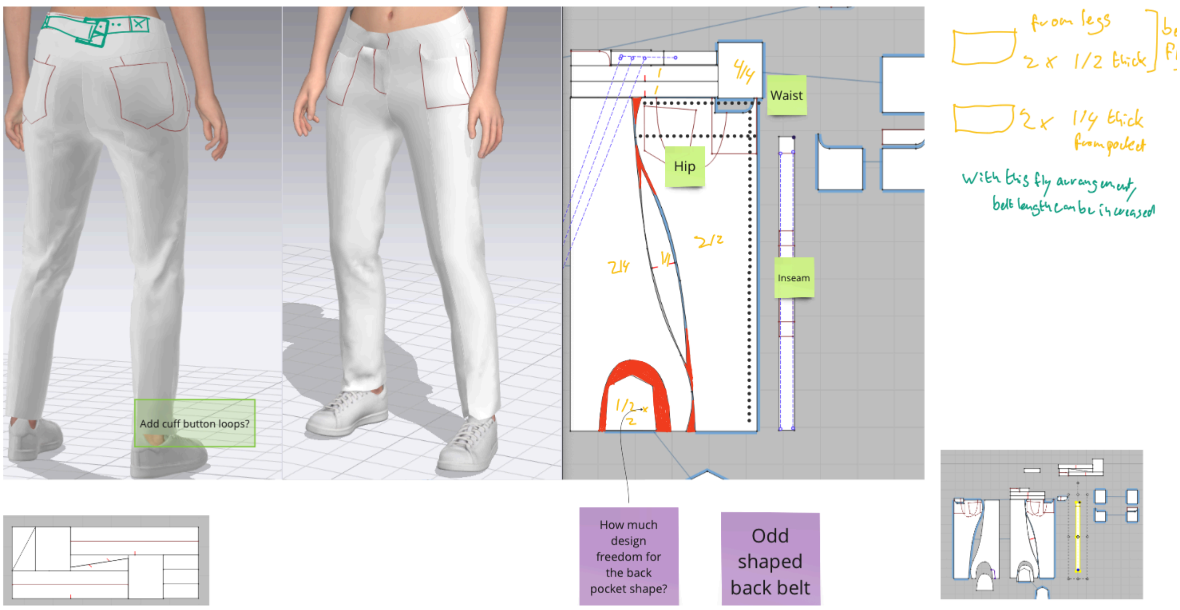



*Figure 17: Digital concept development*

**Cut and sew pattern**

Exploring design elements through sketches and digital design was useful, but to test the assembly of the jeans a cut and sew prototype was made. Alterations and simulations of the design were applied until the design had a seemingly realistic configuration. When everything is ready for cutting and sewing work, the design from clo3d with seam allowances and pattern distribution is transferred to Illustrator.

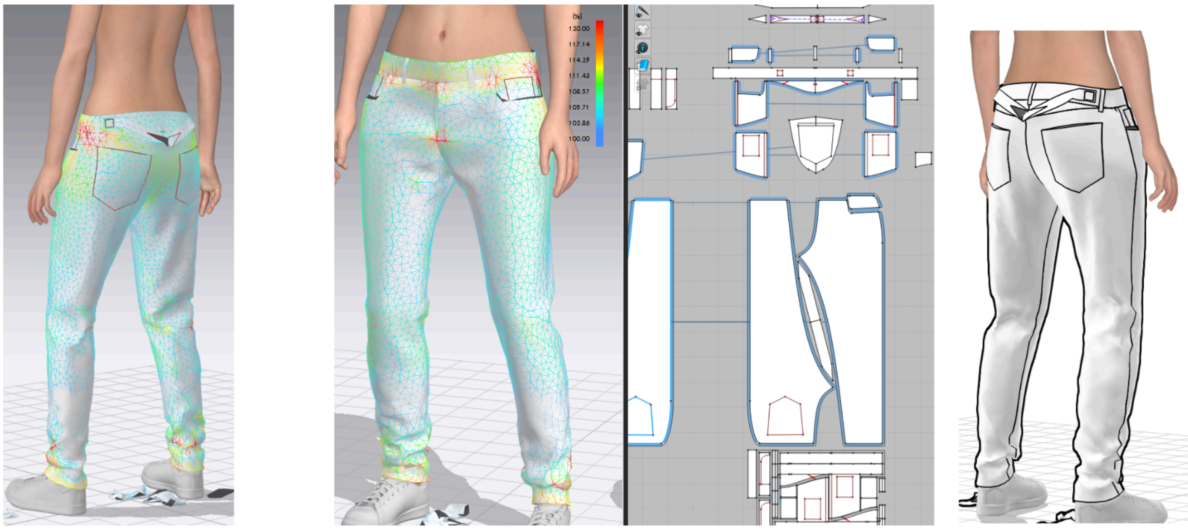


*Figure 18: Preparing garment concept for cut & sew assembly*

This cut and sew pattern was then cut out from 24 A4 sheets and transferred onto folded calico fabric. During this process, several small changes were added to the pattern for better size of the fly and pockets.

After transferring the pattern, the 2 layers of fabric are sewn together where the 3D woven seams would be. After this process, the pattern parts were cut out. Then, the layers were separated at the desired location as would happen with 3D woven fabrics.

*Figure 19: Marker transfer to calico fabric*

**Cut and sew prototype**

With the separate layers available, the sewing process can begin. It starts by turning the legs inside out, and aligning the front pocket curve of both the right end leg and top section. After sewing the pocket in place, the waistband, yoke and fly can be sewn for both sides of the prototype. The result is a cut-and-sewn version of the 3D woven jeans concept. Based on this process, several changes were identified for the design, such as waistband length, ankle width, fly construction, pocket sizing and construction. A full explanation of the assembly of woven prototypes will be discussed in Chapter 4.E.

*Figure 20: Prototype result and assessment*

The insights from this prototype in regards to dimensions and assembly were incorporated in the CLO3D file. The prototype was used for the physical evaluation of the garment. It was also used as a reference during brainstorms with Mohsin Sajid, as well as Holly McQuillan and Milou Voorwinden to optimise the pattern for aesthetics, zero waste and jacquard weaving respectively. The main highlights involved the altering of certain dimensions and angles to improve the look and fit of the garment while maintaining zero waste. Also inclusion of key details that are reminiscent of denim jeans.

The 5 pocket design has been developed over multiple sketches, digital and physical prototypes. The pattern is now ready for the next phase, and will be used for the creation of the map of bindings.

*Figure 22: Mentor session with Mohsin*

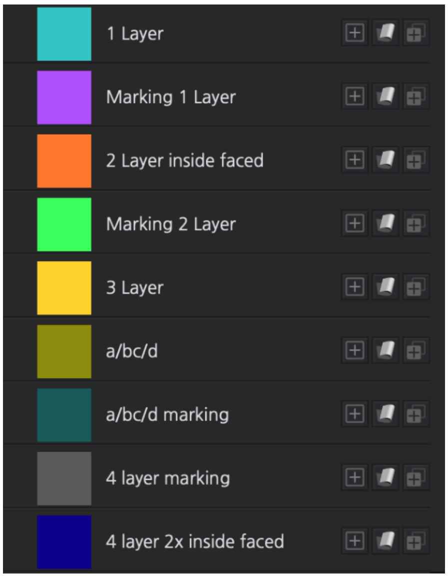
*Figure 21: Concept 1 V2*

***Personal reflection on stage 2: Design & Iteration***

*It was super tricky to balance 3D weaving to have as little sewing and as little waste as possible while still fitting well and looking correct. The efficiency of the pattern amplifies the characteristics of 3D weaving, meaning inefficient pattern construction would lead to excessive waste. I ended up prioritising sustainability first, and only if necessary I'd adapt the results to be more aesthetically pleasing. Previous experience in design processes for innovative technologies provided a much-needed framework through which the new principles of 3D weaving could be explored. Especially mapping the context in Miro and designing endless variation files in CLO3D provided constructive rounds of iteration. A large part of the iterations also focussed on embodiment design, meaning that the fraying edges from the separation of 3D woven layers are designed away as much as possible. Zero waste principles became my standard for pattern design, but a small change to one section quickly leads to a big consequence for another section. For example, since the front and back of the legs are almost symmetrical, there was quite a struggle with adjusting yoke angles. This is because the angle had to be adjusted on just one side, but this angle directly influences some parameters of the waistband and pocket construction as well, and this pocket construction determines the length of the fly etc. Luckily, being able to somewhat flexible design in multiple layers allowed for a final result that seemed to balance everything. Please believe that the development of one base design can be very time-consuming, but hopefully, you'll have one point of reference more than I did.*

## D. Stage 3: Map of Bindings

With the finished design at hand in clo3d, the translation towards a map of bindings can begin. A necessary process that programs the loom for the production of the design. The tools needed for this are Clo3D, illustrator and Nedgraphics. Besides this, the previously developed pattern and list of layer bindings will be used.




**Preparing the pattern in CLO3D**
First, the pattern in CLO3D is altered and all duplicated parts are removed. Sew allowances are created as separate shapes, to be assigned a different colour corresponding to the list of layer bindings in figure 23. This list of layer bindings is also shared with the weaving expert and used during communication.

*Figure 23: List of Layer Bindings*

The result is a combination of tightly packed shapes in a 2D pattern. During the process of pattern design, ensure pattern width does not exceed the repeat width of the loom. A general 1 cm width was used for both markers and woven seams. The progression from CLO3D pattern to MOB can be seen in figure 24.

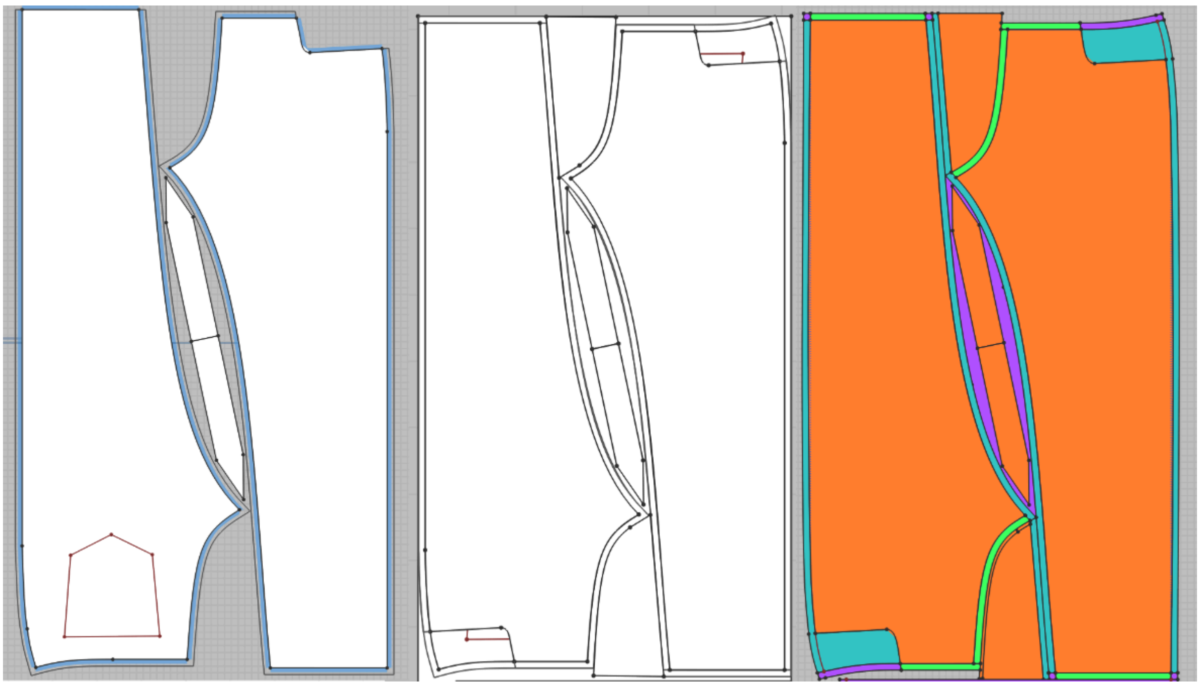


*Figure 24: Translation of pattern into Map of Bindings*

**Transferring the file to Illustrator**

With the pattern fully processed within the software, it's time to export the file. Make sure only the desired pattern pieces are in the file, and check for any gaps between parts. Now export the file to PDF. Make sure to only show pattern outlines, and no scaling is present. When using multiple patterns within the same file, be sure to hide all but one before exporting and name that PDF accordingly.

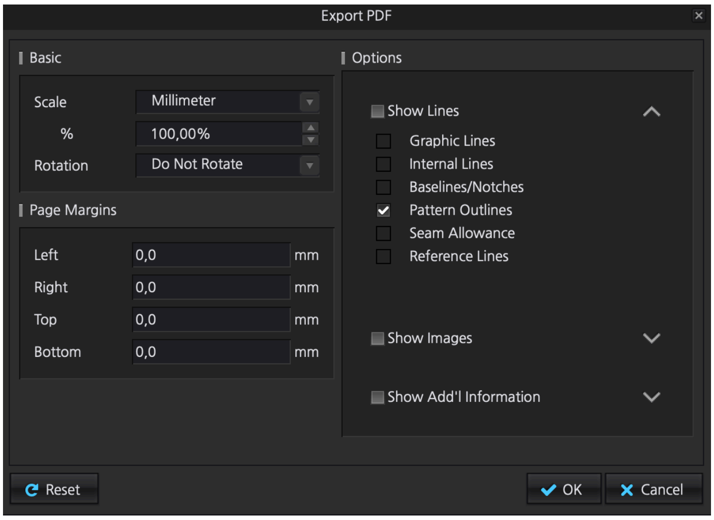



*Figure 25: Export settings in CLO3D*

Open the PDF in Illustrator. Make sure the file shows only the desired pattern shapes and black lines. Make sure that the illustrator graphic fits exactly in the width of the repeat, in our case. These black lines need to be removed. First release the clipping mask by pressing CTRL/CMD + A to select all elements, then right-click and select release clipping mask. Now manually select all the coloured objects and press CTRL/CMD + X. Press CTRL/CMD + A to select everything again, then press CTRL/CMD + F to insert back the shapes. The black lines should be below the coloured shapes and not visible in any location.

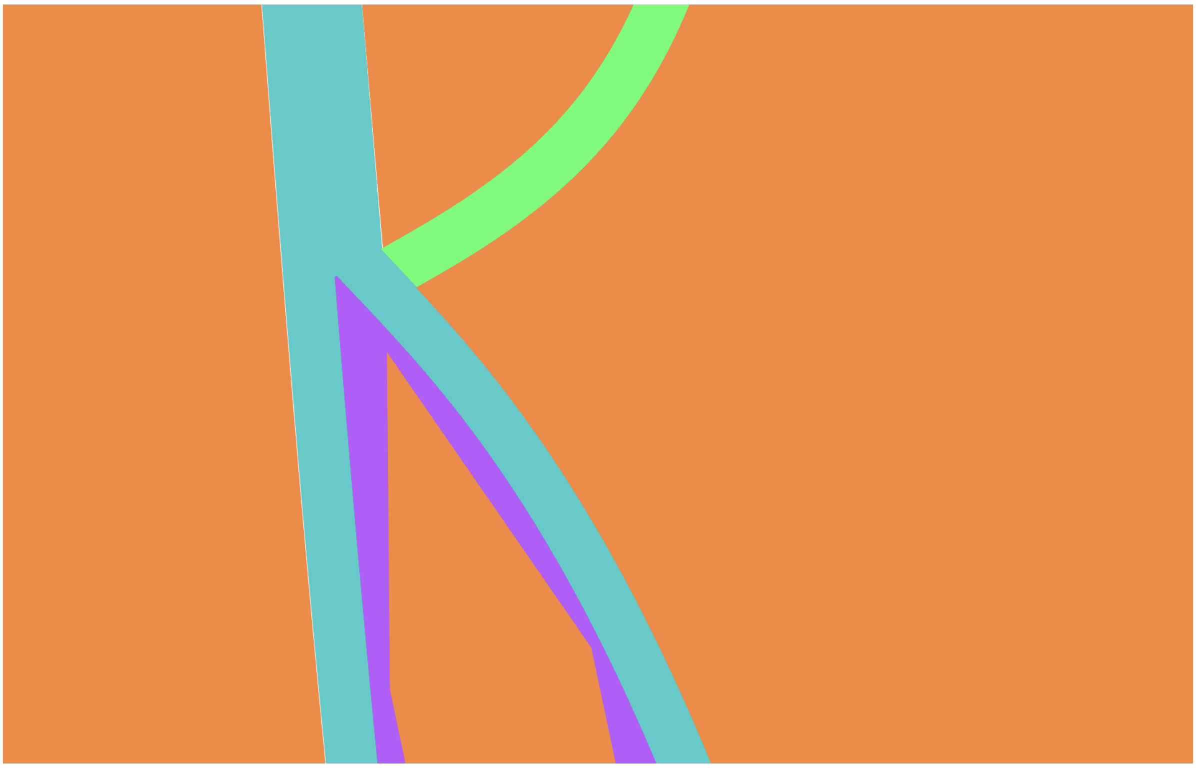


*Figure 26: MOB without gaps and lines*

**Thoroughly check the file**

It could happen that some black lines are still visible. In this case, the lines can be manually hidden by double-clicking the shape it surrounds. All other shapes should now be dimmed, and the layer view in the toolbar should only show the clip group in isolation mode. Only the bottom layer in every clip group is needed, the top layers can be hidden or deleted. The result should be a pattern that shows no black lines.

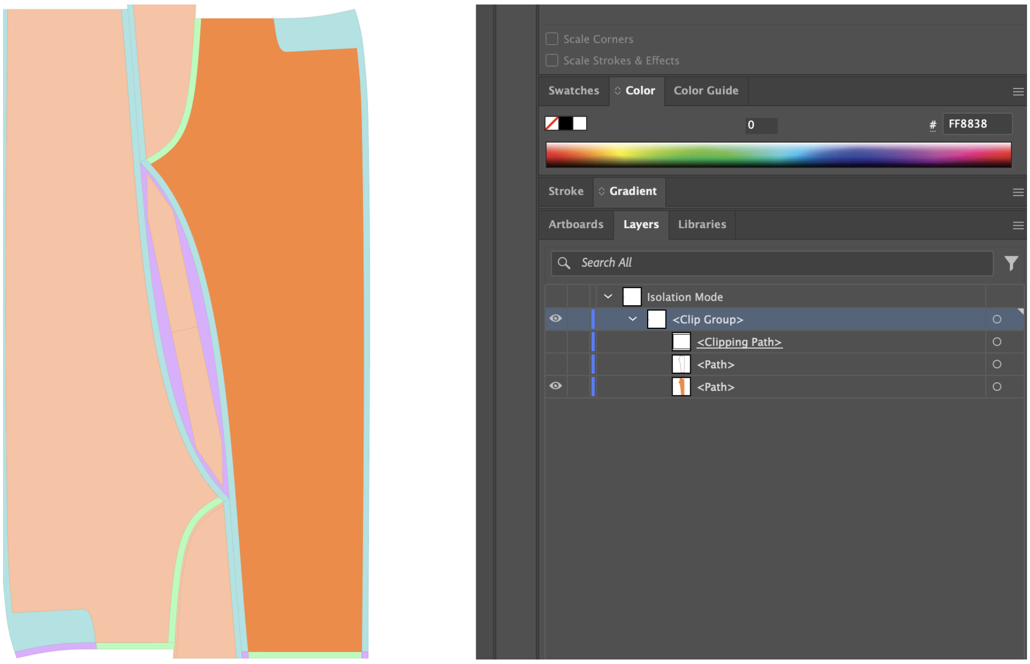



*Figure 27: Hide lines through isolation mode*

It is very important that there are no gaps in the pattern. It often happens that the pattern is perfectly aligned in CLO3D, but there are small gaps when zooming in close in Illustrator. Reorder or shape the pieces in such a way that all gaps are closed without negatively impacting the pattern.

