



**Technical Report Denim Deal –
State of the art for using post-
consumer recycled cotton in
denim**

Green Deal Circular Denim

Colophon

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Summary

In the fashion industry denim is one of the most commonly known fabrics. For the production of denim several raw materials are used, such as cotton, in some cases polyester or other fibers, water, energy and auxiliary chemicals such as dyes and finishes. The production and treatment of the raw materials, such as fibres, yarns and fabrics, involves multiple steps. This makes it a production process with a large footprint (Desore & Narula, 2018; Rabbi, Banna, Mia, Islam, & Hasan, 2023). In order to accelerate the increased usage of post-consumer recycled (POCR) fibers in denim products, the Green Deal on Circular Denim, commonly known as “Denim Deal”, was established. This was initiated by House of Denim together with relevant public and private parties. The deal started with 28 signatories, followed by 26 more signatories later on in the project. The signatories represent the entire value chain from textile collectors to denim brands and other knowledge institutes (DenimDeal, 2023). The signatories agreed to work towards a new standard of 5% of POCR cotton textiles in all denim products, and 20% POCR cotton textiles in three million pair of jeans (C-233 Green Deal, 2020).

The research executed for this report is through a combination of interviews and literature study. For the interviews all signatories of the Denim Deal that are involved in the value chain were approached to participate, in total 19 companies participated. This report gives an overview of the technical possibilities and challenges of the usage of POCR textiles for denim products. Additionally, the report gives an overview of current value chains for denim and their challenges towards circularity.

Textile collection and sorting

During end-of-life textile collection, the quality of the material is influenced negatively when the textiles are polluted or wet. To improve the quality, there are different measures possible such as improving the textile containers or ensuring that the textiles are collected in closed plastic bags. Therefore, clear communication and campaigns towards the residents are necessary. When the textiles are collected, they will go into the sorting system. In order to achieve the best quality of recycled fibers the textiles should be sorted in a larger number of categories of well-defined composition and quality. Different textile products lead to different fibers qualities in recycling, ranking the different categories according to output fiber quality. To obtain this there should be clear communication (i.e. data acquisition and analysis) between the recyclers and the sorters about the product categories and the resulting fiber quality. To scale this process, it is necessary to innovate on textile identification technology as well as improve/faster semi-automated sorting technologies.

Textile recycling and processing

In mechanical recycling, harsh shredding circumstances leads to a degradation of fiber quality. To obtain a better quality the recycling must be improved. This can be achieved by applying lubrication to the fabrics before shredding (pre-treatment) and by using lower production speeds. Additionally, the recycled materials could be used most optimally when divided into different categories. High quality fibers can be used for high quality yarn spinning, medium quality fibers can be used for coarser and medium quality yarns and poor-quality fibers can be used for outputs such as felts, nonwovens and other thermal and acoustical insulation products. The shorter fibers coming from the mechanical recycling are difficult to process in yarn spinning. To obtain better quality yarns the settings of the spinning machines should be optimized. This also includes using lower production speeds and higher twist. Depending on the spinning method more settings on the machines can be optimized. Additionally, thicker yarns are generally stronger and can include more recycled fibers.

When blended textiles have been recycled and processed into yarns some difficulties can be experienced in the dyeing. The denim dyeing process is designed for cotton material and not for

synthetics. If there are synthetic contaminations in the yarn these will not be dyed properly, which will lead to visual irregularities in the fabrics. The fibers that contain contaminations can be used only in the weft yarn, or when using core spinning these fibers can be used in the core of the yarn.

Generally, after dyeing the yarns have been analyzed and should be suitable to process on the weaving loom. When high percentages of recycled fibers have been used the properties of the yarn will be different than for virgin yarns. With lower yarn strength and elongation the yarns can break more easily. During weaving this can be compensated by lowering the yarn tension and the production speeds. Additionally in the product design it could be beneficial to work with a tightly woven fabric, because it can be possible to obtain a better product quality with this compared to loosely woven fabrics. The final garment finishing is done to obtain the desired faded look and a comfortable fit. However, all finishing processes that are used involve, are (slightly) damaging the fabrics. In all cases, to obtain the optimal quality, it would be best to include as little finishing processes as possible. The brands should consider this in the design process, alongside other aspects to improve the quality of the final product, such as light fabrics, thick yarns, and tightly woven fabrics. To improve the recycling in the future design for recycling aspects should be considered, such as using mono materials and making the haberdasheries easy to disassemble.

Moving forward

The design of the fabric and garment highly influence the processability of recycled fibers. In general, the interviewed parties mention that it is possible to add 20% POOCR fibers without having big influences on the product quality and production process. For pre-consumer material this is even 30%. When wanting to include higher percentages of recycled materials this can be at the expense of comfort, appearance, and price. According to this study most customers and brands are not willing to compromise on this. By influencing consumer behavior through increased awareness, supported by legislation providing a level playing field for virgin versus recycled raw materials, the acceptance of higher amounts of recycled content as well as the quality and value can be increased.

Instead of aiming for single showcase products with high percentages of recycled materials it would be better to aim for all products with lower percentages of POOCR textiles, like proposed in the Denim Deal.

Currently, there is no big incentive for brands and manufacturers to use POOCR textiles rather than pre-consumer recycled textiles. Regulation could help increasing the value of post-consumer recycled textiles which will give the industry more financial possibilities to invest in the improvement of the quality textile recycling.

Regulation and certification should make a clear distinction between pre-consumer and post-consumer recycled materials and promote the use of post-consumer recycled materials. Legislation will be the main incentive for brands to implement recycled textiles into their products.

Nederlandse Samenvatting

Denim is een van de meest bekende stoffen in de mode-industrie. Voor de productie van denim worden verschillende grondstoffen gebruikt zoals katoen, in sommige gevallen polyester of andere vezels, water, energie en chemicaliën voor het verven en de veredeling. De productie en verwerking van de grondstoffen tot doek omvat meerdere stappen, het is daarmee een productieproces met een grote ecologische voetafdruk (Desore & Narula, 2018; Rabbi, Banna, Mia, Islam, & Hasan, 2023). Om het gebruik van post-consumer gerecyclede (POCR) vezels in denimproducten te vergroten, werd de Green Deal voor Circular Denim, beter bekend als de 'Denim Deal', in het leven geroepen. Geïnitieerd door House of Denim en in samenwerking met relevante publieke en private partijen. De Denim Deal begon met 28 ondertekenaars, later in het project gevolgd door nog eens 26 ondertekenaars. Gezamenlijk vertegenwoordigen ze de gehele waardeketen, van textielinzamelaars tot denim merken en andere kennisinstellingen (DenimDeal, 2023). De ondertekenaars kwamen overeen om te werken aan een nieuwe norm van 5% POCR katoen in alle denimproducten, en 20% POCR katoen in drie miljoen spijkerbroeken (C-233 Green Deal, 2020).

Het onderzoek voor dit rapport is uitgevoerd door middel van de combinatie van interviews en literatuuronderzoek. Voor de interviews zijn alle ondertekenaars van de Denim Deal die betrokken zijn in de waardeketen benaderd om deel te nemen, in totaal namen 19 bedrijven deel. Dit rapport geeft een overzicht van de technische mogelijkheden en uitdagingen van het gebruik van POCR textiel voor denimproducten. Daarnaast geeft het rapport een overzicht van de huidige waardeketen van denim en de uitdagingen op het gebied van circulariteit.

Textiel inzameling en sortering

Bij de inzameling van afgedankt textiel neemt de kwaliteit van het materiaal af wanneer het textiel vervuild of nat is. Om dit te voorkomen zijn verschillende maatregelen mogelijk, zoals het verbeteren van de textielcontainers, of het zorgen dat het textiel in gesloten plastic zakken wordt ingezameld. Daarvoor zijn campagnes en duidelijke communicatie richting de gebruikers noodzakelijk. Wanneer het textiel is ingezameld, gaat het vervolgens naar het sorteersysteem. Om de beste kwaliteit gerecyclede vezels te verkrijgen, moet het textiel worden gesorteerd in meerdere categorieën. Verschillende textielproducten leiden tot materiaalstromen met verschillende vezelkwaliteiten in de recycling. De kwaliteit kan verbeterd worden als de verschillende categorieën worden gerangschikt op basis van de kwaliteit van de outputvezels. Om dit te bereiken moet er duidelijke communicatie (d.w.z. data-acquisitie en analyses) zijn tussen de recyclers en de sorteersystemen over de gewenste productcategorieën. Om het gehele proces op te schalen is het noodzakelijk om te innoveren in textielidentificatietechnologieën, en om semi-geautomatiseerde sorteertechnologieën te verbeteren en sneller te maken.

Textielrecycling en verwerking

Tijdens de mechanische recycling zorgt de grote kracht die nodig is voor de vervezeling voor een afname van de vezelkwaliteit. Om een betere kwaliteit vezel te verkrijgen moet het recycling proces geoptimaliseerd worden. Dit kan worden bereikt door het textiel vóór de vervezeling te behandelen met bijvoorbeeld een smeermiddel, en door lagere productiesnelheden te gebruiken. Bovendien kunnen de gerecyclede materialen optimaal worden gebruikt als ze in verschillende categorieën worden verdeeld. Vezels van hoge kwaliteit kunnen worden gebruikt voor het spinnen van garen van hoge kwaliteit, vezels van gemiddelde kwaliteit kunnen worden gebruikt voor dikkere garens en garens van middelmatige kwaliteit, en vezels van slechte kwaliteit kunnen worden gebruikt voor producten zoals vilt, nonwovens en isolatieproducten. De vezels afkomstig uit de mechanische recycling zijn vaak lastiger te verwerken tot garens dan virgin vezels. Om de kwaliteit van de garens met mechanisch gerecyclede vezels te verbeteren moeten de instellingen van de spinmachines worden geoptimaliseerd. Dit omvat het gebruik van lagere productiesnelheden en hogere twist, en afhankelijk van de spinmethode kunnen meer

instellingen op de machines worden geoptimaliseerd. Bovendien zijn dikkere garens over het algemeen sterker en kunnen ze meer mechanisch gerecyclede vezels bevatten.

Wanneer textiel bestaande uit meerdere grondstoffen gerecycled is, en tot garens is verwerkt, kunnen er problemen optreden bij het verven. Het verfproces voor denim is specifiek ontworpen voor katoen en niet voor synthetische materialen. Als er synthetische verontreinigingen in het garen zitten, worden deze niet goed aangeverfd, waardoor er visuele onregelmatigheden ontstaan. Een van de mogelijke oplossingen is om de gerecyclede vezels die verontreinigingen bevatten alleen te gebruiken in het inslaggaren, of doormiddel van core spinning kunnen deze vezels in de kern van het garen worden gebruikt waardoor de buitenkant alsnog geverfd kan worden.

Na het verven worden de garens geanalyseerd op de kwaliteitseisen, en zouden ze geschikt moeten zijn om op het weefgetouw te verwerken. Echter, wanneer hoge percentages mechanisch gerecyclede vezels worden gebruikt zullen de eigenschappen van het garen anders zijn dan die van garens met enkel virgin vezels. Dit resulteert vaak in een lagere garensterkte en rek, waardoor de garens gemakkelijker kunnen breken. Tijdens het weven kan dit gecompenseerd worden door de garenspanning en productiesnelheden te verlagen. Daarnaast kan het voordelig zijn om een dicht geweven stof te ontwerpen, hiermee kan een betere productkwaliteit worden verkregen vergeleken met open geweven stoffen. Uiteindelijk wordt de laatste afwerking gedaan op het kledingstuk, om het gewenste vintage uiterlijk en een comfortabele pasvorm te verkrijgen. De meeste processen die worden toegepast in de afwerking gebruiken (mogelijk) schadelijke chemicaliën of energie-intensieve processen. Om de beste kwaliteit te verkrijgen, is het in alle gevallen het beste om zo min mogelijk nabewerkingsprocessen te doen. De merken kunnen in het ontwerpproces hier rekening mee houden, net zoals de andere aspecten om de kwaliteit van het eindproduct te verbeteren, zoals lichte stoffen, dikke garens en dicht geweven doeken. Om de recycling voor de toekomst te verbeteren, moeten design for recycling-aspecten worden overwogen, zoals het gebruik van mono-materialen en het gemakkelijk verwijderen van meubelen.

Hoe verder

De verwerkbaarheid van de gerecyclede vezels is afhankelijk van vele factoren, waaronder de eigenschappen van het product voor de recycling. Over het algemeen geven de geïnterviewde partijen aan dat het mogelijk is om 20% POCR vezels toe te voegen zonder grote invloed op de productkwaliteit en het productieproces. Voor pre-consumer materiaal is dit zelfs 30%. Als er hogere percentages mechanisch gerecyclede vezels worden toegevoegd, kan dit ten koste gaan van comfort, uiterlijk en prijs van het product. Volgens dit onderzoek zijn de meeste klanten en merken niet bereid concessies te doen. De acceptatie van gerecycled materiaal kan gestimuleerd worden door meer bewustzijn te creëren bij de consumenten, ondersteund door wetgeving rondom het gebruik van gerecycled materiaal.

