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Torn to be worn?

- Cotton fibre length of shredded post-consumer garments

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PREFACE

This thesis is written as a diploma work of the European masters degree in advance textile engineering, E-TEAM, at the Swedish School of Textiles.

This thesis has been performed in cooperation with Swerea IVF, a Swedish research institute, located in Mölndal, Sweden. Swerea IVF develops and implements new technologies and working methods for various sectors with focus on product, process and production development.

This thesis would not been possible without great support and help from various persons. I want to thank Emmaus Björkå for providing me with the material. I want to give a special thank to Louise Holgersson, my supervisor at Swerea IVF. With your experience and help you have given me great guidance and support throughout the work. Further I want to thank my supervisor, at the Swedish School of Textiles, Anders Persson, for great support and for given me feedback and reflections keeping my work at an academic level. Last, I want to give a great thank to the students writing their thesis at Swerea IVF for a great support and company.

Julia Aronsson,
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ABSTRACT

In 2015 the global fibre consumption was 96.7 million tonnes, which is an increase of 3.1% from the year before. Our high textile consumption has led to an increasing demand of raw materials and generation of textile waste. Only in Europe, a total amount of 4.3 million tonnes of apparel waste each year is sent to either incineration or landfills. Approximately 50% of the clothes we discard and donate are composed of cotton. In the future, the cotton production is predicted to stagnate since the world population is increasing and arable land to greater extent will be needed for food production. Thereby, it is important that we utilize the cotton waste generated.

One of the most commonly used processes for recycling textile waste is the shredding process. In this method, textile waste is shredded back into their constituent fibres. The drawback with the shredding process is that the fibre length is reduced. The fibre length is an important property since it has a high influence on textile processing such as yarn production and final product quality.

The aim of this thesis was to investigate how post-consumer cotton garments with different degree of wear affects the fibre length obtained in the shredding process. This was performed by analysing the input fibre length as well as the output fibre length. Additionally, several parameters were investigated: fabric construction and yarn structure. Degree of wear was categorized into two levels: low and high degree of wear. The fabric constructions used in this study were single-jersey and denim. The yarn structure were analysed in terms of yarn count, yarn twist and manufacturing process.

The result showed that the fibre length before shredding was statistically significant longer for the materials with low degree of wear compared to high degree of wear. After shredding, it was shown that the fibre length reduction was lower for the materials with high degree of wear. This indicates that longer fibres give higher fibre length reduction. In addition, it was found that finer yarn gives higher fibre length reduction. The result also showed that the yarn manufacturing process has a great influence on the ease of shredding and the fibre length obtained in the end.

Based on the result in this thesis it can be concluded that the shredding process needs to be improved in order to preserve the fibre length. The area of post-consumer textile waste is complex and the result showed that there is many underlying parameters that need to be taken into account to further develop the shredding process.

Key words: Mechanical recycling, shredding, post-consumer textile waste, cotton, fibre length and fibre length distribution.

POPULAR ABSTRACT

The textile consumption is gradually increasing, which has led to an increasing demand of raw materials and generation of textile waste. Cotton is one of our most appreciated fibres and the majority of the clothes we donate or discard are composed of cotton. The cotton production has a high impact on the environment since it requires a great amount of water and chemicals. In order to keep up with our increasing consumption of textiles and to protect our nature, we need to start to take care of the generated waste. One way to do that is by recycling.

The most commonly used method for recycling textiles is the shredding process. In this process, the discarded textiles are torn down into fibres, which are the fundamental elements building up a yarn. The drawback with the shredding process is that it is reducing the length of the fibres. The length of the fibres is important since it to a great extent determines if a yarn can be produced. Today, it is difficult to produce new clothes of these fibres. Common applications are insulation, cleaning cloths and rags.

The aim of this thesis was to investigate how the length of the fibres, after shredding, is affect by how worn out the discarded clothes were prior to recycling. This was done by analysing the length of the fibre before and after shredding. In addition, several parameters were investigated such as fabric construction and yarn structure. The garments used in this study were discarded T-shirts and jeans.

The result showed that the fibre length reduction after shredding was higher for the garments that were less worn out. In addition, it was found that the yarn structure has great influence on the ease of shredding and the fibre length obtained in the end. The result in this thesis further shows that the shredding process needs to be improved in order to preserve the fibre length so new yarns can be produced.

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1. INTRODUCTION

Due to growth in world population, continued improvements of living standards and rapid changes of fashion trends, the textile production and consumption have gradually increased in the past few years. Consequently this has lead to an increasing demand of raw material and generation of textile waste. (EEA 2014; Wang 2010) The textile industry needs to move towards a circular economy since it is one of the most polluting and resource demanding industries due to e.g. high energy and water consumption and use of harmful chemicals (Morley et al. 2014; Payne 2015). Recycling of textiles may be one way to reduce the amount of waste generated and reduced the need of virgin fibres. The most commonly used process for recycling textile waste is the shredding process, which is examined in this thesis.

1.1 TEXTILE CONSUMPTION AND WASTE

In 2015, the global fibre consumption was 96.7 million tonnes, which is an increase of 3.1 % from the year before (The Fibre Year 2016). In Europe a total amount of 7.3 million tonnes of apparel waste is generated each year. Approximately 4.3 million tonnes of this waste is sent to either incineration or landfills. (Morley et al. 2014) According to the waste hierarchy, which is defined in the EU directive 2008/98/EC and presented in Figure 1, landfill is the least preferable option since a great amount of resources will be lost. Incineration is considered as a better option since the energy generated can be utilized. However, according to the waste hierarchy prevention of textile waste is the most preferred option. Secondly, textile waste should be reused to greatest possible extent. Materials unsuitable for reuse should be recycled.

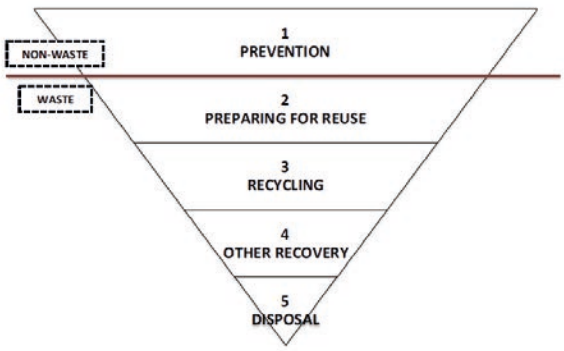

Figure 1 Waste hierarchy [1]

The annual textile consumption in Sweden 2014 was nearly 12.5 kg per person. Of this amount, 7.6 kg were thrown in the household waste, were 59% contained 100% cotton. (Elander et al. 2014; Hultén et al. 2016) In a study by Chang et al.

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[1] Reprinted from Waste Management, vol. 39, M. Gharfalkar, R. Court, C. Campbell, Z. Ali, G. Hillier, Analysis of waste hierarchy in the European waste directive 2008/98/EC, 9 pages, (2015), with permission from Elsevier.

(1999) they reported that the fibre content, by weight, of used apparel donated for recycling and recuse in the US contained 59.3% cotton. Furthermore, in a study by Ward et al. (2013) they reported that approximately 54.7% of donated post-consumer clothes in the UK was composed of cotton. According to Hämmerle (2011) the cotton production will in the future stagnate since the world population is increasing and arable land to a great extent will be needed for food production. In conjunction with that cultivation of cotton requires a great amount of water and chemicals, incitements for recycling of cotton are strong.

1.2 RECYCLING

According to Payne (2015) recycling refers to converting waste material back into raw material in order for the raw material to be used in new products. Depending on what stream the new product enters recycling can be classified as either *open loop recycling* or *closed loop recycling* (Payne 2015). Open loop recycling is the most commonly used strategy within the textile sector. In this approach the material is not recycled repeatedly i.e. the product will ultimately be disposed and excluded from the loop. (Leonas 2017) This system is commonly seen as downcycling, since the quality of the raw material is reduced and can only be used in low quality applications. However, open loop recycling enables postponement of waste to landfills and incineration. In closed loop recycling the raw material is used indefinite and the raw material enters the same product stream as the original repeatedly times. (Payne 2015) According to Payne (2015) both strategies are of high importance for the textile industry, however, closed loop recycling holds a greater potential to move towards a more sustainable textile industry.

Discussing recycling one has to distinguish between different kinds of waste. Recycling involves waste generated from two primary sources: *pre-consumer* and *post-consumer waste.* Pre-consumer textile waste is waste generated in the industry e.g. fibre and textile manufacturing. Post-consumer textile waste is textiles that the consumers no longer have use for, either because they are worn-out, damaged or out-dated. (Hawley 2006; Roy Choudhury 2013; Vadicherla & Saravanan 2014)

Several recycling technologies have through the years been developed and depending on the raw material used and the products obtained in the end four recycling technologies can be distinguished*: primary, secondary, tertiary* and *quaternary*. (Vadicherla & Saravanan 2014)

The primary approach refers to in-plant recycling. This approach is utilizing pre-consumer waste to produce products of equal values as the waste and is therefore considered as closed loop recycling. This process is simple and ensures low costs, mainly since it only dealing with recycling of clean waste with a known history. (Karayannidis & Achilias 2007)

The secondary method involves mechanical processing of post-consumer waste. Fibres produced from the secondary approach are commonly known in the literature as reclaimed fibres. (Gulich 2006 b; Wanassi et al. 2016) Further mechanical recycling applies for thermoplastic polymers e.g. polyester, polypropylene and polyamide and for natural fibres e.g. cotton and wool. Thermoplastic polymers are usually reprocessed into granules or pellets, melted and re-extruded into new products or spun into filaments. (Karayannidis & Achilias 2007; Leonas 2017) This process is commonly used for reprocessing PET-bottles into polyester fibres, hence it is an open loop recycling (Gulich 2006 a). Re-melting polymers does not alter the basic polymer, however, weakening of product properties occur in every cycle due to degradation and reduction of the molecular weight of the recycled polymer. By drying, reprocessing with degassing vacuum etc. reduction of the molecular weight can be prevented. (Karayannidis & Achilias 2007)

Another mechanical recycling technology is the shredding process. In this method textile waste is shredded back into their constituent fibres. (Collier et al. 2007) Compared to the previous explained method, this process is not limited to fibre type. However, there are significant differences between natural fibres, synthetic fibres and blends regarding what quality the recycled material can get. The drawback with the shredding process is that the fibre length is reduced, common applications are therefore low quality products. (Leonas 2017; Östlund et al. 2015) Chapter 1.5.1 will examine the shredding process in greater depth.

The tertiary approach involves chemical recycling processes. Polymers such as polyester and polyamide can be depolymerised into oligomers or monomers that subsequently can be repolymerized and spun into new filaments or fibres. (Karayannidis & Achilias 2007) This process is commonly used for recycling of PET-bottles and fishing nets. Chemical recycling is also valid for cellulose-based fibres were the cellulose is treated with chemicals. This could be done according to the direct method that is used in the production of lyocell fibres or the derivate method, which is the traditional method for producing viscose fibres. (Collier et al. 2007)

The final approach is the quaternary approach or energy recovery. In this approach fibrous solid waste is burnt and the heat generated is utilized. (Vadicherla & Saravanan 2014)

All four approaches, mentioned above, are available for textile recycling, however in limited scale since recycling of textiles involve many challenges. In the following section, two of the major challenges for recycling of textile waste will be discussed.

1.3 CHALLENGES FOR RECYCLING OF TEXTILES

The two major challenges for recycling of textiles are degradation of the fibres and fibre blends (Tham & Fletcher 2014). Pre-consumer textile waste is easier to recycle compared to post-consumer textile waste since it usually is of higher quality and more homogenous compared to post-consumer waste. (Merati & Okamura 2004; Vadicherla & Saravanan 2014) Recycling of post-consumer waste is complex since the material is less homogenous due to variations of degree of wear, material composition, colour and non-textile parts e.g. buttons, zippers and labels (Bartl et al. 2005; Luiken & Bouwhuis 2015). During the user phase the materials are subjected to laundry, drying, abrasion etc., which leads to degradation of the fibres i.e. reduction of fibre and polymer chain length. (Tham & Fletcher 2014) The most apparent degradation of textiles comes from mechanical stress during use and laundering. Laundering is known to cause a decrease in the *degree of polymerisation* (DP) of the cellulose in cotton. The decrease of DP corresponds to a reduction of fibre strength. This correlation is one of the reasons why mechanical recycling of cotton fibres gives a product of low strength even if longer fibres are maintained. (Palme et al. 2014)

Another great challenge is fibre blends. For chemical recycling the challenge is to find an appropriate method to separate the polymers from each other. In the shredding process, polyurethane fibres, e.g. elastan, tends to tangle up in the machine, which is one of the challenges with recycling of denim. Furthermore, synthetic fibres are stronger than natural fibres and a higher amount of energy is needed to tear them down to fibrous form, i.e. there is a risk of damaging the cotton fibres even more. Another great challenge when it comes to dealing with fibre blends is sorting of textiles. Today, there is no commercial technique available for characterization of fibre blends. (Tham & Fletcher 2014) The need for a more accurate fibre characterization is essential, especially for chemical recycling, in order to create waste streams that can be recycled (Luiken & Bouwhuis 2015; Östlund et al. 2015).

The next section aims to give a brief description of how collection and sorting of textile waste is currently performed.

1.4 COLLECTION AND SORTING OF TEXTILE WASTE

Depending on what type of product that is handled, i.e. pre or post-consumer waste, collection of textile waste can take place at several points through the textile supply chain (Leonas 2017). When consumers no longer want their products they can discard, donate or sell them to collectors e.g. charity organisations and retailer collections. (Hawley 2006) An example of the latter is H&M that collects textile waste in their stores, which further is sent to the SOEX group through I: Collect (H&M 2016).

The SOEX group is one of the world's largest textile sorting and recycling company. Each day, the company manually sorts over thousands of textiles, apparel, shoes and accessories. This is done according to 350 different criteria's. Approximately 62% of the sorted waste can be reused, 32% is recycled into different products, e.g. cleaning cloths, and 6% is sent to incineration. (SOEX Group 2017)

Today sorting of textile waste is done mostly manually. Even though it is a work intense process it is the dominant method since it is the only process that can sort textile waste based on quality and trend. However, automatic-sorting technologies should be developed in order to make the processes more efficient and to achieve as pure material fractions as possible. (Östlund et al. 2015; Swedish EPA 2016) In a study by Humpston et al. (2014), three different automatic sorting techniques, that in the future are considered suitable to make the sorting process more efficient has been identified: *Fourier transform infra-red spectroscopy* (FTIR), *radio frequency identification* (RFID) tags and 2D bar codes e.g. *quick response code* (QR).

How collected textiles are handled varies but the first sorting step usually includes removal of heavy items such as blankets, coats etc. The next step usually includes separation of trousers, T-shirts, blouses etc. As the process proceed the sorting gets more refined and complex. Furthermore the garments are sorted based on women and men's clothes, material, quality and condition. The latter refers to e.g. tears, discoloration and missing buttons. (Hawley 2006)

1.5 LITERATURE REVIEW

In this section the conventional shredding process is presented in conjunction with present research within this field. Secondly, fundamental knowledge about cotton will be presented briefly followed by a description of yarn and fabric constructions. Last an introduction to fibre length measurement is reviewed, where two of the techniques presented were used to characterize the fibre length for the recycled staple fibres in this thesis.

1.5.1 SHREDDING PROCESS

In conventional shredding process the waste material is first separated by type and colour. The waste is further pre-treated by means of cutting or picking to 2-6 square inches pieces. (Gulich 2006 b; Gullingsrud 2017) Subsequently, the waste is transported into the machine through a take-in unit where the fabric is shredded to fibrous state. The material is run through a series of high speed cylinders covered with e.g. saw wires or steel pins. (Gullingsrud 2017) The shredding machine generally consists of 3-6 rotating cylinders positioned one after another where the number of steel pins or saw wires usually increases with every cylinder within the machine. (Zonatti et al. 2016)

The damage the materials suffer during the shredding processes is severe. Compared to virgin fibres the fibre length of the recycled staple fibres is significantly lower. A wide spectrum of fibre lengths with a high share in short fibres are obtained in the process. Pieces of fabrics and threads may also be present, thus, the material need to pass through the machine several times in order to become single fibres. (Gulich 2006 b)

According to Gulich (2006 b), present technologies gives between 25-55% of fibres longer than 10 mm in the shredding process. Russell et al. (2016) claims that the amount of fibre breakage during the shredding process is influenced on the level of yarn twist and fabric construction, e.g. worsted woven fabrics such as jackets and coats tend to yield a shorter fibre length after shredding. In a report by Östlund et al. (2015) they underline that a higher quality of the recycled fibres can be maintained in the shredding process if the fibres are loosely bonded to each other as in knitted structures compared to if they are tightly woven.

The shredding process has stayed the same for almost 250 years mainly due to lack of research but also since the price of virgin fibres still is relatively low. This has made mechanical recycling unattractive through an economical perspective. (Fletcher 2014) However, economical viability has shown feasible for recycling of wool. Post-consumer wool garments has been used as raw material for industrial processes for the least 200 years and is applicable for both open and closed-loop recycling. (Gulich 2006 b; Russell et al. 2016) However, according to Russell et al. (2016) the quality of recycled wool depend upon fibre breakage in the shredding process. Gulich (2006 b) and Luiken and Bouwhuis (2015) emphasize that the shredding process has to be improved in order to obtain longer fibres.

In a study by Wanassi et al. (2016) they tried to find an appropriate process to reclaim a good quality fibre. This was done by varying factors such as the pre-cutting length and number of times the material passed through the recycling machine. The raw material used in this study was dyed cotton yarn waste with a yarn count of 80 tex produced by rotor spinning. The yarn waste was shredded back to a fibrous state in a Shirley Analyzer machine containing one cylinder with saw teeth and one perforated take-off cylinder. The study showed that the optimal conditions of the recycling process was achieved when the length of the yarn cut was 10 cm and when the material passed through the machine 4 times. The percentage of recycled fibres recovered after shredding was 79.1% and the recycled staple fibres had a *short fibre content* (SFC) = 25.8%, a *mean length* (ML) = 18.1 mm and an *upper quartile length* (UQL) = 24.5 mm.