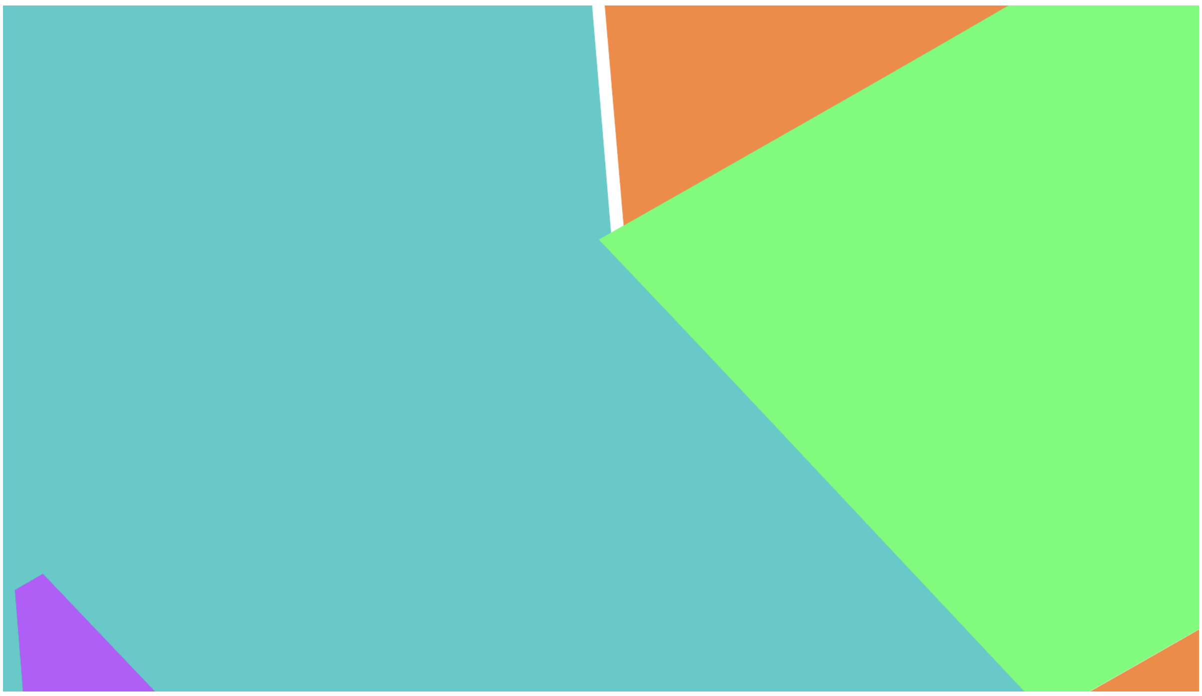
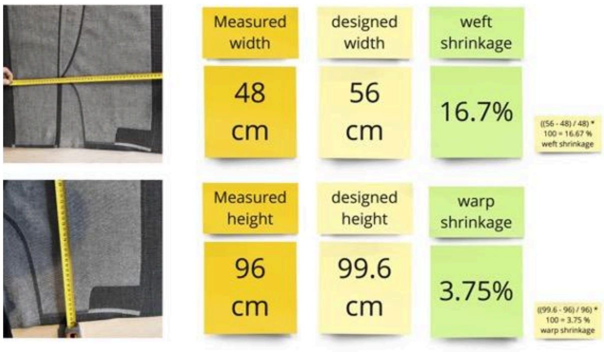


*Figure 28: Example of gaps to avoid*




### Account for shrinkage in the fabric

After the first iterations of 3D weaving, it becomes prominent that the weft and warp shrink relatively differently. This is because the density of warp yarns per layer is considerably lower than the weft yarns, making the width shrink more than the length. It is important to note that if the pattern pieces are rotated at this point, the difference in shrinkage has to be accounted for. The shrinkage was calculated to be 3,75% in the warp direction and 16% in the weft direction.

*Figure 29: Shrinkage calculation of 3D woven fabric*

During the later development of the concept, it is advised to design all patterns in the right orientation in CLO3D, and assign the mean weft and warp shrinkage to the pattern pieces in material settings. This renders the 3D shape's dimensions after shrinkage but keeps the 2D pattern dimensions in their pre-shrunken state. This can easily be done by selecting all relevant pieces and adjusting the weft and warp percentages in material settings at the bottom right corner.

### Prepare files for the weaving expert

Save the file as an AI file in a separate folder. Then also export this file by clicking Export as, then select JPEG (jpg) as the format. Make sure that you select RGB as the colour model, and set anti-aliasing to none. Save this file to the same folder. The weaving expert may choose to work from either AI or JPEG files.

Ensure all the AI and JPEG files are named correctly, and the folder contains only these files. Add the list of layer bindings in the folder and send all documents to the weave expert, who in this project is Milou Voorwinden. Together with the weave expert, develop and assign the desired weave structures to the pattern in Nedgraphics. During this process, be mindful of possible issues in regards to scaling, layer bindings and weave orientation.

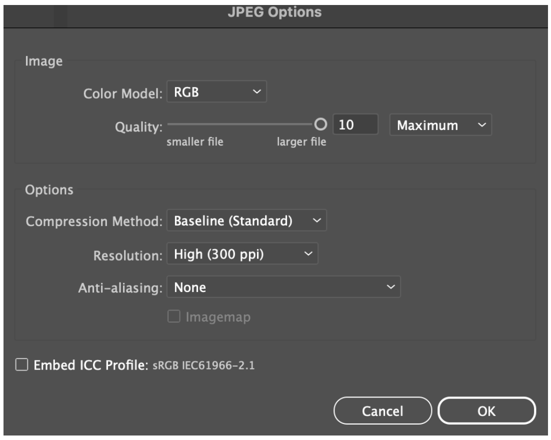



*Figure 30: Export settings in Illustrator*

***Personal reflection on Stage 3: Map of Bindings***

*The process of translating a 2D pattern towards an MOB turned out to work for the most part within CLO3D, but it requires some experimentation with layers and linked editing. It would be better if there was the opportunity to link pattern parameters within the software, adjusting curved lines for zero waste will take up a lot of time otherwise. It helps to discuss 3D weaving together with Milou Voorwinden, as this close collaboration allowed us to spot better ways to implement 3D woven design and production. I would love to learn NedGraphics myself for the specific purpose of programming a Jacquard loom for 3D weaving, unfortunately, there was no time for me to learn this within the timeframe of this project. In hindsight, this was a good thing for the project, as the compartmentalization of skills allowed me to learn from others and dive deep into the design process of 3D weaving.*

## E. Stage 4: Fabric Production and Troubleshooting

The 3D woven design has been completely transferred into a .jc5 file, ready to program the loom. This file is shared with the manufacturing partner Diamond Denim, along with the fabric requirements, repeat counts and level of finish.

During the total span of this project, 5 production runs were done spread over 3 shipments. The process of parallel prototyping spread over 3 sample runs enabled the testing of multiple variations of designs and design elements. The project faced difficulties due to travel restrictions, but frequent use of contingency plans and excellent partners allowed this project to finish without an extension period. Not being able to physically assist at the factory as planned proved to be difficult, more so due to the unevenly distributed workload caused by last moment cancellation of the workweek visit. There were no clear lead times since a new process requires adaptation, and unforeseen errors such as wrong settings have a tendency to cause delays in shipment. This, however, is a fairly normal thing to happen with implementing innovation and was accounted for up to a certain extent.

*Figure 31: Parallel woven prototypes of sample run 2*

***Personal reflection on Stage 4: Fabric Production & Troubleshooting***

*The practical execution of this stage was out of my hands for the most part. It was a bit tricky at first to navigate with changing timelines, simply because it was difficult to estimate development beforehand, and planning needed to fluently adjust every time. Parallel prototyping enabled good results, but it did lead to MUCH added work and sample development compared to the original design process planning. I believe the project would've had even better results if we could've worked together in Pakistan, but unfortunate circumstances made this impossible halfway through the project. Hopefully another time. Communication with Diamond Denim and Milou helped a lot to troubleshoot problems and adjust accordingly, in the end, we still managed to provide beautiful results despite these obstacles.*

**Production errors overview**

During the process of production and troubleshooting, several unique errors came to light for 3D weaving on a jacquard loom without modification. An overview of the 5 distinct issues that were identified is provided with pictures.

**Weft cracks**

These cracks appear when the weft yarns of a multi-layer fabric separate from the weft yarns of a single-layer fabric. These cracks are most prominent when a layer separation happens across a straight line in the weft direction of the design. These issues don't always happen, but to minimise their occurrence, reduce these lines in the design by adding a slight curve or angle.

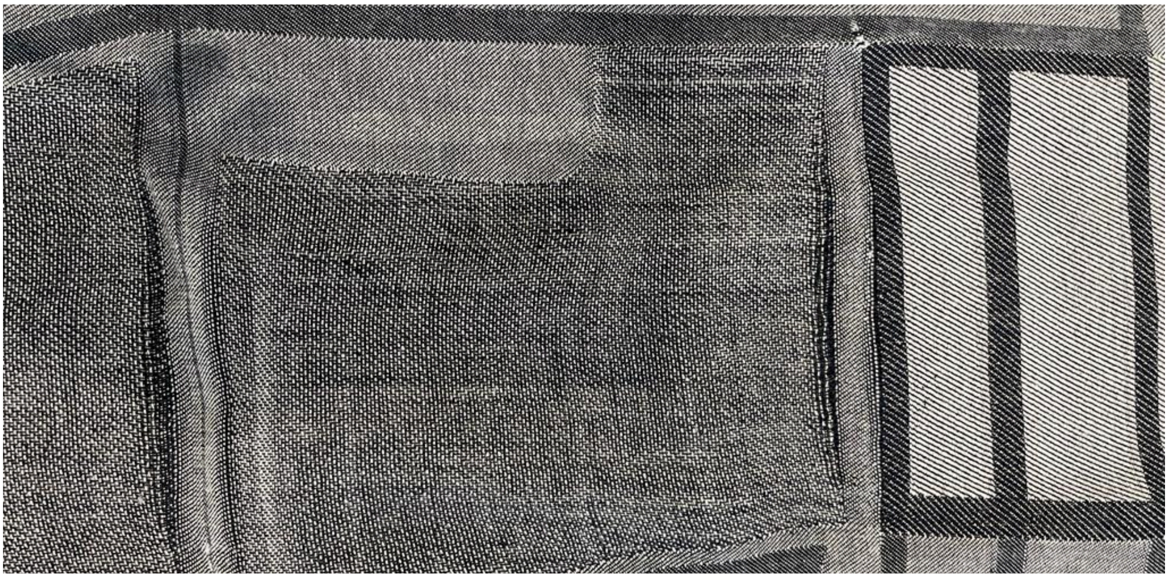


*Figure 32: Weft cracks exposing warp threads*

**Skipped interlacements**

These yarn structures appear when the weft and warp yarns don't interweave, partly or entirely. This issue is likely caused by a faulty weave structure definition in NedGraphics. To fix this issue, redefine the problematic weave in the software and save it as a new version.

*Figure 33: Skipped interlacement*

**Reed cuts**

These cuts appear when the weft yarns break along a certain line, often happening at the intersection between two different wave structures for both single and multi-layer fabrics. The exact reason for this to happen is unsure, but it's most likely caused by high tension in the loom causing the reed to cut into the yarn. Other options include some kind of mechanical issue more commonly seen in traditional weaving.

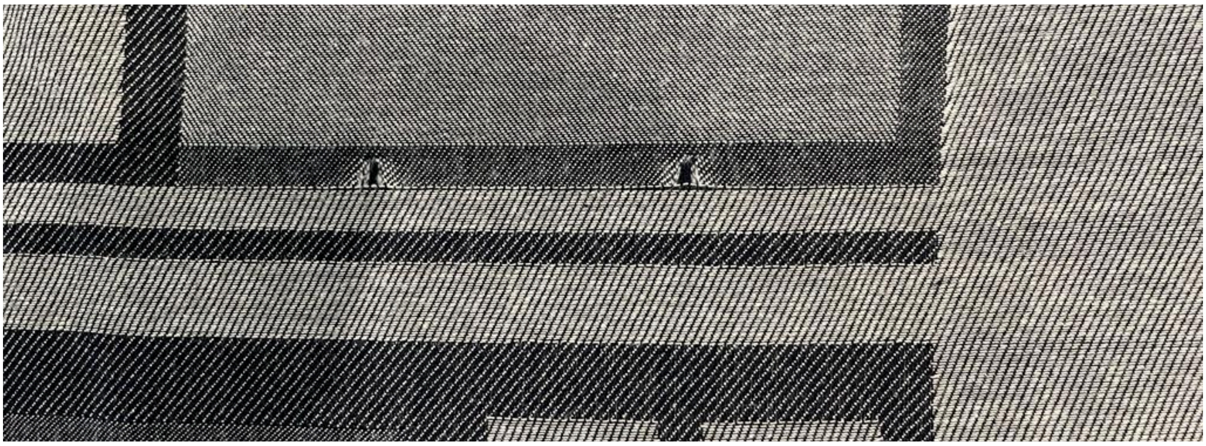


*Figure 34: Reed cuts*

**Wrinkling and/or finishing debris**

These wrinkles appear when uneven tension builds up during the rolling and processing of the fabric, causing the two layers to shift away from each other in the warp direction. The debris is likely caused by the burned fibres from the singing process remaining stuck on the fabric. The debris is removable without stains, and the picture shows the only considerable instance of this issue. Efforts to avoid this issue are extra attention during rolling, adjusting settings for finishing, reducing extended lengths in the warp direction if the design allows for it, and considering optimised machinery.

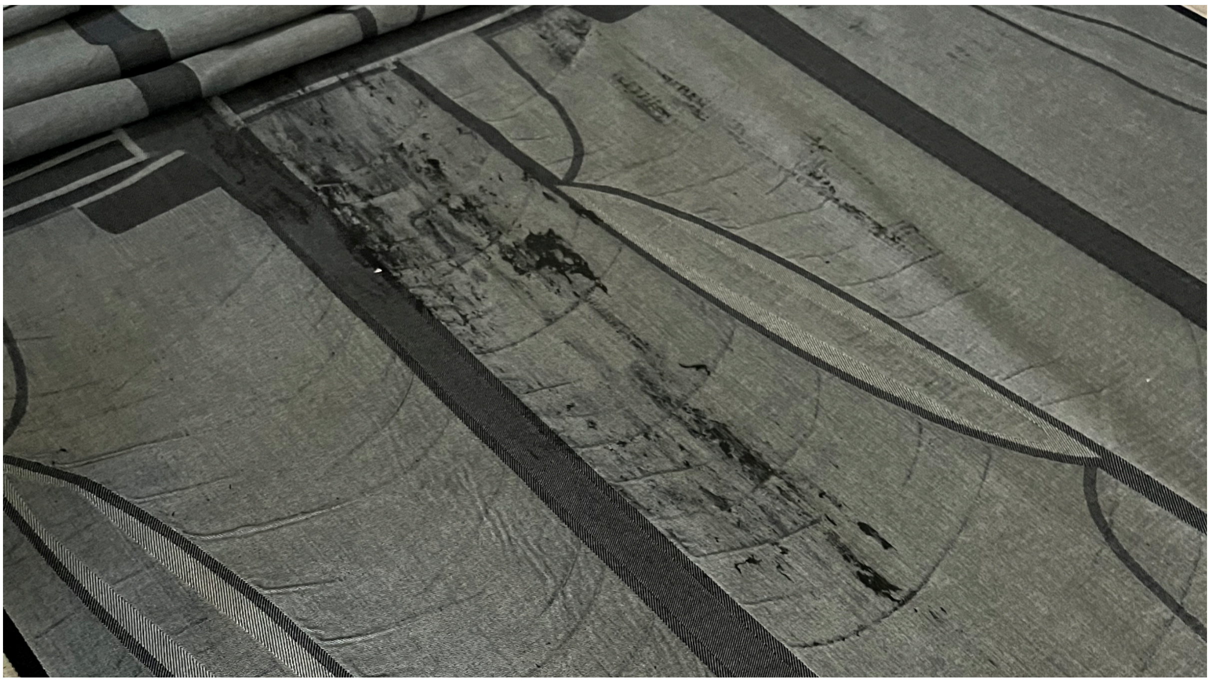


*Figure 35: Wrinkling and finishing debris*

## F. Stage 5: Garment Assembly

All the designs are now woven and all repeats are contained in the roll. The fabrics from the first production round were sent to Delft and manually assembled there. This process was necessary to spot possible design improvements, as well as the documentation for the assembly guide used for later reproduction in Pakistan.