In plaats van te streven naar afzonderlijke showcaseproducten met hoge percentages gerecyclede materialen, zou het beter zijn om te streven naar lagere percentages post-consumer mechanisch gerecycled textiel in alle producten, zoals voorgesteld in de Denim Deal.

Momenteel is er onvoldoende stimulans voor merken en fabrikanten om post-consumer gerecycled textiel te gebruiken in plaats van pre-consumer gerecycled textiel. Wetgeving is hierbij belangrijk en zou ook de waarde van post-consumer gerecycled textiel kunnen verhogen, waardoor de industrie meer financiële mogelijkheden krijgt om te investeren in de verbetering van de hoogwaardige textielrecycling.

Regelgeving en certificering moeten een duidelijk onderscheid maken tussen pre-consumer en post-consumer gerecyclede materialen en het gebruik van post-consumer gerecyclede materialen bevorderen. Wetgeving zal voor merken de belangrijkste stimulans zijn om gerecycled textiel in hun producten te verwerken.

1 Introduction

Denim is one of the most widely known fabric in the fashion industry. What makes a denim a denim is the twill weave that is used and the typical look with indigo warp dyed yarns (Uncu Aki, Candan, Nergis, & Sebla Önder, 2020). Denim contains mostly cotton, around 12% of the global cotton production is used to produce denim fabrics (Manian, Mueller, Bechtold, & Pham, 2023; Periyasamy & Periyasami, 2023). The denim market is very fragmented with lots of local actors but also lots of big global companies. These companies must keep innovating to keep their place in the market. Additionally, the producing market keeps growing, because consumers tend to buy more clothing and use it for a shorter time than 15 years ago (Uncu Aki, Candan, Nergis, & Sebla Önder, 2020). The denim market is continuously growing, with a current market value of around 68 billion U.S. dollars and estimated to grow to nearly 95 billion U.S. dollars by 2030 (Smith, 2023). The current industry is mainly based on a linear system. Where garments are produced, used, and disposed of. In a circular industry it will be necessary to recycle textiles and reuse the recycled fibers into new textile products. This can only be obtained with closed-loop recycling where the recycled fibers are brought back into the same product type (Uncu Aki, Candan, Nergis, & Sebla Önder, 2020; Ellen MacArthur Foundation, 2017; Rabbi, Banna, Mia, Islam, & Hasan, 2023). In order to produce a denim product, water, energy, and chemicals are used. This makes it a production process with a large environmental footprint (Desore & Narula, 2018; Rabbi, Banna, Mia, Islam, & Hasan, 2023). According to McKinsey & Company (2022) the textile fibers production is responsible for around 38% of the total emission. To reduce the total impact of textiles, and in this case specifically denim, it is important to replace the virgin fibers with recycled fibers.

1.1 Denim Deal

To accelerate the use of recycled fibers in denim products, the Denim Deal was created. In 2020 28 parties signed the Dutch Green Deal on Circular Denim, later on more parties joined with in the end a total of 54¹ signatories. These parties together represent the entire value chain from textile collectors to denim brands (DenimDeal, 2023). Regarding the use of recycled materials the signatories agreed to the following (C-233 Green Deal, 2020):

“Brand owners and Retailers will achieve a minimum of 5% post-consumer recycled (POCR) content in their own denim collections during this period by working together closely with other Parties.”

“Named Brand owners and Retailers will commit to individual ambitions designed to achieve the specific, joint goal of using 20% POCR cotton fibres in three million pairs of jeans produced by these parties during the term of this Denim Deal.”

The Denim Deal finished by the end of 2023, the Denim Deal has accelerated an increase of denim products on the market containing post-consumer recycled materials (FFact, 2023). However, there is still some reluctance from the market to use POCR content and not all the goals of the Denim Deal have been achieved.

This report, commissioned by the steering committee of the Denim Deal, will give an overview of the technical possibilities and limitations of the usage of POCR textiles in textile products, specifically for denim. Additionally, it will give an overview of the current value chain and the challenges for moving towards a circular value chain.

¹ The most recent list of participants can be found at <https://zoek.officiëlebezoekingen.nl/stcrt-2023-20636.html>. Document number; stcrt-2023-20636

2 Preliminary Literature Study

This chapter will provide an overview of textile recycling methods available in the industry. Additionally, it will give information on the linear textile supply chain of denim products.

2.1 Textile Recycling

There are different methods to recycle disposed textile products. The three main methods available in the industry are mechanical recycling, chemical recycling, and thermo-mechanical recycling. There are big differences between these methods in terms of technological development and resulting quality of the recycled materials. There is little information available on the exact environmental impact of recycled fibers and the recycling process. In the paper of Ribul, et al. (2021) their study shows that for most cases there is an energy saving of 5% to 20% to produce mechanically recycled fibers versus the production of virgin fibers. There are strong indications that the other recycling processes also have a smaller environmental impact than virgin fibers (Sandin & Peters, 2018; Ribul, et al., 2021; Duhoux, et al., 2021). The research of Oelerich et al. (2017) mentions that the environmental impact of the pulping process of disposed cotton textiles via the SaXcell chemical recycling process can be lower than the impact of the pulping process of the virgin wood input material. Additionally, recycling textiles would reduce the production of virgin materials, but also prevent textiles from ending up in landfills. When the recycling is done more efficiently it could also prevent the future usage of dyestuff which would lead to a significant reduction on the environmental impact (Roos, et al., 2019)

2.1.1 Mechanical recycling

With mechanical recycling physical processes are involved to break the textiles down into fibers. Before mechanical recycling, haberdasheries should be removed from textiles to obtain better recycled quality. The textiles are cut by a guillotine cutter into smaller pieces. Cut pieces will go through a tearing machine where they will pass through rollers with different sizes of needles. The needles will tear the fabric pieces and recycled fibers will be obtained (Roos, et al., 2019; McKinsey & Company, 2022). Mechanical recycling is a process that has already been used in the textile industry for years and is applicable for almost all types of textile materials. Therefore, it is commercialized and a well embedded technology. It's a relatively low cost, dry process with no chemicals, dyes or other wet processes involved. In the past the recycled fibers were mainly used to create products for the automotive industry, cleaning rags and for insulation purposes. In the recent years the technology is more moving towards closed loop recycling, using the recycled materials in yarn spinning (McKinsey & Company, 2022; Accelerating Circularity, 2023; Ribul, et al., 2021) However, mechanical recycling leads to inferior fiber quality, with a significant decrease in fiber length (Piribauer & Bartl, 2019; Aronsson & Persson, 2020) which can be up to 40 percent (McKinsey & Company, 2022).

2.1.2 Chemical Recycling

Chemical recycling is a technology that can vary depending on the material used. It includes the breakdown of textiles into polymers or monomers with suitable chemicals applicable for the type of textile materials. Chemical recycling can be used for some synthetics (polyester and polyamide) and cellulosic (cotton) materials. For the synthetic materials the polymers are broken down into monomers, purified and turned back into polymers. For the chemical recycling of cotton textiles, a pulp needs to be made. This happens with different chemical technologies depending on the recycling technology applied. A pulp is produced that can then be spun into new fibers. The benefit of chemical recycling is the creation of fibers similar to virgin fiber qualities. However, for the chemically recycled cellulose fibers currently on the market, the pulp is still mixed with wood pulp to obtain a spinnable pulp. So, these fibers are not made from 100% recycled cotton. Additionally, the availability of chemically recycled fibers in the market is still low. Since this is a relatively new technology the production plants need to be set up, which involves high investment costs. Furthermore, the process involves higher energy costs and chemical use

compared to the mechanical recycling (McKinsey & Company, 2022; Roos, et al., 2019; Ellen MacArthur Foundation, 2017).

2.1.3 Thermo-mechanical recycling

The thermo-mechanical recycling technology is only suitable for synthetic and thermoplastic fibers. It's based on the usage of pressure and heat to re-melt material into a new shape. Thermo-mechanical recycling is a technology already used in industry but focused on non-textile materials, such as plastic bottles. The technology has a relatively low energy usage and can achieve good quality fibers. However, the technology has very specific requirements and is currently highly affected by contaminations. Therefore, to become more applicable for textiles this technology needs to be further developed (McKinsey & Company, 2022; Ribul, et al., 2021)

2.2 Linear Supply Chain Denim

As previously mentioned, the current denim industry works with a mostly linear supply chain. This means that the fibers are produced, processed into fabrics and garments, and at the end of life the garments are disposed and incinerated or end up on a landfill. In order to go to a circular supply chain, it is necessary to understand the current linear supply chain. Therefore, a short description of the steps of the linear supply chain are described in the following paragraphs.

2.2.1 Fibers

Denim fabrics used to be 100% cotton, but in the current market there are also many jeans that have a blend of cotton, elastane, polyester and lyocell (Annapoorani, 2017; Paul, 2015). Out of the global cotton production it's estimated that 10-12% is used for the denim industry (Periyasamy & Periyasami, 2023; Annapoorani, 2017). Cotton is a plant that grows in many varieties and in many different countries. Therefore, the quality of the fiber also varies depending on the origin of the cotton fibers. The length can vary between 10-65 mm and the dry tenacity can vary from 1.9-3.1 cN/dtex. In general, the denim manufacturers request a cotton with a fiber length of 28 mm with a short fiber content of 40% or less. Cotton is regularly blended with other fibers to obtain certain desired properties such as stretch or strength. (McLoughlin, Hayes, & Paul, 2015).

2.2.2 Fiber preparation for yarn spinning

Cleaning: Through the ginning process the cotton fibers are removed from the seeds. Since cotton is a natural product, the contaminations are also mainly natural such as dust and parts of the plant. To thoroughly clean cotton it will pass through an opening and cleaning step. After cleaning, the cotton fibers will be mixed and blended with other fibers if desired, the mixing system can be seen in Figure 1 below.

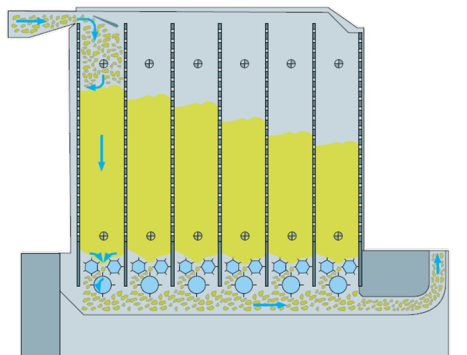


Figure 1. Fiber Mixing

Note. Reprinted from "Volume 2 – Blowroom & Carding" by W. Klein. 2016, *The Rieter Manual of Spinning*, p. 32. Copyright 2016 by Rieter Machine Works Ltd.

Carding: After these preparation steps are completed the fibers are carded. During the carding the fibers are further opened, cleaned, and parallelized. The machine can is shown in Figure 2 below. Carding is an important step that highly determines the final quality of the yarn. A web is created that is formed into a sliver.

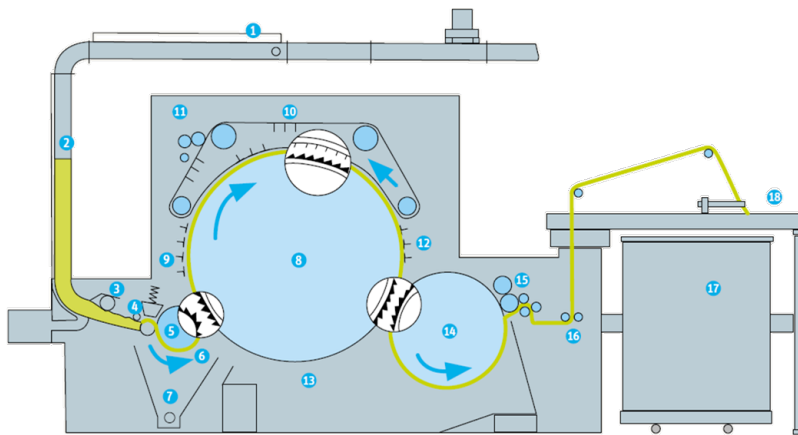


Figure 2. Carding Machine

Note. Reprinted from “Volume 2 – Blowroom & Carding” by W. Klein. 2016, *The Rieter Manual of Spinning*, p. 53. Copyright 2016 by Rieter Machine Works Ltd.

Draw frame: The created sliver during carding is passed through the draw-frame as shown in Figure 3. In this step the slivers undergo the doubling and drafting process. By doing this the desired sliver weight can be determined and a better blended quality will be obtained.