Common applications for recycled staple fibres are low quality products e.g. rags, cloths and insulation. Only a few per cent of the recycled staple fibres are converted into new textiles through so-called fibre-to-fibre recycling. In order to produce a yarn with higher quality a great amount of virgin fibres, e.g. cotton and polyester, need to be added. (Collier et al. 2007) The reason for this is that the fibre length and fibre length distribution to a large extent affects yarn irregularity and strength. Frictional forces with adjacent fibres govern the yarn tenacity. If short fibres are present these forces will be reduced, which in turn will lead to a less efficient spinning process. (Gordon 2007; Zeidman & Sawhney 2002)

In a study by Halimi et al. (2008), where they used cotton waste from spinning mills, an amount of 25% recycled fibres could be added to an open-end spun yarn without alter the mechanical properties of the yarn. Nevertheless, according to Luiken and Bouwhuis (2015) generally 50% of recycled fibres could be added without alter the mechanical properties of the yarn. The authors further states that it is possible to produce yarns, containing 50% post-consumer denim waste, as fine as Nm 30 with open-end spinning process. Furthermore, in a patent by Ball and Hance (1994), a mechanical recycling process of denim is described. This method enables production of denim yarns and fabrics containing 40%-100% recycled cotton fibres, with a mean fibre length of 15 mm, from pre and post-consumer waste.

There are several companies on the market producing yarns from reclaimed cotton fibres. Hilaturas Ferre is a Spanish textile manufacturing company that since 1947 has been focusing on recycling cotton waste. Their recycled yarns, known as Recover® was launched in 2015 together with a number of global brands, collectors and retailers across the world e.g. H&M, Zara and Puma. The company has mainly focused on pre-consumer waste, however, to increase the applications of post-consumer waste the company has joined a collaboration with H&M and I: CO. (Hilaturas Ferre S.A. 2016; Nieder 2015) In their process, which is described in a study by Esteve-Turrillas and de la Guardia (2016), pre-consumer cotton clips are collected from all over the world and sorted based on quality and colour. A small amount of post-consumer waste can also be added. Prior the shredding process the material is cut into smaller pieces. The recycled staple fibres obtained in the process have a fibre length of 10-15 mm. Through open-end spinning process, a yarn with a yield of 90% recycled staple fibres can be produced. By blending the recycled staple fibres with acrylic or virgin or recycled polyester the yarns can be used for knitting, weft or warp yarns.

Another company that are recycling cotton waste is the Finnish company Pure Waste. The raw material used in their process contains cutting clips from manufacturing processes and yarn waste from spinning and weaving mills. The waste material is sorted based on colour and quality prior the shredding process. Depending on the applications the fibres can be mixed with recycled polyester or virgin viscose fibres. Further, the company today are able to produce T-shirts containing 100 % recycled pre-consumer waste. (Pure Waste Textiles LDT. 2017)

1.5.2 COTTON FIBRE

Cotton is the most common natural fibre in the world mainly since it has good properties in terms of moisture absorption and dyeing properties. (Hearle 2007) In 2016/17 the annual cotton production was estimated to 22.8 million tonnes. This number is projected to increases with 2 % during 2017/18 to 23.4 million tonnes. The increase is the result of an increase in planted area, which is predicted to grow 5% to 30.6 million hectares. (ICAC 2017) Additionally, the cotton agriculture requires great amount of water. Cotton is the crop that requires most water in the world. To produce 1 kg of cotton, or one pair of jeans, about 10.000 litres of water is required (Cotton Connect 2017). The cultivation of conventional cotton further uses a lot of pesticides and insecticide. The total pesticide consumption involved in the cotton cultivation stands for approximately 11% of the world pesticide consumption. (Esteve-Turrillas & de la Guardia 2016)

Cotton fibres consist of 88.0 -96.5% cellulose and are the longest single cells in nature. Cellulose is a linear polysaccharide, which is present in the cell wall of plants. The cellulose in cotton is highly crystalline and oriented. (Hsieh 2007) The quality of cotton fibres generally refers to length, strength, titer and colour (Gordon 2007). The fibre length and distribution, fineness and strength of cotton fibres have been linked to many parameters such as genetic trait and growing conditions. The length and the finesse of the cotton fibres are determined in the early stages of the cell growth, which involves four different stages: initiation, elongation, secondary wall thickening and maturation. The fibre length is determined during the elongation stage. Furthermore, the mechanical processes at and after harvest also affect the fibre length and fibre length distribution of the cotton fibres. (Hearle 2007; Hsieh 2007)

Cotton fibres range in various dimensions from superfine Sea Island cotton, which has a fibre length of 50 mm and a linear density of 1 dtex to coarser Asiatic cotton of 15 mm and a linear density of 3 dtex. However, the most common length of the cotton fibres range between 22-35 mm. Additionally, the mean linear thickness ranges between 10-20 µm. (Hearle 2007; Hsieh 2007)

Fibres are the fundamental elements constituting a yarn. The mechanical behaviour of a fabric construction correlates to its structure and internal structure. In order to get a better understanding of what parameters that might influence the length of the recycled staple fibres, the next two following sections aims to give a further understanding of yarn and fabric constructions.

1.5.3 YARN STRUCTURE

Discussing yarn structures, one has to distinguish between different manufacturing processes. The two most common spinning processes for production of cotton yarns are ring spinning and rotor spinning, also known as open-end. The two technologies accounts for approximately 90% of the global cotton yarn production, where ring-spun yarn constitutes 70%. (Hunter 2007) Both ring and rotor spun yarns are used in various applications. However, for the latter the greatest market is denim fabric. (El Mogahzy 2009; Mangat & Hes 2015; Paul 2015)

Ring spun yarns are considered to be the strongest of all spun yarns. The fibres in a ring spun yarn have a greater real twist, often referred to as twist angle, compared to rotor spun yarns. The fibres in a ring spun yarn take a helical path crossing the yarn layers. Some fibre ends are present in the core of the yarn while others are present in the middle or in the outer layer, see figure 2 a). Rotor spun yarns contain a three-layer structure: real twisted core fibres, partially twisted outer layer and belt fibres, see Figure 2 b). In contrast to the ring-spun yarns, were the twist takes place from the outside inwards, the fibres in a rotor spun yarn are less packed since the twist takes place from the inside outwards, contributing to a lower twist in the outer layer of the yarn. This is one of the reasons why rotor spun yarns have lower strength compared to ring-spun yarns. Additionally, this peculiarly structure makes the rotor spun yarns more sensitive to axial rubbing. (El Mogahzy 2009; Rieter 2017 a)

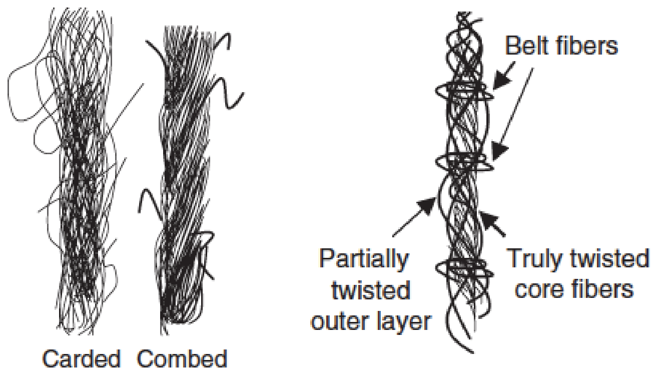

Figure 2 a) Ring spun yarn b) Rotor spun yarn[2]

Besides characterize the manufacturing process of a yarn, it is also of importance to specify the basic structural parameters i.e. yarn count and yarn twist, since they to a large extent determines the mechanical properties of a yarn. The yarn count for rotor spun yarns typically ranges from medium to courser yarn, while ring spun yarns range from low to course. In terms of yarn twist, it depends on the application of the yarns. Different spun yarns require different levels of twist e.g. warp yarns usually have higher twist compared to weft yarns. Additionally, woven yarns have higher twist compared to yarns used for knitting. (El Mogahzy 2009) However, it is important to underline that the yarn tenacity to a large extent depends on how many times the yarn has been twisted around its axis, referring to the angle of inclination. This means that a fine yarn count requires twice as much twist in order to achieve the same angle of inclination and yarn tenacity as a yarn

[2] Reprinted from Engineering textiles, Y.E. El Mogahzy, Structure and types of yarn for textile product design, pp. 240-270, (2009), with permission from Elsevier.

twice as thick. In order to determine the absolute number of yarn twist, *the twist multiplier* or *the twist factor* commonly is used. This factor expresses the degree of twist in a yarn regardless of the linear density. (Rieter 2017 b)

In a study by McNally and McCord (1960) they investigated cotton yarns abrasion resistance. A courser yarn contains more fibres in the cross-section compared to a finer yarn. This result in that the cohesion of friction will be higher and a greater number of fibres must be displaced before failure occurs. However, as recently explained, a finer yarn has more twist compared to a courser yarn. The twist further increases the cohesion of friction between the fibres and contributes to a higher abrasion and tearing resistance. (McNally & McCord 1960)

1.5.4 FABRIC CONSTRUCTIONS

Denim is considered to be one of the most widely used garments in the fashion industry and has been used for over a century. Traditional denim consists of 100% cotton and is a thick woven warp faced 3/1 twill fabric that usually is made of dyed indigo warp and white weft yarn. (Paul 2015) The characteristic of twill fabrics is that they have long floats, less intersections and a more open structure compared to a plain weave. Additionally, twill fabrics are strong and have a natural stretch in bias direction. (Redmore 2011)

Single-jersey is another common fabric construction in the apparel industry. This knitted structure can be manufactured in various weights and is a smooth fabric with even stiches and limited stretch. However, compared to woven structures the stretch for a single-jersey fabric is significantly higher. This can be explained by the crimp in the weft and warp yarns in the woven structures. There is only space for a small extension when a force is applied on a woven structure before the crimp is removed and the yarn is straightened. At this point a higher force is required to stretch the yarns. (Cooke 2011) Constructions that are tightly woven, has a large number of interlacing threads per unit area and short floats will therefore be more difficult to separate due to less freedom of yarn movement. (McNally & McCord 1960) In contrast to woven fabrics single-jersey fabrics are constructed of linear arrays of needle loops connected together horizontally by sinker loops and vertically by interlinking. When a force is applied, horizontal stretch is first achieved in the structure. As the extension proceeds the curved yarn segments continue to straighten until inter-yarn frictional forces occurs at the crossing points. At this point, yarn interchange takes place moving the yarn segments from the vertical sides of the loops to the tops and bottoms of the loops. This is the reason why a single-jersey structure tends to stretch 15-20% in the width without any significant yarn extensions take place. In similar manner extension in the length axis occurs, however, the axial stretch is typically lower compared to the stretch that occurs in the width. (Cooke 2011)

1.5.5 MEASURING FIBRE LENGTH

There are several parameters and testing instrument that through the years have been developed in order to characterize the fibre length of cotton. Parameters that been developed are among others *mean length* (ML), *upper-half mean length* (UHML), *upper-quartile length* (UQL) and *short fibre content* (SFC*)*. (Cai et al. 2013) SFC is defined as the percentage of fibres shorter than ½ inch (12,7 mm) and is one of the most important parameters since it gives an indication of the quality of the cotton. (Bragg & Shofner 1993; Cai et al. 2013) A high amount of short fibre content leads to weaker, hairier and less uniform yarns, which in turn results in a weaker fabric with a less appealing appearance. (Cui et al. 2003) According Bragg and Shofner (1993), UHLM is also an important parameter to determine since it helps control spinning efficiency and to determine machine settings. Additionally, the authors underline that ML also to a large extent affect processing performance and yarn quality.

There are many methods to measure fibre length and distribution. One of the simplest methods is to measure the length by aligning the end length of the fibre against a ruler and observe the length. However, this method is time consuming and since the length of the cotton fibres may vary significantly in a sample measurement in this way is considered highly impractical. (Gordon 2007; Naylor et al. 2014) Another approach to measure the fibre length is based on staple diagram or fibres arrays produced by a comb-sorter apparatus. The comb-sorter apparatus consist of hinged combs separated at approximately 1/8 inches interval to separate and align the fibres from a sample. Further the process gives a description of weight-length or number-length from a sample. This method provides a very accurate determination of the fibre length and can be used to determine parameters such as ML, UQL and SFC. However, these methods are time consuming, expensive in terms of operator costs and to inaccurate for routine testing for commercial products. (Gordon 2007)

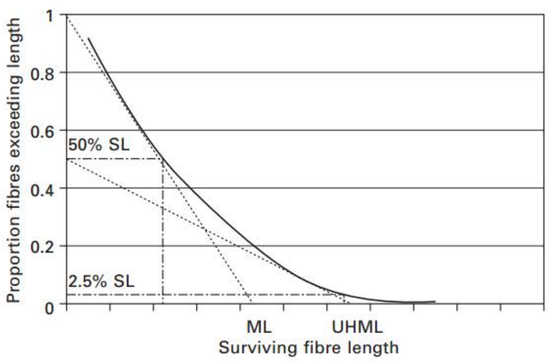

Figure 3 Fibrogram [3]

[3] Reprinted from Cotton: Science and Technology, S. Gordon, Cotton fibre quality, pp.68-100, (2007), with permission from Elsevier.

In the beginning of 1940s the Fibrograph Tester instrument was developed. This device was first used as stand-alone, but later incorporated to the High Volume Instruments (HVI). The HVI instruments are quick modern testing devices, developed by USTER® technologies. The system is able to measure a number of cotton fibre qualities and are measuring the fibre properties from a bundle of fibres. Depending if an old or a newer HVI instrument is used, the fibre beard specimens can be prepared either manually or automatically. The fibre beard is inserted into the instrument where the fibres are scanned by a light source. A photo sensor senses the variations of the light passing through the fibres and reproduces a length-frequency curve, also known as Fibrogram, see figure 3. From this diagram, two different kinds of fibre length measurement can be obtained, mean lengths e.g. ML and UHLM, and span lengths, where the mean lengths are the most commonly used. (Gordon 2007)

Another quick modern testing device is the Advanced Information System (AFIS), also developed by USTER® technologies. Additionally, the AFIS systems also are able to measure various quality parameters such as fineness, trash, dust, neps etc. (Cai et al. 2013; Gordon 2007) In contrast to the HVI instruments, AFIS is based on single fibre testing. The fibres are transported aerodynamically through an electro-optical system, which records two lights, scattered and occluded light. The signals are analysed by a computer and reproduces the mean and distribution of the parameter investigated. (Gordon 2007)

1.6 PROBLEM DESCRIPTION

The main problem with the shredding process is that the fibre length is reduced. The fibre length is an important property since it has high influences on textile processing such as yarn spinning and final product quality. Today most of the mechanically recycled staple fibres are used in low value applications.

Even though the method of mechanical recycling is well known research within this field is limited. There is a lack of research regarding how the shredding process could be made more gently in order to maintain the fibre length. Research and understanding is especially limited when post-consumer waste is used as a raw material. This highlights that there is an urge to develop a deeper understanding within this field regarding what parameters that are influencing the fibre length obtained in the shredding process to further be able to improve it.

1.7 SCOPE AND RESEARCH QUESTIONS

The main objective of this thesis was to obtain deeper knowledge of how different degree of wear of cotton post-consumer waste influences the fibre length obtained in the shredding process. Based on this approach the following research question was developed:

How is the fibre length and fibre length distribution of mechanically recycled cotton fibres affected by the following parameters:

- *Degree of wear of cotton post-consumer waste:*
    - *Low degree of wear*
    - *High degree of wear*
- *Single-jersey or denim constructions*
- *Fibre length of the input material*
- *Yarn structure:*
    - *Yarn count*
    - *Yarn twist*
    - *Manufacturing process*

1.8 LIMITATIONS

The main focus of the work in this thesis was to examine how different degree of wear of cotton post-consumer waste influences the fibre length obtained in the shredding process. This was done by analysing the input and output fibre length. Parameters such as titer and fibre strength were excluded. Additionally, several parameters in terms of degree of wear, fabric constructions and yarn structure were further analysed. Degree of wear was classified into two categorize: low degree of wear and high degree of wear. The fabric constructions used in this study were single-jersey, denim and their combinations. Parameters in terms of yarn structure were limited to yarn count, yarn twist and the manufacturing process.

2. MATERIALS AND METHOD

An overview of the steps performed in this method is shown in Figure 4. The steps include sorting, characterization and shredding of post-consumer waste garments.

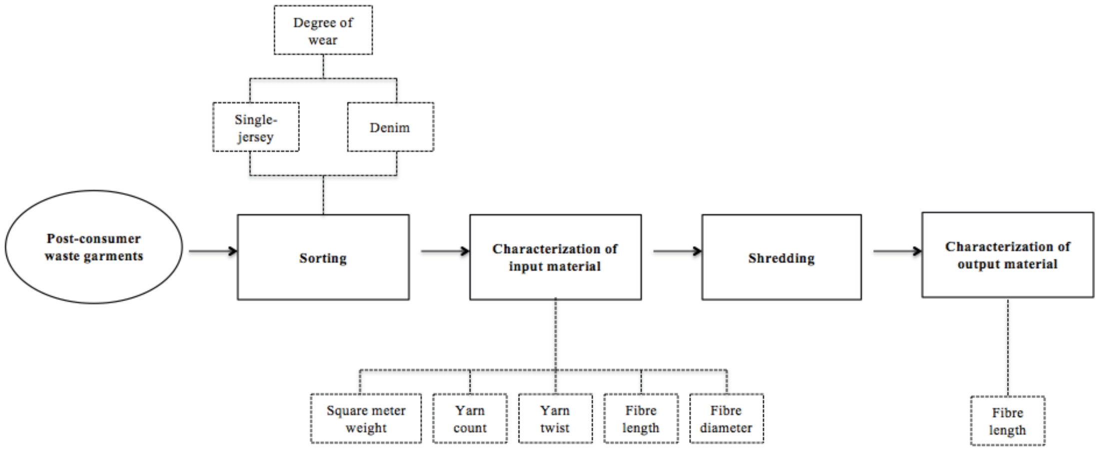

Figure 4 Schematic overview of the steps performed in this thesis.

Fibre and yarn characterization of the non-shredded garments, denoted in this study as *input material*, was performed in order to gain knowledge about the garment waste. The shredded material, denoted as *output material*, was characterized in terms of fibre length and fibre length distribution.