*Figure 36: 3D woven fabric from sample run 1*

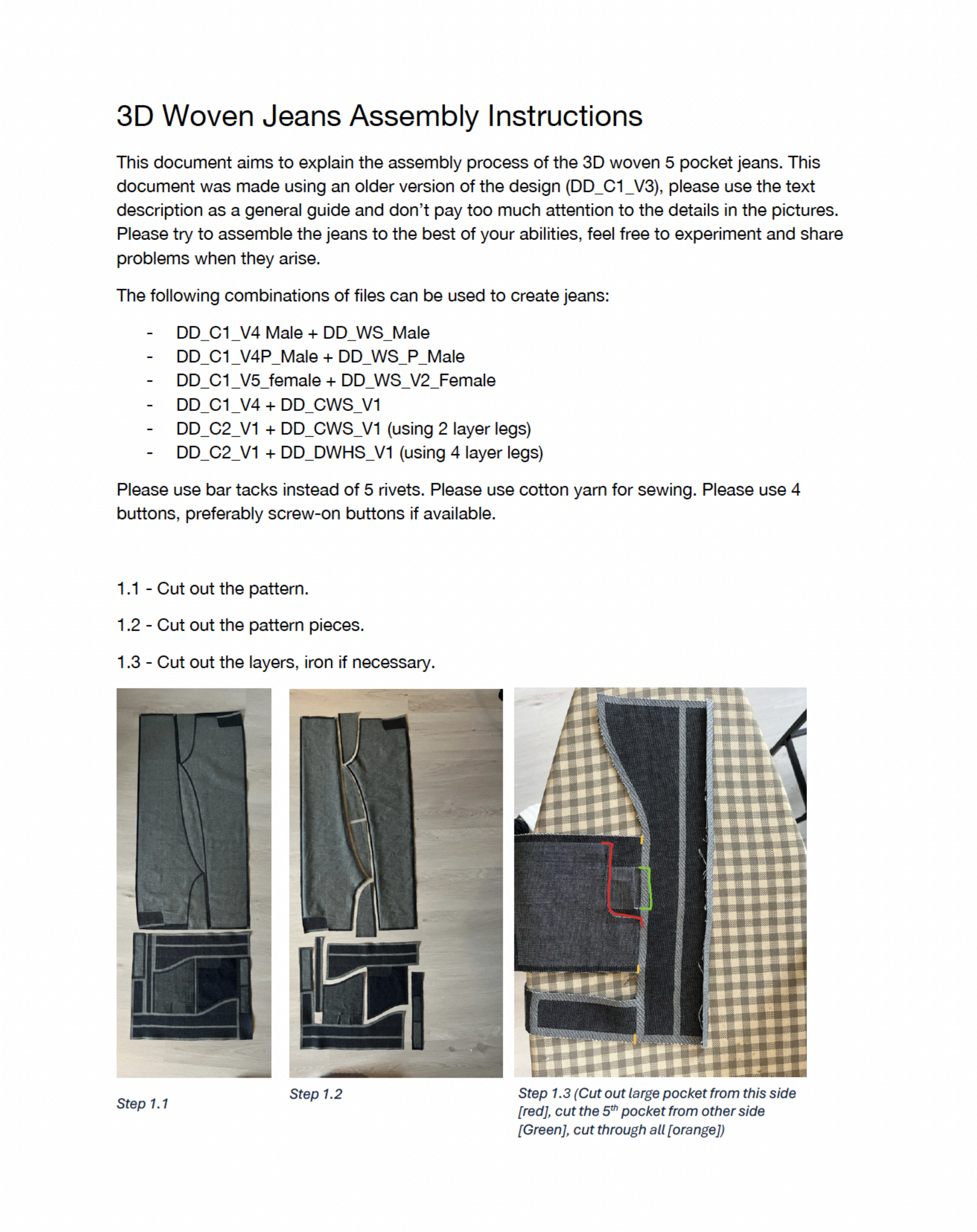
**Logistical challenges**

Due to the unforeseen last-moment change of plans, there was an extended period of time where no production samples could be shipped. The contents of sample run 3 were designed for experimentation during the workweek visit and the results would drive changes in both pattern and assembly. These samples could not be tested before designing sample run 4, resulting in a parallel prototyping approach with up to 12 variations of a single concept. Since there was no sooner option to do physical prototyping, the design approach for run 4 was adjusted accordingly.

Several design improvements were applied to create variations, each testing a certain element housed in a separate file. For example, the crotch cutout, waistband width and pocket section were all tested in separate designs. The majority of designs were also made modular, meaning different combinations of top and bottom sections could be assembled together. Besides this, some designs were given additional width seam allowances to be used for tailoring. This parallel approach allowed for the testing of various improvements of fit and design simultaneously but posed a risk as well, as it had to be created without evaluation of the previous 2 design iterations. Due to this, no accurate assembly guide could be made before starting assembly in Pakistan. Simply because the design itself had to be assembled first in Delft to create the content. The solution was to send all the fabrics after finishing, except the ones required for assembly. With one of each design in Delft, the final design can be iterated and documented for assembly. This, while the staff in Pakistan can start to set up assembly. By the time the final design is ready, everything is in place to produce the last run.

**Assembly guide**

Since 3D weaving has an entirely different assembly process, it can take a little getting used to sewing with this fabric. To assist during the assembly process of the integrated zero waste patterns, the assembly guide provides step-by-step instructions. The document also explains combinations of files and criteria for assembly. The first page can be seen here, the full assembly guide can be found in Appendix C. Assembly guide.



## 3D Woven Jeans Assembly Instructions

This document aims to explain the assembly process of the 3D woven 5 pocket jeans. This document was made using an older version of the design (DD_C1_V3), please use the text description as a general guide and don't pay too much attention to the details in the pictures. Please try to assemble the jeans to the best of your abilities, feel free to experiment and share problems when they arise.

The following combinations of files can be used to create jeans:

- DD_C1_V4 Male + DD_WS_Male
- DD_C1_V4P_Male + DD_WS_P_Male
- DD_C1_V5_female + DD_WS_V2_Female
- DD_C1_V4 + DD_CWS_V1
- DD_C2_V1 + DD_CWS_V1 (using 2 layer legs)
- DD_C2_V1 + DD_DWHS_V1 (using 4 layer legs)

Please use bar tacks instead of 5 rivets. Please use cotton yarn for sewing. Please use 4 buttons, preferably screw-on buttons if available.

1.1 - Cut out the pattern.

1.2 - Cut out the pattern pieces.

1.3 - Cut out the layers, iron if necessary.

*Step 1.1*

*Step 1.2*

*Step 1.3 (Cut out large pocket from this side [red], cut the 5th pocket from other side [Green], cut through all [orange])*

*Figure 37: Page 1 of assembly guide V1*

**Tech pack**

This document is made to provide instructions and details about the design to the manufacturer. It embodies visual references, detailed flat sketches, materials to use, types of stitches etc for the manufacturer to translate into a finished garment. The tech pack, or specification sheet, acts as a blueprint for the garment. Similar to technical drawings in product design, it is a tool for communication and a reference for quality. The first page of the tech pack used for assembly in the supply chain can be seen here. The updated tech pack includes pictures and dimensions of the reference design assembled in the Netherlands.

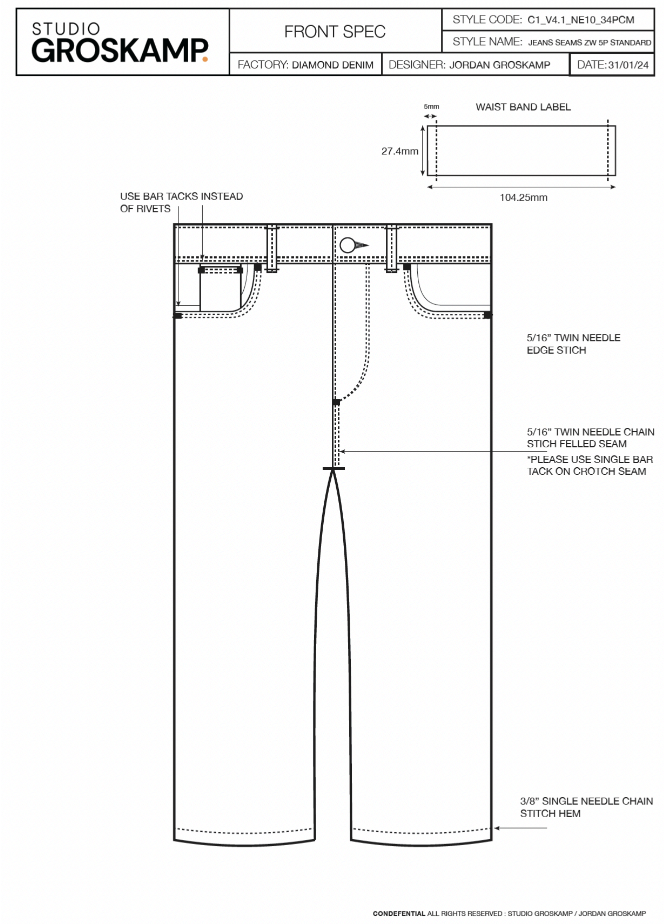



*Figure 38: Page one of Tech Pack V1*

***Personal reflection on Stage 5: Garment Assembly***

*Even though I wanted to get hands-on, I didn't expect to spend SO much time sewing. This was a necessary process to check if the design was correct, and particularly check my understanding of assembly techniques as I've never assembled a garment in my life. This ended up taking way more time than expected, but particularly waiting to receive fabric that would've been assembled on site a month earlier was a mentally challenging process. I'm especially happy here that I switched to parallel prototyping almost immediately. I had exactly 2.5 days between receiving sample run 2 and delivering the final design + assembly guide. Testing all the aesthetic opportunities in run 2 was beautiful, as I could essentially copy the tested principles in the final design. The same goes for testing fit variations, as I had to partially assemble 3 designs and assess 16 variations to test which worked the best.*

## G. Stage 6: Evaluation of Industry Feedback

During the iterative development of the concept, several points of evaluation guide the next steps in terms of design. This section pays special attention to the perception and acceptance of 3D weaving by people from the industry. It's not necessarily these specific 5-pocket jeans, but the principles of 3D weaving it represents that form the product for which the industry is the consumer. For an elaborate overview of intermediate prototype evaluations and resulting design steps, please refer to Chapter 4.G. Iterative design improvements. A detailed description and discussion of the final design results are documented in chapters 5 and 6 respectively.

*Figure 39: Fit test of the first 3D woven prototype, concept 1 V3*

**Industry meeting: Setup**

To ensure the 3D woven jeans meet expectations, the new way of production needs to feel applicable to industry experts. To increase the practical application of this novel production process, their insights and feedback have been incorporated during this project. This was done by inviting several professionals from the denim industry experts to a 3D weaving online showcase. The experts were invited by stakeholders of the project, and a respectable number participated in the meeting from a variety of roles within the industry.

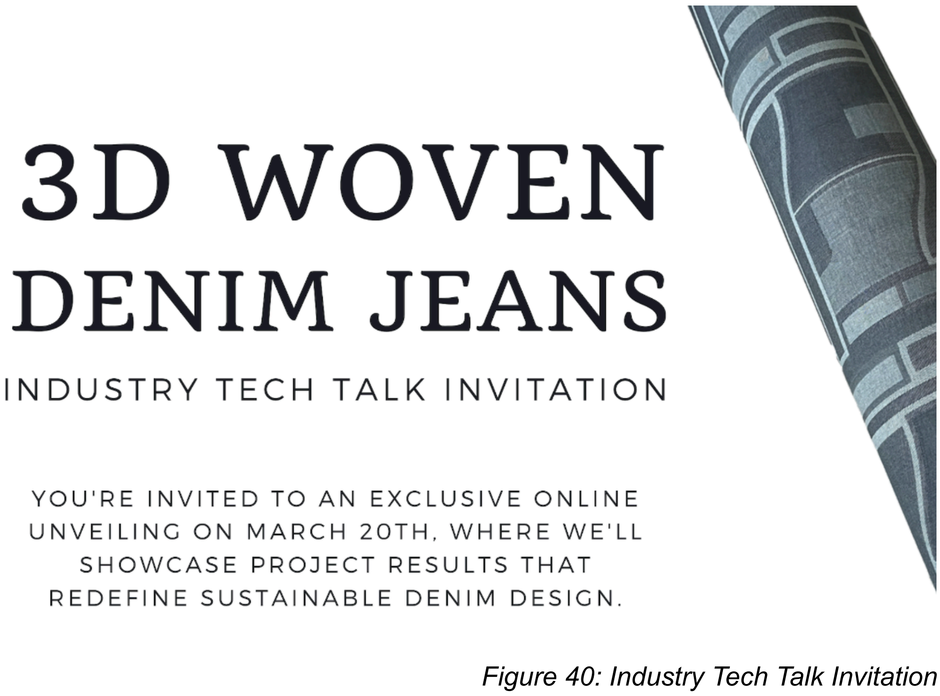



*Figure 40: Industry Tech Talk Invitation*

During this meeting a 20 min presentation on project context, results and future applications of 3D weaving was shared based on the design DD_C1_V4. The storyline was balanced in a way that it offered new insights for both experienced designers, while also remaining comprehensive for industry experts who have less experience with the garment development process. There was an opportunity for the attendees to ask questions to the involved stakeholders after the presentation, leading to a rich discussion where ideas were shared. Finally, the presentation ended with a short survey to be filled in by the experts. The survey was shared in a QR code on the last slides.

Filtering of research participants has taken place to ensure the right target audience was reached:

1. Invitation of industry experts by stakeholders.
2. Only sharing the survey invitation with industry meeting participants who stayed until the end of the presentation.
3. Allowing for filtering of responses through the generalised description of role.

**Industry meeting: Survey introduction**

The survey consists of 3 sections: opening statement, generalised description of role and impression of 3D weaving. The survey was made to be 100% anonymous and voluntary. A clear opening statement was presented at the beginning of the Google Forms survey.

Opening Statement (Informed Consent)

You are being invited to participate in a research study titled Design for Sustainability: 3D Weaving for Denim Jeans Production. This study is being done by Jordan Groskamp as part of the masters graduation project of Integrated Product Design at TU Delft, under supervision of Holly McQuillan and Milou Voorwinden, with production partner Diamond Denim and denim consult by Endrime.

The purpose of this research study is to evaluate the application of 3D weaving within existing supply chains through the development of 3D woven 5-pocket denim jeans. The showcase provides a realistic impression of the current opportunities in regard to business, people, and the environment. You are asked to anonymously provide your professional feedback on the project results, which will take you approximately 5-10 minutes to complete. The data will be used for evaluation of industry interest, and the derived anonymous data may be used in publication, teaching and further improvement of 3D weaving as a production process. We will be asking you to select a generalised description of your role, as well as your preferences and concerns in regard to 3D weaving being developed for commercial garments. You will also be given the opportunity to provide additional comments and insights at the end of the survey.

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimise any risks by avoiding the collection of data that could be used for personal identification. Please refrain from including information in your open answers that enables personal identification such as name, address, specific company or brand association etc. No data will be collected for this study besides the responses filled in by the participants, and all filled in responses may be used as previously stated.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. Due to the complete anonymous nature of this survey, it is not possible to withdraw, remove of recollect your response once the survey has been submitted.

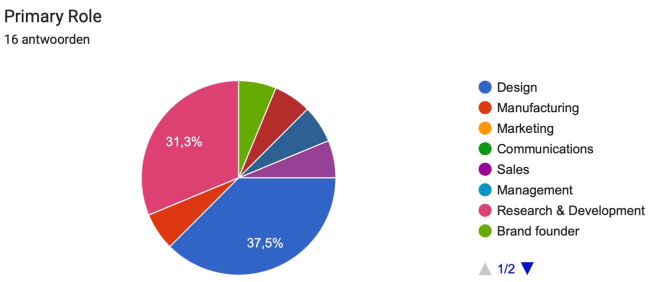
The following contact information will remain valid for 3 months after receiving this survey. Feel free to contact Jordan Groskamp (j.d.groskamp@student.tudelft.nl) when questions arise in regard to this study. Project supervisor: Dr. Holly L. McQuillan

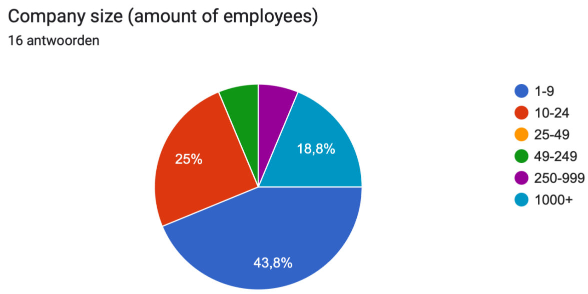
By clicking through to the next page of this online survey, you agree to the conditions mentioned in this opening statement.

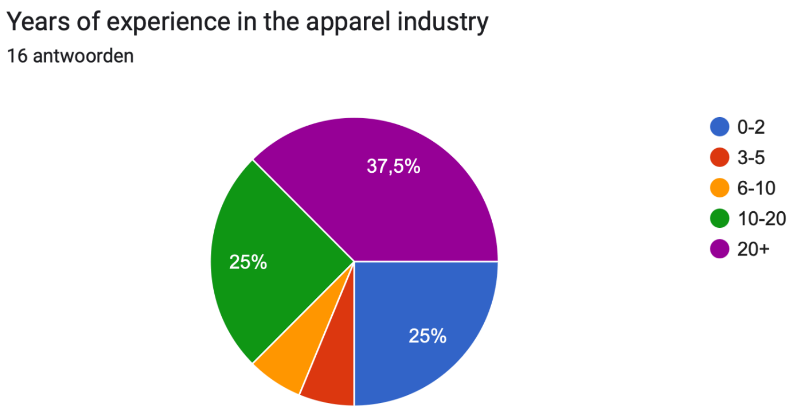
*Figure 41: Opening statement of survey*

**Industry meeting: Survey questions and results**

As mentioned, the only way for participants to fill in the survey was when they witnessed the entire presentation on 3D weaving. From the 50+ people who participated in the online meeting, 16 responses were collected. This section documents the questions with their respective responses.



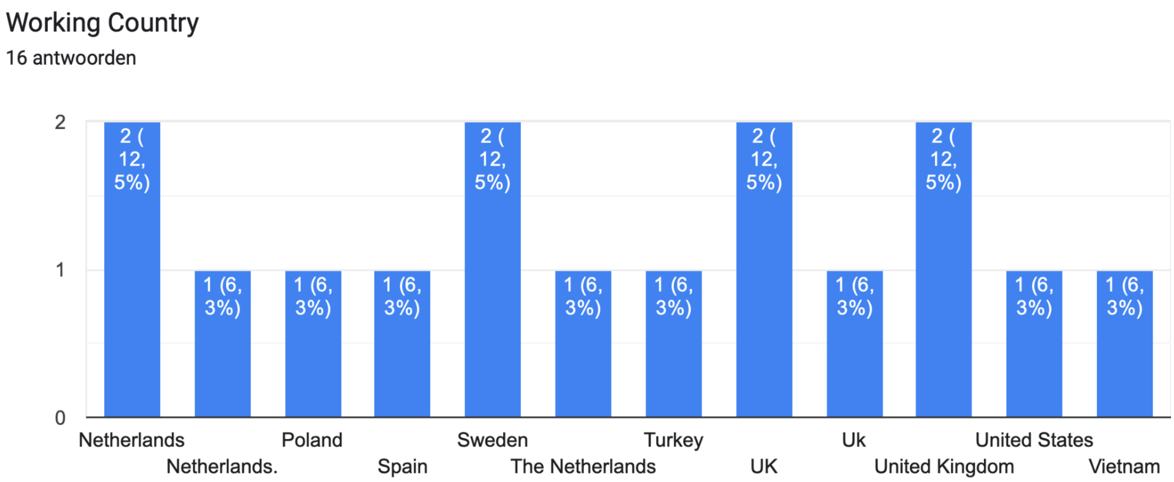
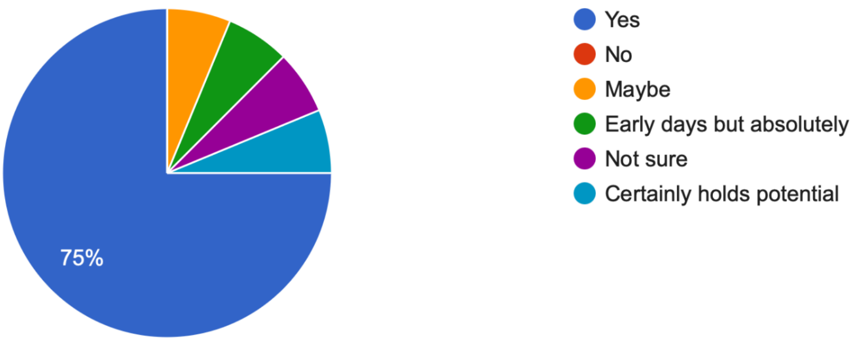




*Figure 42: Survey section 1, Generalised description of role*

Do you think 3D woven jeans provide value for a more sustainable future?

16 antwoorden




What seems the most interesting benefit/opportunity of 3D weaving from your professional perspective?

14 antwoorden

I think it's the start of a new way of working and can see this developing into other sectors with custom made jacquard looms made specifically for this purpose.

Digitizing the design process. Although the industry is slowly digitizing, I think efforts like this will push towards more algorithmic ways of working, which I'm interested in.