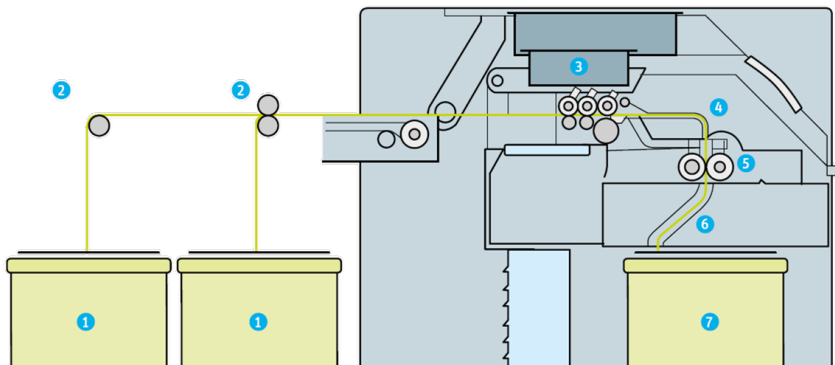


Figure 3. Draw frame

Note. Reprinted from “Volume 3 – Spinning Preparation” by W. Klein. 2016, *The Rieter Manual of Spinning*, p. 44. Copyright 2014 by Rieter Machine Works Ltd.

Roving frame: For ring spinning this additional step is required before spinning is possible. To produce ring spun yarns, the sliver should be thinner than for open-end spinning. Therefore, the sliver is turned into a thinner roving by drawing and applying some twist. This is done with the machine that is shown in Figure 4 below.

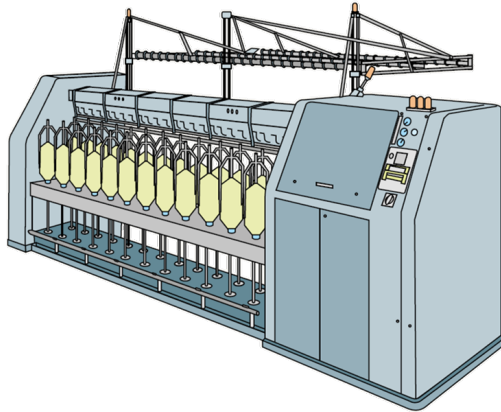


Figure 4. Roving frame.

Note. Reprinted from “Volume 3 – Spinning Preparation” by W. Klein. 2016, *The Rieter Manual of Spinning*, p. 57. Copyright 2014 by Rieter Machine Works Ltd.

2.2.3 Yarn spinning

There are different methods that are used for the denim production. The most frequently used ones are ring spinning and rotor spinning.

Ring spinning: The roving is inserted into the spinning machine and by drawing and twisting the yarns are shaped, as shown in Figure 5. To obtain the desired yarn count the drafting system is used to determine the size of the fiber bundle. While the fibers are leaving the drafting system they are twisted into a yarn. With ring spinning a wide range of yarn counts can be achieved, ranging from very fine yarns to coarse yarns. Ring spinning leads to high quality, smooth yarns. This is however, a relatively slow spinning method (McLoughlin, Hayes, & Paul, 2015).

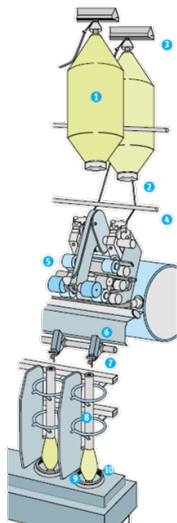


Figure 5. Ring spinning system

Note. Reprinted from “Volume 4 – Ring Spinning” by W. Klein and H. Stalder. 2016, *The Rieter Manual of Spinning*, p.13. Copyright 2016 by Rieter Machine Works Ltd.

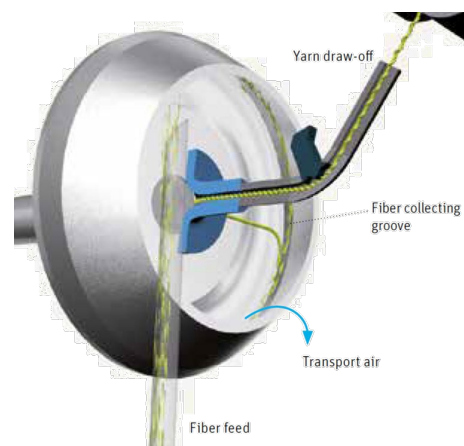


Figure 6. Rotor spinning system.

Note. Reprinted from “Volume 5 – Rotor Spinning” by H. Ernst. 2016, *The Rieter Manual of Spinning*, p. 24. Copyright 2014 by Rieter Machine Works Ltd.

Rotor spinning: In the past rotor spun yarns were only occasionally used for the weft of denim products. Now however, rotor spun yarns are increasingly used in both warp and weft direction. Rotor spinning has a higher productivity than ring spinning and no roving preparation and winding are necessary, which makes it a more cost-effective process. However, with rotor spinning the range of yarn counts is smaller, and it is not possible to create very fine yarns with this method. The sliver is inserted into the rotor frame they pass through the spinhead where the fibers are opened and by centrifugal force the fibers are shaped into a yarn, this is shown in Figure 6. This creates yarns with a harder grip and lower strength than ring spun yarns (McLoughlin, Hayes, & Paul, 2015).

2.2.4 Dyeing

Preparation: For denim fabrics typically only the warp yarns are dyed. In order to do this, the yarns need to be prepared for dyeing. This is done by ball warping or beam warping. For ball warping the yarns are collected into a rope form and the rope is collected on a small beam. For the beam warping the number of yarns necessary for the weaving are collected directly on the warp beam and are dyed as such (McLoughlin, Hayes, & Paul, 2015).

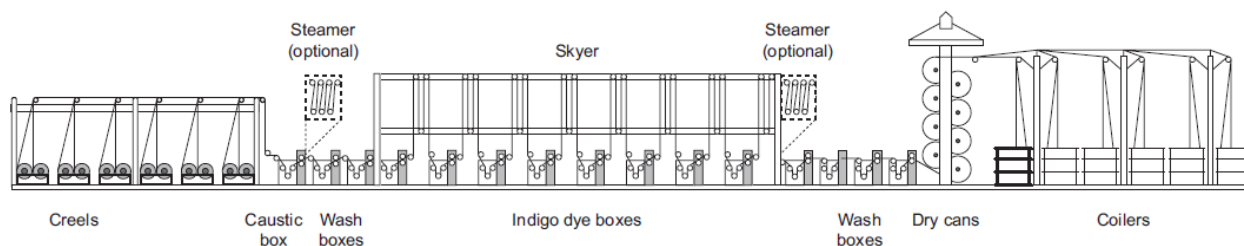


Figure 7. Rope Dyeing System

Note. Reprinted from “4. Indigo dyeing technology for denim yarns” by N. Meksi and M.F. Mhenni. 2015, *Denim; Manufacture, Finishing and Applications*, p.76. Copyright© 2015 Elsevier Ltd. All rights reserved.

Dyeing: Denim is typically dyed with indigo, which is considered a vat dye, sometimes other dyestuff is used such as sulfur dyes. This is done on the warp yarn and only the outer layer of the warp yarn is dyed. The dyeing process for denim is generally done with two different dyeing methods (Chavan, 2015). The ball warp is used for the rope dyeing method, which can be seen in Figure 7. In this method multiple ropes are fed through the scouring bath at the same time. The process starts with cleaning the cotton ropes, this is done to achieve a uniform dyeing performance. After cleaning the ropes are fed through multiple dyeing baths containing indigo dyestuff. Between each bath the ropes are exposed to the air for oxidation. How many times the ropes are fed through a dye bath depends on the desired color. The darker the color the more dye baths are used. At the end of the dyeing procedure the ropes are washed again to remove excess dye (Meksi & Mhenni, 2015).

The other frequently used dyeing method is the slasher dyeing. Slasher dyeing is faster than the rope dyeing method because the warp beam is directly fed into the dyeing bath. After the desired numbers of dyeing baths, the warp beam is immediately fed through a sizing system. So, less machines are required for this process, but the downside of this method is the color quality and there is more shade variation within the warp beam (Meksi & Mhenni, 2015).

2.2.5 Weaving

After the dyeing the yarns dyed with the slasher method are ready for weaving. The yarns dyed with the rope dyeing method first need to be converted into a warp beam and then go through the sizing procedure. The warp beam is supplied to the weaving machine and the weaving can be done according to desired construction. The principles of a weaving loom can be seen in Figure 8 below. For denim most often a twill weave 3/1 is used. After weaving the fabrics will be washed to remove the sizing agent.

When desired additional chemical or machinal finished can be applied to achieve the desired look and feel to the fabric (Raina, Gloy, & Gries, 2015).

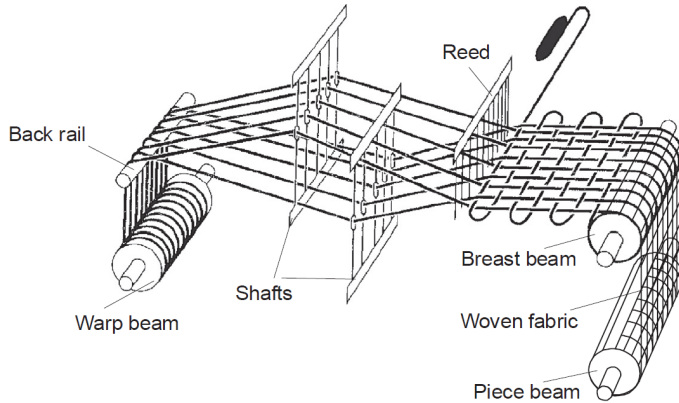


Figure 8. Principles of a weaving loom

Note. Reprinted from “6. Weaving technologies for manufacturing denim” by M.A. Raina, Y.S. Gloy and T. Gries. 2015, *Denim; Manufacture, Finishing and Applications*, p.170. Copyright© 2015 Elsevier Ltd. All rights reserved.

2.2.6 Garment production

After the weaving is finished the final product needs to be made. The patterns will be cut accordingly and sewn together. The main sewing techniques used for joining the fabrics is the superimposed seam and the double lapped seam, as shown in Figure 1 (Hayes & McLoughlin, 2015).

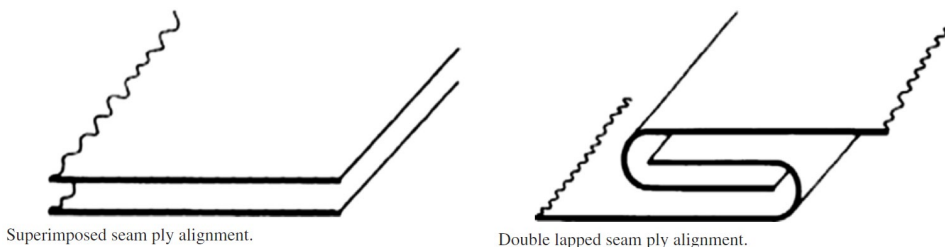


Figure 9. Joining techniques jeans.

Note. Reprinted from “Joining techniques for denim jeans” by S. Hayes and J. McLoughlin. 2015, *Denim Manufacture, Finishing and Applications*, p222-223. Copyright© 2015 Elsevier Ltd. All rights reserved.

Additionally, parts such as pockets and belt loops are sewn to the fabric. Furthermore, haberdasheries such as a zipper, button and rivets are added. Most sewing yarns used for denim products contain polyester (Hayes & McLoughlin, 2015)

2.2.7 Finishing

The significant denim look includes the worn look on the legs, where the white core of the warp yarns appears. To obtain this desired look the garments need to be finished. There are different methods to obtain this desired worn look.

Washing treatments: The simplest washing treatment is the regular washing. This is done to improve the uniformity of the garments and increase the softness and comfort of the denim. Another treatment is the bleach washing, which is used to decolor the denim. Furthermore, it is possible to apply stone washing to denim. For this method the garments are washed in an industrial laundering machine mixed with

volcanic rocks or pumice stones. Some of the surface color will be removed with this treatment, the duration of the treatments and the ratio of stones determines the degree of wear. The final method that is frequently used is enzyme washing. This is done with the cellulase enzyme and promotes the color fading of therefore creates the worn look (Kan, 2015)

Local finishing treatments: Next to the washing treatments there are many other treatments to create the desired look for denim products. Waterjet fading can be used to fade color on specific areas. Whiskering can be used to age specific areas of the jeans, this is often done with some kind of sandpaper as shown in Figure 10. There are many more methods where sandpaper is used to create desired effects on jeans. Additionally, this can also be done by laser treatment. Next to the dry treatments the local finishing can also be done with a wet process such as ozone treatment (Kan, 2015).