2.1 MATERIALS

The material used in this study was post-consumer waste garments received from the Swedish charity organisation Emmaus Björkå. The received material was selected based on fibre type and fabric constructions. Manually and visually sorting was performed to eliminate garments that did not contain 100% cotton, single-jersey and denim constructions. In order to obtain materials containing 100% cotton the labels in the garments were controlled. Garments containing blends or other material and that did not have a label were excluded from the study.

After sorting, the garments were washed and tumble dried according to standard ISO 6330:2012. This step was performed in order to remove contaminants from the garments. The garments were washed in soft water at 40°C according to program 4N in an Electrolux FOM71 CLS. The machine loads for the T-shirts and jeans was (3±0.5) kg/ wash and (4±0.5) kg/ wash respectively. An amount of (20±1) g of references detergent 3- ECE was used and measured on a WVR SE-1202 with a resolution of 0.01 g. Furthermore the T-shirts were tumble dried in an Electrolux T5190 with a maximum temperature of 80°C for 40 min and for 5 min with the heat turned off. The jeans were tumbled dried in an Electrolux T3650, which is not a standardized machine, with a maximum temperature of 80°C for 55 min and for 5 min with the heat turned off.

2.1.1 SORTING BASED ON DEGREE OF WEAR

The materials selected in chapter *2.1* were classified into two categories: *low degree of wear* and *high degree of wear*. In the industry, this type of sorting is not performed prior to shredding. All materials are handled in the same way. Therefore, a third category, referred to as *mixture,* was achieved by combining low and high degree of wear.

Since there is no sorting technology that can sort material based on degree of wear this step was done visually and manually. Post-consumer textile waste is complex since the degree of wear of the material may diverge both between and within garments. Thus, this step was done differently for the T-shirts and the jeans.

Additionally, seams, plastic prints, non-textile parts etc. were manually cut out from the garments with a pair of scissors and discarded.

2.1.1.1 SINGLE-JERSEY

Two different levels of degree of wear for the single-jersey material was distinguished based on the following aspects; holes, tears, faded colours, discolorations, shrinkage and pills. Two unbiased persons, independent of each other, performed this step. Figures 5 and 6 a) and b) shows the differences between low degree of wear and high degree of wear. The number of T-shirts, obtained in this step, for low and high degree of wear respectively, was 20 T-shirts.

Figure 5 Fade colour single-jersey

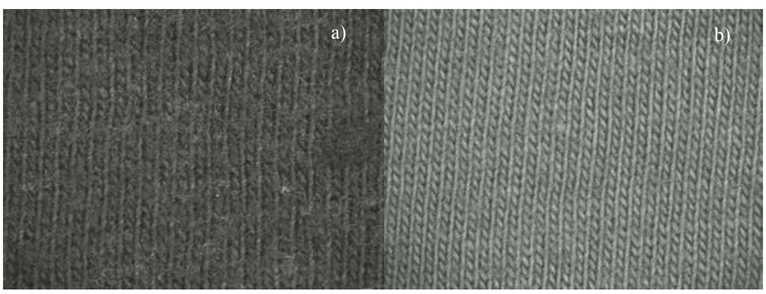

Figure 6 Pilling
a) high degree of wear front b) low degree of wear front

2.1.1.2 DENIM

Different treatments and/or finishing are done on jeans in order to give them a worn-out look already at purchase. The most evident abrasion zones on the jeans are around knee, upper leg, front pocket and hip regions. Therefore, the jeans were divided in three different zones according to Figure 7. All zones were cut out manually with a pair of scissors. Zone 3 was discarded since it contained buttons, zippers etc. Zone 1 was classified as having low degree of wear and Zone 2 as having high degree of wear. Figure 8 a) and b) shows the differences between low and high degree of wear. The number of jeans, obtained in this step, for low and high degree of wear respectively, was 30 jeans.

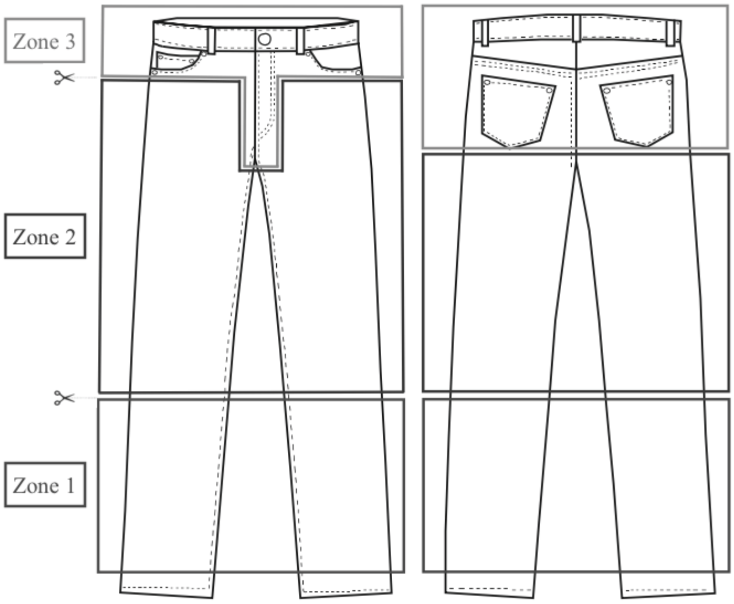

Figure 7 The three different zones cut out from the jeans.

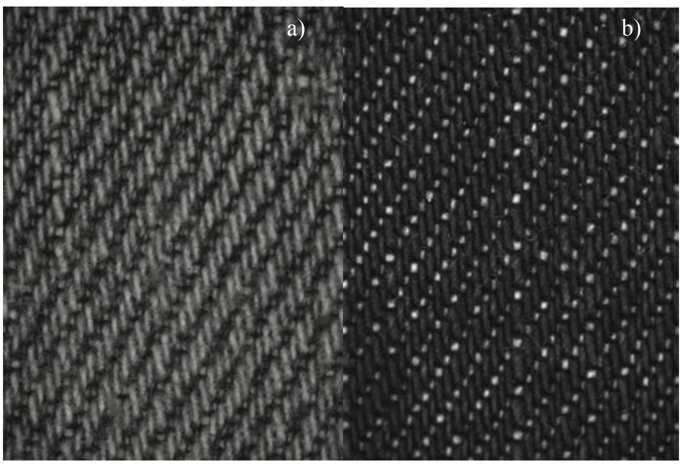

Figure 8 Differences between high and low degree of wear
a) high degree of wear b) low degree of wear

2.2 PRE-STUDY

A pre-study was carried out in order to examine if the input material should be conditioned before the shredding process. Since this thesis has been dealing with a mixture of cotton materials the pre-study further aims to examine how many zones and yarns that should be selected from each garment for analysis.

This step was conducted on 2 kg single jersey fabrics, which accounted for twelve T-shirts. Degree of wear was not taken into account. In order to decide which of the garments that should be selected for measurement of the input fibre length, a random sampling technique was performed. This technique was conducted to ensure that each garment had equal chance to be selected and to produce unbiased samples. Each single jersey garment was randomly given a number ranging from 01-12. The garments were manually mixed in a bag and then randomly picked one after another. The first garment drawn from the bag was given number 01, the second garment number 02 etc. In subsequent step Excel was used to create random samples. The selected garments were picked out for further analysis. A quarter of the garments were selected for analysis.

Parts of this method were influenced from the ISO standard 12751:1999. According to the standard no single sampling technique can be used that will serve in all circumstances.

In order to include yarns and fibres that may vary from one and another, three circular dm^2 pieces with a diameter of 113 mm were punched out with the machine FIPI AF16, from each garment selected for analysis, see Figure 9. In addition, three yarns from each piece were selected for measurement of fibre length. The fibres were measured according to the method explained in section *2.5.1.*

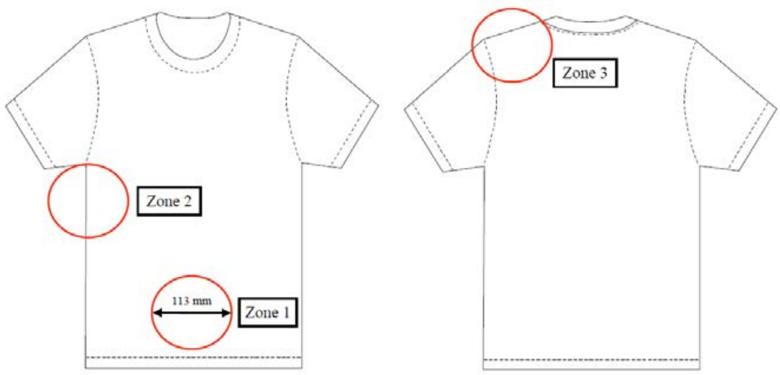

Figure 9 The zones selected from the T-shirts for fibre analysis.

After the fibre length had been measured each garment was cut in half and separated into two piles. Each pile were then cut into smaller pieces, see section *2.4.* Before shredding, one pile was placed in room atmosphere for 24 h while the other pile was conditioned in an atmosphere having a relatively humidity of (65±2)% and a temperature of (20±2) °C for 24 h.

2.3 MAIN STUDY

The purpose of this thesis was to examine how cotton post-consumer garments with different degree of wear influences on the fibre length obtained in the shredding process. Therefore, this section aims to give a description of how sampling of specimens for characterization of the input material, was performed based on degree of wear. The method explained in this section is based on the result from the pre-study, hence, this step is partially performed in a different manner compared to the pre-study.

2.3.1 SINGLE-JERSEY

This step was conducted on twenty T-shirts, for each category, low and high degree of wear. The single jersey garments, for the both categories, were randomly given a number ranging from 01-20. Half of the garments, of each category, were picked for analysis according to the sampling step explained in *section 2.2.*

One circular dm^2 piece with a diameter of 113 mm were punched out from different places on each T-shirt, see Figure 10. A total of 20 pieces for the single-jersey were punched out of each category, low and high degree of wear. All pieces were weighted on a Mettler AE-200 with a resolution of 0.1 mg in order to examine the square meter weight. Additionally, three yarns from each piece were selected for measurement of fibre length, yarn count and yarn twist. The methods for measurement of these parameters are further explained in section *2.5.1, 2.6.1* and 2.6.2.

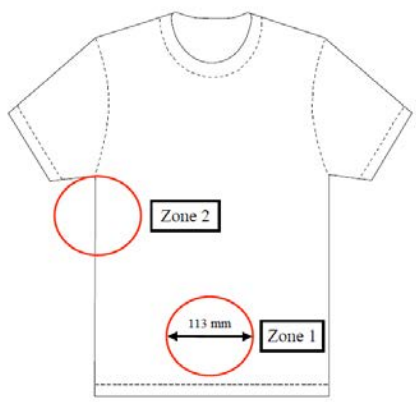

Figure 10 The zones selected from the T-shirts for fibre analysis.

2.3.2 DENIM

This step was conducted on thirty jeans, for each category, low and high degree of wear. The jeans, for both categories, were randomly given a number ranging from 01-30. Half of the jeans, of each category, were picked for analysis according to the sampling step explained in *section 2.2.* For the denim material, one circular dm^2 piece was punched out from each specimen, see Figure 11 a) and b). A total of 15 samples of each category were punched out. Each piece was weighted on a Mettler AE-200 with a resolution of 0.1mg in order to examine the square meter weight. Subsequently, three warp yarns and three weft yarns were selected from each piece for analysis of the fibre length, yarn count and yarn twist, which further are explained in section *2.5.1, 2.6.1* and 2.6.2.

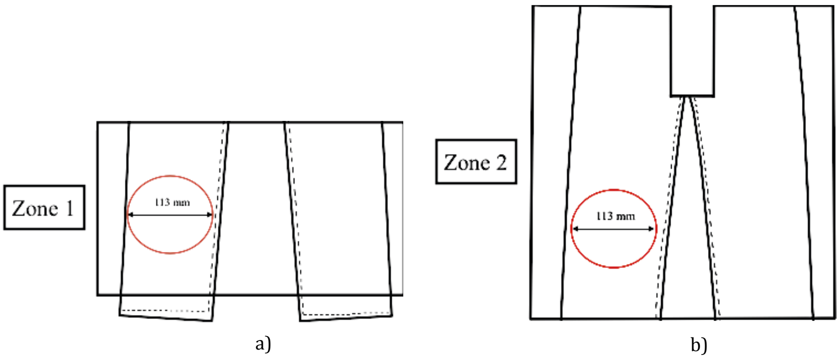

Figure 11 The selected zones for fibre analysis
a) low degree of wear b) high degree of wear

2.4 SHREDDING

Before the material was shredded it was cut into smaller pieces. This was done with the cutting machine NSX-QD350, consisted of rotary blades. The material went through the machine three times and pieces of ~14x7.25 cm were obtained. A more detailed specification of the cutting machine can be found in Appendix 1.

The shredder used in this study had 4 rotating cylinders positioned one after another. The machine was an assembly of two apparatus, NSX-FS1040 and NSX-QT310. The first part of the machine (NSX-FS1040), denoted as the opener, had a cylinder with 8 mm long saw teeth. The second part (NSX-QT310) consisted of three cylinders covered with 4 mm long saw teeth. A more detailed description of the machines can be found in Appendix 1.

The material was conveyed into the machine with the aid of two feeding rollers. Furthermore, the material was transported through the four cylinders by means of a conveyor belt and shredded to a fibrous condition. Occasionally the material had to be manually fed into the different cylinders. At the end of the process the material was collected and the fibre length was measured according to the method explained in section 2.5.2. All material passed through the machine one time.

An additional test was performed in the shredding process by combining 50% of the single-jersey mixture and 50% of the denim mixture.

2.5 FIBRE MEASUREMENT

The first two sections in this chapter describe the methods used for measurement of fibre length for the input material and the output material. The output material was further sent to an independent company, Mesdan S.p.A, which measures fibre length distribution. This method is discussed briefly and is denoted as *reference method*. Last, the procedure used for measuring the fibre width for the input material will be described. All measurements performed in this section was conducted in an atmosphere having a relatively humidity of (65±2)% and a temperature of (20±2) °C.

2.5.1 FIBRE LENGTH OF INPUT MATERIAL

An overview of the sampling for fibre length measurement for the input material is shown in Figure 12.

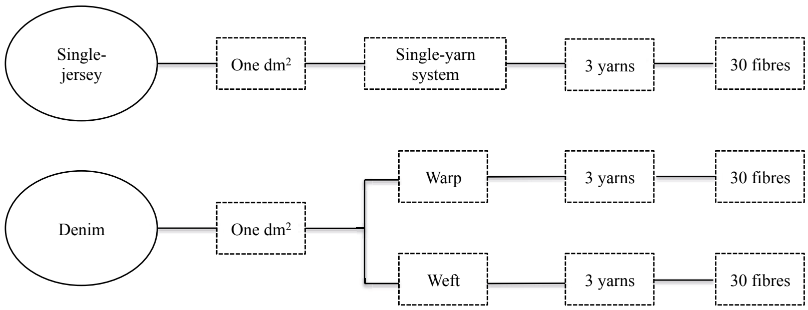

Figure 12 Schematic overview of sampling for fibre length measurement

From each dm^2 selected in section *2.2, 2.3.1* and *2.3.2*, three yarns were selected. Subsequently, ten fibres were taken from each yarn for fibre length measurement.

The fibre length for the input material was measured visually and manually according to ISO standard 12751:1999, but with some modifications. The squaring method was not used in this study. Instead, the yarns selected for analysis, were opened by manually untwisting the yarns. Subsequently, the yarn was placed on a velvet board. Depending on the colour of the yarn either a white or black velvet background was used. The fibres in the yarn end of the untwisted yarn were removed one by one with a pair of curved forceps. These fibres were excluded from the study in order to prevent measuring broken fibres. The new fibre ends exposed was chosen one by one for measurement. In order to straighten the fibres a light tension was manually applied on the fibres with a pair of curved forceps. A ruler was used to measure the fibres. The fibre length was documented in mm in a frequency table. The fibre length distribution was summarized in a graph, where high columns indicate the most frequent fibre lengths.

Additionally, according to the standard untwisting of yarns to withdraw fibres for length measurement is suitable for all ring spun yarns. For yarns produced by other techniques it has to be proven that the fibres can be separated without damaging the fibres. This was not taken into account in this study.

2.5.2 FIBRE LENGTH OF OUTPUT MATERIAL

An amount of 25 g of the output material for each category and construction was selected at random for analysis. This was done according to standard ISO 1130:1975 but with the following modification. According to the standard, a minimum of hundred tufts, each of 0.25 g to 0.50 g should be selected to obtain the laboratory test. Instead ten tufts with a weight of 2.5 g each were selected. The fibre bulk was spread out in an even layer and ten tufts were randomly taken. The tufts were weighted on a Mettler AE-200 with a resolution of 0.1 mg.

The fibre length and fibre length distribution for the recycled staple fibres were measured according to method A - ISO 6989:2004, but with some modifications. Instead of a polished glass plate with a millimetre scale, an engraved millimetre graduated ruler and a black and white velvet background was used. In addition, a magnifying glass was used to enhance the observation of the fibres. A light tension was applied to the fibres with the aid of a pair of curved forceps. Liquid paraffin or white petroleum jelly was not used. The length of the fibres was measured and recorded in mm in a frequency table. The fibre length distribution was summarized in a graph. Additionally, the mean fibre length (ML) and short fibre content (SFC) was calculated.

2.5.3 REFERENCE METHOD

The output material was sent to Mesdan S.p.A for additional tests. A classifibre of model KCF-V/LS was used to measure the fibre length distribution. The process contains of two units: a flat carding sampler (KCF/LS-SP) and a measuring unit (KCF/LS-ME).

The fibre tufts is pinched on a sampler comb which is produced by the flat carding device. The sample is placed in the measuring unit. In this device the specimens are exposed to homogeneous light by a linear filament lamp. A photo sensor detects the variations of the light passing through the fibres that is converted into electrical signals that gives the fibre length distribution.

2.5.4 FIBRE WIDTH

From the yarns selected in section *2.3.1* and *2.3.2*, an amount of 1.0 mg of fibres were picked from each yarn and weighted on Mettler AC 100. The fibres were then manually mixed within each category e.g. single-jersey low degree of wear. Subsequently, one fibre after another was drawn from the bulks. The width of the fibres was measured through an optical microscope NIKON Eclipse Ci POL with the software NIS-element, see Figure 13. A total amount of 40 fibres was measured for each category and fabric constructions.