The most compelling benefit of 3D weaving is its capacity to significantly reduce waste in garment production while offering opportunities for increased customization and design innovation.

Zero waste

Opportunity to create fresh new looks that are sustainable from the outset

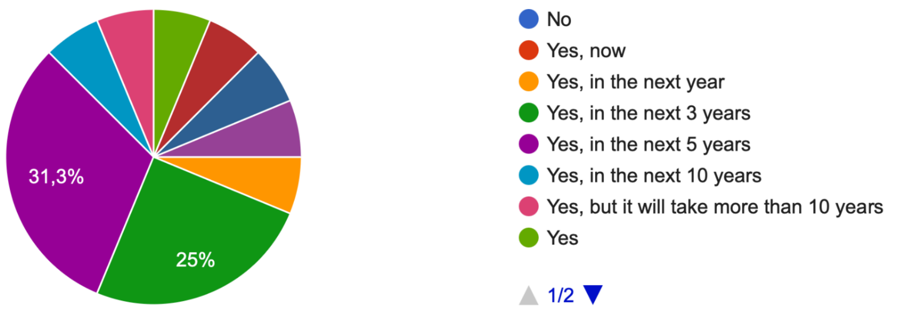
The possibility to waeve customized Denim, made to order

Making better use of materials, so less pre consumer waste. And it is a design for recycling as it is mostly mono material. Without the seams made from polyester a larger percentage of the fabric can be used as feed stock.

*Figure 43: Survey section 2.1, Evaluation of interest*

Do you think 3D woven Jacquard denim production can be adopted by brands

16 antwoorden




What is currently your biggest concern/doubt for 3D weaving to gain more widespread adoption

14 antwoorden

As a selvedge person, what will fades and wear look like.

Minimum order quantities

Durability of the fabric based on information given in the presentation

The reproducibility

We want a jean to look and feel like a jean - so I think there's work to be done in this area, but this project is proof of concept. I don't think it will take long to develop this further.

Supply chain restructuring

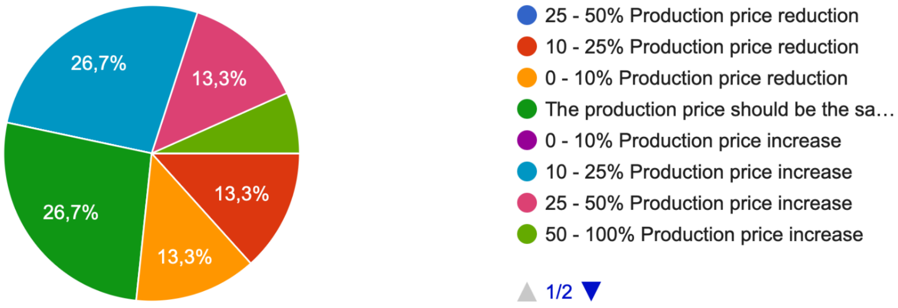
My primary concern for 3D weaving to achieve widespread adoption is its scalability within current supply chains and its competitiveness in terms of cost and efficiency compared to traditional manufacturing methods.

More susitable for more Luxury brand and on demand production

*Figure 44: Survey section 2.2, Adoption and concerns*

Starting from which price range do you think 3D woven denim is commercially interesting compared to conventional denim jeans production

15 antwoorden




Is there any feedback you would like to give on the design and/or process?

10 antwoorden

Design really needs to be more conventional.

Very interesting and will watch where the tech goes

I would like to know what your higher goal is; is it to have denims only 3d woven ?

It would be great if the jean is fully indigo but I don't know if that is a restriction or a design feature.

I want see a garment pattern than is uniquely a product of 3D weaving. This design is an iteration of something classic.

I would suggest further exploration of the scalability challenges within existing supply chains and strategies for optimizing cost-effectiveness, alongside emphasizing the environmental benefits of 3D weaving in denim production.

The jeans would be more commercial with a vintage wash with whiskers and spray

Without an insight into coatings it is challenging to answer some of the above questions.

*Figure 45: Survey section 2.3, Price sensitivity and remarks*

Is there any feedback you would like to give on this presentation in particular?

9 antwoorden

I would explain what 3D design is earlier on in the presentation and maybe explain that a conventional jean is one layer and the woven jean is up to 4 layers

Your crowd work and ability to be flexible while presenting is commendable.

My feedback on this presentation would be to commend the thoroughness in explaining the research study's objectives, methodology, and potential implications. Additionally, it might be helpful to provide some visual aids or examples to illustrate the concepts discussed, enhancing clarity and engagement for participants.

Great to see the industry challenged. Congratulations on your interesting research and for sharing your outcomes.

No

Thank you for your presentation. It was very clear to me.

It was wonderful. Very clear and informative

General comments

6 antwoorden

Very interesting, always great to see production being moved forward with lots of benefits to it.

Good presentation well done

Thank you and good luck with your future endeavours

Great innovation, still WIP but has definitely potentials

I'm researching design for repair and design for recycling, in fashion.My experience is 3D knitting, but im curious to see how this can be implemented as design for recycling. In order to close the loop and prevent garments to end up in the trash.

Congratulations this is wonderful and I am so excited to hopefully bring this to the market.

*Figure 46: Survey section 3, Project feedback and general comments*

**Interpretation of results**
The responses gathered provide valuable insights into the perceptions and considerations from industry professionals surrounding 3D weaving and its potential benefits.

The largest group of respondents mention their role is in the field of design (37.5%), followed by research and development (31,3%). Other roles described are Brand founder, manufacturing, pattern cutting and a combination of research and design. 75% of respondents have been in the field for more than 2 years, with 62,5% having more than 10 years of experience. Respondents work in a variety of company sizes and countries. This survey by no means provides a conclusive answer for the industry as a whole, but the feedback that was shared does provide a foundation to work from for further development of 3D weaving.

**Interest and Potential Adoption:**
From the 16 respondents, an overwhelming majority of 87.5% express optimism regarding the value of 3D weaving technology for the industry. This optimism is particularly present among individuals involved in research and development, design, and brand management, suggesting a widespread interest in exploring the possibilities offered by this innovative approach to garment production. This interest is further strengthened by the responses related to the most interesting opportunities. Half of the respondents mention zero waste, followed by a combination of flexible design customization and/or on-demand production. Its potential to further innovate supply chains is also mentioned through the use of better materials, custom machinery, and different manufacturing techniques.

While the majority of participants believe 3D weaving could be adopted by brands at some point, the timeframe in which this happens differs. The largest group (31.3%) believes it can be adopted in the next 5 years, followed by a quarter of the respondents who believe it could be adopted within the next 3 years. Two respondents do not give a specific timeframe, one of them mentions it should be cost-effective (25-50% price increase) in terms of design flexibility and production.

**Concerns and Doubts:**
While the interest in 3D weaving is considerable, a significant proportion of respondents express reservations as is expected with developing technology. 7 respondents raised concerns related to the look and feel of 3D woven garments compared to traditional denim jeans, with variations in focus on durability or the look and feel of the design result. This can be partly influenced by the fact that the pre-final design (V4) could only be seen during the online presentation. Interestingly, the majority of concerns from respondents with 20+ years of experience in the field relate to the qualities of the final product (Fabric durability, feel and aesthetics), not necessarily the implications on processes. Additionally, 6 respondents voice apprehensions regarding the process's scalability, production cost, and supply chain restructuring. These apprehensions highlight the need for further research and development. This research should aim to address technical challenges and optimise the feasibility of 3D weaving for widespread adoption, while also sharing knowledge on the implementation of 3D weaving for commercial purposes.

**Price Sensitivity:**
Opinions about the commercial viability of 3D woven denim are generally positive considering the technology's early stage of development. A 0-10% reduction in production costs compared to traditional denim production would render 3D weaving commercially interesting for 86,7% of participants. 46,7% of participants believe that an increase in production price is acceptable. 26,7% of participants expect commercial viability when the maximum increase in production price is no more than 25%. 20% of respondents indicate a willingness to accept even higher price differentials up to +200%. These differing perspectives highlight the complexity of pricing strategies for 3D woven products and the importance of understanding market dynamics and consumer preferences. Its positioning and application in different markets call for different perceived values.

**Feedback on Design and Process:**
Feedback on the design and process of 3D weaving for denim jeans in this project is varied. The majority of responses compliment the potential of the design to revolutionise garment design. Depending on the perspective of the respondent, the design should either look more conventional or more unique to 3D weaving specifically. Some further interest is expressed in sharing more details on possible finishes, colours, washes and design elements. Addressing these points will be crucial for enhancing the appeal and practicality of 3D woven garments in the market.

Qualitative results from this industry meeting indicated a positive response, and several valuable insights were gained that helped to increase the acceptance of 3D weaving within the current industry. It has become clear that not only the potential of environmental benefits are interesting, but also the opportunity for brands to explore new design opportunities unique for 3D weaving. The combination of novel design elements and environmental benefits position 3D woven jeans with key selling points that justify the likely higher initial development costs. These conclusions suggest that while there is significant interest and potential for 3D weaving technology in the apparel industry, addressing concerns related to durability, scalability, and cost-effectiveness will be crucial for widespread adoption. Additionally, continued refinement of design aesthetics and production processes, along with effective communication of the technology's benefits, will be essential for overcoming barriers to adoption and realising the full potential of 3D weaving in denim production.

**Personal reflection on Stage 6: Evaluation of Industry Feedback**

*Overall I'm very pleased with the development results, and I'm glad to see the industry representatives share this optimism. I prioritised the involvement of the industry because I personally believe their involvement is valuable for the project and the adaptation of 3D weaving as a sustainable means of production. I was a bit nervous to present, as the meeting transformed from a 10 people interview to 200 people attending on LinkedIn. I'm forever grateful for Mohsin's help, in particular for getting everyone together, as it was an amazing opportunity for me to share the insights of this work. I've spent a lot of time optimising the presentation's storyline to be understandable for everyone, yet insightful for the more experienced people. Eventually, 50 people showed up and everyone seemed very interested and excited, including myself. I'm somewhat sad the project is coming to an end, as I feel this way of sharing knowledge came surprisingly natural and I would love to do it more often. It was unfortunate that I could not ask participants for further development of the project, simply because the presentable results came relatively late in the project. However, I gave people the open invitation to reach out on LinkedIn if they liked the presentation @JordanGroskamp, and some very nice people did. Luckily, the project is gaining some interest from the industry, as the final design could not be presented during this project. I'm sure the final design will find its audience through other means of sharing, such as trade shows, articles or possible future collaborations.*

## H. Iterative Design Improvements

As the previous section of chapter 4 has captured the 3D woven design process in a somewhat chronological fashion, this section observes all separate design activities that were conducted parallel to the main design development. Each of these activities provided insights that drove decisions in the design, the design decisions made and results are shared in this section.

*Figure 47: Iterative concept improvements*

**Sample blanket testing**

The use of sample blankets aided the design process in the early stages, specifically for experimenting with overall fabric quality. In terms of weave structure, the main varieties were: plain weave, 2/1 Twill, 3/1 twill, box weave and compound twill structures to explore the most resemblance of conventional denim. The main layer varieties included: 1, 2, 3 and 4 layers with various distributions to assess desired layer thickness. Variations in weft yarn count included 30, 34, 38, 42, 46 to influence fabric density and feel. Finally, for the weft yarn Ne 10 & Ne 8 (60HE/40CO) blend was used, as well as Ne 10 & Ne 8 cotton to test differences in fabric feel. Both unfinished and finished soft hand-feel fabrics were created. It was confirmed by empirical results that the addition of 60% hemp weft did not negatively influence the denim look and feel. Due to the folding structures within the 5-pocket jeans, it was determined that the top section could utilise the thinner Ne 10 yarn to balance out the overall rigidity of the jeans. This allows the bottom section to be comfortably sturdy made with Ne 8 yarn, while the top section feels strong yet supple when closing the fly. Other insights from the sample blankets show that there is a balance to be found between a strong multilayer fabric that is not too dense at the single-layer woven seams. We settled for a majority 2-layer composition with each layer being about 12 OZ gauge after finishing, or roughly 400 gsm.

**4-layer production testing**

During the sample runs, one topic of interest was to explore the potential for 4-layer garment production. Besides this having a considerable impact on production time and design flexibility, it also poses some challenges. Unforeseen production delays caused the inability to troubleshoot the issue. 3 designs were initially developed to be tested with 4 layer constructions. To test both the feeling of the previous designs with half the fabric, as well as one concept to test a whole garment manufactured parachute jeans. We were able to overcome the challenges that come with loose 4-layer fabrics on small runs, but due to the limited timeframe of the project and previous delays, these experiments could not be executed. The use of 4-layer constructions was not necessary for the final 5-pocket jeans, but these avenues do provide more possibilities for future development of automated whole garment weaving with lightweight fabrics.

**Explore key design differentiators of jacquard fabric**

It's good to realise that this entire project hasn't necessarily honed in on any of the traditional jacquard design features yet. Since we're already using this process for environmental purposes, the added complexity that comes with jacquard fabrics is a welcome aesthetic bonus that comes free of charge. By balancing unique aesthetics possibilities, sustainable design practices and multi-layer production, the overall value proposition of 3D weaving grows increasingly larger. To test the design differentiators, various types of patterns and techniques were tested in DD_P and DD_C1_P version design files. From the experiment designs that were created, 3 distinct and flexibly applicable design opportunities were defined. Manipulation of Jacquard 3D woven denim for aesthetic purposes can be done through alternating weave structure orientation, the weave structure itself, or just its orientation of weft/warp resulting in graphic opportunities. Washing patterns can be easily implemented in further research, this however did not fit within the timeframe of this project.

| **orientation** | **structure** | **graphic** |
| --- | --- | --- |
| Alternate weave structure (left/right twill) | Alternate weave structure types (binding manipulation) | Alternate weave structure direction (Weft/warp faced) |

*Figure 48: 3D weaving flexible design opportunities*

The process of applying these design elements is quite simple, and consists of matching the desired weave structure with the right colour in the MOB. In most cases, this can simply be done by overlapping the desired shape with the pattern in Illustrator and matching the colours to those used for the pattern. This example shows the process for graphics, but can be applied for the other elements as well. Photoshop was also used for these particular 2 tone graphics.

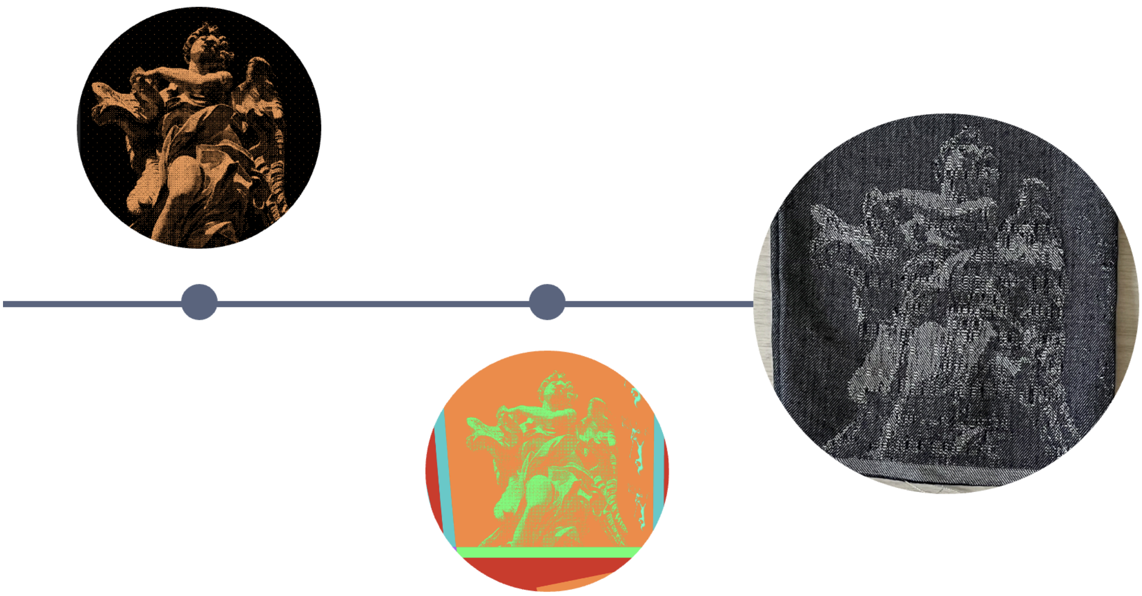


*Figure 49: Example of MOB manipulation for graphics*

**Backlog of design iterations**

The following section provides a visual overview of the iterative design development from start to V5.


*Figure 50: Timeline of design iterations*

**5 pocket jeans iterations from C1_V4 to C1_V5 (Final 3D woven)**

- The top section single layer weave structure is changed to show a saturated indigo colour as opposed to the weft-facing white cotton.
- The angle at which the pant and yoke connect is slightly adjusted to minimise excess fabric near the tailbone.
- The marker indication is changed across the middle seam between the two legs to allow for asymmetric angles between the back and front.
- Markers on the belt loop were added to indicate where to cut.
- A version with one piece fly was created, but the first attempt resulted in mismatched dimensions for zero waste purposes.
- Optimization of small measurements for waste reduction.
- Variation designs that utilise intricate patterns and graphics.

**5 pocket jeans iterations from C1_V3 to C1_V4 (Second 3d woven)**

- The pockets will be flipped inside out. The current prototype shows fraying lines from separating the layers, hiding this enables a more aesthetic finish.
- The cut-out section of the 5th pocket will be moved upward so that it hides under the waistband once attached. The pocket is also slightly changed in position and size, the widening of the pockets accommodates for sewing of the safety trim.
- Fraying lines can be seen in the fly area. This could be prevented by folding over the fabric. this additional fabric could also potentially strengthen the fly section from stress. The fly section is likely the thickest section of the jeans.

- The waistband and belt loops are quite thick. A version will be made with these being a 2 layer construction. One with the waistband on 2 separate layers, and one with them being a folding structure. This does mean that the pockets become a 4-layer construction, which I don't suppose decreases the strength that much, but only the 5th pocket will need to be manually sewn on. This experiment design was created but not produced due to unforeseen circumstances.
- The top section of the design will have a reduced weft yarn thickness of Ne 10 compared to the legs Ne 8.
- The belt loops were also lengthened to allow for better attachment underneath the waistband top layer.
- A fold seam across the crotch will be used to strengthen the construction and remove fraying from sight.
- Incorporate shrinkage percentages in CLO3D fabric.
- The waistband was made less wide with a slight angle at the yoke.
- I noticed that besides the general list of improvements for the 2nd prototype, there is also little space in the fabric to account for personal tailoring. Some additional cutting space was added to the waistband and crotch area that allows for cutting according to the person's size, perhaps deviating from the symmetric pattern. This extra addition allows for tailoring within a specific size without altering the weave structure of the pattern.

**5 pocket jeans iterations from C1_V2 to C1_V3 (first 3D woven)**

- The height of the yoke was increased.
- The pockets were increased in both height and width.
- Angle at hips adjusted to be about 90 degrees.
- A 2 layer fly was integrated onto the waistband.
- About 50mm waistband length was added between the pocket and fly on wearer's right half to improve fit.
- Crotch cutout slightly decreased in size.
- Woven seam allowances were added.
- Optimization of small measurements for waste reduction.