Figure 10. Whiskering effect on jeans

2.3 Monitoring of the Denim Deal

The monitoring of the Denim Deal on 2022, done by FFact gives a summary of the results and challenges resulting from the quantitative and qualitative monitoring. The challenges proposed in this report are visualized as shown in Figure 11. The report indicates five main challenges for the industrial scale-up. The first challenge identified is the need for more demand for recycled fabrics by brands. More demand from participating parties will also lead to more demand from non participants. The brand can also promote the use of recycled textiles, or decide to implement the recycled fibers without any communication to the customers. The second challenge is the supply of feedstock for recycling. According to the report in the collection the municipalities should gain more awareness about the dry and clean collecting of textiles. When it comes to sorting, the sorting for recycling, specifically streams with 100% cotton, should be stimulated. Trade barriers are another big issue for textile sorting. These barriers prevent sorted textiles from being imported into some of the manufacturing countries. The third challenge is design for easier recycling. Designers need to consider different aspects when designing a product that contains post-consumer recycled cotton. Additionally, the designers should consider the end of life of the product to make it suitable for recycling. The fourth challenge is the knowledge sharing regarding material specification of PCR feedstock and innovation in recycling technology. The recyclers and sorters should share knowledge and have a close communication about the desired feedstock. The final challenge

is regarding the awareness among the customers. Transparency and communication from the brand to the customers is important to increase the awareness (FFact, 2023).

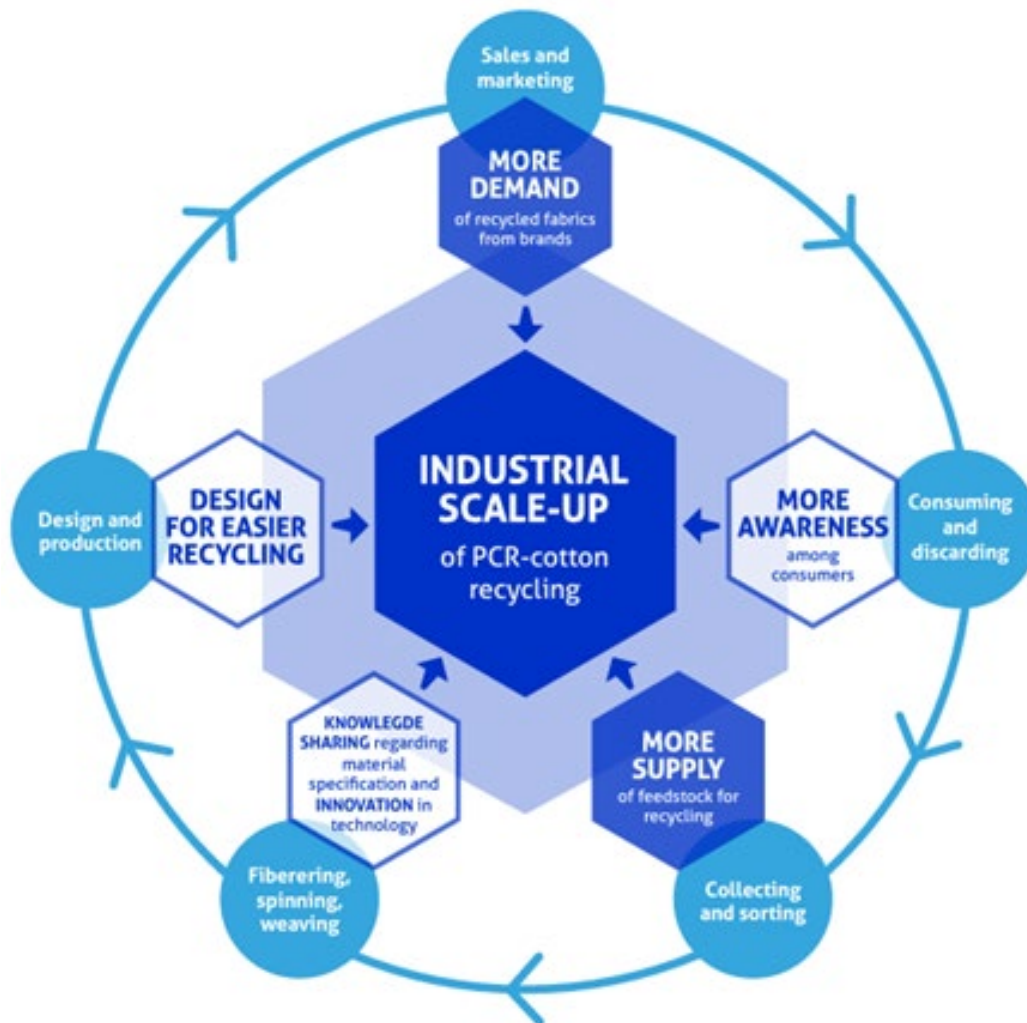


Figure 11. Denim Deal Monitoring, Challenges of Industrial Scale-up

Note. Reprinted from “Monitor Denim Deal Results quantitative and qualitative monitoring 2022” by FFact. 2022

3 Methods

In order to create an overview of the circular value chain for denim interviews and a literature study were executed. All participants of the Denim Deal were approached to participate in the interviews and some companies in the network of the Denim Deal were also asked to participate. In total 40 parties were contacted to participate in the Interviews. For each step in the value chain a separate set of questions was created, and the goal was to interview at least three companies for each step of the value chain. The following steps were considered;

- Textile collection
- Textile sorting
- Mechanical textile recycling
- Yarn Spinning
- Dyeing and Weaving
- Garment finishing and Retail.

The questions (see Appendix I-VI) were prepared and shared with the parties. The goal of conducting the interviews was to obtain information about the status when it comes to recycling textiles and the usage of recycled textiles in denim garments. Additionally, the interviewees were asked questions about the difficulties they experience with the feedstock and the processing of the materials. Finally, they were asked questions about how to improve the quality of the feedstock and the processing. The interviews were held as semi-structured interviews. Which means the questions that were shared in advance were leading, but sometimes some additional questions were asked during the interview. The interviews with the participants located in Türkiye were done in person on site alongside a factory visit. The other interviews were performed online through Teams.

To provide an environment where the interviewee feels freely to speak about the issues the data is anonymously processed in this report. This was important, to get the honest input and perspective from the companies. In total 19 companies took part in the interviews; the list of the participants and their location can be found in Appendix VII. The participants were mostly signatories of the Denim Deal, but in some cases also other expert companies. As mentioned before throughout the whole value chain companies were interviewed, from the textile collectors to the denim brands. Three waste/textile collecting organizations and four textile sorting companies have been interviewed. Seven different companies were interviewed that are involved with the textile recycling. Some of these companies are vertically integrated and also do the yarn spinning, dyeing, and weaving in house. Therefore, they also participated in the interviews for these processes. Regarding the yarn spinning eight companies were interviewed. For the dyeing and weaving, seven companies were interviewed. For the garment production, finishing and the retail perspective in total four companies were interviewed. All information provided by the interviewees was analyzed and categorized according to the challenges and possible solutions per process step. It is important to note that for some steps of the value chain all participating interviewees are from the same country. In that case only the perspective of that specific country is given.

Alongside the interviews, literature was searched that was necessary to provide background information about each step of the value chain. For textile collection the literature that was searched mainly concerning the European textile collecting industry. With the main goal of finding information on the methods used for textile collection and the amounts of textiles that are collected. For textile sorting literature was searched about the methods used in textile sorting and new technologies that are introduced to the sorting industry. For textile recycling literature was searched about the differences of pre- and post-consumer recycled textiles and the technological limitations of mechanical recycling. For the yarn spinning, dyeing, weaving, and garment finishing the focus of the literature was on the difficulties perceived when processing mechanically recycled fibers. For the literature for the brands the focus of the literature research was on the customers perspective and adaptation to recycled materials.

4 Results

The results are described starting with the textile collectors, followed by the other process steps along the textile value chain up to the denim brands. For each step in the value chain relevant information is given based on literature. Followed by the challenges and possible solutions based on the interviews.

4.1 Textile Collection

Currently throughout Europe only a small percentage, between 30% - 38%, of the total disposed textiles are collected for reuse or recycling (McKinsey & Company, 2022; EEA, 2023). The collection is often organized by cities and municipalities, they play an important role in optimizing the collection rate. Each country has its own collecting and reusing culture. To implement and improve the collection systems throughout the world, it is important to understand these different cultures (Ellen MacArthur Foundation, 2017). To collect in larger quantities capital investments will be necessary. When this is done it's expected that this sector can be a self-standing profitable sector (McKinsey & Company, 2022). Implementing an Extended Producer Responsibility (EPR) system in France has shown to increase the collection and recycling rate of post-consumer textiles (Bukhari, Carrasco-Gallego, & Ponce-Cueto, 2018). Out of the collected textiles it should be possible to obtain 90% that can be reused or recycled. Out of this 90%, there is 50% that is directly suitable for reuse in the secondhand market (Bukhari, Carrasco-Gallego, & Ponce-Cueto, 2018).

4.1.1 Challenges

All interviewees provided the perspective of the collection system of the Netherlands. When it comes to the quality of the collected textiles the main issue is the contamination of the textiles as well as the moisture content. This was also noted in the Denim Deal Monitoring report (FFact, 2023). Pollution occurs when trash is thrown into the textile container. When a prestruck is used to empty the textile containers the pollution can be spread over all textiles. All interviewees mention that they mostly work with collection through containers. However, they all participated in projects where textiles were collected, for example within clothing stores. This leads to good quality and clean textiles. However, this only has a very low yield. It is mentioned that most citizens only hand in their textile waste when the collection points are nearby and easily accessible.

Regarding the moisture content, it is important to prevent textiles from being wet. Wet textiles will be disposed to garbage because it is unsuitable for recycling. This occurs more often with underground containers, due to leakages through seals on these containers, where rain can easily penetrate inside. When it comes to the unloading of the disposed textiles there are different methods. This can be done by crane or by hand. Both methods have benefits and downsides. Unloading by crane is mostly automatic whereas unloading by hand requires a lot of manual labor and can be physically strenuous. Furthermore, with the unloading by hand a preselection can be done, and non-textile waste can be removed before the disposed textiles are thrown in the container, or before starting the sorting. Some municipalities prefer hand unloading because it creates more jobs for people with differing abilities.

The final issue regarding the collection of textiles is highly competitive prices requested from the municipalities. The collectors have to pay high prices to the municipalities for each kg of collected textiles. There are limited resources put into optimizing the textile collecting systems.

4.1.2 Possible solutions

- Making sure all textiles are disposed to the containers in closed plastic bags. When this happens consistently the problem of water contamination and waste contamination of the textiles will become less.
- Unloading the containers by hand can help removing the contaminations and trash at an early stage. However, there are some risks involved because of the highly physical straining labor.

- Replacing the underground containers with above ground containers will help with decreasing the percentage of wet textiles in the containers.
- Another option is to improve the structure of the underground containers to make the seal tighter, so water won't leak inside. Combined with more enforcement to prevent household waste from ending up in the textile container.
- A strategic location of the containers can help to reduce the pollution in the textile, for example on a different location than the household waste.
- Clear communication with residents on what they can and cannot dispose to the textile container, and where they can find the textile containers.
- Having containers available in many locations will increase the amount of textiles collected
- Having more money available for improving and increasing the textile containers, and for communication with the residents.
- For the textile collection a combination of above-mentioned interventions is necessary. The solutions are dependent on the already existing infrastructure which can vary for each municipality.



Figure 12. Bales of collected textiles.

4.2 Sorting

All interviewees provided the perspective of the sorting industry in the Netherlands. The textiles obtained from the collection will be sorted in different categories. The main categories are reuse, recycling, and incineration. These categories can be further divided into more specific categories for example according to material or color (McKinsey & Company, 2022). The sorting of textiles is still mainly done manually, but with the rising need for more specific sorting this becomes more difficult to manually differentiate (McKinsey & Company, 2022). To improve the recycled fiber quality, it is important that the sorting is done in multiple categories. The high-quality textile streams should be sorted separately from the low-quality streams to improve the outcoming fiber quality (McKinsey & Company, 2022). When the textile feedstock is sorted on color, this can prevent future redyeing of the materials which directly results in a reduced environmental impact (Roos, et al., 2019). To comply with this desire for more specific sorting there are several technologies that can be used. There are technologies to determine the composition

of the textile products such as Near Infrared (NIR) and Fourier Transform Infrared Spectroscopy (FTIR). These technologies can help sort clothing on composition and color (Ellen MacArthur Foundation, 2017; Englund, Wedin, Ribul, de la Motte, & Östlund, 2018). However, there are some limitations to these technologies, such as detecting compositions of multiple layer textiles, and for example core spun yarns. Additionally, these technologies often require a lot of data input, which is not yet available in most cases (Fashion for Good, 2022).

Another technological development for more specific sorting is adding tracer materials to the textile products so the composition can be traced back to the production. This can for example be done by adding a QR code, Radio frequency identification (RFID) or Near field communication (NFC) transponders in production. The tags will be added in production and stay with the product all throughout the user phase and can give information to the sorters about the product. To implement this the same method should be standardized throughout the whole industry, and it is not applicable for the currently available textiles in the market (Englund, Wedin, Ribul, de la Motte, & Östlund, 2018).