Figure 13 Image of the fibre width measurement

2.6 ANALYSIS OF YARN STRUCTURE

The yarns selected in section *2.3.1* and *2.3.2*, was analysed in terms of yarn count, yarn twist and manufacturing process. This chapter gives a description of the methods used to analyse these parameters. In addition, all measurements performed in this chapter was conducted in an atmosphere having a relatively humidity of (65±2)% and a temperature of (20±2) °C.

2.6.1 YARN COUNT

In order to examine the yarn count of the input material each yarn selected in section *2.3.1* and *2.3.2*, was measured and weighted. The yarns were measured with a millimetre graduated ruler and weighed on a Mettler AE-200 with a resolution of 0.0001 g. The tex-count (g/1000 m) was calculated.

2.6.2 YARN TWIST

Determination of yarn twist was performed according to ISO standard 2061:2015. The test was performed on a FRANK type KU-212. The device consisted of a pair of clamps. One of the clamps was rotatable in both directions and connected to a revolution counter. The other clamp was set, but movable vertical to allow the testing length of the yarn, which according to the standard should range between 10 mm-500 mm. The test length for the single-jersey yarns and the warp yarns of the denim fabric were 12 cm. For the weft yarns the length was set to 7 cm. Before the yarn was attached to the clamps, the direction of the twist was determined. This was done by placing the yarns vertically between the hands. The yarn was twisted to the right by the means of the right hand. If the twist decreased the twist direction was set as "Z". If the twist increased, the twist direction was designated as "S". The yarn was then attached to the clamps with a pretention of (0.5 ± 0.1) cN/tex without unsettling the twist. Additionally, a weight equal to half of the yarn count was attached. Subsequently, the yarn twist was removed by turning the rotatable clamp. According to the standard, this should be done until a needle could pass through the yarn from one end to another. However, in this test this was not applicable. Instead the number of turns was noted when the yarn fell apart.

The average yarn twist was calculated according to equation (1) where t_x= average twist/meter, l= initial length of the yarn, x= the total number of turns observed. Subsequently, the twist factor or twist multiplier (TM) was calculated according to equation (2). The twist factor presents the twist of fibres in the yarn, regardless of the yarn count.

$$t_x = \frac{x}{l} \qquad (1)$$

$$TM = t_x \times \sqrt{tex} \qquad (2)$$

2.6.3 YARN MANUFACTURING PROCESS

The microscope Nikon SM2 1500 was used to visually analyse the yarn spinning technology that had been used to manufacture the yarns, sampled from the post-consumer waste selected in section *2.3.1* and *2.3.2*.

2.7 STATISTICAL ANALYSIS

For every test performed in this study, the *mean value* ($\bar{x}$), *standard deviation* (σ) and *coefficient of variation* (CV) were calculated. CV was calculated according to equation (2). It was used to analyse the frequency distribution of the measured values and to get an indication of the variability in relation to the mean value of the measured parameters.

$$CV\ (\%) = \frac{\sigma}{\bar{x}} \quad , \qquad (2)$$

Statistical analysis, analysis of variance (*ANOVA*) and Tukey test, were calculated in Minitab software to examine if there was a significant difference between the calculated mean values. The Tukey method is a single-step multiple comparison method commonly used in combination with ANOVA. Compared to a t-test, the Tukey test is more appropriate for multiple comparisons since it correct the probability of making a Type I error, i.e. reject a true null hypothesis. A confidence interval of 95% was used where p-value < 0.05 was accepted for a significant result.

3. RESULT

The first part of this chapter presents the result from the pre-study that examined if the input material should be conditioned prior to shredding. Additionally, the pre-study examined how the fibre length was varying within a garment. Secondly, the result from the main study is presented and last, a brief analyse of the shredding process is described.

3.1 PRE-STUDY

In the first part of this section, the mean fibre length and fibre length distribution of the disintegrated yarns from the disassembled single-jersey material is presented. Subsequently, the mean fibre length and fibre length distribution of the shredded material is reported.

3.1.1 INPUT FIBRE LENGTH

The average fibre length for the input material, single-jersey, was 26 mm, CV was 15%. Figures 14, 15 and 16 gives an overview of the fibre length distribution for the input material in conjunction with the three different zones taken from each garment in section *2.2* The x-axis in the graphs represents the fibre length in mm. The y-axis is the frequency of the fibre length. High columns indicate the most frequent fibre lengths.

The mean value for the fibre length of zone 1 was 25 mm, CV was equal to 17.0%. The fibre length distribution for zone 1 is presented in Figure 14. Both zone 2 and 3 had and average fibre length of 26 mm and a CV of 13.6%. Figure 15 and 16 shows the fibre length distribution for these zones. Statistical analysis showed that there was no significant difference between the three zones with a P-value of 0.3258. The measured values and statistics are presented in Appendix 2.

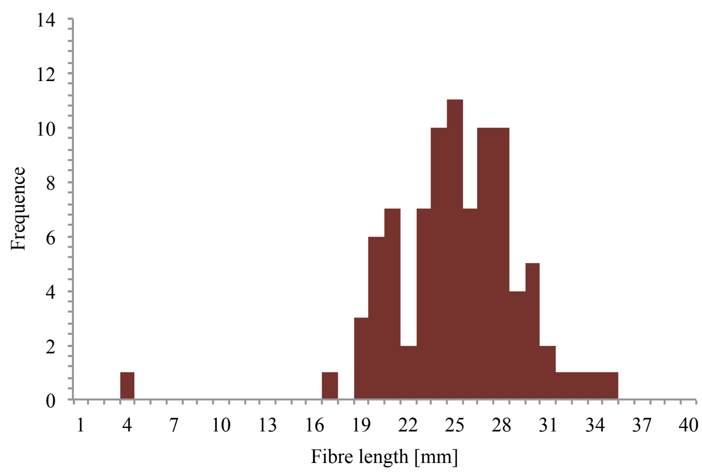

Figure 14 Fibre length distribution, pre-study, zone 1.

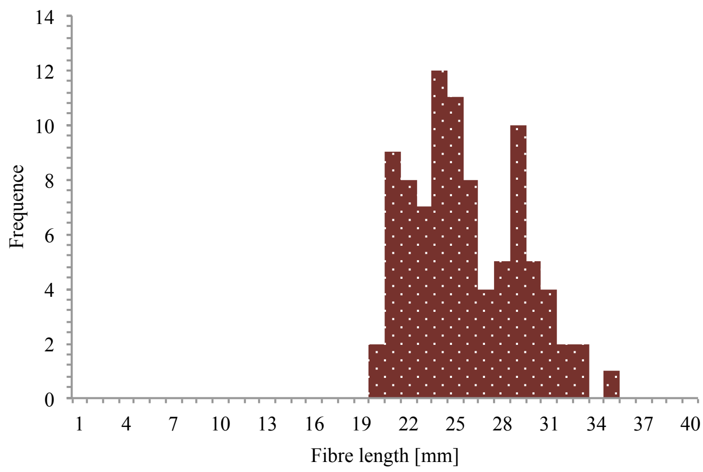

Figure 15 Fibre length distribution, pre-study, zone 2.

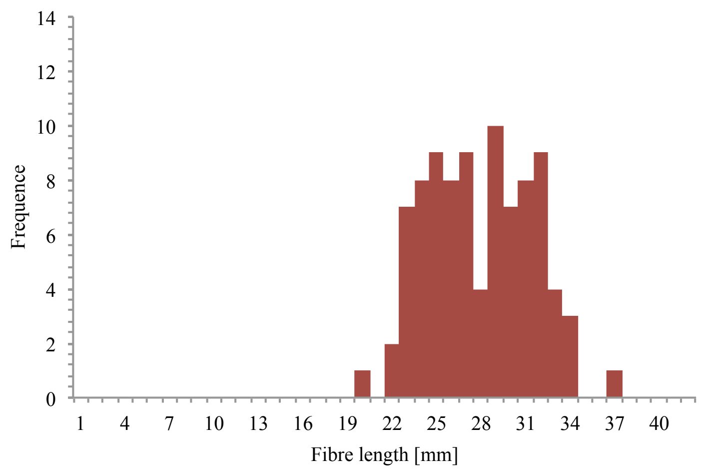

Figure 16 Fibre length distribution, pre-study, zone 3.

3.1.2 OUTPUT FIBRE LENGTH

The result of the fibre length distribution for the output material single-jersey is presented in Figure 17 and 18. The mean length of the fibres placed in a room temperature for 24 h was 13 mm. CV was 45%. The material conditioned in an atmosphere having a relative humidity of (65±2)% and a temperature of (20±2) °C for 24 h, had a mean fibre length of 13 mm and a CV equal to 44%. Statistical analysis, with a P-value of 0.9630, showed that there was no significant difference regarding the mean values. The measured values and statistics are presented in Appendix 3.

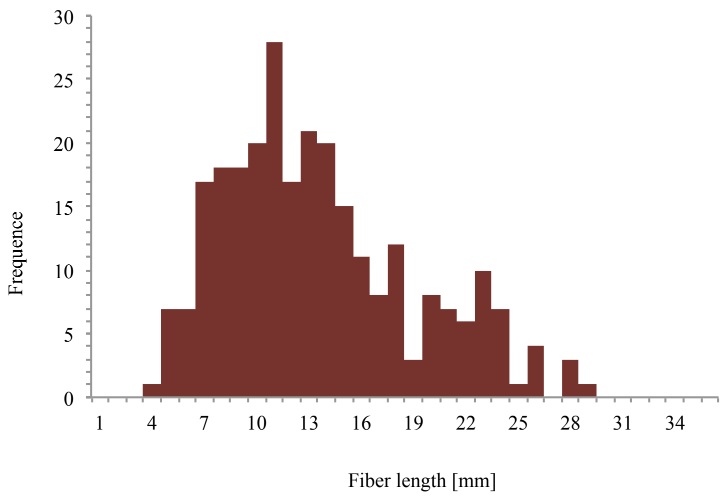

Figure 17 Fibre length distribution of the output material without conditioning prior to shredding, pre-study.

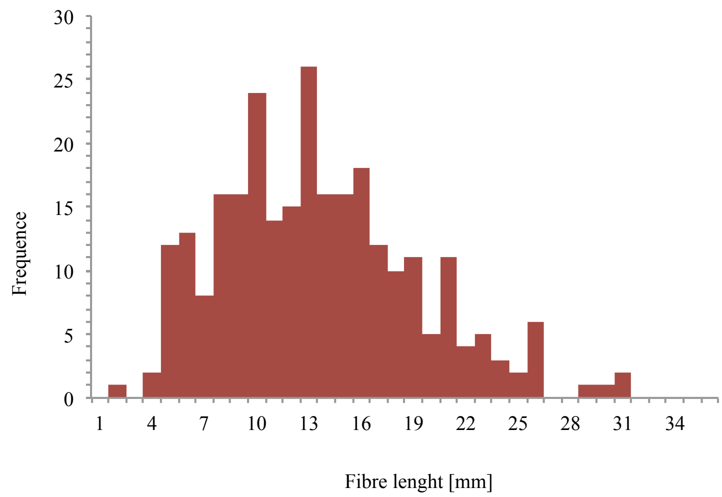

Figure 18 Fibre length distribution of output material with conditioning prior to shredding, pre-study.

3.2 MAIN STUDY

This section begins with a presentation of the result from the analysis of the input material based on degree of wear. The parameters examined were square meter weight of the garments, yarn count, yarn twist, twist factor, manufacturing process and fibre width. The parameters are further presented in that order. Subsequently, the result for the input and output fibre length is presented and last the result from the reference method.

3.2.1. SQUARE METER WEIGHT

The mean square meter weight for the input material is shown in Figure 19. Additionally, the graph presents the mean value between the different zones taken within the single-jersey garments in section *2.3.1*.

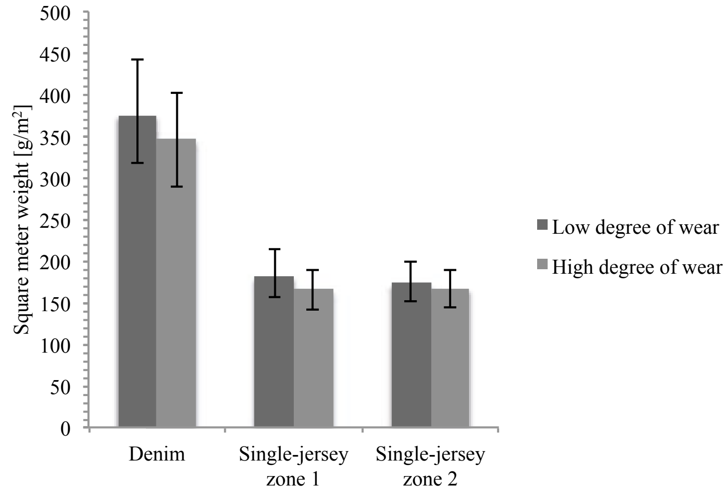

Figure 19 Mean square meter weight single-jersey, error bars σ (+/-).

The mean square meter weight for zone 1 and 2, single-jersey low degree of wear was 181 g/m^2 and 173.2 g/m^2 respectively. CV was calculated to 18.2% and 15.6%. For zone 1 and 2, single-jersey high degree of wear, the mean square meter weight was 165.5 g/m^2 and 166.6 g/m^2. CV was 14.8% and 13.4% respectively. The adjusted P-values from the statistical analysis are presented in Table 1 and shows that there is no significant difference between the square meter weight for low and high degree of wear. All values and statistics are presented in more detail in Appendix 4.

Table 1 Statistical comparison between zone 1 and 2, single-jersey low and high degree of wear.

Difference of levels	Adjusted P-value
2 (low) - 1 (low)	0.9162
1 (high) - 1 (low)	0.5787
2 (high) - 1 (low)	0.6351
1(high) – 2 (low)	0.9190
2 (high) - 2 (low)	0.9468
2 (high) - 1 (high)	0.9997

For denim, low and high degree of wear, the average square meter weight was 374.8 g/m^2 and 346.1 g/m^2 respectively, see Figure 19. CV was 18.0% and 16.4%. Statistical analysis, with a P-value of 0.2188, showed that there was no significant difference between the square meter weight for low and high degree of wear. All values and statistics are presented in more detail in Appendix 4.

3.2.2 YARN COUNT

Figure 20 presents the mean value of the yarn count of the disassembled input fabrics. The average yarn count for single-jersey low degree of wear was 21.48 tex, CV was 24.2%. Single-jersey high degree of wear had an average yarn count of 23.16 tex with a CV equal to 18.1%. Statistical analysis gave a P-value of 0.0544, which indicates that there is no significant difference between the yarn count for single-jersey low and high degree of wear. All measured values and statistics are presented in more detail in Appendix 5.

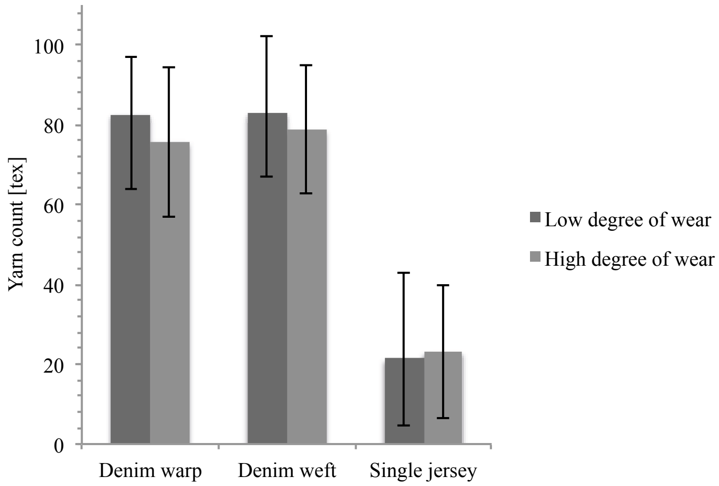

Figure 20 Mean yarn count [tex], error bars σ (+/-).

The mean yarn count for the warp and weft yarns for denim constructions, low degree of wear, was 82.7 tex and 83.0 tex respectively, see Figure 20. CV was 17.3% and 22.8%. For denim high degree of wear, the warp yarn had an average yarn count equal to 75.7 tex. CV was 24.8%. The average yarn count for the weft yarn was 78.8 tex, CV was calculated to 20.3%. Statistical analysis showed that there was no significant difference between the yarn count for low and high degree of wear. The adjusted P-value is presented in Table 2. All measured values and statistics are further presented in Appendix 5.

Table 2 Statistical comparisons between warp and weft, denim low and high degree of wear.

Difference of levels	Adjusted P-value
weft (low) - warp (low)	0.9997
warp (high) - warp (low)	0.2185
weft (high) - warp (low)	0.7083
warp (high) - weft(low)	0.1830
weft (high) - weft (low)	0.6514
weft (high) - warp (high)	0.8244

3.2.3 YARN TWIST

The mean value of the yarn twist, for single-jersey and denim, is presented in Figure 21. Furthermore, the twist direction of all yarns was Z-twist.

For single-jersey low and high degree of wear the mean yarn twist was 314 twist/m and 344 twist/m respectively. CV was 22.8% for low degree of wear and 27.9% for high degree of wear. Statistical analysis gave a P-value of 0.0544, which indicates that there is no significant difference between the yarn twist for single-jersey low and high degree of wear. All values and statistics are presented in Appendix 6.

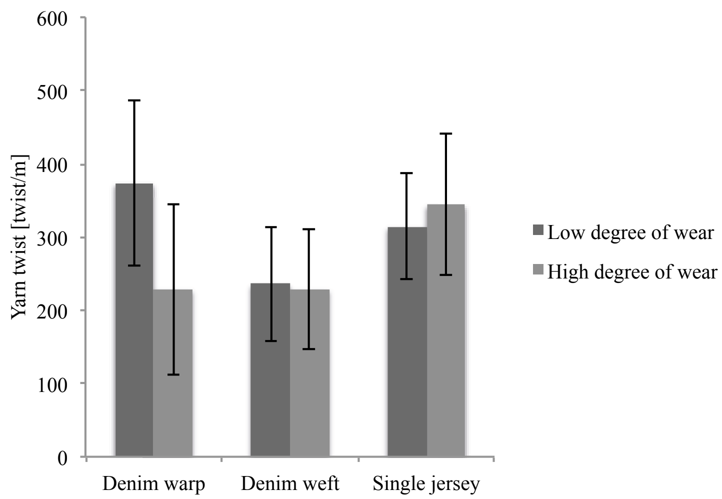

Figure 21 Mean value yarn twist [twist/m] single-jersey, error bars σ (+/-).