**5 pocket jeans iterations from C1_V1 to C1_V2 (Cut & sew proto)**

- The yoke curve was added.
- Curve of the pocket equals the curve of the yoke bottom.
- Seam allowances were added.
- The back pockets are fashioned from the cutouts of the crotch area.
- A slight angle is added at the inseam near the crotch and pants at the hips.
- A 2 layer fly was added.
- Pattern separation in top and bottom sections.
- Optimization of parts layout for waste reduction in 3D woven form.

**5 pocket jeans iterations to C1_V1 (Sketch to first 3D models)**

- Folding structures and seam locations were tested.
- Analysis of existing patterns to identify key pieces.
- Analysis of previous research design by Holly McQuillan, Milou Voorwinden, and Barbara Vroom for 3D weaving inspiration.
- Countless ideas and iterations in CLO3D were eventually refined into 2 concepts for further development. They were made through primarily zero waste digital pattern design, resulting in symmetric or mirror-able parts.

# 5. Results

In this chapter the results of the design project are shared, as well as an assessment of environmental benefits, production efficiency gains, and overall feedback on the design. Design V4 is analysed and discussed to examine the implications of results in the context of sustainable fashion. Design V5 considers colour, design details and fit optimization. It is in production for future showcases, but its results are unfortunately not available at the time of this publication. Final design V5 will be added as an additional appendix after graduation. Please consider that the following images represent the opportunities of 3D weaving, and not the final design.

*Figure 51: Design Concept 1 V4*

## A. Final Garment and Aesthetics

The integration of extensive research, iterative design processes, and sustainable innovation has resulted in the creation of the final 3D woven jeans design V5. This innovative garment not only embodies principles of zero waste and production efficiency gains, but also integrates 30% hemp to enhance sustainability and durability. This is not just any pair of denim; it's a thoughtfully designed product that minimises waste while maximising efficiency.

*Figure 52: V4 front assembled in Pakistan*

The final garment features an integrated 3D woven 5th pocket, fly with removable buttons, a back cinch for waist adjustment, bar-tacks all around and traditional back pockets with vertical 3D woven seams. This particular design is a straight-fit male size 34, resulting in a classic silhouette with characteristic details. Drawing inspiration from both historic and modern denim, as well as influences from research projects and streetwear for the (P) versions of design V5. The jeans resemble a base design that looks and feels like traditional jeans, but their aesthetic qualities can be easily manipulated to influence the structure, texture and colour of any given element of the pattern. This way, several thematic product variations can be created which require little additional development and no additional cost from the base design.

*Figure 53: V4 back assembled in Pakistan*

Each of the 2 layers has a density of about 12 OZ, or 400 gsm, resulting in comfortable mid-weight jeans that are both durable and breathable. This design is made using existing industrial Jacquard looms and digital design tools, allowing for an optimal balance between fit and material use. The top section is created with Ne 10 weft yarns as opposed to Ne 8, resulting in a more supple waistband and pocket construction that balances the overall light but sturdy feel of the jeans.

*Figure 54: V4 fit test male 34*

In addition to its sustainable attributes, the final garment prioritises comfort and functionality, ensuring a reasonably tailored fit for most sizes. Through scaling the overall pattern and possibly tweaking key dimensions, several gradings of the jeans can be created as illustrated by this female size 34. Showcasing that 3D woven jeans can achieve tight fits without the use of polyester-based materials.

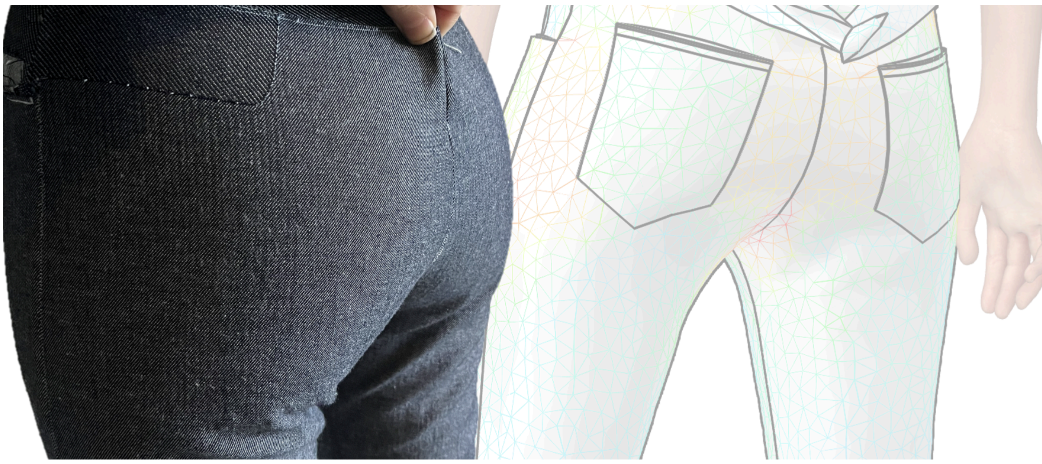


*Figure 55: Fit test scaling to female size 34*

The aesthetic appeal of the jeans lies in their subtle way of adhering to traditional looks while occasionally breaking away with unique characteristics of 3D weaving. One other characteristic of 3D woven denim in standard supply chains is that the fabric with a soft hand-feel finish is only treated on the inside of the legs. This results in a somewhat preshrunk garment that feels like a second skin, while leaving the outside raw. The design's colour saturation can also be modified as desired by utilising dyed weft yarns, the current pastel-like saturation is the natural state of 3D woven warp-dyed denim. Because the yarn is ring-dyed, it should experience natural fading as normal jeans would.

*Figure 56: Sample blanket design opportunities experiments*

The advanced capabilities of Jacquard looms can be harnessed to incorporate a variety of intricate patterns and design features, such as textures, layers and graphics. Since these looms are already being used for their efficiency gains and waste reduction, these additional design features can be flexibly implemented to your heart's content. This not only elevates the design, but also serves as a testament to the innovative capabilities of 3D weaving technology. This novel avenue in denim design can lead to unique ways of self-expression for brands and consumers alike, especially in user-customizable made-on-demand scenarios.

Overall, the final 3D woven jeans design represents a harmonious blend of sustainability, functionality, and aesthetics, resulting in significant potential benefits across the board. This design process demonstrates that significant improvement in efficiency and environmental impact can be achieved. Particularly when sustainable design practices are holistically integrated throughout development, the impact of which is discussed in the following chapter. Even more improvements lay on the horizon as industry players start to adopt these practices and drive innovation further. As a symbol of change, the garment not only embodies the values of sustainability, innovation, or craftsmanship, but also paves the way for the fashion industry towards a more circular and sustainable economy.

*Figure 57: Woven graphic denim*

## B. Environmental Impact Discussion

This section highlights the environmental and sustainability impact of this 3D weaving approach compared to traditional denim production.

**Life cycle estimations**
LCA data proved to be difficult to gather, as numbers provided by the industry require at least one year of data with somewhat sizable runs. The unique way of Jacquard operation and manual assembly also provide obstacles that are difficult to measure in these relatively small sample runs. The kind partners at Diamond Denim have opened an investigation to provide more data on 3D weaving and its environmental impact within their supply chain in Pakistan. This data however is unfortunately not available at the time of this publication.

Some estimations can be made based on an average of 20% less need for raw material input, based on the industry average pre-consumer waste of 15-25% per garment. The made-on-demand and consumer customization potential also provides an opportunity to reduce the 30% unsold garments average, which should result in a 1.3x multiplication of the traditional jeans data for comparison.

Material use also plays a large factor in environmental impact, and while 3D weaving works exceptionally well with hemp, it is only considered for design V5 and not for 3D weaving as a whole. The 60% hemp weft yarns allow for a 30% hemp fabric content, reducing the overall water usage by roughly 25%. Correctly sourced and retted hemp holds potential for near carbon-negative impacts with proper development. It can also grow in a wider variety of climates, increasing the potential for localised production down the road. Removal of metal hardware by consumers results in a 100% biodegradable, 100% renewable and 100% recyclable cellulose-based fabric. Even the stitching is designed without polyester-based threads. Some feedback from the industry meeting also wondered if the variability of thicknesses and weave structures could have implications for the mechanical recycling of fibres, which is a potential topic for further research.

| WATER NEEDED PR KG FINISHED TEXTILE | | | |
|---|---|---|---|
| | COTTON | ~ | HEMP |
| IRRIGATION: | 5000 L | | 200 L |
| RETTING*: | 0 L | | 500 L |
| SPINNING ETC.: | 200 L | | 200 L |
| TOTAL: | 5200 L | | 900 L |

* Hemp stalks are soaked in water (3-6 weeks) to free the textile fibres. Source: Unesco and other

*Figure 58: Comparison of water use for hemp and cotton (Hemp Copenhagen Co., n.d.)*

### Rough estimation of water savings based on material choice

*Pure hemp water savings estimation*

- *1 KG Cotton = 5200 L*
- *1 KG Hemp = 900 L*
- *82.7% water reduction compared to cotton*

*Blended fabric water savings estimation*

- *1 KG Cotton = 5200 L*
- *1 KG 70% Cotton 30 % hemp blend = 3910 L*
- ***24.8% water reduction** compared to cotton*

This overall accumulation of data points suggests that this particular application of 3D weaving could promise a significant reduction in water use (25%), material use (20%), manual labour (40%), overstockage (30%), and end-of-life waste as it can be fully recycled. Once 3D weaving is more integrated as a process, the cost of making a pair using these better materials should come closer to that of conventional jeans. This is because 20% less material and 40% less manual sewing save costs that could be leveraged for otherwise too-expensive materials. Besides this, the previously mentioned percentages can be increased through refinement of processes.

### Labour & stitch length reduction

Exact efficiency gains in terms of labour are also difficult to acquire due to overseas production. An estimation, however, can be created by calculating the stitch length of all the seams in the jeans (as is done with traditional denim), and comparing this to the total stitch length with all 3D woven seams excluded. This does not provide a definitive answer, but indicates that a significant reduction in labour time is likely from the assembly stage only.

First, an estimation of the total seam length is required, for this, all the sewing dimensions are taken from CLO3D for the straight-fit male size 34.

*One leg*

- **Outseam: 1171 mm*
- **Inseam: 922 mm*
- *Leg end: 428 mm*
- *Back pocket: 632 mm*
- **Front pocket lining: 643 mm*
- *Top section assembly: 475 mm*
- *Cinge side: 724 mm*
- *Safety stitch: 220 mm*
    - *Total for one leg: 5215mm*
        - *Total for both legs: 10430mm*

*Joining legs*

- *Belt loops: 375 mm*
- *Crotch: 576 mm*
- *Yoke: 172 mm*
- *Fly: 360 mm*
- *5th pocket: 425 mm*
- *Waistband: 1144 mm*
- *Bartacks, button holes and belt loop attachment are roughly 200 mm*
    - *Total for joining parts: 3252 mm*

*Total seam length estimation:* ***13.7 m***

For this simplified example, all the measurements marked with * indicate a 3D woven seam. While there are considerable differences between this pattern and those of traditional jeans, this gives the most honest example for traditional cut & sew vs 3D woven sewing reduction.

The combined length of all marked measurements for one leg is 2736 mm, resulting in a total of 5472 mm of 3D woven seams in this design. In reality, this number might be higher, as some elements of the yoke, waistband and fly are also integrated to reduce seams. But even with these numbers left out of the equation, that's still an estimated 5.5 m stitch length reduction from a total length of 13.7 m.

With the 3D woven version having a total stitch length of 8.2 m, the amount of manually sewn stitch length is reduced by 40%. In other words, about 40% of the seam length in this design is 3D woven and does not require manual sewing. As 3D weaving might require a learning curve for assembly, this does not necessarily translate into an assembly time decrease of 40%. When comparing the 3D woven assembly method to conventional construction as covered by CottonWorksTM (2023), it becomes apparent that 3D weaving saves steps in some regards. Especially markers, transfers and pattern layouts are removed from the manual process. Besides this, the sewing steps have been reordered and reduced. However, specifically separating layers through cutting requires additional steps and precision. Some additional steps in layer cutting might also add extra time as the whole cutting process is not yet automated.

**Personal reflection on Results**

*This project started with somewhat of a wild guess. "I bet it's possible to create zero waste 3D woven jeans'. I had no idea and trusted the process that I developed over the past years as a designer. Well, trusting the process and plenty of context-inspired iterations later, there it is. It was an everlasting challenge to balance all the complexities within this project. Sustainable choices on all fronts while still being produced and overall desirable. Fixing the fly, only to move the pocket, and then the yoke is off etc. Every obstacle provided an opportunity for improvement, both in my skills and the 3D woven design. I ended up adding a little cutout waste to the base design, as these little alterations allowed for an overall good fit. It is technically possible to leave these small cutouts attached, but due to limited time, we didn't want to complicate assembly even further. Another part that I would've loved to develop further was the 3D woven labels, which are part of the zero waste top section pattern. Their space is reserved in the pattern but their design could not be achieved due to time limitations. The final results should be amazing. Unfortunately, the last design was not finished before the official end of this project. However, I'm certain these final optimised designs (with super cool variations if I may add) will see the light of day soon. The design doesn't only look good, it feels good as well. Not too tight, but properly fitted and not afraid of a little karate kick. Oh, I have so many more ideas for 3D woven denim design, this design is just the tip of the iceberg, But hey, almost everyone likes vanilla, and I hope this first taste will create a desire for the different flavours in the future.*

## C. 3D Weaving as an Integrated System

The potential of 3D weaving extends far beyond the scope of this project, offering countless opportunities for the textile industry to explore sustainable means of production.

**Efficiency Gains:**
By weaving complex structures of garments directly into the fabric, 3D weaving streamlines production processes and offers new ways to design out material waste. As this technology is further integrated with other sustainable initiatives, even greater efficiency gains are anticipated, leading to cost reductions and improved resource utilisation. 3D weaving presents a paradigm shift in the fashion industry (De Jager, 2023), enabling further improvements as the elements in conventional systems are optimized for 3D weaving.

**Made-on-Demand Customization:**
The concept of made-on-demand garments becomes a tangible reality with further adaptation of 3D weaving. Instead of mass-producing standardised garments, manufacturers can tailor products to individual specifications and preferences in real-time. This not only reduces inventory costs but also enhances customer satisfaction by delivering personalised needs with increasingly shorter lead times. The versatility of 3D weaving enables unprecedented levels of user customization. Consumers can choose from a wide range of design options, from patterns and textures to fit and functionality. This level of on-demand customization fosters a deeper connection between consumers and their clothing, as previously suggested by McQuillan et al. (2018), driving further brand loyalty and differentiation in the market.

**Localised Production:**
The decentralised nature of 3D weaving opens doors to future localised production hubs. By bringing manufacturing closer to consumers, transportation costs and carbon emissions associated with global supply chains can be minimised. Furthermore, localised production could foster economic resilience by empowering local communities and reducing their dependence on centralised manufacturing facilities.

**Overstockage Reduction:**
One of the most significant challenges in the fashion industry is overstockage (World Cleanup Day Organisation 2022), which leads to massive waste and environmental degradation. 3D weaving offers a solution by enabling made-on-demand production, thereby eliminating the need for excessive inventory and reducing the risk of overstockage. This not only mitigates environmental impact but also creates potential to optimise inventory management for businesses.

**Circular Economies:**
At the heart of 3D weaving lies the potential to create circular economies within the textile industry. By using recyclable materials and implementing efficient production processes, 3D weaving can minimise waste and maximise resource efficiency. Additionally, 3D weaving facilitates the integration of recycled materials into new products with fine adjustability of yarns, furthering the transition towards a circular economy model.

In conclusion, the future of 3D weaving is full of potential. From enhancing efficiency and customization to promoting localised production and circular economies, this technology can play a key role in transforming the textile industry for the better.

# 6. Discussion

This chapter interprets the results in the context of the project scope, objectives, and the reviewed literature. It also discusses unexpected outcomes and their significance. Broader implications of this work for the field of sustainable fashion design are explored as well.

## A. Interpretation of Results

The findings of this project have significant implications for sustainable fashion design and the application of 3D weaving technology. The results emphasise the potential of 3D weaving to bring about transformation in the industry, not only as an innovative and sustainable manufacturing technique, but also as a catalyst to explore previously uncharted design possibilities in the denim industry.

One important aspect highlighted by the findings is the intricate nature of 3D woven design, particularly in terms of multilayer pattern layouts with zero-waste design methods. This hybrid way of design benefits greatly from digital 3D tools, which enable new workflows to articulate the relationship between form, pattern cutting and waste (McQuillan, 2020b) Empirical evidence demonstrates that successfully implementing 3D weaving requires a nuanced understanding of design principles and practical experience in strategies to reduce waste. Achieving an optimal balance between aesthetic considerations, waste reduction goals and labour efficiency is crucial in this process.

In addition, this project brings attention to the constraints that come with this balancing act. Although 3D weaving presents great opportunities for innovation and sustainability, certain limitations need to be navigated. These limitations may involve difficulties in achieving desired aesthetics while still meeting waste reduction goals, as well as complexities in optimising labour efficiency during the production process. The exact implementation differs greatly between supply chains and knowledge of the 3D woven denim process covered in this report may aid the implementation in different contexts. Insights from related work by Vroom (2022) allowed the process to address 3D woven design difficulties early on, such as new aesthetics, fraying, waste and sewing steps. The design has proven to some extent that it provides an elegant solution for several industry problems, but in this early stage of development both the design and implementation provide plenty supplychain dependent hurdles. This is, simply put, because the current supply chains have years of experience with traditional methods that differ quite a lot. This positions 3D weaving for denim jeans production as a promising solution for the industry’s environmental challenges, but this solution requires continuous effort to adapt and align with the industry.

Overall, the analysis of the findings emphasises the intricate relationship between design, sustainability and manufacturing efficiency within the realm of 3D weaving technology. Understanding these dynamics and addressing the associated challenges is essential to fully harness the potential of 3D weaving. When done right, it can drive positive change in the fashion industry and pave the way for a more sustainable and forward-thinking future.

## B. A New Discipline in Fashion Design

The fashion industry faces an urgent need to adapt new processes, systems and supply chains to address pressing environmental challenges (Ellen MacArthur Foundation, 2021). The integration of 3D weaving emerges as a pivotal tool, offering significant potential to revolutionise traditional garment design and production methods. This chapter delves into how the adoption of 3D weaving contributes to the evolution of garment design as a new discipline, emphasising its role in moving towards circular economies while fostering innovation in the industry.

**3D Weaving: Catalyst for Design Innovation**
As the fashion industry is continuously confronted with the need for sustainability, there is a growing recognition of the importance of innovation in garment design. 3D weaving emerges as a catalyst for such innovation, offering designers a versatile tool to explore new creative avenues. By enabling the creation of intricate three-dimensional textiles with minimal waste, 3D weaving redefines the parameters of garment design, pushing the boundaries of traditional aesthetics and paving the way for novel forms of expression. The discipline of 3D weaving represents a paradigm shift in design practices (De Jager, 2023), requiring designers to adopt new approaches and methodologies. Unlike conventional methods that rely on two-dimensional patterns and flat textiles, 3D weaving introduces designers to a world of possibilities (and challenges) where form, texture, and structure intertwine seamlessly. This evolution in design practices encourages experimentation, collaboration, and interdisciplinary exchange, fostering a dynamic and innovative design culture within the industry.