It is expected that these scanning technologies will be an addition to the manual sorting and will not fully take over the manual sorting in the near future. However, it can help in increasing the productivity and accuracy of the sorting (Englund, Wedin, Ribul, de la Motte, & Östlund, 2018)

As mentioned before, textiles are sorted in the categories reuse, recycle and incineration. However, there is another 'waste' stream that is not classified as such. Out of the sorted textiles for reuse some are shipped to different parts of the world amongst which to the African market. There is a demand for used European clothing on the African market, so part of these textiles are partly reused. What cannot be reused will end up on the local landfills, this is estimated to be around 40% (EEA, 2023). With the increase of the fast fashion industry the quality of clothing has been decreasing (Fashion for Good, 2022). The low quality clothing is less suitable for reuse and when shipped to African countries it will be likely disposed to landfills (EEA, 2023). African countries are thinking about banning the import of these textiles to promote their local textile industry (Bukhari, Carrasco-Gallego, & Ponce-Cueto, 2018; Pensupa, 2020). This will leave Europe with a larger stream of textiles suitable for reuse or recycling.

4.2.1 Challenges

According to the data from the interviews between 65-75% of the collected textiles from the Netherlands are suitable for reuse. Out of the total collected textiles between 4-10% is not reusable or recyclable so will go to incineration. This leaves between 20-35% from the total collected textile for recycling. The infographic circular textiles (Ministry of I&W, 2020) shows that the percentage suitable for reuse is 53%, 33% is suitable for recycling and 14% will go to incineration. The amount of textiles that are suitable for reuse are also shrinking due to the fast fashion industry. The quality of fast fashion products is usually low and the garments will reach their end of life sooner.

According to the sorters the sorting for the reusable textile stream is often the easiest. This can be done mainly visually in categories such as; trousers or shirts, summer or winter, color, etc.. Additionally, the textiles for reuse have the highest value, therefore the focus of the sorters is on sorting for reuse. When the textiles are sorted for recycling the composition and construction of the textiles is much more important. This is more difficult for the sorting, especially since most textiles consists of material blends. It takes more time and experience to sort textiles for recycling, additionally the value of this stream is lower than for reuse. Technologies such as NIR could help improve the sorting, but are not fully optimized yet and are also relatively expensive to invest in. Another difficulty is finding qualified people to do the sorting. As mentioned it is difficult to distinguish between different compositions therefore the people need to be highly qualified or have an extensive training. For fiber to fiber recycling some companies request the removal of haberdasheries. This is a very labor intensive job, and a lot of material will still end up as waste.

Since denim consist mainly of cotton, the preferred recycled material is also cotton. However, this is only a small percentage of the total collected textiles. The highest demand is for 100% white cotton fabrics, this is however only around 1-5% of the total textile stream for recycling. Additionally, discarded denim garments can also be used which is between 2-8%, and other colored cotton streams which is between 3-7% out of the total textile stream for recycling. Together this covers only a small portion of the total textile stream suitable for recycling and does not provide a solution for the other textile streams.

4.2.2 Possible solutions

- Increasing the economic value of the feedstock for recycling would create more financial possibilities to invest in optimization
- Optimizing in scanning technologies that detect fabric composition
- Improve collaboration and communication between sorters and recyclers regarding data exchange and analysis
- Automated sorting
- Finding an industrial solution to recover cotton out of blended textiles
- Stimulating industrial applicable and economical viable technical developments to improve the removal of haberdasheries without losing textile material and make it less labor intensive
- Stimulating design for disassembly
- Stimulating the use of monomaterials, and design for recycling



Figure 13. Sorted pre-consumer textiles.

4.3 Mechanical Recycling

For textile recycling there are different streams available. There are pre-consumer textiles that became waste before they were used by consumers. The pre-consumer waste can be divided into two categories (McKinsey & Company, 2022);

- Post-industrial waste. This includes the waste arising during the production process. This can be for example fiber or yarns waste, or fabric pieces.
- Pre-consumer waste. This includes finished textile products that have not been used. For example, unsold garments or overstock. This can partly be resold to traders and partly recycled.

Post-consumer textiles are the textiles that are disposed after personal or commercial use. These textiles have been submitted to wear, tear, laundering and possible other processes. This can be for example, disposed garments or bedsheets from the hotel industry (McKinsey & Company, 2022).

Since the fibers from post-industrial and pre-consumer waste have not been subjected to the use phase, these fibers are often of better quality compared to post-consumer waste. When the textiles haven't been dyed yet they can be processed like virgin fibers. Overall, the post-industrial and pre-consumer fibers are easier to process than post-consumer fibers and can be added to the yarns in higher percentages (Ellen MacArthur Foundation, 2017).

Physically it is possible to recycle almost all types of fabrics. There are a few aspects that make textiles more difficult to recycle and should preferably be avoided. Aspects such as coatings, sequins, big prints, and many different fabric layers are very difficult, if not impossible to recycle. For sure these materials will give an output that is not suitable for yarns spinning (McKinsey & Company, 2022; Fashion for Good, 2022) There are different factors that are important in obtaining the best quality of mechanically recycled textile fibers. Fabric structure is an important factor in the resulting fiber quality (Roos, et al., 2019; Ütebay, Celik, & Cay, 2019). In general, tightly bound fabrics such as woven fabrics, like denim, are more difficult to mechanically recycle than loose fabrics such as knitwear. Additionally, products with very fine yarns can also result in lower quality of the recycled fibers (Aronsson & Persson, 2020; Norup, Pihl, Damgaard, & Scheutz, 2018).

4.3.1 Challenges

As told by the interviewed parties a main issue in the recycling is blended materials. Even though in mechanical recycling there are no difficulties in recycling blended textiles, in the further processing, mainly dyeing, this gives some issues. Therefore, the spinners often do not want to work with these materials, even if the biggest stream coming from the sorters contains blended textiles. As mentioned in the paragraph about sorting, the 100% cotton textile streams are only a small percentage of the total disposed textiles stream. All the recyclers would like to use white 100% cotton fabrics because these are the easiest to process after recycling.

As previously described mechanical recycling leads to inferior fiber quality. The quality of the recycled fiber is highly dependent on the input materials. Poor quality textiles lead to poor quality fibers and high-quality textiles lead to higher quality fibers. Since the fiber quality of pre-consumer materials is better, these will also lead to better quality recycled fibers. As previously described due to the popularity of fast fashion the quality of the garments is decreasing. Generally lower quality fibers are used for fast fashion products which also results in lower quality recycled fibers. Additionally, fabric structure can highly influence the resulting recycled fiber quality. As described in literature and confirmed by the interviewed parties, loose fabrics and yarns are easier to recycle than tightly woven fabrics and very fine yarns.

When it comes to defining the fiber quality it can be mentioned not all interviewed parties use specific measuring tools to analyze the fiber quality. The parties that do use a tool all use different testing and analyzing methods. This makes it difficult to determine and compare the quality of recycled fibers.

The quality of mechanically recycled fibers can be improved by making some changes to the recycling process. This would involve pre-treating textiles before shredding with lubricants to promote more gentle shredding. Additionally, this would include lower speeds on the machines. On the downside having lower speeds would reduce the output and therefore increase the price of the recycled materials. With the textile industry being a highly price driven industry it is very difficult for the recyclers to increase their fiber price.

Furthermore, the interviewed parties mention that sometimes in the industry virgin fibers are sold as if they were recycled. Or pre-consumer material is sold as post-consumer material. This can be due to lack of knowledge by the sellers, or it can have other reasons, but it creates problems with quality expectations. Pre-consumer recycled fibers have a higher quality than post-consumer recycled fibers. Having these fibers in the market classified a different fiber creates false expectations from the industry.

The yarn spinners can get good quality 'recycled' fibers from some suppliers, and the actual mechanical recyclers can only supply lower quality fibers.

As shown in the preliminary literature study denim jeans are produced with different types of seams. All seams include multiple layers and are often stitched with polyester stitching yarn. These multiple layers are more difficult to open with the mechanical recycling process. Additionally, the polyester sewing yarn and polyester care labels contributes to the polyester contamination.

Since there is no distinction made between pre-consumer and post-consumer textiles in recycling certifications, it is more common to use pre-consumer recycled fibers (Textile Exchange, 2017). This material is easier to process and gives a better-quality product. Therefore, the motivation to use post-consumer recycled fibers is very limited for many parties across the value chain. Many of the denim manufacturers are vertically integrated companies. This means that they do all processes in house from recycling up to fabric finishing. This creates a difficulty for the recyclers that are located in Europe. There is hardly a demand for their recycled fibers in the yarn spinning industry, so it goes through open loop recycling to other industries such as for the nonwoven industry or for insulation materials.

4.3.2 Possible solutions

- One standardized method to analyze fiber quality of recycled fibers.
- For the denim industry is cotton the most important input material, but most available feedstock with cotton is blended with other materials. Therefore, there should be technological developments available on industrial scale and economical viable to separate cotton from other materials before the mechanical recycling. However, this solution is not yet available on industrial scale.
- Stimulate the use of tracing technology for recycled fibers to increase the transparency in the value chain.
- Economical viable technical developments on industrial scale to separate haberdasheries from the garments without losing much textile material.
- Certification that distinguishes between pre-consumer and post-consumer textiles
- Creating different categories within the recycled fibers, based on their quality. An example of this is proposed in the research of Rieter, where they introduce the Rieter Recycling Classification (Schwippl, 2020). Each fiber can then be processed accordingly. High quality can be used for textile products that require high quality fibers. Medium Quality fibers can be processed in products that do not need very high-quality material. And poor-quality fibers can be processed into nonwovens or can be used for chemical recycling.
 - o This would require optimization of the sorting, with a more specific sorting system where fabrics will already be selected on resulting quality fibers. The current systems available on the market are not able to identify the quality of the fibers.
- Optimize recycling process with lower speeds and pre-treatments to the fabrics.
- Governmental interference/incentives to use post-consumer recycled textiles.
- There is a good collection and sorting system of textiles in most parts of Europe. Additionally, there are many textile recycling companies in Europe that have been in the recycling business for a long time. For them an ideal situation would be that the vertically integrated companies buy the post-consumer recycled fibers from them. This would also be beneficial for the import of textiles since it is not possible to import whole garments into some of the manufacturing countries.
- Stimulating design for disassembly
- Stimulating design for recycling



Figure 14. Recycling of pre-consumer textiles

4.4 Yarn spinning

Yarn spinning is often done with blends of recycled fibers and virgin fibers, to create yarns of sufficient quality. Since polyester is a cheap fiber, has a stable fiber length and has very good strength properties in some cases this fiber is used to compensate the poor quality of the mechanically recycled fibers (Ellen MacArthur Foundation, 2017). In other cases, the fibers are blended with virgin cotton or man-made cellulosic (Radhakrishnan, 2017). In the denim industry it is highly dependent on the requirements of the brand what virgin material is used for blending.

It is easier to process recycled fibers in open-end spinning than in ring-spinning. This is due to the need for strong fiber alignment in ring-spinning, which is difficult to achieve with the shorter recycled fibers. Therefore, more recycled fibers can be used in open-end spinning than in ring-spinning (Schwippl, 2020). However, as mentioned in the literature of paragraph 2.2.3, ring-spinning can often lead to stronger and smoother yarns.

4.4.1 Challenges

Based on the interviews it can be said that out of all the processing steps to create denim, the biggest impact of using recycled materials is on the yarn spinning. Shorter fibers make it difficult to obtain a good yarn quality. When searching for the optimal percentage of recycled fibers, it is not possible to give one value. As mentioned by the interviewees, how much mechanically recycled fibers can be used in a yarn is highly dependent on the quality of the recycled fibers and the type of yarn that is made. In thinner yarns less recycled fibers can be used than for thicker yarns. Additionally, as previously mentioned from pre-consumer recycled fibers more can be used than for post-consumer recycled fibers. There are different factors that determine how much recycled fibers you can add in the yarn, such as:

- Desired look and feel of the fabric.
- Yarn count
- Pre- or post-consumer mechanically recycled fibers
- Quality of the recycled fibers regarding
 - o Fiber length
 - o Degree of opening
 - o Short fiber content

- Contaminations
- Blend type
- Spinning method; ring spinning, compact spinning, open-end spinning

The yarn spinning with recycled fibers also leads to lower productivity and higher costs. Due to the short fibers, more fibers will get lost in the process and won't end up in the yarn. This makes the waste percentage higher and therefore also increase the price per kg fibers that can be used. These high percentages of short fibers that get lost in the process also fly around in the production facility. This makes the environments dusty, and this can be perceived as an uncomfortable working environment. Additionally, it is necessary to spin with lower speeds when using short fibers, decreasing productivity. Lastly, the parts of the spinning machines are subjected to more wear and tear and need to be replaced quicker compared to only working with the same virgin material. These higher costs often interfere with the perspective of the customer. They expect recycled materials to be cheap because it is 'waste' material. Due to previously mentioned reasons these yarns are more expensive to produce than virgin yarns. So eventually lead to a more expensive product.