The mean yarn twist, for the warp and weft yarns, of the denim constructions, low degree of wear, was 374 twist/m and 236 twist/m respectively. CV was calculated to 30.2% and 33.1%. For denim high degree of wear the warp yarn had an average twist equal to 229 twist/m. CV was 51.1%. The average yarn twist for the weft yarns was 229 twist/m, CV was equal to 35.8%. The adjusted P-values from the statistical analysis are presented in Table 3, where a P-value <0.05 is accepted for a significant result. The three first rows in Table 3, shows a significant difference. A more detailed description of the measured values and statistics is presented in Appendix 6.

Table 3 Statistical comparisons between warp and weft, denim low and high degree of wear.

Difference of levels	Adjusted P-value
weft (low) - warp (low)	<0.001
warp (high) - warp (low)	<0.001
weft (high) - warp (low)	<0.001
warp (high) - weft(low)	0.9889
weft (high) - weft (low)	0.9854
weft (high) - warp (high)	1.0000

3.2.4 TWIST FACTOR

The twist factor, which is used to describe the degree of twist in a yarn, regardless of the linear density of the yarns, is presented in Figure 22.

The mean twist factor for single-jersey low and high degree of wear was 1458 twist m^{-1} $tex^{1/2}$ and 1643 twist m^{-1} $tex^{1/2}$ respectively. Statistical analysis gave a P-value of 0.0240, which indicates that there is a significant difference between the twist factor for single-jersey low and high degree of wear. The statistical analysis is presented in more detail in Appendix 7.

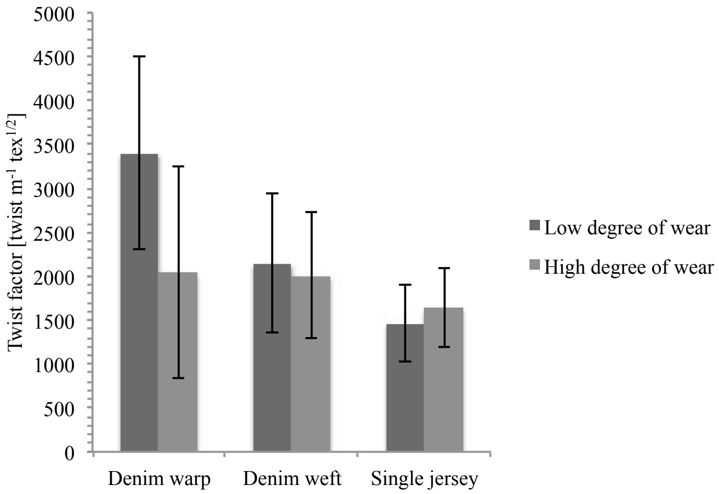

Figure 22 Mean twist factor [twist m^{-1} $tex^{1/2}$], error bars σ (+/-).

For denim, low degree of wear, the mean twist factor for the warp yarns was calculated to 3402 twist m^{-1} $tex^{1/2}$. The weft yarns had a mean twist factor of 2148 twist m^{-1} $tex^{1/2}$. For the warp yarns, denim high degree of wear, the mean twist factor was 2049 twist m^{-1} $tex^{1/2}$. The weft yarns had a twist factor equal to 2009 twist m^{-1} $tex^{1/2}$. The adjusted P-values from the statistical analysis are presented in Table 4, where a P-value <0.05 is accepted for a significant result. The three first rows in Table 4, shows a significant difference. The statistical analysis is presented in more detail in Appendix 7.

Table 4 Statistical comparisons between warp and weft, denim low and high degree of wear.

Difference of levels	Adjusted P-value
weft (low) - warp (low)	<0.0001
warp (high) - warp (low)	<0.0001
weft (high) - warp (low)	<0.0001
warp (high) - weft (low)	0.9634
weft (high) - weft (low)	0.9057
weft (high) - warp (high)	0.9973

3.2.5 YARN MANUFACTURING PROCESS

The single-jersey yarns, visually analysed in section *2.6.3,* were distinguished as rings-spun yarns, see Figure 23 a) and b).

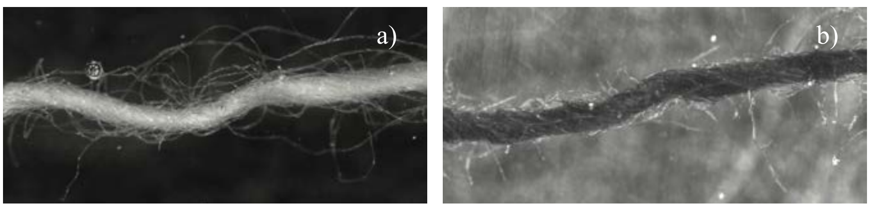

Figure 23 Single-jersey yarns a) ring-spun b) ring-spun

For the denim constructions it was difficult to make a general judgement of the yarn spinning technology. Majority of the warp and weft yarns could be distinguished as rotor-spun yarns, see Figure 24 a). However, some of the warp yarns could also be distinguished as ring-spun yarns, see Figure 24 b).

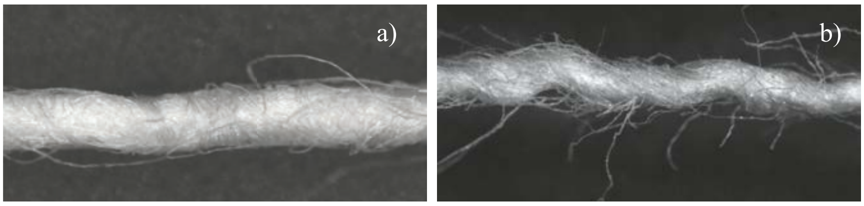

Figure 24 Denim yarns a) rotor-spun b) ring-spun

3.2.6 FIBRE WIDTH

The mean value of the fibre width for the input material is presented in Figure 25. The average fibre width for single-jersey low degree of wear was 19.8 µm, with a CV equal to 15.2%. The mean value for high degree of wear was 20.0 µm, CV was 17.1%. Statistical analysis, with a P-value of 0.8134, showed that there was no significant difference between the fibre width for single-jersey low and high degree of wear. All values are presented in more detail in Appendix 8.

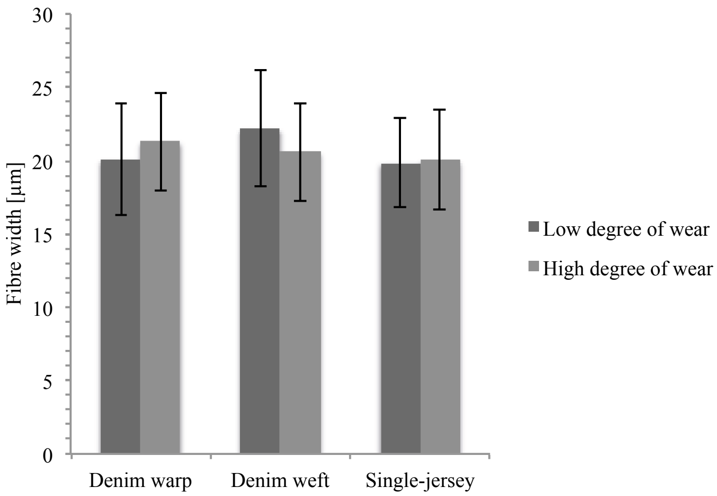

Figure 25 Mean value fibre diameter [µm], error bars σ (+/-).

For denim, low degree of wear, the average fibre diameter for the warp yarn was 20.1 µm. CV was calculated to 18.8%. The mean fibre diameter for the weft was 22.2 µm, with a CV was equal to 17.8%. The mean fibre diameter for warp and weft, high degree of wear, was 21.4 µm and 20.6 µm respectively. CV was 15.6% and 16.3%. Statistical analysis, with a P-value of 0.0557, showed that there was no significant difference between the fibre diameter for low and high degree of wear. The measured values are presented in Appendix 8.

3.2.7 FIBRE LENGTH AND FIBRE LENGTH DISTRIBUTION

In the first two parts of this section, the mean fibre length of the disintegrated yarns from the disassembled input material will be presented in conjunction with the fibre length distribution. In the two subsequent sections the mean fibre length and fibre length distribution of the shredded material will be presented. Last, the result of the reference method from Mesdan S.p.A is reported.

3.2.7.1 INPUT SINGLE-JERSEY

The mean fibre length for the input material, single-jersey low degree of wear was 22 mm. CV was 23%. The mean value for single-jersey high degree of wear was 18 mm with a CV equal to 32%. Statistical analysis showed that there was a significant difference of the mean fibre length between low and high degree of wear, see Table 5. Appendix 9 presents a more detailed overview of the measured values and statistics.

Table 5 Statistical comparison of fibre length between zone 1 and 2, single-jersey low and high degree of wear.

Difference of levels	Adjusted P-value
2 (low) - 1 (low)	0.7247
1 (high) - 1 (low)	<0.0001
2 (high) - 1 (low)	<0.0001
1 (high) - 2 (low)	<0.0001
2 (high) - 2 (low)	<0.0001
2 (high) - 1 (high)	0.9503

Figure 26 and 27 shows the fibre length distribution for the measured fibres of each zone taken from the two levels of degree of wear in section *2.3.1.* The x-axis in the graphs represents the fibre length in mm. The y-axis is the frequency of the fibre length. High columns indicate the most frequent fibre lengths. Statistical analyses showed that there was no significant difference between the two zones for low degree of wear with an adjusted P-value of 0.7247, see Table 5 or Appendix 9. The fibre length distribution for these zones is further shown in Figure 26. The fibre length distribution for the two zones taken from single-jersey high degree of wear is shown in Figure 27. Statistical analysis showed that there was no significant difference between the two zones for high degree of wear with an adjusted P-value of 0.9503. Based on this result, the average fibre length, for low and high degree of wear, was calculated.

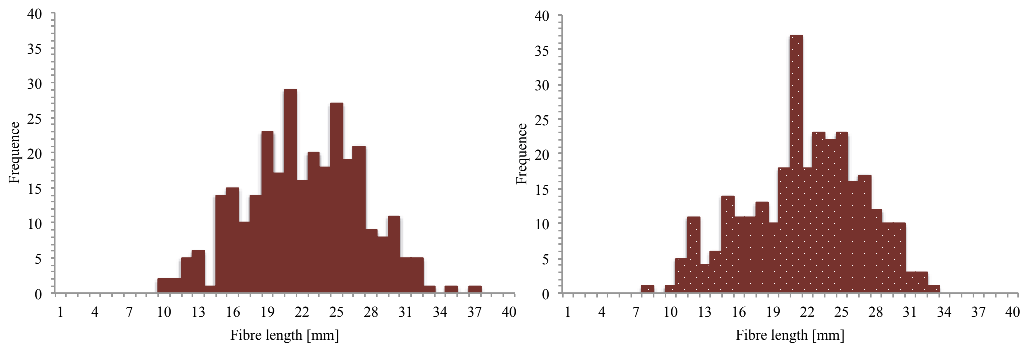

Figure 26 Fibre length distribution of single-jersey low degree, right: zone 1, left: zone 2.

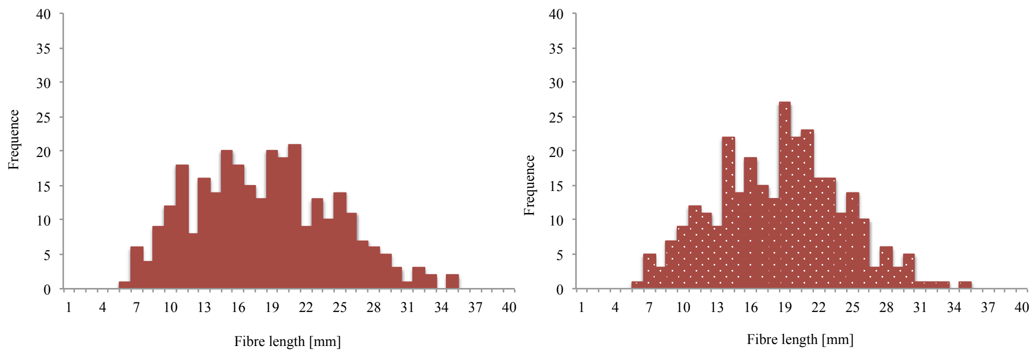

Figure 27 Fibre length distribution of single-jersey high degree, right: zone 1, left: zone 2.

3.2.7.2 INPUT DENIM

The mean value (ML) and CV of the fibre length for warp and weft, low and high degree of wear, is presented in Table 6.

Table 6 ML and CV of the fibre length in warp and weft yarn respectively.

Degree of wear	Yarn	ML [mm]	CV [%]
Low	Warp	21	28.6
	Weft	22	27.3
High	Warp	20	30.0
	Weft	17	35.3

The adjusted P-value from the statistical analysis is presented in Table 7. The test showed that there was no significant difference, with an adjusted P-value of 0.5621, between the warp and weft yarns for denim low degree of wear. The statistical analysis showed that there was a significant difference between warp and weft yarn, for high degree of wear, at an adjusted P-value of <0.0001. Additionally, the test showed that there was a significant difference between low and high degree of wear. All values are further presented in Appendix 10.

Table 7 Statistical comparison of fibre length between warp and weft, denim low and high degree of wear.

Difference of levels	Adjusted P-value
weft (low) - warp (low)	0.5621
warp (high) - warp (low)	<0.0001
weft (high) - warp (low)	0.0001
warp (high) - weft (low)	<0.0001
weft (high) - weft (low)	<0.0001
weft (high) - warp (high)	<0.0001

The fibre length distribution for denim low degree of wear is presented in Figure 28. The fibre length distribution for denim high degree of wear is presented in Figure 29. Additionally, the figures show the fibre length distribution for the warp and weft yarns respectively. High columns in the figures indicate the most frequent fibre lengths.

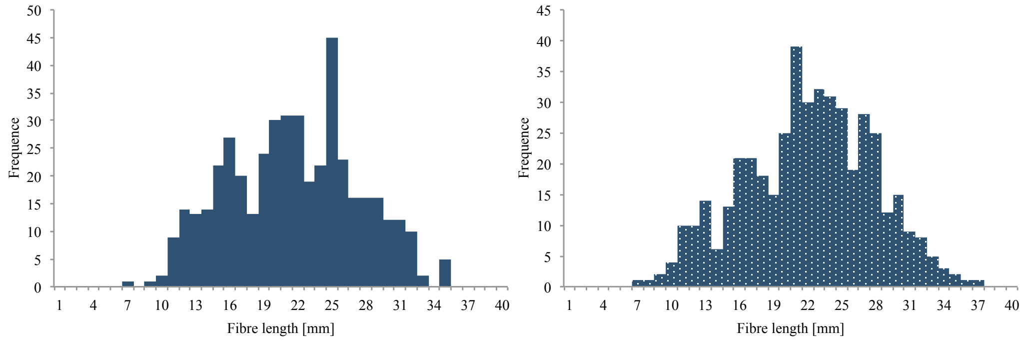

Figure 28 Fibre length distribution of denim low degree, right: warp, left: weft.

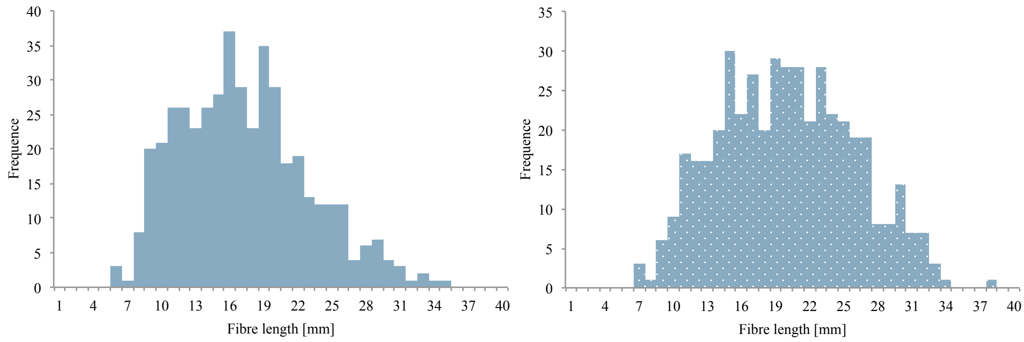

Figure 29 Fibre length distribution of denim high degree, right: warp, left: weft.

3.2.7.3 OUTPUT SINGLE-JERSEY

The mean fibre length (ML), short fibre content (SFC) and CV for single jersey low and high degree of wear and the mixture are presented in Table 8. Statistical analysis showed that there was a significant difference between low degree and high degree of wear at an adjusted P-value of 0.0024. Furthermore the test showed that there was a significant difference between high degree of wear and mixture with an adjusted P-value of 0.0026. There was no significant difference between low degree of wear and mixture at an adjusted P-value of 0.9996. The measured values and statistics are presented in Appendix 11.

Table 8 ML, SFC and CV for single-jersey low and high degree of wear and mixture.

Degree of wear	ML [mm]	SFC [%]	CV [%]
Low	10	71.2	57.6
Mixture	10	70.2	63.5
High	12	61.6	62.6

The fibre length distribution for single-jersey low degree of wear, after shredding, is presented in Figure 30, were high columns indicate the most frequent fibre lengths. The fibre length distribution for high degree of wear and mixture is presented in Figure 31 and 32.