**Navigating Towards Sustainability**
At its core, the emergence of 3D weaving as a new discipline in garment design reflects the industry's collective journey towards sustainability. By prioritising resource efficiency, waste reduction, and environmental impact, designers embrace 3D weaving as a means to align their creative vision with broader sustainability goals. This shift in mindset transcends individual design projects, shaping a culture of sustainability that influences every aspect of garment production and consumption. A defining feature of 3D weaving as a new discipline in garment design is its accessibility and inclusivity. Unlike some advanced technologies that require extensive expertise or specialised equipment, 3D weaving can be implemented using existing machinery and attainable skills. This democratisation of technology empowers a diverse range of designers and manufacturers to participate in the movement towards sustainability, driving collective progress and fostering a more inclusive design community.

The integration of 3D weaving technology into garment design marks the emergence of a new discipline that is defined by innovation, sustainability, and inclusivity. By embracing 3D weaving as a versatile tool for creative expression, designers can navigate towards a more sustainable future while pushing the boundaries of traditional design practices. As the industry continues to evolve, 3D weaving stands as a beacon of hope, inspiring designers to reimagine the possibilities of fashion and shape a more environmentally conscious world.

## C. Limitations and Challenges

While this research aims to explore innovative solutions and advancements in 3D weaving technology, it is essential to acknowledge and address the limitations and challenges encountered. By identifying these constraints, future endeavours can better navigate potential obstacles and strive towards more effective and efficient outcomes.

**Novel skill set**
During this project the necessary skills were developed to execute this novel design approach to 3D weaving. While this process was guided by design and not current systems, it must be acknowledged that learning 3D woven zero waste design principles and translating this into digital tools such as CLO3D, is not necessarily an easy task. Background knowledge in (digital) pattern design, industrial engineering, sustainable practices and manual craftsmanship will provide a reference when exploring new frontiers. This project illustrates how a well-thought-through design can tackle several issues, and while the base design is easily customizable to endless versions, initial development takes a considerable amount of time.

**Last-Minute Work Week Visit Cancellation:**
One significant challenge faced during the project was the unexpected cancellation of a crucial workweek visit, intended to optimise production processes on-site. This unforeseen event disrupted planned activities and hindered the implementation of vital improvements, leading to delays and affecting project outcomes.

**Repeat Width of Loom:**
Another limitation encountered was the constraint posed by the repeat width of the loom used in the weaving process. The fixed width-restricted the design possibilities and required adjustments to accommodate desired patterns or structures, impacting the flexibility and scalability of production with this particular machine.

**Picks per Centimetre of Warp:**
The limitation in the number of picks per centimetre of warp posed challenges in achieving desired weave densities and varieties. This constraint affected the intricacy and complexity of woven designs, limiting the range of textures and patterns that could be achieved within the project parameters.

**Lead Times and Delays:**
Lead times and delays emerged as significant challenges throughout the project timeline. Unforeseen delays in material procurement, equipment maintenance, or logistical issues disrupted planned schedules and milestones, affecting project progression and delivery timelines.

# 7. Conclusion

This chapter summarises the main contributions, key findings and the practical implications of this graduation project. It also reflects on the contextual limitations of this project and suggests potential directions for future research in this field.

## A. Summary of Contributions to Knowledge and Key Findings

The main findings and their relevance to the field of sustainable fashion design.

**Proof of concept for 3D woven jeans made using existing machinery**

- Jeans made using this 3D Jacquard weaving design methodology can already be made within existing supply chains, but initial development takes longer for emerging methods like this.
- Jeans made using this 3D Jacquard weaving design methodology can look and feel like commercially viable garments, with proof of concept jeans for 34 females to 34 males with an average BMI.

**3D woven jeans with a conventional aesthetic can be made using zero waste principles**

- Increasing material efficiency by an estimated 20%.
- Jeans made using this 3D Jacquard weaving design methodology can be 100% recycled in cellulose-based waste streams once the screw-on buttons and buckle are removed.
- The amount of sizes that can be offered in zero waste configurations highly depends on the (variable) width of the looms repeat, specialised machinery for 3D weaving can further improve efficiency, flexibility and cost of production.

**Jeans made using this 3D Jacquard weaving design methodology can reduce sewing length**

- Decreasing manual sewing labour by an estimated 40%.
- A single layer of the final showcase design has an average weight of 400gsm, made from indigo ring dyed ⅓ twill 70% Cotton/Hemp blended 3D woven fabric (10 Ne 40Picks/cm).

**Demonstrating a TRL between 6-7 for 3D weaving as a denim garment production process**

- Taking it to the level of commercially viable products but requiring further refinement and adaptation.
- Consider that early development may result in significant waste as fabric outside the main repeat may not be used, not all Jacquard looms have a bed without repeat.

**87,6% of industry respondents think 3D weaving provides value for a more sustainable future**

- Jeans made using this 3D Jacquard weaving design methodology could be adopted by brands within the next 5 years, according to 63% of the industry respondents.
- Almost half of respondents would render 3D woven denim commercially viable when the production price does not increase by more than 25% compared to traditional production.

**A novel holistic approach to sustainable fashion design**

- Execution and refinement by an industrial design engineer.
- Improved material selection can reduce environmental impact significantly more. A higher amount of hemp, Tencel or recycled cotton is very feasible.

**Definition of unique design features and applications**

- Besides the sustainable benefits and efficiency gains of 3D weaving, this process offers unique design opportunities that provide new ways for brands and consumers to express themselves without additional changes to the development process.
- While possible automated customisation seems feasible, the 3D woven design process itself requires time for each new base garment. Once the base design is finished, it becomes easy to adjust sizes or add specific patterns and details.

**instructive starting point for future designers**

- A practical design guide to 3D weaving that provides designers interested in sustainable innovation with a point of reference.
- Settings and key concepts used in the process.

**3D weaving limitations and future potential**

- Further potential of production automation in 3D weaving is high, with plausible future integration of parametric pattern adjustments, automated laser cutting, made-on-demand processes and localised production.
- 3D weaving for Industry 4.0 offers opportunities in automated production, user customization, made-on-demand supply chains and reduction of online returns and overstock age.

## B. Future Research

3D weaving technology creates new avenues for future research and innovation in sustainable fashion design. This section highlights potential subjects for further exploration and improvement.

**4-Layer Constructions:**
Investigating the feasibility and practicality of utilising 4-layer constructions for summer-weight fabrics presents possible applications that harness the full potential of 3D weaving. Patterns were designed during this project that allow for such constructions, but their development had to be halted to prioritise the primary design. By optimising layering techniques, researchers can develop garments that offer increased efficiency, further impact reduction and overall labour reduction. The main limitations in this sector are currently overcoming the fractional layer densities and developing a fabric that's neither too dense or thin.

**Extendable Folding Structures:**
3-layer constructions offer potential for creating extendable folding structures, unlocking possibilities for multi-morphic and adaptable textile designs. This use of 3D weaving was left unexplored in this project, as the results did not aid the development of the main 5-pocket jeans design. However, through further experimentation and prototyping in this area, researchers can explore innovative folding mechanisms and structural configurations facilitating efficient applications of 3D weaving in future garment design, wearable technology and possibly architectural textiles.

**Parametric design for Future Automation:**
Parametric design principles for future automation through software offer further efficiency gains and custom design flexibility for 3D weaving. Basic principles of computer thinking enable variable human dimensions to be linked to specific parameters of the pattern, allowing for automatic and highly customised clothing that fits like a glove. By developing algorithms in software such as Rhino Grasshopper, researchers can streamline the design process, enable rapid prototyping, and facilitate customization from 3D body scans, eventually advancing the capabilities of 3D weaving technology.

**Smart Creel for Variable Warp Widths on a repeatless Jacquard loom:**
Designing a smart creel system capable of accommodating variable warp widths on a repeatless Jacquard loom presents a novel challenge. By integrating sensor technology, adaptive controls, and machinery add-ons, researchers can further optimise loom efficiency, minimise material waste, and unlock new possibilities for intricate and customizable textile designs.

**Automated Laser Cutting:**
Exploring automated laser cutting techniques for post-weaving processes holds promise for enhancing efficiency and precision in garment production. By integrating laser cutting technology with 3D woven fabrics, researchers can achieve intricate patterns, seam sealing, and finishing touches, revolutionising the manufacturing process while reducing environmental impact.

**Washing & Finishing Through Graphic 3D Woven Techniques:**
Investigating graphic 3D woven techniques for washing and finishing processes opens avenues for creative expression and textile innovation. By incorporating graphic elements directly into the fabric structure, researchers can explore novel aesthetic effects, texture manipulation, and surface treatments, pushing the boundaries of traditional textile design.

**Variable Shrinkage Manipulation to Create 3D Shapes in 2D Planes:**
Exploring variable shrinkage manipulation techniques offers a new dimension to 3D weaving technology. By selectively controlling shrinkage patterns within the fabric, researchers can create intricate 3D shapes and textures on a 2D plane, opening possibilities for sculptural textiles, architectural surfaces, and functional fabrics with tailored performance properties.

**Defining and Developing a Highly Automated, Localised, Made-to-Order, User-Customised Supply Chain:**
Pioneering a highly automated, localised, made-to-order, user-customised supply chain represents the future of sustainable fashion production. By integrating advanced manufacturing technologies, digital fabrication methods, and data-driven insights, researchers can establish a responsive and efficient supply chain ecosystem, delivering personalised products with minimal environmental footprint. The implementation of such systems requires a combination of strategy and supply chain-specific limitations.

In conclusion, the future of 3D weaving technology and sustainable fashion design is ripe with possibilities. Each of the above-mentioned topics could provide a starting point for further development. By embracing innovation, collaboration, and interdisciplinary research, researchers can drive meaningful advancements that shape the future of fashion and 3D woven textiles. These suggested avenues for future research serve as a roadmap for continued exploration and discovery, paving the way for a more sustainable, resilient, and creative fashion industry.

# 8. Recommendations

This chapter offers practical recommendations for fashion designers, manufacturers, and policymakers aiming to adopt sustainable practices. As well as educational recommendations which may help to accelerate the implementation of findings and insights generated through this project.

## A. Practical Recommendations

As daunting as the process seems, trial and error goes a long way in developing the novel skill set that is 3D woven design. While this process has significant potential to influence most parts of the garment life cycle, its development is still in the early stages and adaptation will further shape its application. This section provides practical recommendations for anyone looking to explore 3D woven design.

Gaining expertise in 3D weaving design methods requires a variety of skills, experience from traditional practices may help adaptation but is not an absolute must. This process was executed with industry-standard machinery and software. It could be recreated on any Jacquard loom with a wide enough programmable repeat. It helps to look at the foundational disciplines that together shape 3D weaving. In particular, Jacquard weaving, zero waste design techniques, and digital pattern design.

This report should provide a starting point for manipulating Jacquard looms with 3D woven design. Relevant insights for designers are extensively covered in Chapter 4 Design and Implementation. As well as reference points for key concepts, settings and material selection. The best results in this project were achieved with 30-40 yarns per cm of Ne 8-10 thickness for both weft and warp, equally split in two layers with a 1⁄3 twill, resulting in around 12 OZ weight per layer with 16,7% weft shrinkage and 3,75% warp shrinkage after soft-hand feel fabric finishing. Variations in structures and layers can be further iterated from there. Creating a sample blanket together with the weave expert or production partner is recommended, as it helps to define the desired results for each different setting (e.g. variety in looms, yarns and structures will yield different results even with the same starting point). Close collaboration with weave experts plays a central role in the design process from the MOB onwards. As a designer, knowledge of the process is valuable for better iterations, but the programming of the loom is primarily done by weave experts in NedGraphics. An Introduction to Weave Structure for HCI (Devendorf et al., 2022) provides reference for working with 3D weaving. Future research publications by the involved academic stakeholders of this project strive to make 3D weaving more accessible and the ongoing PhD research of Milou Voorwinden aims to shed more light on 3D weaving.

An introduction to zero waste design for 3D weaving has been covered in chapter 4 as well. A deeper understanding of zero waste principles may help in creative approaches for 3D woven pattern layouts. Zero waste is a re-emerging discipline in fashion design extensively covered in previous research named Zero Waste Systems Thinking: Multimorphic Textile-Forms (McQuillan, 2020) and Zero Waste Fashion Design (Rissanen & McQuillan, 2023). Work from Danielle Elleser and the Zero Waste Design Collective also inspired the early stages of getting acquainted with zero waste garments. Developing prototypes with paper and calico is highly advised, as they provide physical reference for digitally designed patterns before moving to fabric production.

Although the process could be recreated without digital garment design tools, its use highly speeds up the iterative process of zero waste 3D woven pattern design. CLO3D proved to be a vital component in this design process, and while it does require some improvisation to simulate 3D woven designs, all the base patterns were iteratively designed in the 2D pattern workspace from CLO3D. Mirroring pattern pieces, rescaling them and layering several pieces on top of each other becomes a fluent process in this software.

Since patterns imported in Illustrator are already finished, little alternation is required to export a proper MOB. Seam allowances, layer indication and pattern layout are all done in CLO3D before exporting. It is technically possible to create the pattern from scratch in Illustrator and other tools, but due to the lack of 3D simulation this is not advised.

As the process of 3D woven design may be difficult to master alone, feel free to reach out to the author or involved stakeholders for further questions.

## B. Educational Recommendations

This section focuses explicitly on educational recommendations regarding 3D weaving, suggesting how research can and should inform educational programs in the field of industrial design and sustainable fashion.

I once heard in a lecture that 80% of the environmental impact of garments can be reduced at the design stage. One spark and about a year later, this inspiration kept the project going until the very end. I now believe that we as a species can tackle the current environmental problems with new approaches, but it's hard to see the way until it has been designed. Considerable time was spent developing this design process, exploring and balancing several ways of integrating 3D weaving. Even though the technology offers tremendous potential for businesses, consumers, and sustainability, the way to mass adaptation has just begun. I hope these contributions to the field of 3D weaving may inspire more holistic thinking fashion designers to pave the way for the masses.

It's important to involve students now as they can drive innovation further when they hit the field. Education should not only focus on students but also provide a platform for interested businesses and academics to share ideas. Transparency and collaboration are driving pillars for sustainable practices and can be promoted through education.

It's also important to note that this approach to research through design can be seen as risky within a commercial setting. While the need for sustainable innovation is increasingly gaining importance in the fashion industry, many opportunities that are still in early development pose risks to a business's bottom line. Innovations such as 3D weaving may find resistance while gaining wider adoption as their implications require a major shift in current processes, often straying away from common practices that feel safer from an economic perspective. Research such as this helps to push the technology past the early stages of production, outside the context of quarterly reports and free of risk for the current industry. Mitigating some of the risks through development in academic settings may help to persuade businesses to adopt pivotal methods like 3D weaving sooner, as the groundwork has already been done for them. This underscores the need for academic research through design projects focussing on sustainable innovation, and highlights the possible edge that students can acquire when they develop unique skills in such a context.

It's interesting to note that even though the results of this project are positive, the majority of design skills were developed and executed within just 6 months. The right personal motivation and dedication in combination with a subject like this may provide the ideal playground for rapid development. This emphasises the importance of academic environments that support the development of novel processes and foster new ways of thinking, perhaps highlighting the key role that the supervisory committee played in this project.

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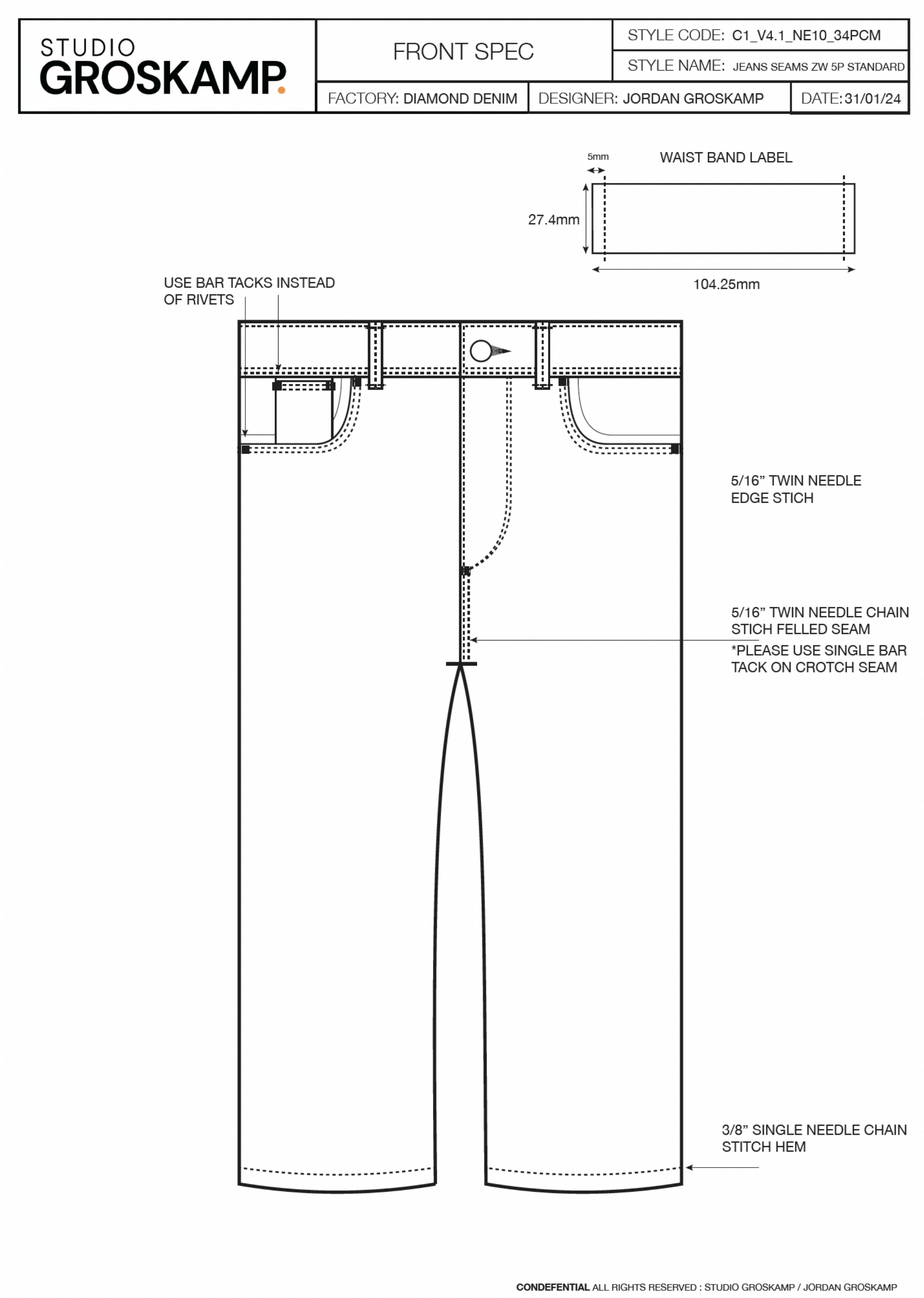
*Information gathered through field research, stakeholders and discussions has been utilized in the practical implementation of this project. There is a possibility that an overlapping source may not have been, or may not have been fully, cited. The author apologizes in advance for any omission or incomplete referencing of these sources.*