With the high fiber loss of the recycled fibers the final blend of the yarn will also change. The percentage of recycled content in the yarn is based on the percentages inserted in the beginning of the yarn spinning process. However, more of the recycled fibers will be lost in the production process than the virgin fiber. The final blend of the yarn will most likely be different than the blend inserted in the machine.

The interviewees mention that the quality problems and processability problems mainly occur when higher percentages of recycled textiles are added. For the pre-consumer recycled textiles up to 30% of material can be added without having big difficulties in the production and without decreasing the product quality. For post-consumer this percentage is a bit lower, where 20% post-consumer recycled textiles can be added before the processability, and quality are highly influenced. Of course, these values are also highly dependent on the product type that is created.

4.4.2 Possible solutions

- Adjusting some settings on the spinning machines
 - For ring spinning this can be the twist settings, speed settings and the spacer clips.
 - For open-end spinning things that can be changed are the opening comber, the rotor diameter, the nozzle, the twist settings, and the speed setting.
- Mechanical compact spinning could improve yarn quality when ring spun yarns are required.
- Higher yarn counts can include more recycled content.
- When mechanically recycled fibers are blended with high quality fibers such as lyocell or polyester, more recycled fibers can be added. However, when keeping design for recycling in mind it's preferred to use as much mono-materials as possible. Therefore, in denim it would be best to blend mechanically recycled cotton fibers with other cellulosic fibers such as lyocell or chemically recycled cotton fibers.
- Brands/customers should be aware that using recycled materials results in yarns with a higher price due to the difficult processability.
- Core spinning with a core of recycled fibers and outside of virgin cotton, this could help create a more regular look of the yarn and can help with some dyeing problems.
- As mentioned, when adding 30% pre-consumer recycled textiles to a product or 20% post-consumer recycled textiles the processability and product quality are hardly affected. Therefore, it should become standard to add these low percentages of recycled textiles in the product. An optimal percentage should be found for the combination of pre-consumer and post-consumer recycled textiles. Most of the interviewees also mention that chemical recycling will be part of the solution. Since the quality of chemical recycled fibers are similar to those of virgin fibers. However, it will never 100% replace the mechanical recycling.



Figure 15. Yarn spinning facilities.

4.5 Dyeing

As previously mentioned in paragraph 2.2.4 in the preliminary literature study indigo is the dyestuff used most often for denim dyeing. Indigo has affinity with cotton material but has low affinity for synthetic materials. Since recycled fibers can contain contaminations of synthetic fibers this can cause complications in the dyeing process. Some research has been done on the dyeing of polyester with indigo dye, and the dyeing can be achieved by exhaust dyeing in an acidic environment (Baig, 2011). However, it has not been researched if this would also work for cotton polyester blends. It's unlikely that the same effects, of dyed outside of the yarn and white inside of the yarn, can be obtained with the exhaust dyeing method. Another option to dye the yarns with polyester contaminations could be using non-indigo dyes. However, in many cases the yarns will be dyed completely, and it will not be possible to obtain the desired faded look (Sanchez, 2015). Research is also done on the removal of dyestuff from the recycled materials to prevent future problems with dyeing. For cotton materials it can be possible to remove some dyestuff. The research of Määttänen, et al. (2019) showed that it is possible to remove cotton dyestuff. It was more difficult to remove the blue vast dyes and it was not possible to achieve the same bright whiteness as for some of the other dyestuffs. The method also involves several process steps and chemical usage; therefore, the environmental impact should also be analyzed (Määttänen, et al., 2019).

4.5.1 Challenges

Mentioned by the interviewed parties the biggest problem in dyeing is the synthetic fiber contaminations. In most cases these blends are cotton with elastane and/or polyester. When warp dyeing the yarns, the synthetic fibers won't take up the dyestuff the same way as cotton does. Therefore, there are some visual color differences in the fabric.

Post-consumer textiles have already undergone different treatment processes. Therefore, these fibers have a different dye uptake compared to virgin fibers. This will give different dyeing results, and the colors are not as bright and homogeneous as they are with virgin fibers.

Additionally, colored post-consumer textiles can have different colors shades, and these shades can vary for each batch. The darker shades are more difficult to dye than light shades and cannot be dyed into lighter colors. Furthermore, the traditional look of denim is the indigo dyed warp yarn, where only the

outside is dyed, and the inside is white. It's not possible to obtain this faded effect when dark colored fibers are used in the warp.

4.5.2 Possible Solutions

- It would be possible to work with a core spun yarn, where the recycled fibers with contaminations are inside the core and wrapped with virgin cotton fibers. Therefore, you won't have the effect of the contaminations on the surface.
- Since only the warp yarns are dyed it would be possible to use the fibers that contain some contaminations only for the weft yarns.
- In small percentages the colored post-consumer fibers can be used. As mentioned by the interviewees as long as the inside is lighter than the outside you will still get the desired faded shade. Only when the products are brushed or treated with laser this can create a more faded shade, compared to the virgin cotton.
- Using darker colors to cover the irregularities.
- There are some methods to remove dyestuff from the fabrics before recycling this is for example used in chemical recycling. This will help with a lot of the previously mentioned problems since the fibers will be white from the start. However, these methods still need some optimization and an environmental analysis to determine the impact.

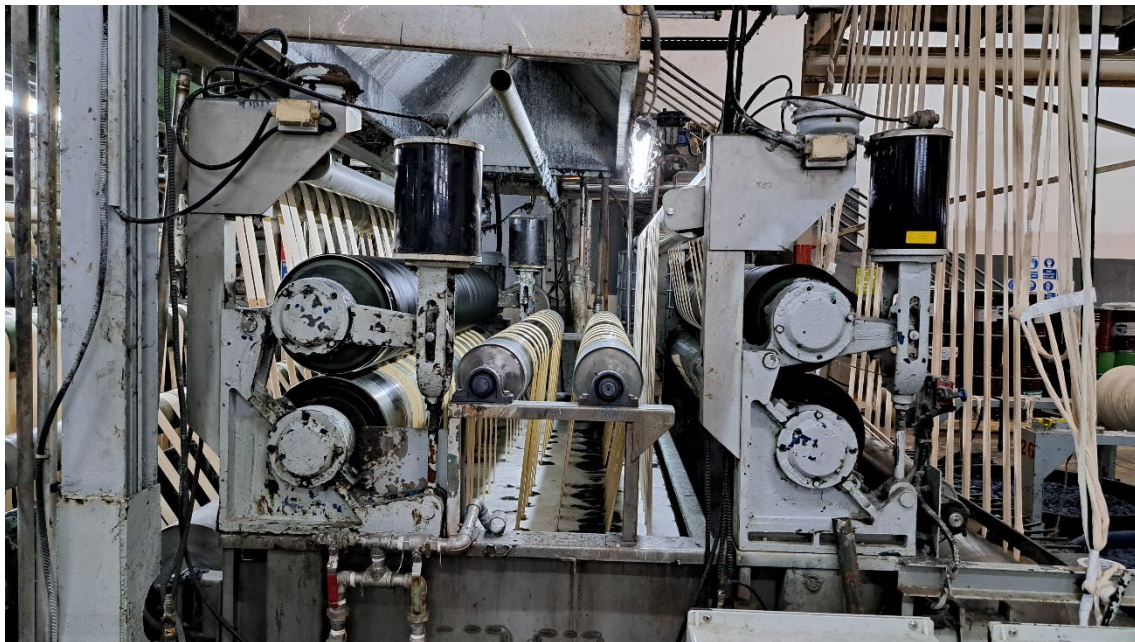


Figure 16. Indigo rope dyeing

4.6 Weaving

There is little literature available on the impact of recycled textiles on the weaving. Some of the problems that can be encountered during the weaving with recycled textiles can mainly occur because of the quality decrease of the yarns. The yarns can have lower strength properties, lower elongation, and more irregularities. Especially the low elongation and low strength can lead to yarn breakage during the weaving (Faysal, Azad, Repon, Hossain, & Jalil, 2022).

4.6.1 Challenges

As mentioned by all interviewed parties weaving is not really a big problem when it comes to the usage of recycled fibers. It is always necessary to create a good quality yarn before the weaving will start.

However, there are some challenges and difficulties that are different when weaving with yarns that contain recycled fibers.

Similar to the problem in yarn spinning, because of the high content of short fibers in recycled fibers more dust is created during the weaving process. However, not all interviewees encounter this problem.

With high percentages of recycled fibers, the yarn quality can be lower. This can influence the strength of the yarn and therefore also increase the yarn breakage during weaving. Some of the interviewees mention that because of these changes in yarn quality some adjustments are made in the weaving process. In some cases, the speed and tension on the yarn are slightly decreased, this is only the case when the yarns are too weak. This decreases the productivity and therefore also increases the production costs.

4.6.2 Possible Solutions

- To overcome the problems with the lower tenacity of the yarns it is possible to reduce the tension during weaving. To reduce tension, it is also better to use 2 cones instead of 1 for the weft. Additionally, it helps to reduce the weaving speed.
- For the problems with the fiber dust, there are machines in the market with a special suction system that can reduce this problem.
- Increase the amount of sizing, to increase the strength.
- The appearance of the fabric changes less when the recycled materials are used only in the weft direction.

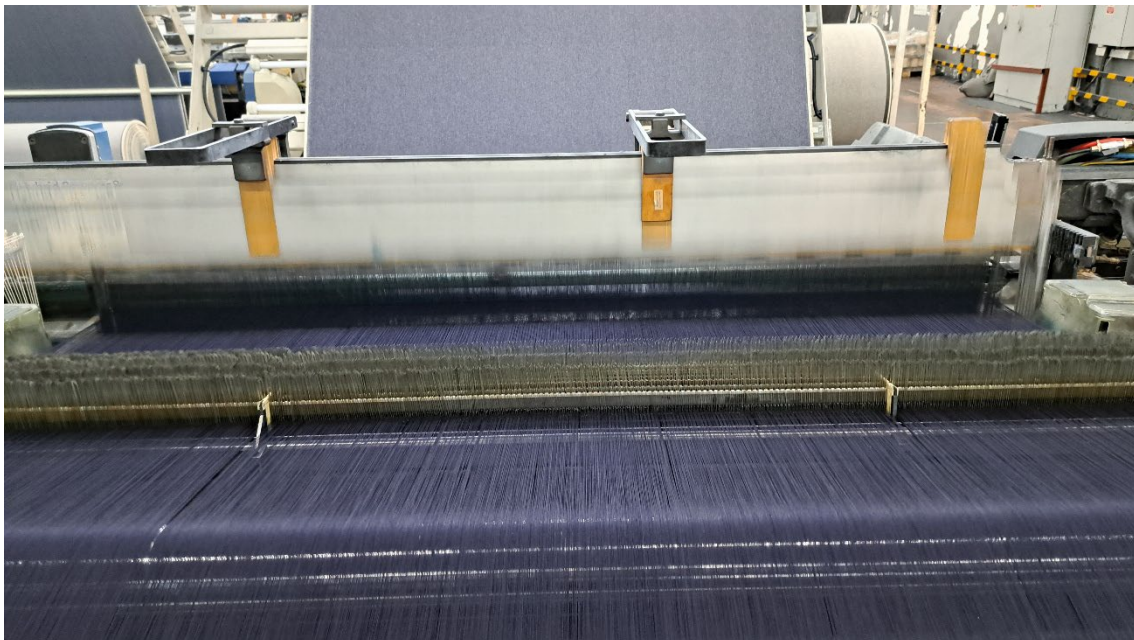


Figure 17. Weaving of denim fabric

4.7 Garment production & Retail

Before the development of the washing treatments to the garments, the denim products used to be stiff and uncomfortable when newly bought. The first implementation of a washing process around 1960 made the denim products more comfortable and gave a lightly faded look. People were willing to pay more for these jeans, so this sparked more developments in the washing with for example the pumice stone and bleach wash (Kan, 2015). Around the world clean water gets highly polluted, around 20% of this pollution comes from the textile industry. Mainly from the dyeing and finishing processes (McKinsey

& Company, 2022). As mentioned in the preliminary literature 2.2.7 Finishing enzymatic treatment has gained popularity and can be a more sustainable alternative for the pumice stone wash. The cellulase enzyme can replace the pumice stone but can also decrease the treatment time and causes less damage to the fabric. Next to the enzymatic treatment there are more developments for more sustainable finishing. This can be for example sustainable bleaching or biopolishing (Periyasamy & Periyasami, 2023). A frequent acknowledged problem is that customers are aware and worried about climate change problems. However, in many cases this does not lead to direct action when it comes to buying products. Due to the lack of knowledge or the lack of willingness to spend more money. The average customer is not aware of the meaning of eco-labels, and they pay little attention to this (Vukasovic & Zver, 2021; Soyer & Dittrich, 2021)

4.7.1 Challenges

Denim garments are fashion products and are designed to be good looking and comfortable otherwise they will not sell. Consumers have become used to having stretchy comfortable jeans, since the introduction of elastane and polyester in denim. It would be very difficult to reverse this development and go back to jeans with only 100% cotton. Additionally, treated jeans with different washing effects are still very popular. Often designers don't consider the environmental impact of these processes, or the influence on the recyclability. There are some more sustainable garment finishing methods available in the industry. However, there seems to be limited research available on the effect of different garment finishing processes on garments with recycled materials. It was mentioned by some interviewees that enzyme treatment goes more into the fiber than surface treatments like pumice stone. This can be a problem with recycled materials because of the lower quality due to short fibers. The pumice stone finish however, has a high impact on the environment.