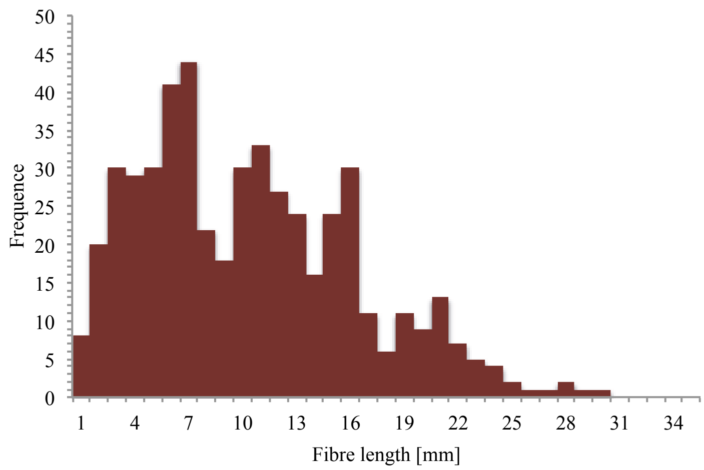

Figure 30 Fibre length distribution after shredding single-jersey low degree of wear

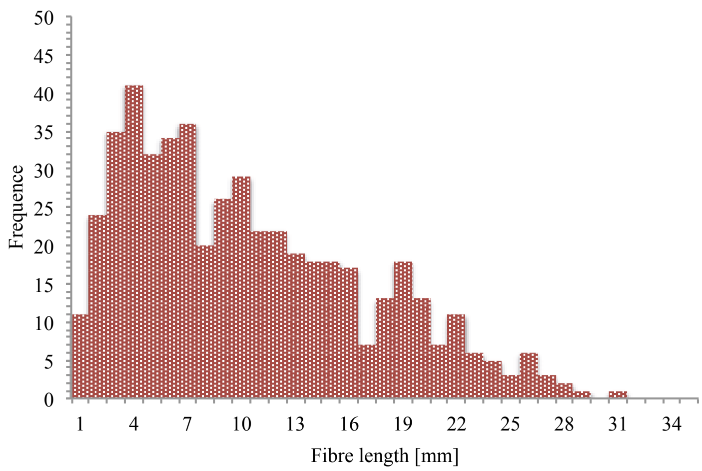

Figure 31 Fibre length distribution after shredding single-jersey mixture

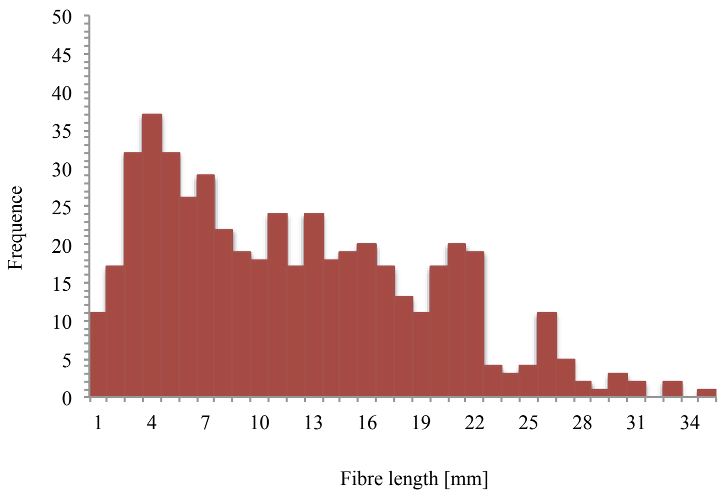

Figure 32 Fibre length distribution after shredding single-jersey high degree of wear

Figure 33 shows the mean fibre length difference before and after shredding, for single-jersey low and high degree of wear and the mixture respectively. The reduction of the fibre length, in percentage, for single-jersey low degree of wear was 54.5%. For mixture and high degree of wear, the reduction of the fibre length was 50% and 33.33% respectively.

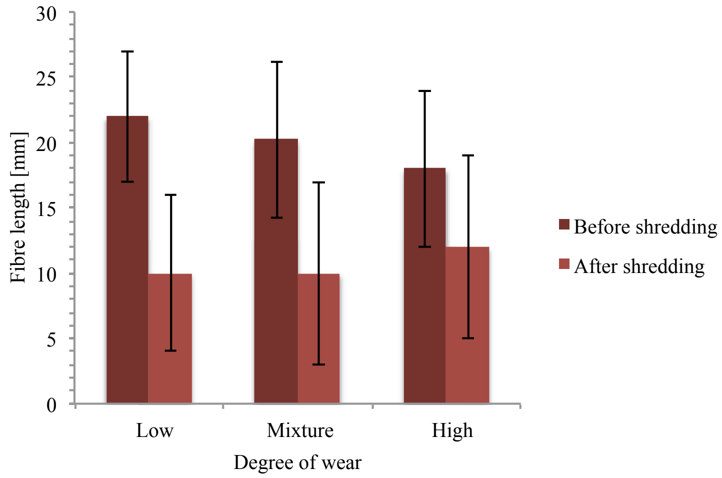

Figure 33 Mean fibre length difference of single-jersey before and after shredding, error bars σ (+/-).

3.2.7.4 OUTPUT DENIM

The mean fibre length (ML), short fibre content (SFC) and CV for denim low and high degree of wear and the mixture are presented in Table 9. Statistical analysis showed that there was a significant difference between high degree of wear and mixture at an adjusted P-value of 0.0237. Furthermore the test showed that there was no significant difference between low and high degree of wear with an adjusted P-value of 0.6823. There was also no significant difference between low degree of wear and mixture at an adjusted P-value of 0.1733. The measured values and statistics are further presented in Appendix 12.

Table 9 ML, SFC and CV for denim low and high degree of wear and mixture.

Degree of wear	ML [mm]	SFC [%]	CV [%]
Low	13	55.0	55.0
Mixture	12	61.4	55.0
High	13	53.4	53.0

The fibre length distribution for denim low degree of wear, after shredding, is presented in Figure 34, were high columns indicate the most frequent fibre lengths. The fibre length distribution for denim high degree of wear and mixture is presented in Figure 35 and 36.

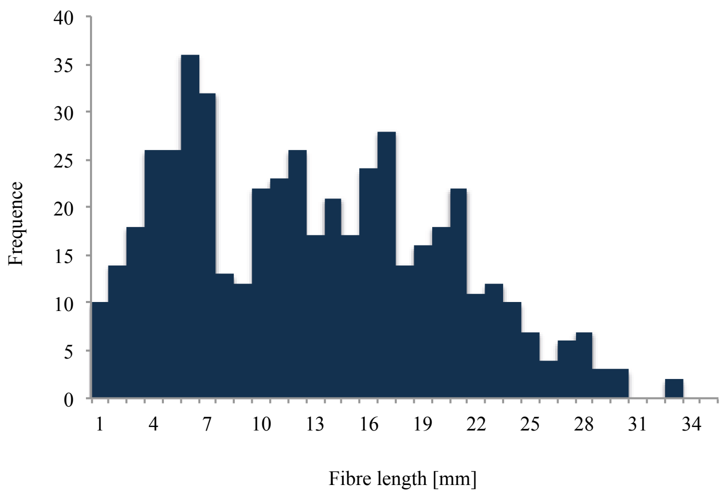

Figure 34 Fibre length distribution after shredding denim low degree of wear

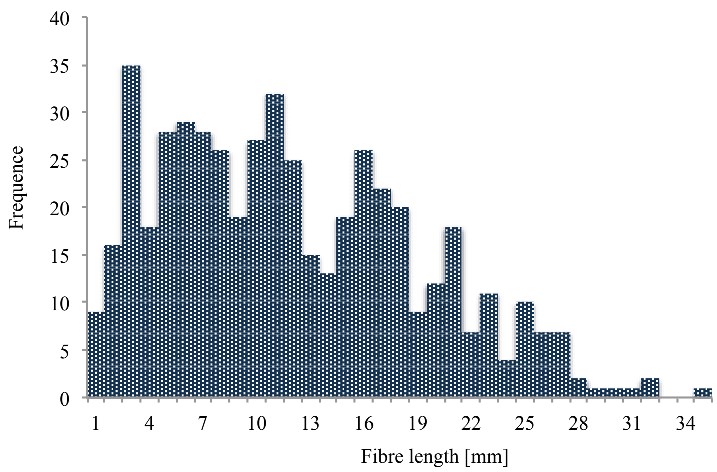

Figure 35 Fibre length distribution after shredding denim mixture

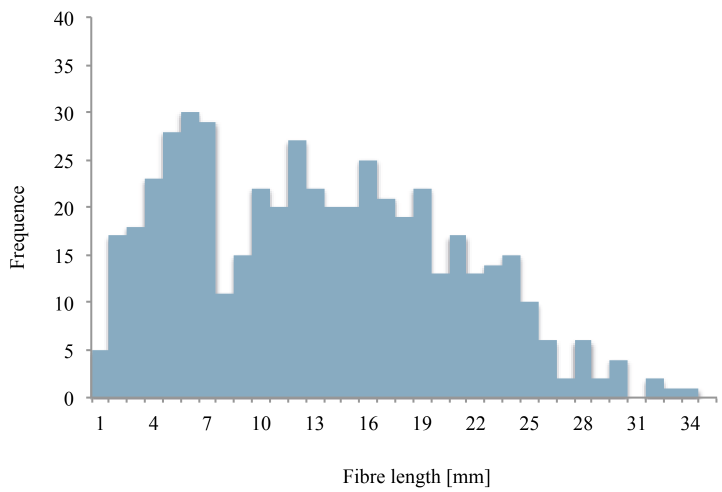

Figure 36 Fibre length distribution after shredding denim high degree of wear

Figure 37 shows the mean fibre length difference before and after shredding, for denim low and high degree of wear and mixture respectively. The reduction of the fibre length, in percentage, for denim low degree of wear was 40.9%. For mixture and high degree of wear, the reduction of the fibre length was 40% and 31.6% respectively.

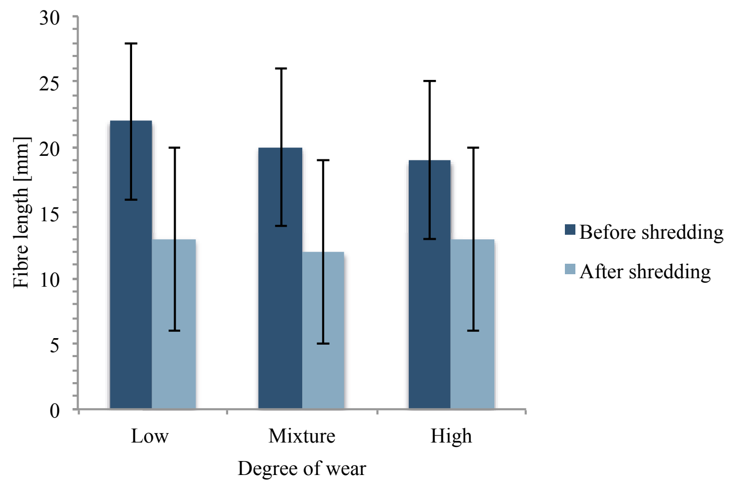

Figure 37 Mean fibre length difference of denim before and after shredding, error bars σ (+/-).

3.2.7.5 COMBINATION OF SINGLE-JERSEY AND DENIM

As mentioned in section *2.4,* 50% of single-jersey mixture and 50% of denim mixture were combined in the shredding process. The fibre length distribution of the shredded material is shown in Figure 38. The mean fibre length of the output material was 11 mm. CV was 62.1% and the SFC was 60.6%. The measured values are presented in Appendix 13.

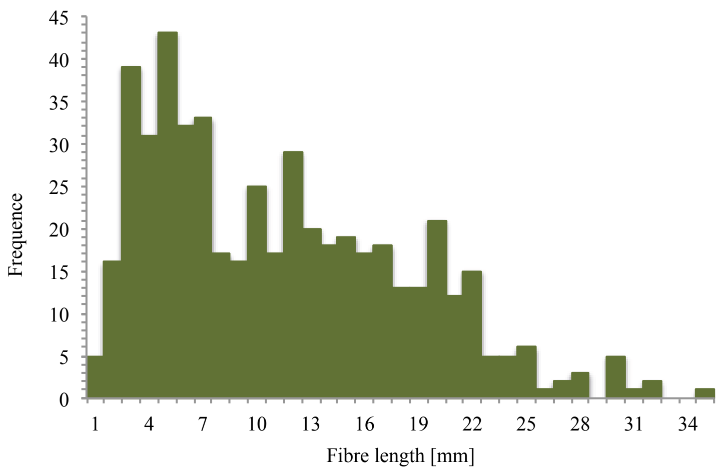

Figure 38 Fibre length distribution, 50% single-jersey and 50% denim shredded together

3.2.7.6 REFERENCE METHOD

The result of the fibre length measurement conducted by Mesdan S.p.A is presented in Table 10.

Table 10 Fibre length measurement Mesdan S.p.A

Fabric construction	Degree of wear	ML [mm]	SFC [%]	UHM [mm]	CV [%]
Single-jersey	Low	8.2	89.5	11.1	34.2
	High	7.8	88.1	10.6	39.1
	Mixture	7.5	88.1	10.6	39.1
Denim	Low	8.5	88.9	11.5	34.2
	High	8.3	84.4	11.2	32.4
	Mixture	9.2	89.7	12.7	38.4
50% Single-jersey + 50% denim	Mixture	7.9	88.5	11.2	38.1

Figure 39 shows the mean fibre length difference between the manually measured fibres and the fibres measured by Mesdan S.p.A. The mean fibre lengths presented in Figure 39 is for the single-jersey material after shredding in conjunction with low and high degree of wear and the mixture. The difference, in percentage, for single-jersey low degree of wear was 18%. For high degree of wear the difference was 35% and for the mixture 25%.

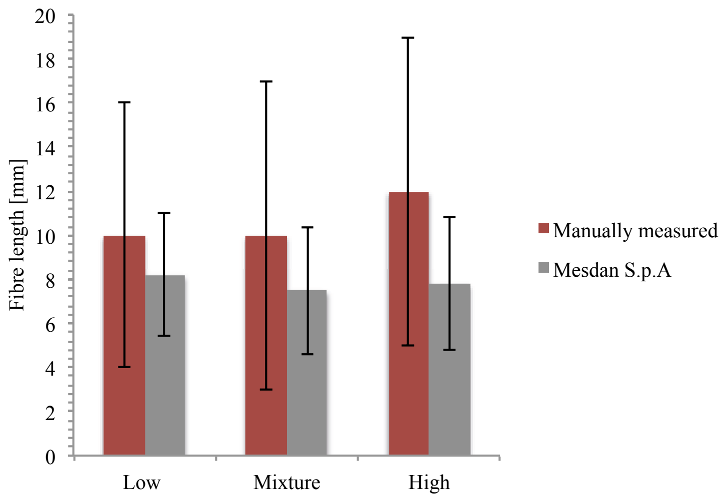

Figure 39 Mean fibre length difference between the manually measured fibres and the fibres measured by Mesdan S.p.A, for the shredded single-jersey material, error bars σ (+/-).

Figure 40 shows the mean fibre length difference between the manually measured fibres and the fibres measured by Mesdan S.p.A. The mean fibre lengths presented in Figure 40 is for the denim material after shredding in conjunction with low and high degree of wear and the mixture. The difference for denim low degree of wear was 35%. For high degree of wear the difference was 36% and for the mixture 23%.

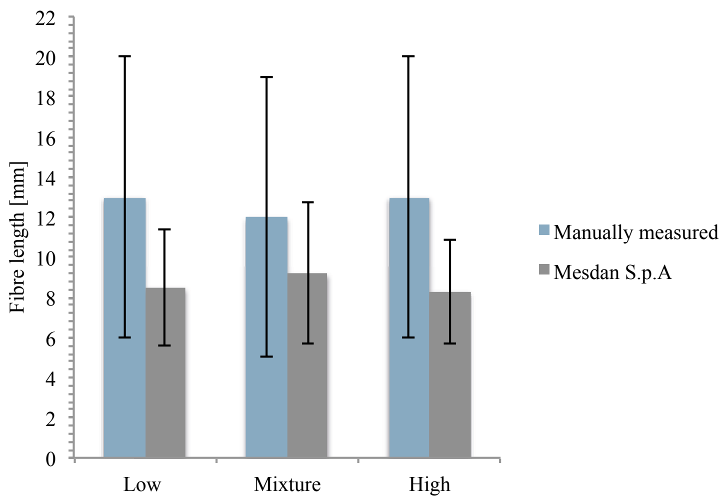

Figure 40 Mean fibre length difference between the manually measured fibres and the fibres measured by Mesdan S.p.A, for the shredded denim material, error bars σ (+/-).

3.3 SHREDDING

The material flow in the shredding process was perceived as significantly better for the denim material compared to the single-jersey. Visually, the single-jersey fractions contained a higher amount of threads and pieces of fabrics compared to the denim fractions after shredding. Figure 41 and 42 shows the differences between the two fabric constructions after the shredding process.

Figure 41 Single-jersey shredded low degree of wear

Figure 42 Denim shredded low degree of wear

4. DISCUSSION

The main objective of this thesis was to investigate how different degree of wear of cotton post-consumer garments influences the fibre length obtained in the shredding process. Additionally, parameters such as the input fibre length, fabric constructions and yarn structure were analysed.

The post-consumer textile waste used in this study was selected based on fabric constructions and fibre type. For the latter, it was done manually by controlling the labels in the garments. No further analysis was performed to ensure that e.g. elastane was not present in the materials. However, the use of chemical characterization techniques in the sorting step could ensure more pure fractions.

It is important to stress that the fibre measurements performed in this study has been done manually and is based on a subjective assessment, which could have influenced the result. According to Gordon (2007) and Naylor et al. (2014), measuring fibre length manually is considered highly impractical since shorter fibres might be excluded, which can result in a misleading result. The fibre length measurement, of the recycled staple fibres, received from Mesdan S.p.A, presented in Table 10, further confirms this statement. Figure 39 and 40, shows that there was a high deviation between the manually measured recycled staple fibres and the once measured by Mesdan S.p.A. Figure 39, shows the difference between the manually measured fibres and the fibres measured by Mesdan S.p.A, for the single-jersey material. The fibre length difference between the two methods for single-jersey low degree of wear was 18%. For high degree of wear the difference was 35% and for the mixture 25%. In Figure 40, which shows the fibre length difference, for the denim material, between the two different measuring methods, it can further be seen that the differences were high. The difference for denim low degree of wear was 35%. For high degree of wear the difference was 36% and for the mixture 23%. Additionally, it can be seen in Table 8 and 9 that the coefficient of variance (CV) for the manually measured fibres, after shredding, are higher compared to the fibres measured by Mesdan S.p.A, see Table 10. However, it should further be discussed that there is a correlation between the values of the upper-half mean length (UHM) from Mesdan S.p.A, see table 10, and the calculated mean length (ML) of the manually measured fibres, see Table 8 and 9. This indicates that there is a possibility that shorter fibres have been difficult to measure manually resulting in higher mean length of the reclaimed fibres measured in this study.