# 10. Appendices

*Supplementary materials such as tech pack drawings, project brief and assembly guide.*

## A. Tech Pack

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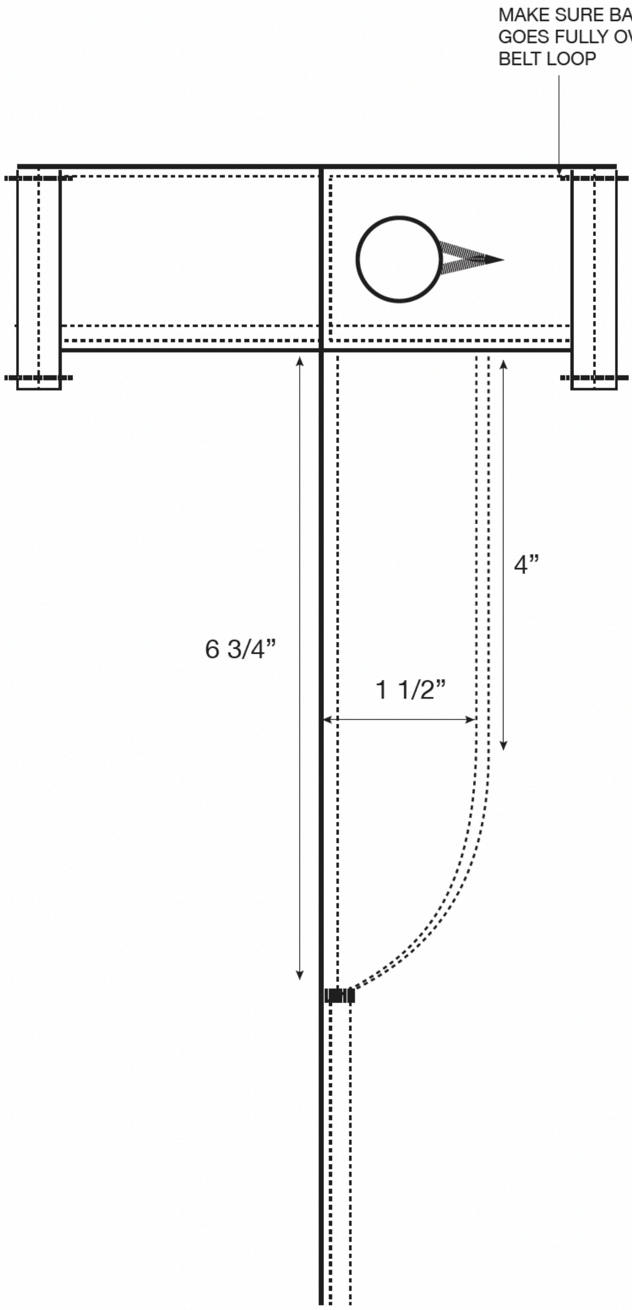

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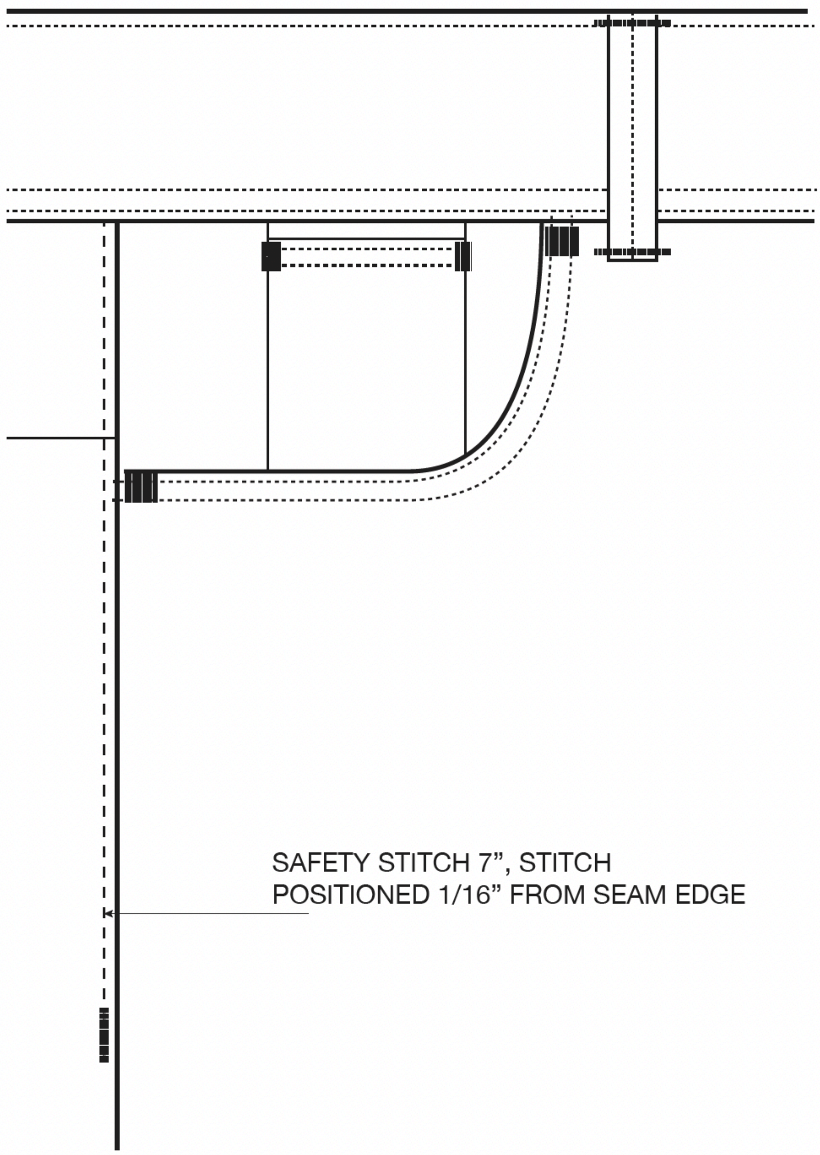

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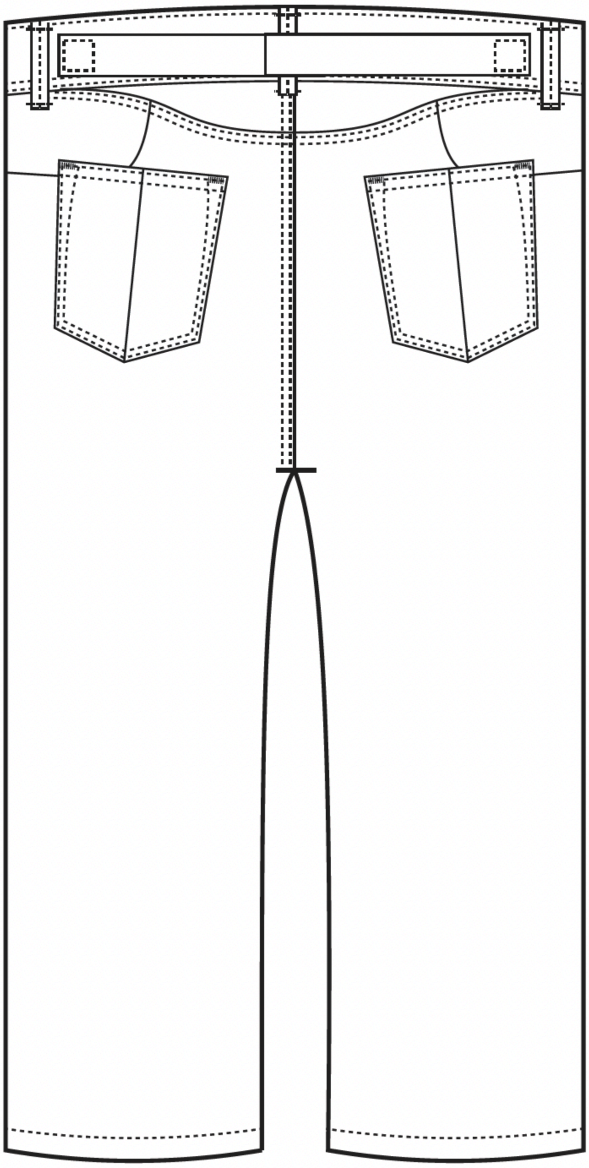

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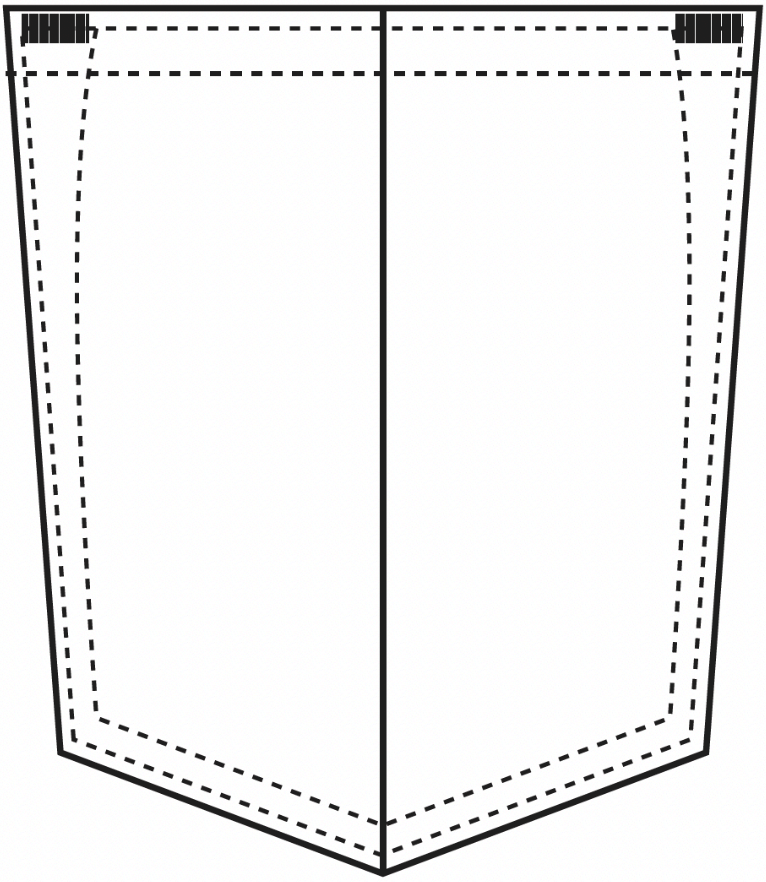

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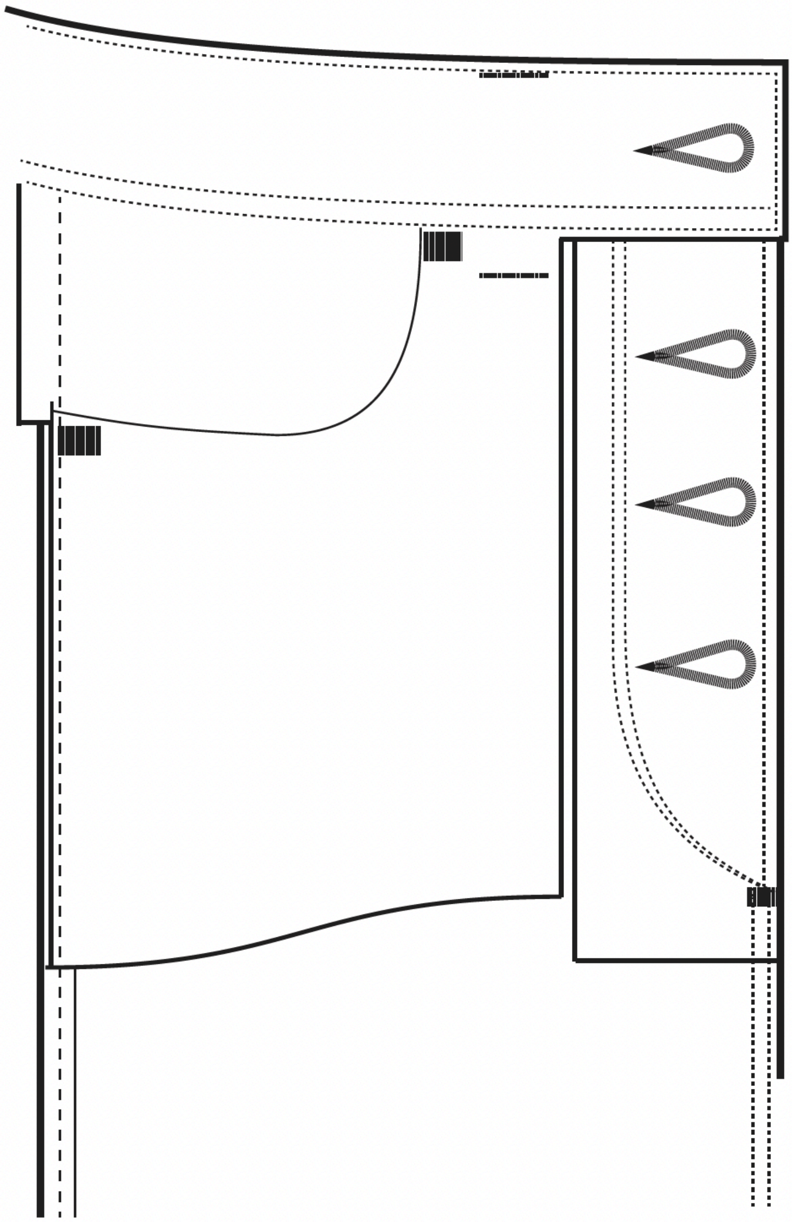
| | | STYLE NAME: JEANS SEAMS ZW 5P STANDARD |
| FACTORY: DIAMOND DENIM | DESIGNER: JORDAN GROSKAMP | DATE: 31/01/24 |



| STUDIO GROSKAMP. | POCKET BAG SPEC R | STYLE CODE: C1_V4.1_NE10_34PCM |
|---|---|---|
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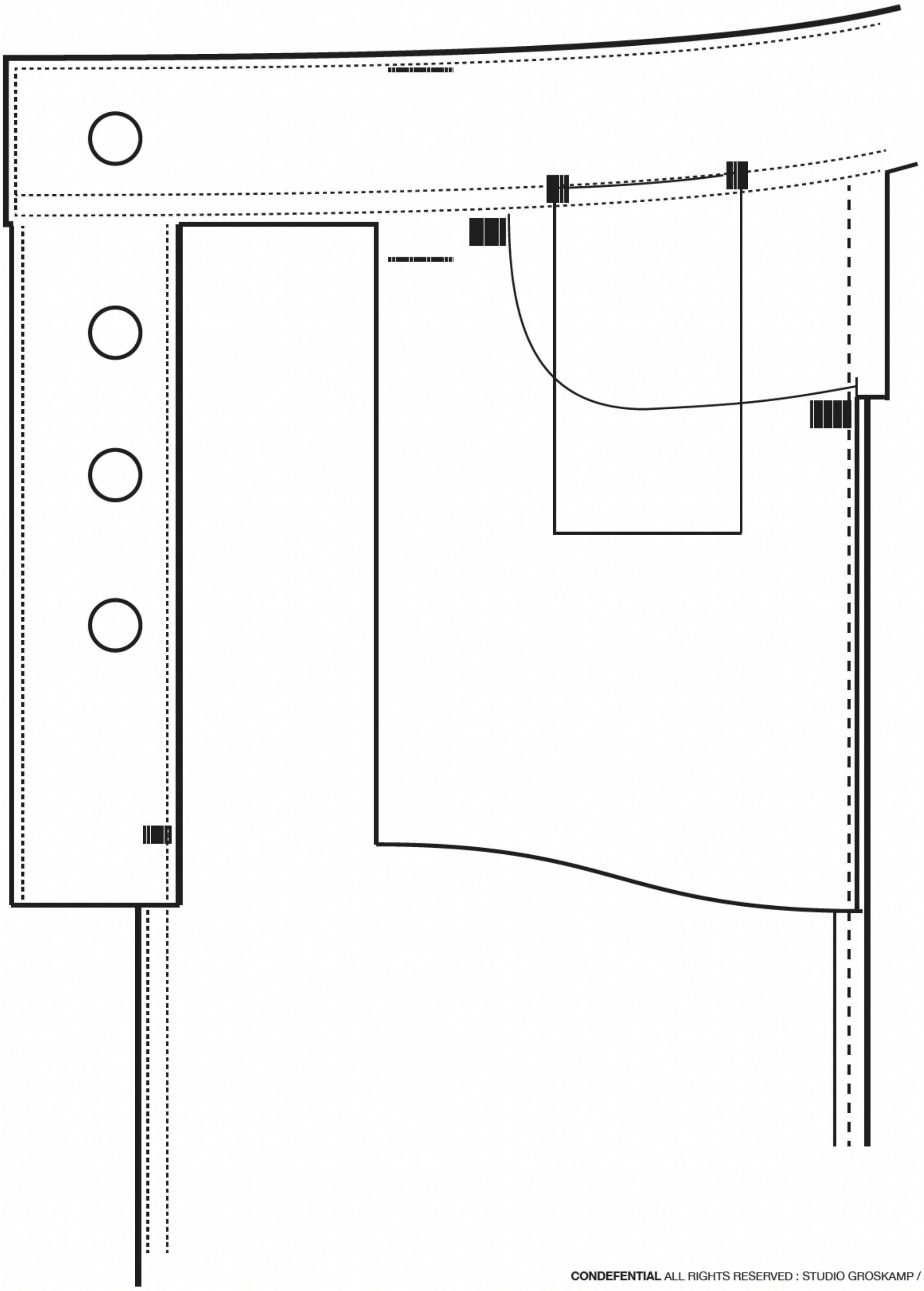

# B. Project Brief

**Personal Project Brief** - IDE Master Graduation

TUDelft

Design for sustainable fashion: 3D weaving for denim jeans production — project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 29 - 09 - 2023 | 28 - 03 - 2024 end date

**INTRODUCTION ****

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

3D woven denim garment design using industrial jacquard looms offers great opportunities for a more sustainable fashion industry, but requires an innovative approach to implement in a way that is desirable from the perspective of 1) business, 2) people and 3) the planet. The context of this project is around applications of 3D weaving for the design of sustainable fashion through (near) whole garment manufacturing. This project is done in collaboration with Diamond Denim, a producer of denim garments located in Pakistan and participating party in previous research projects.

3D woven garment design is a relatively new discipline in the field of sustainable fashion design, and the technology yields great potential for impact reduction in terms of waste, material use, production time and manual labor. Which are desirable design characteristics for manufacturers, brands and consumers alike looking for sustainable garments. By integrating several steps of the production process in 3D woven sub assemblies of garments, and considering near zero-waste design and conventional production pipelines, a design can be made to showcase the sustainable potential of 3D weaving for the fashion industry.

This will be done by leveraging various integrated product design strategies, insights from previous projects and research methods. I would also like to incorporate digital design and visualization methods, as well as qualitative interviews with brands and quantitative interviews with consumers. Some time and resources should be reserved for meetings and the development of prototypes on the company side, the degree of which will be determined together with the company throughout this project. Besides the development of an optimally balanced concept for the project context, I'd like to take the final embodiment design one step further to be as close to a market ready product as possible.

- The main interest from a TUDelft research perspective is to develop a design that showcases the environmental benefits of 3D weaving for garment production. Holly McQuillan (Chair) and Milou Voorwinden (Mentor) are involved for their previous contributions on the topic of and 3D weaving and general expertise on sustainable textiles.