Due to the lower production speeds the production price for fabrics with recycled materials increases. For the brands that use post-consumer recycled textiles, it can be more difficult to sell their garments. Due to of the quality differences and the higher prices that comes with post-consumer material, and the unawareness of the customers. It is likely that an uninformed customer will choose the cheaper product without irregularities over the more expensive product with some irregularities. The main goal for brands therefore remains to create a good-looking product, because otherwise it will not sell. Additionally, a lot of customers and brands are not aware of the difference between pre- and post-consumer recycled textiles. The most used recycling certificates don't distinguish between pre- and post-consumer recycled textiles. Therefore, the brands and customer will only see the certificate that says it contains recycled materials but won't be informed what kind of recycled materials are used. This comes with the problem that for the brands it is impossible to check whether pre- or post-consumer recycled fibers have been used in the final products. This creates some uncertainty when it comes to the composition of their products. Therefore, in some cases they prefer to go for the 'safer' choice and use organic cotton instead of recycled fibers. Another issue mentioned is that most brands want to have the GOTS certification when they use organic cotton. However, you only get this when you use at least 70% organic cotton. For some brands this is a reason to not increase the percentage of recycled content to 30% or higher because then they cannot use the GOTS certification.

4.7.2 Possible Solutions

- All treatments applied to the garments can be damaging to the fabric. It is hardly possible to obtain the faded look without damaging the textiles. The best would be to stop using all garment finishing. However, the product should still be attractive and comfortable for the customers, therefore it is recommended to use more gentle finishing on the garments containing recycled content.

- There are different ways to obtain stretch in denim fabrics. The industry could investigate biodegradable elastane alternatives. Or creating mechanical stretch by adjusting the design of the yarns and fabric structure.
- When legislation makes it obligatory to use recycled content all brands will have the same departure point. This will leave the customer without a choice. They will then always buy a product with recycled content.
- A method should be developed to analyze recycled content in products, but also check how much recycled content is inside and distinguish between pre- and post-consumer recycled content. However, this method is not yet available on the market so more research needs to be done on this.

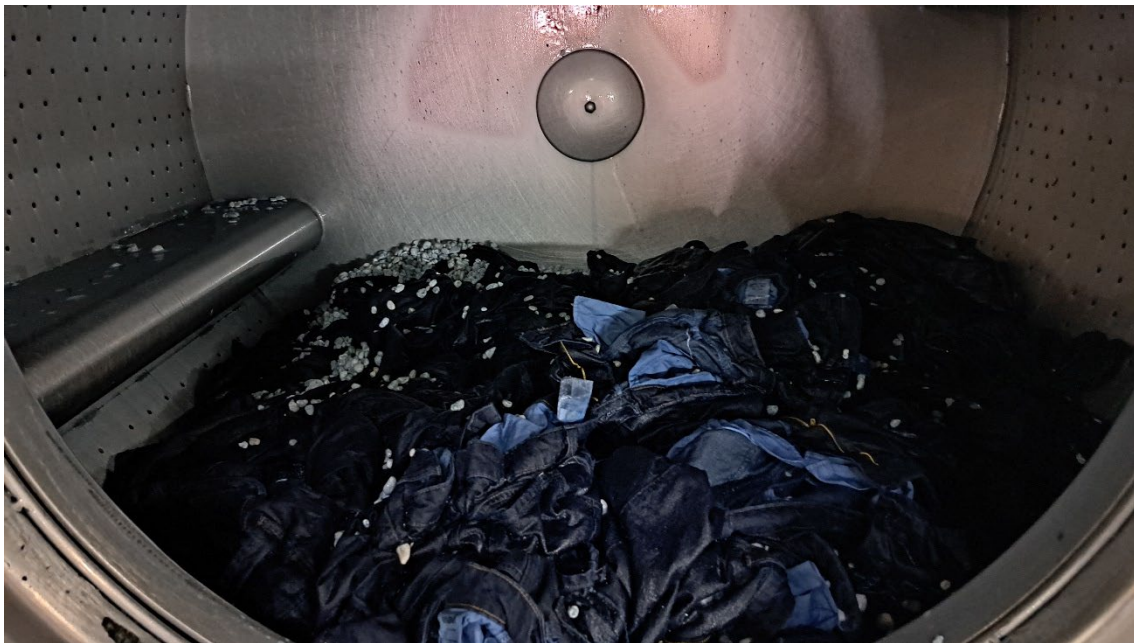


Figure 18. Pumice stone washing treatment on denim.

4.8 Regulation for a Circular Economy

According to the interviewees when it comes to the usage of recycled materials Europe is the front runner. However, not only in Europe but worldwide legislation is being adopted regarding sustainability, circular economy or EPR.

The European Union strives for mandatory Extended Producer Responsibility (EPR) programs for all member states. In the EPR the producers are responsible for covering the costs for the management of waste textiles. The EPR should give the producers the motivation to produce more circular textile products and reduce waste (European Commission, 2023). In the Netherlands and France the EPR has already been introduced (Norton Rose Fullbright, 2023).

Even though the USA currently has no legislation when it comes to textile recycling, they are working towards increasing the recycling rate to 50% by 2030. This includes improving the quality of the collected materials, make the recycling industry more efficient, and creating more marked demand for recycled materials (EPA, 2023). California adopted the SB-707 Responsible Textile Recovery Act of 2030, where producers are required to set up a program for the collection and recycling of textiles (Senator Newman, Senator Skinner, & Senator Wiener, 2023).

Australia is also working towards a more circular and sustainable textile supply chain. Seamless, developed with the Australian Fashion Council, is focusing on transitional to a circular fashion economy

by 2030. The program will be financed by the brands, where the contribution is 4 cents for every new piece that is brought to the market. A program will be created that should encourage the design of more recyclable and durable clothing (Australian Fashion Council, 2024).

Since 2016 Chile has EPR legislation (Law 20.920), but this does not specifically focus on textiles. However, the Chilean government also has a plan to obtain a circular economy by 2040, which also includes textiles (Ministerio del Medio Ambiente, 2021).

5 Conclusion

To optimize the quality of recycled textiles it is necessary for each partner in the value chain to optimize their processes. All steps of the value chain are connected to each other, therefore one cannot improve without the other. The most important observations are given per step of the value chain, afterwards an overall conclusion will be given.

Collecting: When it comes to textile collection the most important change to improve the quality of the recycled textile that can be implemented is making sure that all textiles are dry and clean. This can be done by a combination of interventions. The most important ones being improving the textile containers to make them waterproof and ensuring that textiles are collected in closed plastic bags. This is also connected to the education of residents on what textiles to hand in and in what way.

Sorting: For textile sorting, the most important change to improve the quality is enabling sorting in more different fractions, resulting in different categories of recycled textiles. To achieve this, it will be necessary to further develop the sorting technologies to detect the exact fiber blends and possible fiber qualities. Close collaboration between the sorters and recyclers is necessary for data exchange and analysis. These technologies often come with high investments costs, therefore also increasing the costs for sorting. **The value of post-consumer recycled textiles should be increased to give more financial incentives to improve the sorting.**

Mechanical recycling: The mechanical recycling can be optimized by more gentle shredding, which can be obtained by using a pre-treatment on the fabrics and lower production speeds. The outcoming recycled fibers can be divided according to the suitable outputs such as high-quality yarns, medium quality yarns, or insulation materials. When the value of post-consumer recycled fibers is higher this will give the recyclers more reasons to improve the quality of the fibers.

Yarn Spinning: To optimize the quality of the yarn using recycled materials, some settings can be changed. For all spinning methods the production speed should be lowered when using (high) percentages of recycled fibers and twist can be increased to increase strength. Additionally, for the ring spinning the spacer clip can be changed, and a mechanical compacting system can be added. For the rotor spinning the system can be optimized by adjusting the opening roller the rotor and the nozzle.

Dyeing: The dyeing can mainly be optimized by (visually) getting rid of the polyester contaminations. When having light denim jeans, these contaminations are less visible so it can be an option to choose for light denim jeans. However, there is a need for more research and technical developments regarding this topic when darker jeans are preferred. **Additionally, the environmental impact can be drastically reduced when the yarns and fabrics are no longer dyed but the color of the recycled fibers is used as the final color.**

Weaving: When it comes to weaving it can be necessary to weave at a lower production speed when high percentages of mechanical recycled materials are used.

Finishing: During finishing, the best quality product is achieved without harsh washing treatments. The washing procedures are harmful for the product and therefore can decrease the lifetime of the product. The garment finishing is mainly done for comfort and aesthetic reason, because of the environmental impact of these processes it would be best to reduce these additional treatments as much as possible.

Retail: For brands the technical adjustments that can be done are mainly in the designing process. It is easier to use more recycled materials when thicker yarns are used, and a more tightly woven fabric can

increase the product strength. To reduce the environmental impact of the product it can be considered to not dye the garment and to keep the garment finishing treatment to the minimum. For future recycling it is also important to consider design for recycling and design for disassembly in the design process.

As shown above the quality of recycled fibers can be improved by optimizing each step of the value chain for fiber-to-fiber recycling. **Like proposed in the Denim Deal the industry should aim for adding small percentages in all products, rather than creating one product or collection with high percentages.** The processability and quality of a product is highly influenced by the product design, yarn count, fabric density and additional treatments. Even though, it was mentioned by the interviewed parties that in most cases when pre-consumer recycled textiles are added up to 30% this hardly influences the product quality or processability. For post-consumer recycled textiles this percentage was given as 20% before the quality and processability are affected. So, technically a lot is possible when using recycled materials. There are many ways to include more than 20% post-consumer recycled content in denim fabrics. However, this might be at the cost of comfort, appearance, and price. Most customers and brands are not willing to compromise on this, according to the interviews and literature research performed for this report. **To optimize the quality of the product containing recycled textiles, each partner in the value chain can take steps to improve.**

Law and certification should make a clear distinction between pre-consumer and post-consumer recycled materials. Additionally, they should promote the use of post-consumer recycled materials. Using recycled textiles, and specifically post-consumer recycled textiles involves higher costs, lots of dust in the production process, lower productivity, decrease in quality, more irregular looks of the fabrics and garments. All in all, this makes it more difficult and unattractive to work with recycled fibers. So, either the willingness to contribute to textile recycling and the aim for a more sustainable denim industry should be in the core values of businesses. Or there should be legislation in place that forces the use of (post-consumer) recycled textiles in new products. All the additional process steps that come with the textile recycling are expensive, regulation should therefore also enforce that the true costs are being paid in each part of the value chain. Together the parties of the Denim Deal are working on overcoming these hurdles and move towards a more circular value chain. Increasing the value of the post-consumer textile materials would give all the parties in the value chain more space to improve their processes and therefore the quality of the recycled materials.

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I Appendix: Interview Textile Collection

After starting the Denim Deal in 2020 several steps have been taken to reach the desired goals. To bring the Denim Deal to a good end a report needs to be written that gives an overview of the technical results that were obtained as part of collaboration in the supply chain and innovative technical practices. The report will be an addition to the monitoring done by FFact and will focus more on the technical results and opportunities, as well as a state-of-the-art overview of using mechanically recycled fibers in denim in the industry.

The interview will be held by Maud Kuppen, researcher at research group Sustainable & Functional Textiles of Saxion University. The report written by Saxion will be a scientifically independent report covering the view from all the Denim Deal parties involved based on a field study (seeing the innovative technical practices in process at the different companies). The Denim Deal parties that are involved with the manufacturing of the denim are given the opportunity to provide input regarding their process steps. Their input will help give an overview of the different steps in the supply chain and the difficulties with recycling. Therefore, this interview will be conducted. In this interview questions will be asked regarding the bottlenecks and opportunities of part of the supply chain your company is involved in.