Generally, it can be seen that the CV for the yarn structure and output fibre length in this study are high. A possible reason for this is that all experiments are done manually and is based on a subjective assessment. In addition this thesis has been dealing with cotton post-consumer waste. This waste is heterogeneous and since the history in terms of use, laundering and manufacturing of the garments is unknown, this might led to a high variation of properties between and within the garments. Since there is no established method for categorizing post-consumer waste this thesis has aimed to get an understanding of the material that was used.

In the beginning of this study, a pre-study was carried out in order to investigated if the material should be conditioned before shredding. The result showed that there was no statistical significant difference, with a P-value of 0.9630, of the mean fibre length between the non-conditioned material and the conditioned material after shredding, see Appendix 3. Therefore, conditioning of the material before shredding was excluded from the study. However, more tests should be conducted in order to establish this theory.

As mentioned, there are no established methods for categorizing post-consumer waste. The pre-study further aimed to examine how the fibre length might vary within these garments. Therefore, three different pieces were taken from different places on the single-jersey garments, see Figure 9. Statistical analysis showed that there was no significant difference, with an adjusted P-value of 0.3258, of the mean fibre length within these zones, see section *3.1.1*. To further confirm this theory two pieces were taken from each single-jersey garment in the subsequent experiments based on degree of wear, see Figure 10. Statistical analysis, presented in Table 5, showed again that there was no significant difference between the zones for both low and high degree of wear respectively. However, the adjusted P-values, presented in Table 5, showed that the mean input fibre length for single-jersey low degree of wear was significantly longer compared to single-jersey high degree of wear.

The statistical analysis for the square meter weight, based on degree of wear for the single jersey material showed that there was no significant difference between the zones for both high and low degree of wear, see Table 1. Additionally, the test showed that there was no significant difference between high and low degree of wear, see Table 1. The statistical analysis further showed that there was no significant difference between the square meter weight for denim low and high degree of wear, see section *3.2.1*. Based on this result, it is difficult to make any further analysis regarding the square meter weight.

The sorting step, based on degree of wear, was done objectively on each individual garments for the t-shirt. However, for the jeans it was not possible to distinguish between garments, due to the high degree of wear of all jeans. Therefore, the low and high degree of wear for the denim constructions were selected within the same garment, see Figure 7. The result of the fibre length measurement of the input denim material, presented in Table 6, showed that there was a statistically significant difference between low and high degree of wear, see Table 7. Furthermore, the statistical analysis showed that the fibre length in the warp yarns, high degree of wear, was significantly lower compared to the weft yarn for high degree of wear, see Table 7. This result could further be stated with the knowledge that denim is a warp faced twill construction i.e. these yarns will be subjected to a higher degree of abrasion compared to the weft yarns, which might damage the fibres. Table 7 further show that there was no significant difference between the mean fibre lengths of the warp and weft yarns for denim low degree of wear.

After shredding, the statistical analysis showed that the fibre length for single-jersey high degree of wear, was significantly longer compared to low degree of wear and mixture, see section *3.2.7.3*. There was no significant difference between single-jersey low degree of wear and the mixture. For the denim constructions the statistical analysis showed that there was no significant difference between the fibre lengths for high degree of wear and low degree of wear, see section *3.2.7.4*. The statistical analysis further showed that there was no significant difference between mixture and low degree of wear. However, the analysis showed that there was a significant difference between high degree of wear and mixture, even though the calculated mean values for low and high degree of wear of denim were the same, see Table 9. This can be explained by the fact that Minitab, that was used to conduct the statistical analysis, calculates the mean value with more significant figures than used in the study, see Appendix 12. Therefore, this result may be misleading.

The fibre length reduction during the shredding process is high. Figure 33 and 37 shows that the fibre length is significantly reduced for both type of fabric constructions and degree of wear. Nevertheless, what could be seen in both Figure 33 and 37 is that the fibre length reduction was lower for the material with high degree of wear for both types of fabric constructions. The single-jersey construction, high degree of wear, had a fibre length reduction of 33.3% compared to low degree of wear, where the fibre length reduction was 54.5%. For the denim material, high degree of wear, the fibre length reduction was 31.6%. Low degree of wear had a fibre length reduction of 40.9%. This result indicates that material with a low degree of wear and longer fibres tends to give a higher fibre length reduction.

Figure 26 and 27, presents the fibre length distribution for the single-jersey constructions based on degree of wear, before shredding. Figure 30, 31 and 32 shows the fibre length distribution, after shredding. A comparison between these figures shows that fibre length distribution before shredding has a more homogenous distribution, which is desirable. While the fibre length after shredding has a wider spectrum of fibre lengths. From the fibre length distributions the mean fibre length and short fibre content (SFC) was calculated. The result showed that the SFC for the single-jersey construction, high degree of wear, had the lowest short fibre content (SFC), see Table 8.

Figure 28 and 29 shows the fibre length distribution for the denim constructions, based on degree of wear, before shredding. Figure 34, 35 and 36 presents the fibre length distribution after shredding. It could also here be seen that the fibre length distribution, after shredding, was broad and contained a wide spectra of fibre lengths. From the distribution graph it was found that the denim constructions low degree and mixture had the lowest SFC, see table 9. The fibre length distribution is important to take into account during yarn production, since it, compared to the mean fibre length, gives a fully description of the fibre length. The fibre length distribution for the recycled fibres in this study, indicates that there will be challenging to produce a yarn and that a high amount of virgin fibres probably need to be added. Due to the broad and varying spectrum of fibre lengths obtained in this study it is difficult to make any statements of how the fibre length distribution is affected by degree of wear, yarn structure and fabric construction. In addition, other parameters e.g. upper-quartile length (UQL) and UHM should further be determined.

It was visually perceived that the material flow in the shredding machine and the disintegration of the garments was better for the denim material compared to the single-jersey. After the shredding process it was visually seen that the single-jersey constructions still contained a high amount of threads and fabric pieces compared to the denim constructions, see Figure 41 and 42. One possible reason could be that four cylinders, which was used in this study, was not enough to shred the single-jersey material back to fibrous form. In addition, it is of importance to underline that the material flow and shredding of the material also may vary depending on the machine used. Thus, using another type of machine could have led to different result.

In order to investigate how the fibre length of the mechanically recycled cotton fibres was affected of the yarn structure, parameters in terms of yarn count, yarn twist and manufacturing process of the input material was analysed. Based on the result regarding the yarn count, it was found that the yarns used in the single-jersey constructions were finer compared to the yarns used in the denim constructions, see Figure 20. Statistical analysis showed that there was no significant difference between the mean yarn count for single-jersey low and high degree of wear, see section 3.2.2. The statistical analysis further showed that there was no significant difference between the mean yarn count for denim low and high degree of wear, see Table 2. The fibres in a finer yarn usually have a higher cohesion of friction between the fibres compared to a coarser yarn, since the twist usually is higher. If taken into account that there still was a high amount of threads and fabric pieces after shredding the single-jersey constructions compared to the denim constructions, it is possible that yarn count has an effect on the ease of shredding and the fibre length obtained in the end.

In this study, the yarns in the single-jersey constructions were characterised as ring-spun yarns, see Figure 23 a) and b). The majority of the yarns in the denim constructions were distinguished as rotor-spun yarns, see Figure 24 a). Analysis of the twist factor, or the absolute number of yarn twist, which takes the linear density of the yarn into account, showed that the twist factor for single-jersey high degree of wear was statistically significant higher compared to single-jersey low degree of wear, see section 3.2.4. For the denim material, the statistical analysis showed that twist factor for the warp yarns, low degree of wear, was significantly higher compared to the weft yarns for low degree of wear and for both the weft and the warp yarns for high degree of wear, see Table 4. According to El Mogahzy (2009), warp yarns usually have a higher twist compared to weft yarns. For the denim yarns, high degree of wear, it can be seen in Table 4 that there was no significant difference between the twist factor for the warp and the weft yarns. It should further be discussed that untwisting the warp yarns for high degree of wear was more difficult compared to the other yarns. The reason was that these yarns easily fell apart during the test. Based on the knowledge that denim is a warp faced twill construction and that these yarns might have been subjected to more abrasion during the user phase compared to the weft yarns, it is possible that the yarns might have been damaged. Analysis of the yarn twist, see section 3.2.3, showed that the CV for the warp yarn, denim high degree of wear, was 50.1% compared to the other denim yarns, where the CV ranged between 30-35%. This result further confirms that there possibly were difficulties of untwisting the warp yarn for high degree of wear and that this result might be misleading. However, it should further be mentioned that untwisting rotor-spun yarns are considered difficult due to the presence of the belt fibres or warp fibres along the yarn, see Figure 2 b) or 24 a). Compared to the ring-spun yarns, see section *3.2.3*, were the CV ranged between 17-24% this theory could further be confirmed.

According to El Mogahzy (2009), yarns used for knitting usually have a lower twist factor compared to a yarns used for weaving, which can be seen in Figure 22. Additionally, for rotor-spun yarns the twist factor usually is higher than ring-spun yarns, since the process requires higher twist. According to Russell et al. (2016) and Gulich (2006 b) the amount of fibre breakage during the shredding process is highly influenced on the level of yarn twist. However, it should be emphasized that even though the twist factor in this study was higher for the woven structure, a ring-spun yarn has a greater real twist compared to a rotor-spun yarn. In a ring-spun yarn the twist takes places from the outside inwards, contributing to a more parallel arrangement and denser packing of fibres. In contrast, the fibres in a rotor spun yarn are less packed since the twist takes place from the inside outwards, contributing to a lower twist in the outer layer of the yarn, see Figure 2 a) and b). (El Mogahzy 2009; Rieter 2017 a) Based on this, it is possible that the yarn structure, regarding the manufacturing process of the yarn, has a great influence on the ease of shredding a material back to a fibrous condition and the fibre length obtained in the end.

The mechanical behaviour of a fabric construction does to large extent correlates to its internal construction. Since the yarn structure in this study was different for the yarns used in the single-jersey compared to the yarns in the denim constructions, it is difficult to determine how the fabric constructions affects the fibre length of the recycled staple fibres. Therefore, further studies have to be conducted, using a yarn structure, in terms of yarn manufacturing process, linear density and twist, identical for both types of fabric constructions.

It is also of importance to characterize the fibres constituting the yarns, in terms of strength, titer and length. Thus, the input fibre length and fibre width was considered in this thesis. Statistical analysis of the fibre width showed that there was no significant difference between low and high degree of wear for both the single-jersey and the denim constructions, see section *3.2.6*. However, further studies should be implement regarding the fibre properties in terms of strength and titer.

Based on the result in this thesis it is evident that the shredding process needs to be improved in order for the process to move towards a more closed loop system. However, even though the shredding process reduces the length of the fibres and that it is difficult to reach fibre-to-fibre recycling, especially when post-consumer textile waste is used as raw material, the process has great potential. It should be underlined that even though a great amount of virgin fibres need to be added when producing a yarn, a reduction of virgin fibres still can be reached. In addition, the recycled staple fibres can be used in various applications e.g. reinforcement in composites. Thus, shredding of post-consumers garments enables another cycle of use for these fibres before sending them for incineration or landfills.

In order to reach fibre-to-fibre recycling, when using cotton waste as raw material, it should further be discussed if the shorter fibres could be extracted and used to make dissolving pulp for viscose fibres. In addition, if the short fibres are removed a more homogenous fibre length distribution of the recycled staple fibres possibly could be obtained. This in turn could enhance the spinning process and reduce the amount of virgin fibres that needs to be added during the spinning process.

The shredding process has many advantages compare to other recycling techniques e.g. no water or chemicals are added during the process. This is not only good for the environment but also for the working conditions. However, during the shredding process, dust, particles etc. are generated, which can be dangerous for human health.

The area of post-consumer textile waste is complex and the result in this thesis showed that there are many underlying parameters that need to be taken into account when shredding a material back to fibrous form. Not only do the shredding technique need to be improved, but also processes such as sorting and garment design. The fibre choice during the design phase has a great influence on the environmental impacts. Choosing a homogenous material will contribute to easier sorting and recycling. More accurate and automatic sorting techniques are required, not only for characterization of fibre type, but also in terms of the history of the garments e.g. manufacturing process and use of chemicals. Such knowledge would contribute to better working conditions and enable waste streams to easier be recycled.

5. CONCLUSION

The main objective of this thesis was to investigate how different degree of wear of cotton post-consumer garments influences the fibre length obtained in the shredding process. This was investigated by analysing the following parameters in post-consumer garments:

- *Degree of wear*
- *Single-jersey or denim constructions*
- *Fibre length of the input and output material*
- *Yarn structure: yarn count, yarns twist and manufacturing process of the yarn*

Based on the result, it was found that the input fibre length for both the single-jersey and denim constructions, low degree of wear, was statistically significant longer compared to the materials with high degree of wear. The result after shredding showed that the fibre length reduction was lower for the materials with high degree of wear. Therefore, it can be concluded that materials with low degree of wear and longer fibres gives higher fibre length reduction.

In addition, the result after shredding showed that the fibre length was lower for the single-jersey construction compared to the denim construction. If taken into account that there still was a high amount of threads and fabric pieces after shredding the single-jersey constructions compared to the denim constructions, it can be concluded that finer yarns are more difficult to shred and gives a higher fibre length reduction. Findings further indicate that the yarn manufacturing process has more affect on the ease of shredding and the fibre length obtained in the end compared to the twist.

No conclusion can be drawn regarding how the fabric construction affects the fibre length. The result from the yarn analysis showed that the yarn structure was different for the both fabric constructions and no comparison can therefore be made.

Based on the result in this thesis it can be concluded the shredding process needs to be improved in order to preserve the fibre length. The area of post-consumer textile waste is complex and the result shows that there is many underlying parameters that need to be taken into account in order to further develop the shredding process.

6. FUTRURE WORK

The work presented in in this thesis resulted in several new questions, which will be outlined in this section.

Since it was difficult to draw any conclusion of how the fabric constructions are affecting the length of the recycled staple fibres, further studies have to be conducted regarding this. As discussed, one essential parameter that might influence the length of the recycled staple fibres is the yarn structure. To gain understanding on the effect of fabric construction, fabrics of different constructions, with identical yarns in terms of manufacturing process of the yarn, linear density and twist, should be compared. In addition, studies regarding how the manufacturing process of the yarn influences on the length of the recycled staple fibres should be performed in order to confirm the theory deducted from this thesis.

Parameters such as fineness and strength of the fibres were not considered in this thesis. It is something that could be interesting to further investigate. Such a characterization on fibre level, could lead to a better sorting and shredding of input and output material in the shredding process.

The shredding machine used in this thesis had four cylinders. After the single-jersey material had passed through the machine it still contained a high amount of threads and fabric pieces. It would further be interesting to investigate how the fibre length is affected of how many times the material pass through the machine. Parameters such as drum revolution and distances between the cylinders would further be interesting to optimize.

In the beginning of this study, conditioning of the input material prior to shredding was examined. However, only one test was conducted. A more accurate study regarding the moisture content of the input material would further be needed to examine if it has an affect of the fibre length.

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APPENDIX 1.

Model	NSX-QD350 (cutting machine)
Producer	Qing Dao New Shunxing Environmental Protection and Technology Co
Capacity	1000-1500 kg/h
Rotary blades (diameter)	320 mm
Speed (rotary blades)	230 turns/min
Cut size	5-250 mm
Voltage	380 V (50 hz)
Conveyor belt	380 x 4000 x 3 mm
Machine size	3550 x 960 x 1200 mm
Weight	~800 kg

Model	NSX-FS1040
Producer	Qing Dao New Shunxing Environmental Protection and Technology Co
Capacity	100-120 kg/h
Cylinder (diameter)	400 mm
Speed (cylinder)	1350 turns/min
Needle gauge	4.5/25.4 needles/ mm
Engine	1.5 kw
Fan	1.1 kw
Machine size	2100 x 1450 x 1550 mm

Model	NSX-QT310
Producer	Qing Dao New Shunxing Environmental Protection and Technology Co
Capacity	100-120 kg/ h
Cylinder (diameter)	250 mm
Speed (cylinder 1)	1900 turns/ min
Speed (cylinder 2 & 3)	2000 turns /min
Needle gauge (cylinder 1)	4.5/25.4 needles/ mm
Needle gauge (cylinder 2 & 3)	6/25.4 needles/ mm
Engine	5.5 kw
Fan	1.1 kw
Machine size	4610 x 1720 x 1160 mm
Weigh	1600 kg

APPENDIX 2. PRE-STUDY

Frequency table of measured fibre length [mm] prior to shredding

Single-jersey	
Zone 1	
Fibre length [mm	Frequence
1	
2	
3	
4	1
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	1
18	
19	3
20	6
21	7
22	2
23	7
24	10
25	11
26	7
27	10
28	10
29	4
30	5
31	2
32	1
33	1
34	1
35	1
36	
37	
38	
39	
40	
TOTAL:	
n=	90
$\bar{x}$=	25
σ =	4
CV=	17,01%

Single-jersey	
Zone 2	
Fibre length [mm	Frequence
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	
20	2
21	9
22	8
23	7
24	12
25	11
26	8
27	4
28	5
29	10
30	5
31	4
32	2
33	2
34	
35	1
36	
37	
38	
39	
40	
TOTAL:	
n=	90
$\bar{x}$=	26
σ =	3
CV=	13,58%

Single-jersey	
Zone 3	
Fibre length [mm	Frequence
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	
18	1
19	
20	2
21	7
22	8
23	9
24	8
25	9
26	4
27	10
28	7
29	8
30	9
31	4
32	3
33	
34	
35	1
36	
37	
38	
39	
40	
TOTAL:	
n=	90
$\bar{x}$=	26
σ =	4
CV=	13,59%

APPENDIX 2. PRE-STUDY

Statistical analysis of the input fibre length [mm], single-jersey, zone 1-3

One-Way ANOVA: Zone 1; Zone 2; Zone 3

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	3	Zone 1; Zone 2; Zone 3

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	2	32,14	16,0704	1,13	0,3258
Error	267	3809,88	14,2692		
Total	269	3842,02			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3,77746	0,84%	0,09%	0,00%

Means

Factor	N	Mean	StDev	95% CI
Zone 1	90	25,1000	4,2692	(24,3160; 25,8840)
Zone 2	90	25,7111	3,4907	(24,9271; 26,4951)
Zone 3	90	25,9111	3,5209	(25,1271; 26,6951)

Pooled StDev = 3,77746

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
Zone 3	90	25,9111	A
Zone 2	90	25,7111	A
Zone 1	90	25,1000	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
Zone 2-Zone 1	0,6111	0,5631	(-0,7069; 1,9291)	1,09	0,5232
Zone 3-Zone 1	0,8111	0,5631	(-0,5069; 2,1291)	1,44	0,3201
Zone 3-Zone 2	0,2000	0,5631	(-1,1180; 1,5180)	0,36	0,9328

Individual confidence level = 98,00%

APPENDIX 3. PRE-STUDY

Frequency table of measured fibre length [mm] after shredding

Single-jersey	
Room temperature	
Fiber length [mm]	Frequence
1	
2	
3	1
4	7
5	7
6	17
7	18
8	18
9	20
10	28
11	17
12	21
13	20
14	15
15	11
16	8
17	12
18	3
19	8
20	7
21	6
22	10
23	7
24	1
25	4
26	
27	3
28	1
29	
30	
31	
32	
33	
34	
35	
TOTAL:	
n=	270
$\bar{x}$=	13
σ =	5
CV=	43,65%

Single-jersey	
humidity of (65±2)% and (20±2) °C	
Fiber length [mm]	Frequence
1	1
2	
3	2
4	12
5	13
6	8
7	16
8	16
9	24
10	14
11	15
12	26
13	16
14	16
15	18
16	12
17	10
18	11
19	5
20	11
21	4
22	5
23	3
24	2
25	6
26	
27	
28	1
29	1
30	2
31	
32	
33	
34	
35	
TOTAL:	
n=	270
$\bar{x}$=	13
σ =	6
CV=	44,79%

APPENDIX 3. PRE-STUDY

Statistical analysis of the output fibre length [mm], single-jersey

One-Way ANOVA: Room temp.; Cond.