- The main interest from the perspective of Diamond Denim is to develop an innovative final design that people can envision in a store, looks good and feels good. Diamond Denim is a Pakistan based manufacturer of denim garments, who facilitate the prototyping and production using industrial Jacquard Looms.

Main opportunities are reductions in overproduction, material waste, lead times, labor costs and garment returns from online purchases. While potentially increasing consumer customization for the look, feel and fit of their garments.

Limitations to be mindful of are: Weaving structures, preprocessing of to-be-cut patterns for fraying prevention, repeats in the loom, prototype lead times, minimum sample quantity, post-processing, environmental impact for production and materials, washing, shrinkage, seam orientations, grid orientations, negative relation between layer thickness and stacked layer count, and finally improving the current technology readiness which I aim to be at TRL 7-8 at the end of this project.

The primary objective is the learning situation achieved within this graduation project, and the benefit of this working situation for the client is derived from that

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introduction (continued): space for images

GRADUATION PROPOSAL DRAFT

3D WOVEN DENIM 5 POCKET JEANS FOR SUSTAINABLE FASHION DESIGN

**PERSONAL INTRODUCTION**

Hi, my name is Jordan Groskamp and I'm graduating in the MSc Integrated Product Design at the Technical University of Delft. I like to tackle complex challenges that seemingly don't have one right answer, and I'm currently expanding my design expertise in the field of sustainable fashion design. I feel like this project in 3D woven denim is the ideal crossroad between technological innovation, better businesses and a better world. I'm excited to work on this project and grateful for the opportunity to work together. I'm a musician in my free time, and a part-time creative coach helping teenagers with autism to develop their talents in design, engineering and music.

**PROJECT BRIEF**

3D woven denim garment design using industrial jacquard looms offers great opportunities for a more sustainable fashion industry, but requires an innovative approach to implement in a way that is desirable from the perspective of 1) business, 2) people and 3) the planet. Besides determining the most optimal jeans concept design for these 3 factors, I would like to take the final embodiment design one step further to be as close to a market ready product as possible.

This will be done by leveraging various integrated product design strategies, insights from previous projects and research methods. I would also like to incorporate digital design and visualization methods, as well as qualitative interviews with brands and quantitative interviews with consumers. Some time and resources should be reserved for meetings and the development of prototypes on the company side, the degree of which will be determined together throughout this project.

**TIMELINE 2023-2024**

- August 22 - Preperation meeting
- September 29 - Official kick off
- December 07 - Mid-term (40%)
- January (TBA) - Working visit week
- February 22 - Green-light (80%)
- March 28 - Graduation & deliverables

**DELIVERABLES**

- Final report with insights
- Public presentation
- Prototypes (if any)
- Final product concept with recommendations

**OTHER NOTES**

The exact project brief can be defined in communication with Diamond Denim, me and the TUDelft supervisory board (details follow during the preparation meeting). A company mentor should be defined if possible. The company mentor or other representative should dedicate time to participate in meetings and communications with the student during the project. An example contract will be provided by TUDelft. Feel free to ask any additional questions, see the TUDelft GRADUATION MANUAL or my personal LINKEDIN for more background information.

Student: Jordan Groskamp - Email: j.d.groskamp@student.tudelft.nl

image / figure 1: Graduation proposal draft sent to diamond denim before holiday period

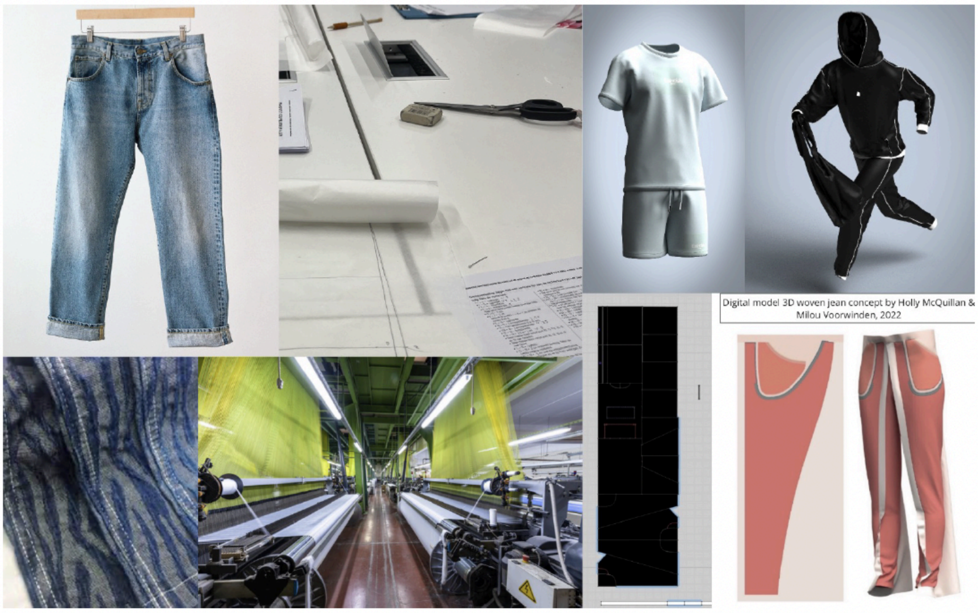



image / figure 2: Visual examples of project subjects

## PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

This project scope focuses on the development and application of 3D weaving for garment production as a driver for sustainable change in the fashion industry

The solution space is therefor a final concept denim jeans design utilizing 3D weaving, applied in the current fashion industry context that is desirable from the perspective of business, people and the planet.

Issues that are to be addressed:

- Limitations and workarounds for 3D woven design.
- Strategic planning of multi-track testing to effectively iterate on insights gained by developed samples
- Designing for continuously developing technologies.
- How 3D weaving aids a sustainable fashion industry as opposed to a fast fashion industry.
- Applying 3D woven techniques in a way that saves production time and waste.
- Balancing novel aesthetics with recognizable denim jeans characteristics
- Post processing for market ready products.
- Desirability of opportunities for fashion brands and consumers.

## ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... . In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

- Design applications of 3D woven Jacquard fabrics for reduced environmental impact of garments.
- A final concept design of a 3D woven denim jeans (Product protoype that looks and feels as a cohesive final product).
- Implications and recommendations for further development.

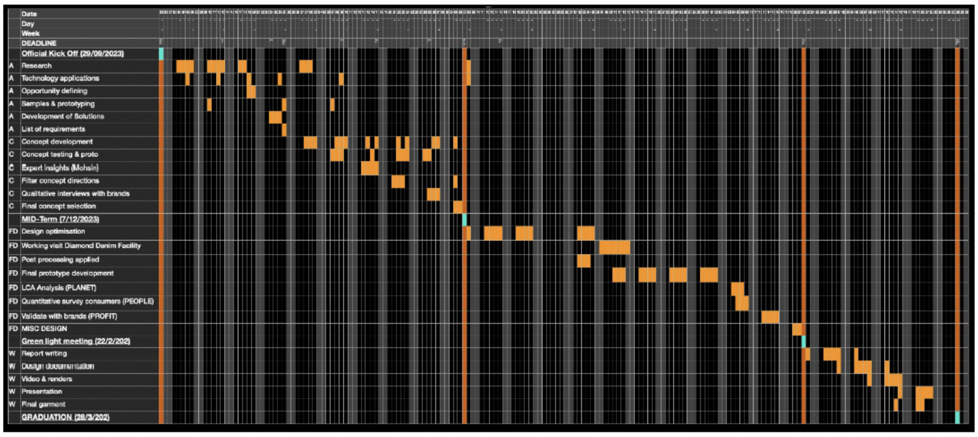
The final result of the project will be a pair of 3D woven denim jeans, which showcases that this integrative approach to sustainable fashion design is market viable, technologically feasible, and desirable by the consumers.

Deliverables:
Final report with insights & appendix
Public presentation, video/poster & visualizations
Embodiment design of 3D woven denim jeans
Final product concept with recommendations

## PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 29 - 9 - 2023 28 - 3 - 2024 end date




I will work on the project 4 days a week for a period of 25 weeks, with an exception of week 52 of 2023. (100 days total) I aim to use personal adaptations on the TUDelft way of design I've picked up over my career, the process is comparable to the triple diamond approach. Where I will diverge and converge to iterate on the problem level (20%), and concept level (20%) which ends with a clear concept direction. The third phase of development (40%) starts around the mid-term, and focuses on optimization of the concept and the final embodiment design. This phase is concluded with a design freeze aimed before the green-light. The last 20% is spend on documentation and presentation materials.

It is desired from the company to be available for collaboration during the project. This is in the form of (bi-)weekly meetings, email, the below mentioned dates, regular production and postage of prototype samples towards the Netherlands.

Timeline:
August 22 - Preparation meeting with chair, mentor & company
September 29 - Official kick-off
December 07 - Mid-term (40%)
January (TBA) - Working visit week
February 22 - Green-light (80%)
March 28 - Graduation & deliverables



Initials & Name J.D. Groskamp Student number 4668642

Title of Project Design for sustainable fashion: 3D weaving for denim jeans production

## MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... . Stick to no more than five ambitions.

I like to tackle complex challenges that seemingly don't have one right answer, and I'm currently expanding my design expertise in the field of sustainable fashion design. I feel like this project in 3D woven denim is the ideal crossroad between technological innovation, better businesses and a better world. I'm excited to work on this project and grateful for the opportunity to work together with the involved stakeholders. I've been preparing myself for a graduation topic focused on sustainable fashion through electives, small digital fashion design jobs, basic fashion design evening workshops, conversations with various people in the field and a prolonged preparation period to ensure the project tackles relevant opportunities for sustainable change in the fashion industry.

I aim to (im)prove the application of my skillset as an integrated design engineer to tackle challenges in sustainable fashion, as well as managing project development in a professional interdisciplinary context, and showcasing my expertise as a rounded designer with a design approach that creates value for all stakeholders.

Learning ambitions:

- Broadening my design skills for sustainable fashion applications
- Experimenting and prototyping with innovative production techniques for 3D woven garment design
- Integrating and managing interdisciplinary insights from a complex context into a cohesive design
- 3D visualization techniques such as Clo3D, Solidworks, or other visualization tools such as Photoshop, Indesign and Procreate etc.
- Applying my insights from the design agency internship to shape a professional design project.

## FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

As communicated during the preparation meeting, rights will be shared fairly between stakeholders. The extent of which is described in the NDA created for this project.

# C. Assembly Guide

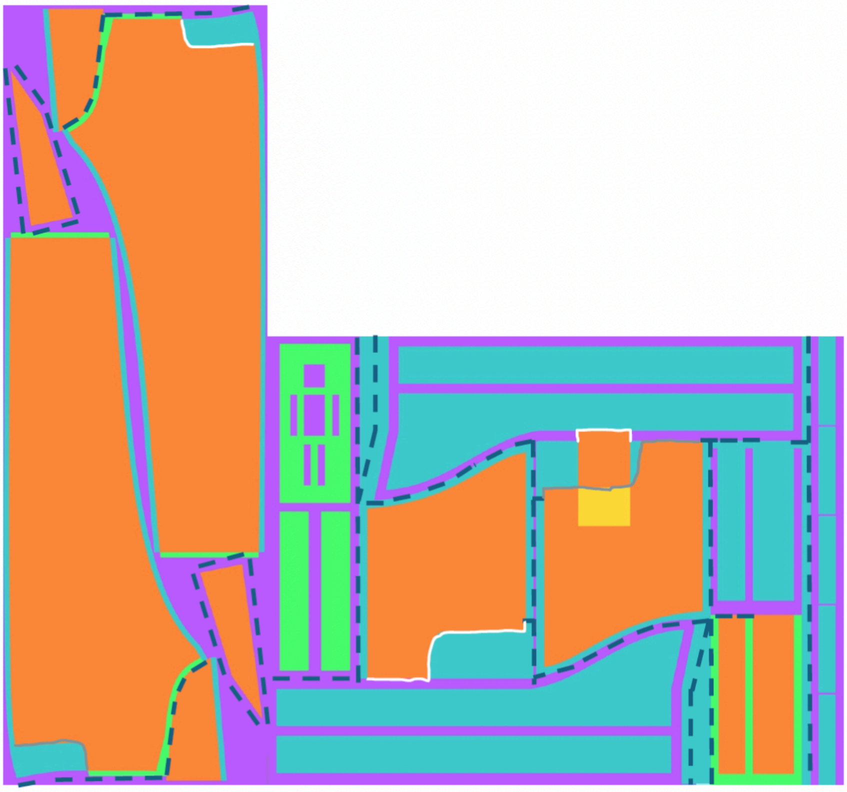
## 3D Woven Jeans Assembly Guide (C1_V4)

This document aims to explain the assembly process of the 3D woven 5 pocket jeans. This document was made using version (DD_C1_V4_Male) + (DD_WS1.2_Male). Please try to assemble the jeans to the best of your abilities, feel free to experiment and share problems when they arise. The first time with 3D woven fabrics may take extra time, .

The following combinations of files can be used to create jeans:

- DD_C1_V4 Male + DD_WS_Male
- DD_C1_V4P_Male + DD_WS_P_Male
- DD_C1_V5_female + DD_WS_V2_Female
- DD_C1_V4 + DD_CWS_V1
- DD_C2_V1 + DD_CWS_V1 (using 2 layer legs)
- DD_C2_V1 + DD_DWHS_V1 (using 4 layer legs)

Please use bar tacks instead of rivets. Please use cotton yarn for sewing. Please use 4 buttons, preferably screw-on buttons if available.



Cutting instructions: Striped – cut all layers, white – cut top layer, Gray – cut bottom layer

1.1 - Cut out the pattern.

1.2 - Cut out the pattern pieces.

1.3 - Cut out the layers, folding inside out and ironing is advised.

*Step 1.1*

*Step 1.2*

*Step 1.3 (Cut out large pocket from the other side [red], cut the 5th pocket from this side [Green], cut through all [orange])*

2.1 – Fold pants with the dark side facing out. Align opening of pocket pattern over pants pocket opening (The seams of the pocket are now facing out), the fly section and 5th pocket should be on the wearers left side of the jeans.

2.2 - Sew pocket curve on both sides.

2.3 – Make a 1 cm cut underneath waistband marker and pocket. Fold the pockets inside out and sew the 5th pocket opening. (The markers of the pocket and legs should align as can be seen in pictures from step 3.2 and 3.3).

*Step 2.1*

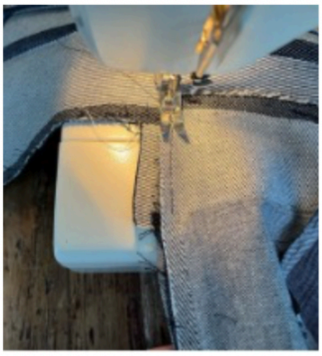
*Step 2.2*

3.1 - Vertical edge of pocket should align at 1 cm distance from vertical edge of legs, the horizontal legs marker should align over the horizontal pocket marker.

3.2 - Sew along entire vertical edge of pocket (The cut-out edges of the pocket should be on the inside of the jeans.

3.3 - Sew along opening of pocket (The fraying lines from separating the layers should not be visible from the outside.

(x2)



*Step 3.1*

*Step 3.3*

4.1A Cut the right side of this fly and fold it over the left side.

4.1B Fold the bottom 2 layers open

4.1C Fold the right layers over the left layers

4.1D Fold the double layers so that they are on the outside of the jeans

*Step 4.1A* *Step 4.1B* *Step 4.1C* *Step 4.1D*

4.2 - Align the top marker of front legs onto waistband marker, fold and topstich legs onto waistband and fly until 2 cm above the middle fly marker. Sew the other side of the waistband until 6-7 cm from the edge of the legs at the fly area.

4.3 - Fold and top stich legs onto yoke. (Both sides)

4.4 - Align inside edges of both legs and trim as seen in picgure 4.4, fold the layers into each other and sew (comparable to a French seam) along the crotch from waistband until 2 cm above the fly.

*Step 4.2* *Step 4.3*

Step 4.4

5.1 Align and assemble other side of fly. Sew across the entire length of the fly with the cut edges facing inward. The middle fly layer should not be sewn onto the legs. The top layer of the fly should be sewn together with the edge of the legs at the fly area, the middle layer should remain “Loose”.

5.2 - Ensure the top marker of the fly is in-between the waistband and legs. Now sew this side of the legs and fly to the waistband.

5.3 – Finish crotch, sew j stitch and crotch bar tacks.

5.4 – Cut away 5 cm or fold away the waistband so that it aligns with the fly.

Step 5.1

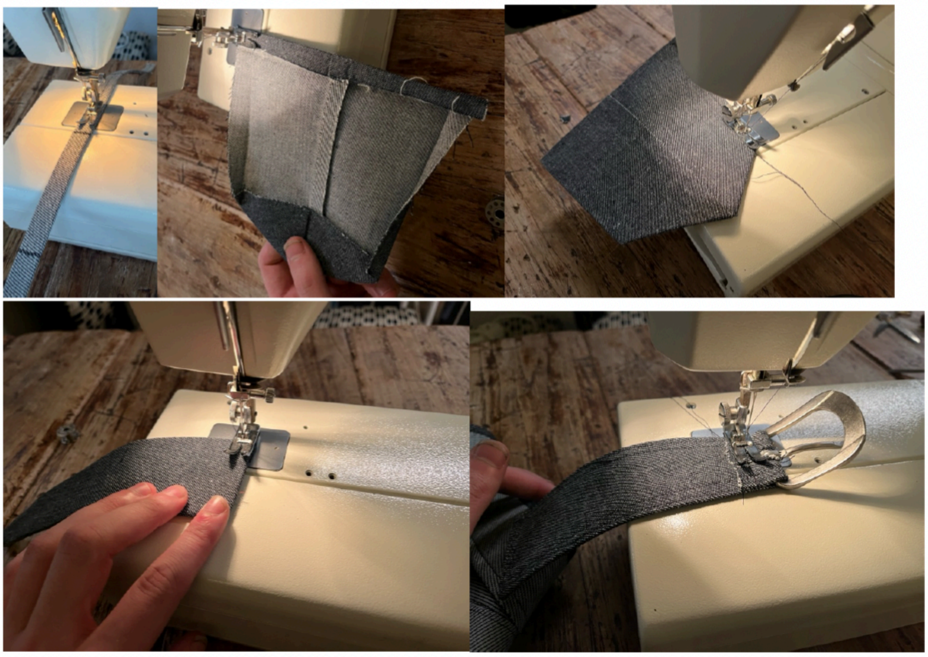
Step 5.3

Step 5.4

6.1 - Prepare back pockets, back belts and beltloops.

6.2 - Sew bottom of beltloops onto bottom of waistband marker.

6.3 - Sew the waistband and create the 4th button hole on the waistband.



*Step 6.1*

*Step 6.2*

7.1 - Sew top of beltloops and cinge bands.

7.2 - Sew back pockets, use bartacks at rivet locations, and sew safety stich across sides of the jeans.

7.3 - Finish leg ends and screw on buttons, bar tack instead of 5 rivets.

*Step 7.1*

*Step 7.2*

*Step 7.3*

It is very likely that some errors may occur during the process. 3D weaving is still in early development and the assembly steps vary significantly , please let us know if you find any problems and we will do our best to solve them.