Textile Collection

- Can you please tell me what your position in the company is?
- Can you give a short description of the work your company does.
- Where do you get your textile materials from?
- Where do you supply the collected textile materials to?
- How is the textile collection organized in your country?
- Out of all the textile streams you receive what percentage is denim?
- Is there a difference between the collection of denim, or other textile streams?
- What are the biggest issues with the way the textiles are handed in/collected?
- Do you receive feedback from your customers (textile sorters) on the quality of the collected textiles? If so, what is the feedback?
- Do your customers (textile sorters) also provide guidelines on how they want to receive the textiles?
- Do you have any ideas on how to improve the quality of the collected textiles?
- Do you educate your suppliers of textiles on how to hand in the textiles?
- What is in your perspective needed to improve the collection process?
- Do you perceive that your customers (textile sorters) want to process more textiles than that you can currently provide to them? If so, what is, in your perspective needed to increase the quantity of collected textiles?
- In your opinion, what is the biggest challenge the textile industry is facing regarding textile recycling?
- How do you see the future of the textile collection?

II Appendix: Interview Textile Sorter

After starting the Denim Deal in 2020 several steps have been taken to reach the desired goals. To bring the Denim Deal to a good end a report needs to be written that gives an overview of the technical results that were obtained as part of collaboration in the supply chain and innovative technical practices. The report will be an addition to the monitoring done by FFact and will focus more on the technical results and opportunities, as well as a state-of-the-art overview of using mechanically recycled fibers in denim in the industry.

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Textile Sorting

- Can you please tell me what your position in the company is?
- Can you give a short description of the work your company does.
- Where do you get your textiles from?
- Where do you supply your sorted textiles to?
- What percentage of the sorted textiles goes to textile recycling?
- Out of all the textile streams you receive what percentage is denim?
- What are the biggest issues with the textiles coming into your company?
- Could you share according to what specifications you sort the textiles?
- According to what specifications do you sort the denim products that you receive?
- Do you have certain textile streams that are easier to sort than others?
- In the sorting of denim, are there specific things you need to consider?
- Do you give feedback to the textile collectors on how to improve the collecting of textiles? If so, can you say what the feedback is?
- Do the recyclers give you guidelines on how to sort the textiles optimal for recycling? If so, can you say what the guidelines are?
- Do you have any ideas on how to improve the quality in the textile collection?
- Do you have any ideas on how to improve the quality of the sorted textiles?
- Do the textile recyclers want more sorted textiles than you can currently provide to them? If so, what is in your perspective needed to increase the quantity of sorted textiles?
- In your opinion, what is the biggest challenge the textile industry is facing regarding textile recycling?
- How do you see the future of the textile sorting?

III Appendix: Interview Textile Recycling

After starting the Denim Deal in 2020 several steps have been taken to reach the desired goals. To bring the Denim Deal to a good end a report needs to be written that gives an overview of the technical results that were obtained as part of collaboration in the supply chain and innovative technical practices. The report will be an addition to the monitoring done by FFact and will focus more on the technical results and opportunities, as well as a state-of-the-art overview of using mechanically recycled fibers in denim in the industry.

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Textile Recycling

- Can you please tell me what your position in the company is?
- Can you give a short description of the work your company does.

Incoming textiles

- Where do you get your textile materials from?
- What type of materials do you receive from the textile sorters?
- What are the biggest issues with the textiles coming into your company?
- Do you have a preference for receiving certain types of textiles?
- Do you give guidelines to the textile sorters? If so, what kind of guidelines do you provide?
- In the best-case scenario, what type of textiles would you receive from the sorters and in what shape?
- Do you have any ideas on how to improve the quality of the sorted textiles?
- Do you experience any problems with the quantity of textiles supplied to you?
- What is, in your perspective needed to increase the quantity of sorted textiles?

Recycling

- Out of all the textile you recycle what percentage involves the recycling of denim?
- What are the biggest issues you run into during recycling?
- What do you do to overcome these issues?
- Regarding Denim, where do you see the most opportunities to improve the quality.
- Do you have certain textile streams that are easier to recycle than others? If so, could you specify why this is?
- Do you recycle both post and pre consumer textiles? If so, what is the biggest difference in the recycling of these two streams?

Outgoing recycled fibers

- Where do you supply your recycled fibers to?
- What percentage of your outgoing recycled fibers goes to yarn spinning?
- How much do you (have to) educate your customers on fiber quality and textile recycling?
- Do the spinners give you guidelines on how they want to receive the recycled fibers? If so, can you say what guidelines they give?
- How do you analyze the quality of the recycled materials?
- How is the quality of recycled denim compared to other recycled textile streams?
- Do you have any ideas on how to improve the quality in the recycled fibers?

- Do you perceive the market of recycling to be a push or a pull market?
- In your opinion, what is the biggest challenge the textile recycling industry is facing?
- How do you see the future of the textile recycling?

IV Appendix: Interview Yarn Spinning

After starting the Denim Deal in 2020 several steps have been taken to reach the desired goals. To bring the Denim Deal to a good end a report needs to be written that gives an overview of the technical results that were obtained as part of collaboration in the supply chain and innovative technical practices. The report will be an addition to the monitoring done by FFact and will focus more on the technical results and opportunities, as well as a state-of-the-art overview of using mechanically recycled fibers in denim in the industry.

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Yarn spinning

- Can you please tell me what your position in the company is?
- Can you give a short description of the work your company does.

Incoming fibers

- Where do you get your textile fibers (recycled and not recycled) from?
- Do you see a difference between your suppliers of quality of recycled fibers?
- What type of recycled fibers do you use in yarn spinning?
- Do you have a preference for using certain types of recycled fibers? Why do you have this preference?
- Out of the recycled fibers you use, what percentage is denim?
- Do you have requirements for the quality of fibers you use? If so, do you provide these requirements to the recyclers? Could you share these requirements?
- Do you have minimum requirements for fiber quality to use fibers for spinning? If so, how did you determine these requirements?
- Are these requirements different for virgin fibers than for recycled fibers?
- Do you perceive a difference between different types of recycled fibers?
- Do you use post-consumer recycled textiles as well as pre consumer recycled textiles? If so, what is the biggest difference you perceive between these two?
- Do you analyze the fibers before using them in yarnspinning?
- Do you have any ideas on how to improve the quality of the recycled fibers?
- Do you experience any problems with the quantity of recycled fibers supplied to you?

Yarn spinning

- What type of spinning methods do you use?
- What spinning method do you use for the production of yarns for denim products?
- What are the main issues of the usage of recycled fibers in yarn spinning?
- Have you tested the limits of the usage of recycled fibers?
- Do you see a difference in processability of recycled denim fibers and other recycled fibers?
- What are the biggest issues you run into during spinning with recycled fibers?
- What do you do to overcome these issues?
- Regarding Denim, where do you see the most opportunities to improve the quality?
- Do you have any ideas on how to improve the quality in the yarns containing recycled fibers?
- What percentage of recycled fibers do you currently use in denim products?

- What maximum percentages of recycled materials do you can use?

Outgoing yarns

- Do you have different requirements for yarns with and without recycled fibers?
- Are these requirements the same for virgin yarns as for yarns with recycled content?
- Do you get guidelines from the weavers for the quality of yarns you should supply?
- Being involved in the spinning and weaving, is there feedback given from the weaving department to the yarn spinning department? If so, what is the feedback?
- How do you see the future of the usage of recycled fibers in yarn spinning?

V Appendix: Interview Weaving

After starting the Denim Deal in 2020 several steps have been taken to reach the desired goals. To bring the Denim Deal to a good end a report needs to be written that gives an overview of the technical results that were obtained as part of collaboration in the supply chain and innovative technical practices. The report will be an addition to the monitoring done by FFact and will focus more on the technical results and opportunities, as well as a state-of-the-art overview of using mechanically recycled fibers in denim in the industry.

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Weaving

- Can you please tell me what your position in the company is?
- Can you give a short description of the work your company does.

Incoming yarns

- Where do you get your yarns (recycled and not recycled) from?
- Do you see a difference between your suppliers of quality yarns?
- Do you ever check the composition of the yarns you use?
- Do you analyze the yarns you receive from the spinners in any other way?
- Have you woven any denim fabrics before?
- What type of yarns do you use for the denim industry?
- Could you provide the minimum quality requirements you set for yarns? How did you determine these requirements?

Weaving

- Out of your total production what percentage is for the denim industry?
- Do you use yarns with recycled fibers in both warp and weft direction?
- What are the main issues you experience of the usage of yarns with recycled content?
- What do you do to overcome these issues?
- Do you use yarns with post-consumer recycled textiles as well as pre consumer recycled textiles? If so, what is the biggest difference you perceive between these two?
- Have you tested the limits of the usage of content of recycled fibers in your fabrics? If so, what are these limits?
- Do you see a difference in processability of yarns with recycled denim fibers and other recycled fibers?
- Do you have any ideas on how to improve the quality in the fabrics containing recycled fibers?

Outgoing Fabrics

- What is the maximum total percentage of recycled fibers you have in your products?
- What is the maximum total percentage of recycled fibers you have in your denim products?
- In your perception, do your customers understand the difference between pre- and post-consumer recycled fibers?
- Do your customers ask specifically for pre- or post-consumer recycled fibers?
- How are the quality requirements for the fabrics determined?
- Are these quality requirements the same for fabrics with and without recycled fibers?

- How much do you (have to) educate your customers on fabric quality when it comes to recycled materials?
- In your opinion, what is the biggest challenge the textile industry is facing regarding the use of recycled fibers?
- How do you see the future of the usage of recycled fibers in weaving?

VI Appendix: Interview Brands

After starting the Denim Deal in 2020 several steps have been taken to reach the desired goals. To bring the Denim Deal to a good end a report needs to be written that gives an overview of the technical results that were obtained as part of collaboration in the supply chain and innovative technical practices. The report will be an addition to the monitoring done by FFact and will focus more on the technical results and opportunities, as well as a state-of-the-art overview of using mechanically recycled fibers in denim in the industry.

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Retail

- Can you please tell me what your position in the company is?
- Can you give a short description of the work your company does.

Incoming Products

- Is your company involved/responsible for the design process of the denim products? If so, do you consider design for recycling for these products?
- Do you know where your suppliers get their (recycled) materials from?
- Do you check the percentage of recycled fibers in the final products?
- Do you check the quality of the final product?
- What is the highest percentage of recycled fibers you have in your products/denim?
- Do you provide requirements to your producers for the garments? If so, how did you determine these requirements?
- Would you say these requirements are really the minimum requirements for the use of the denim products?
- Do you adjust the requirements of the garments when using recycled material?
- In your products do you use post-consumer or pre-consumer recycled textile, or both? If so, what is the biggest difference you perceive between these two?
- Do you have different suppliers for your products with recycled content? If so, do you see a difference between these suppliers in quality of the products?
- In your opinion what should be changed to improve the quality of the products with recycled content?
- Do you perceive a difference in quality for products with recycled content and without recycled content? If so, what difference do you perceive?
- Do you perceive a difference between the product quality including pre- or post- consumer recycle textiles?
- Regarding Denim, where do you see the most opportunities to improve the quality?
- Do you experience any problems with the quantity of products with recycled content that supplied to you?

Outgoing Products

- Out of your total sales what percentage is denim products?
- What are the main issues you experience of the usage of denim with recycled content?

- Do you ever get feedback from your customers on the quality of your denim? If so, is the feedback different for denim with recycled content than without recycled content?
- Do you communicate whether there is post-consumer or pre-consumer recycled textiles in the products?
- In your perception, do your customers understand the difference between pre- and post-consumer recycled fibers?
- Do your customers ask specifically for products with pre- or post-consumer recycled fibers?
- Do you perceive the market of recycling/recycled products to be a push or a pull market?
- How much do you (have to) educate your customers on products quality when it comes to recycled materials?

- In your opinion, what is the biggest challenge the textile industry is facing regarding the use of recycled fibers?
- How do you see the future of the usage of recycled fibers in clothing?

VII Appendix: List of Participants Interviews

| Company Name | Country |
|---------------------|---------------------------|
| Circulus-Berkel | The Netherlands |
| Rd4 | The Netherlands |
| Stichting Sympany | The Netherlands |
| Wolkat Products | The Netherlands & Marocco |
| Andritz Laroche | France |
| PurFi | Belgium |
| Brightfiber | The Netherlands |
| ReMatters | Türkiye |
| Gama Recycled | Türkiye |
| Bossa | Türkiye |
| Kipas Textiles | Türkiye |
| Orta Anadolu | Türkiye |
| Sharabati Denim | Türkiye & Egypt |
| Çalık Denim Tekstil | Türkiye |
| DNM Textile | Türkiye & Egypt |
| Ereks Konf. | Türkiye |
| Kuyichi | The Netherlands |
| MUD Jeans | The Netherlands |
| Garcia | The Netherlands |