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	Room temp.; Cond.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	0,1	0,0667	0,00	0,9630
Error	538	16626,5	30,9043		
Total	539	16626,6			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
5,55917	0,00%	0,00%	0,00%

Means

Factor	N	Mean	StDev	95% CI
Room temp.	270	12,5556	5,4829	(11,8910; 13,2201)
Cond.	270	12,5778	5,6344	(11,9132; 13,2424)

Pooled StDev = 5,55917

APPENDIX 4. SQUARE METER WEIGHT

Single-jersey low degree of wear		
Square meter weight [g/m2]		
Count	Zone 1	Zone 2
1	261	232
2	177	169
3	164	157
4	205	193
5	167	152
6	159	161
7	144	136
8	171	171
9	168	167
10	194	194
TOTAL		
n=	**10**	**10**
$\bar{x}$=	**181**	**173,2**
σ =	**32,9**	**27,1**
CV=	**18,2%**	**15,6%**

Single-jersey high degree of wear		
Square meter weight [g/m2]		
Count	Zone 1	Zone 2
1	223	218
2	165	168
3	153	156
4	151	145
5	179	179
6	132	141
7	153	151
8	153	159
9	172	173
10	174	176
TOTAL		
n=	**10**	**10**
$\bar{x}$=	**165,5**	**166,6**
σ =	**24,5**	**22,3**
CV=	**14,8%**	**13,4%**

Denim		
Square meter weight [g/m2]		
Count	Low degree of wear	High degree of wear
1	280	314
2	335	312
3	454	416
4	261	210
5	481	435
6	305	335
7	354	299
8	304	285
9	405	355
10	380	348
11	451	372
12	444	399
13	378	358
14	400	372
15	390	382
TOTAL:		
n=	**15**	**15**
$\bar{x}$=	**374,8**	**346,1**
σ =	**67,5**	**56,8**
CV=	**18,0%**	**16,4%**

APPENDIX 4. SQUARE METER WEIGHT SINGLE-JERSEY

Statistical analysis square meter weight [g/m^2], single-jersey

One-Way ANOVA: Single-Jersey 1 (LDOW); Single-jersey 2 (LDOW); Single-jersey 1 (HDOW); Single-jersey 2 (HDOW)

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	4	Single-Jersey 1 (LDOW); Single-jersey 2 (LDOW); Single-jersey 1 (HDOW); Single-jersey 2 (HDOW)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	3	1531,3	510,425	0,70	0,5578
Error	36	26222,5	728,403		
Total	39	27753,8			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
26,9889	5,52%	0,00%	0,00%

Means

Factor	N	Mean	StDev	95% CI
Single-Jersey 1 (LDOW)	10	181,00	32,94	(163,69; 198,31)
Single-jersey 2 (LDOW)	10	173,200	27,055	(155,891; 190,509)
Single-jersey 1 (HDOW)	10	165,500	24,505	(148,191; 182,809)
Single-jersey 2 (HDOW)	10	166,600	22,267	(149,291; 183,909)

Pooled StDev = 26,9889

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
Single-Jersey 1 (LDOW)	10	181,00	A
Single-jersey 2 (LDOW)	10	173,200	A
Single-jersey 2 (HDOW)	10	166,600	A
Single-jersey 1 (HDOW)	10	165,500	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
Single-jersey 2 (LDOW)-Single-Jersey 1 (LDOW)	-7,80	12,07	(-40,32; 24,72)	-0,65	0,9162
Single-jersey 1 (HDOW)-Single-Jersey 1 (LDOW)	-15,50	12,07	(-48,02; 17,02)	-1,28	0,5787
Single-jersey 2 (HDOW)-Single-Jersey 1 (LDOW)	-14,40	12,07	(-46,92; 18,12)	-1,19	0,6351
Single-jersey 1 (HDOW)-Single-jersey 2 (LDOW)	-7,70	12,07	(-40,22; 24,82)	-0,64	0,9190
Single-jersey 2 (HDOW)-Single-jersey 2 (LDOW)	-6,60	12,07	(-39,12; 25,92)	-0,55	0,9468
Single-jersey 2 (HDOW)-Single-jersey 1 (HDOW)	1,10	12,07	(-31,42; 33,62)	0,09	0,9997

Individual confidence level = 98,93%

APPENDIX 4. SQUARE METER WEIGHT SINGLE-JERSEY

Statistical analysis square meter weight [g/m^2], denim

One-Way ANOVA: Denim (Low); Denim (High)

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	Denim (Low); Denim (High)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	6163	6163,33	1,58	0,2188
Error	28	109034	3894,08		
Total	29	115197			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
62,4025	5,35%	1,97%	0,00%

Means

Factor	N	Mean	StDev	95% CI
Denim (Low)	15	374,80	67,51	(341,80; 407,80)
Denim (High)	15	346,13	56,84	(313,13; 379,14)

Pooled StDev = 62,4025

APPENDIX 5. YARN COUNT SINGLE-JERSEY

Yarn count [tex] single-jersey low degree of wear			
T-shirts	Yarn	yarn weight 30 cm [g]	tex [g/1000m]
1	1	0,0099	33,00
	2	0,01	33,33
	3	0,0084	28,00
	4	0,0109	36,33
	5	0,0108	36,00
	6	0,0105	35,00
2	7	0,0062	20,67
	8	0,0067	22,33
	9	0,0068	22,67
	10	0,0065	21,67
	11	0,0073	24,33
	12	0,0073	24,33
3	13	0,0057	19,00
	14	0,0053	17,67
	15	0,0051	17,00
	16	0,0047	15,67
	17	0,0056	18,67
	18	0,0053	17,67
4	19	0,0057	19,00
	20	0,0065	21,67
	21	0,0057	19,00
	22	0,0065	21,67
	23	0,006	20,00
	24	0,0065	21,67
5	25	0,0072	24,00
	26	0,0075	25,00
	27	0,0072	24,00
	28	0,0071	23,67
	29	0,0074	24,67
	30	0,0073	24,33
6	31	0,0056	18,67
	32	0,0061	20,33
	33	0,0059	19,67
	34	0,0054	18,00
	35	0,0056	18,67
	36	0,0058	19,33
7	37	0,0057	19,00
	38	0,0053	17,67
	39	0,0052	17,33
	40	0,0045	15,00
	41	0,0041	13,67
	41	0,0047	15,67
8	43	0,0072	24,00
	44	0,0059	19,67
	45	0,0076	25,33
	46	0,0062	20,67
	47	0,0061	20,33
	48	0,0074	24,67
9	49	0,0066	22,00
	50	0,0068	22,67
	51	0,0071	23,67
	52	0,0073	24,33
	53	0,0068	22,67
	54	0,0063	21,00
10	55	0,0045	15,00
	56	0,005	16,67
	57	0,0047	15,67
	58	0,0042	14,00
	59	0,0049	16,33
	60	0,0045	15,00

TOTAL:

n= 60
x̄= 21,48
σ = 5,20
CV= 24,22%

Yarn count [tex] single-jersey high degree of wear			
T-shirts	Yarn	yarn weight 30 cm [g]	tex [g/1000m]
1	1	0,0072	24,00
	2	0,0067	22,33
	3	0,0074	24,67
	4	0,0067	22,33
	5	0,0074	24,67
	6	0,0065	21,67
2	7	0,0087	29,00
	8	0,0075	25,00
	9	0,008	26,67
	10	0,007	23,33
	11	0,0083	27,67
	12	0,0076	25,33
3	13	0,0084	28,00
	14	0,0094	31,33
	15	0,01	33,33
	16	0,0091	30,33
	17	0,0085	28,33
	18	0,0092	30,67
4	19	0,0088	29,33
	20	0,0093	31,00
	21	0,0086	28,67
	22	0,0082	27,33
	23	0,0087	29,00
	24	0,008	26,67
5	25	0,006	20,00
	26	0,006	20,00
	27	0,0061	20,33
	28	0,0055	18,33
	29	0,0066	22,00
	30	0,0065	21,67
6	31	0,0072	24,00
	32	0,0069	23,00
	33	0,0064	21,33
	34	0,0084	28,00
	35	0,0069	23,00
	36	0,0079	26,33
7	37	0,0056	18,67
	38	0,0061	20,33
	39	0,006	20,00
	40	0,0061	20,33
	41	0,0062	20,67
	41	0,006	20,00
8	43	0,0058	19,33
	44	0,0057	19,00
	45	0,0057	19,00
	46	0,0066	22,00
	47	0,0057	19,00
	48	0,0063	21,00
9	49	0,0049	16,33
	50	0,0057	19,00
	51	0,0057	19,00
	52	0,0066	22,00
	53	0,0057	19,00
	54	0,0052	17,33
10	55	0,0057	19,00
	56	0,0059	19,67
	57	0,0059	19,67
	58	0,0064	21,33
	59	0,0059	19,67
	60	0,0058	19,33

TOTAL:

n= 60
x̄= 23,16
σ = 4,20
CV= 18,12%

APPENDIX 5. YARN COUNT SINGLE-JERSEY

Statistical analysis yarn count [tex], single-jersey, low and high degree of wear.

One-Way ANOVA: Single-jersey (LDOW); Single-jersey (HDOW)

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	Single-jersey (LDOW); Single-jersey (HDOW)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	84,34	84,3363	3,78	0,0544
Error	118	2635,28	22,3328		
Total	119	2719,61			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
4,72576	3,10%	2,28%	0,00%

Means

Factor	N	Mean	StDev	95% CI
Single-jersey (LDOW)	60	21,4785	5,2019	(20,2703; 22,6867)
Single-jersey (HDOW)	60	23,1552	4,1960	(21,9470; 24,3633)

Pooled StDev = 4,72576

APPENDIX 5. YARN COUNT DENIM

Yarn count denim: low degree of wear [tex]				
Denim		Yarn	yarn weight 8 cm [g]	tex [g/1000m]
1		1	0,0064	80,00
	warp	2	0,0063	78,75
		3	0,0049	61,25
		4	0,0055	68,75
	weft	5	0,0058	72,50
		6	0,0062	77,50
2		7	0,006	75,00
	warp	8	0,0059	73,75
		9	0,0064	80,00
		10	0,0063	78,75
	weft	11	0,0064	80,00
		12	0,007	87,50
3		13	0,0088	110,00
	warp	14	0,0079	98,75
		15	0,0088	110,00
		16	0,0091	113,75
	weft	17	0,0088	110,00
		18	0,01	125,00
4		19	0,0048	60,00
	warp	20	0,0052	65,00
		21	0,0042	52,50
		22	0,0043	53,75
	weft	23	0,0048	60,00
		24	0,005	62,50
5		25	0,0074	92,50
	warp	26	0,0085	106,25
		27	0,0089	111,25
		28	0,0066	82,50
	weft	29	0,006	75,00
		30	0,0065	81,25
6		31	0,0055	68,75
	warp	32	0,0053	66,25
		33	0,0051	63,75
		34	0,0086	107,50
	weft	35	0,008	100,00
		36	0,0077	96,25
7		37	0,0075	93,75
	warp	38	0,0065	81,25
		39	0,006	75,00
		40	0,006	75,00
	weft	41	0,0064	80,00
		41	0,0063	78,75
8		43	0,0068	85,00
	warp	44	0,0075	93,75
		45	0,0062	77,50
		46	0,0042	52,50
	weft	47	0,0039	48,75
		48	0,0048	60,00
9		49	0,0067	83,75
	warp	50	0,0065	81,25
		51	0,0068	85,00
		52	0,0072	90,00
	weft	53	0,0059	73,75
		54	0,007	87,50
10		55	0,0053	66,25
	warp	56	0,0054	67,50
		57	0,0065	81,25
		58	0,0059	73,75
	weft	59	0,0064	80,00
		60	0,0063	78,75
11		61	0,0068	85,00
	warp	62	0,0077	96,25
		63	0,0076	95,00
		64	0,0091	113,75
	weft	65	0,0093	116,25
		66	0,0093	116,25
12		67	0,0087	108,75
	warp	68	0,0075	93,75
		69	0,0072	90,00
		70	0,0087	108,75
	weft	71	0,007	87,50
		72	0,0083	103,75
13		73	0,0063	78,75
	warp	74	0,0065	81,25
		75	0,0062	77,50
		76	0,005	62,50
	weft	77	0,0051	63,75
		78	0,0047	58,75
14		79	0,0072	90,00
	warp	80	0,0069	86,25
		81	0,0071	88,75
		82	0,0064	80,00
	weft	83	0,0069	86,25
		84	0,0077	96,25
15		85	0,0069	86,25
	warp	86	0,0052	65,00
		87	0,0059	73,75
		88	0,0064	80,00
	weft	89	0,0063	78,75
		90	0,0058	72,50

TOTAL:
n= 90
$\bar{x}$= 80,60
σ = 16,83
CV= 21%

Yarn count denim: high degree of wear [tex]				
Denim		Yarn	yarn weight 8 cm [g]	tex [g/1000m]
1		1	0,0052	65,00
	warp	2	0,0071	88,75
		3	0,0034	42,50
		4	0,0052	65,00
	weft	5	0,0045	56,25
		6	0,0047	58,75
2		7	0,0046	57,50
	warp	8	0,0044	55,00
		9	0,0043	53,75
		10	0,0056	70,00
	weft	11	0,0062	77,50
		12	0,006	75,00
3		13	0,0083	103,75
	warp	14	0,0054	67,50
		15	0,0064	80,00
		16	0,0074	92,50
	weft	17	0,0087	108,75
		18	0,0087	108,75
4		19	0,0035	43,75
	warp	20	0,0035	43,75
		21	0,0037	46,25
		22	0,0038	47,50
	weft	23	0,0044	55,00
		24	0,005	62,50
5		25	0,0076	95,00
	warp	26	0,0081	101,25
		27	0,0087	108,75
		28	0,0064	80,00
	weft	29	0,0059	73,75
		30	0,0064	80,00
6		31	0,0048	60,00
	warp	32	0,0044	55,00
		33	0,0041	51,25
		34	0,0069	86,25
	weft	35	0,0068	85,00
		36	0,0069	86,25
7		37	0,0063	78,75
	warp	38	0,0051	63,75
		39	0,0062	77,50
		40	0,0058	72,50
	weft	41	0,0058	72,50
		41	0,0062	77,50
8		43	0,0074	92,50
	warp	44	0,0079	98,75
		45	0,0073	91,25
		46	0,004	50,00
	weft	47	0,0049	61,25
		48	0,0051	63,75
9		49	0,0074	92,50
	warp	50	0,0075	93,75
		51	0,0078	97,50
		52	0,007	87,50
	weft	53	0,0065	81,25
		54	0,0064	80,00
10		55	0,0063	78,75
	warp	56	0,0082	102,50
		57	0,0061	76,25
		58	0,0063	78,75
	weft	59	0,0066	82,50
		60	0,0074	92,50
11		61	0,0046	57,50
	warp	62	0,0052	65,00
		63	0,0043	53,75
		64	0,0082	102,50
	weft	65	0,0083	103,75
		66	0,0077	96,25
12		67	0,0054	67,50
	warp	68	0,0065	81,25
		69	0,0067	83,75
		70	0,0065	81,25
	weft	71	0,0064	80,00
		72	0,0072	90,00
13		73	0,0052	65,00
	warp	74	0,0057	71,25
		75	0,0058	72,50
		76	0,0055	68,75
	weft	77	0,0057	71,25
		78	0,0042	52,50
14		79	0,0065	81,25
	warp	80	0,0073	91,25
		81	0,006	75,00
		82	0,0077	96,25
	weft	83	0,0082	102,50
		84	0,0086	107,50
15		85	0,0072	90,00
	warp	86	0,0067	83,75
		87	0,0085	106,25
		88	0,0066	82,50
	weft	89	0,0051	63,75
		90	0,0064	80,00

TOTAL:
n= 90
$\bar{x}$= 77,28
σ = 17,43
CV= 22,56%

APPENDIX 5. YARN COUNT DENIM

Statistical analysis yarn count [tex], denim, low and high degree of wear.

One-Way ANOVA: Denim (LDOW) warp; Denim (LDOW) weft; Denim (HDOW) warp; Denim (HDOW) weft

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	4	Denim (LDOW) warp; Denim (LDOW) weft; Denim (HDOW) warp; Denim (HDOW) weft

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	3	1623,1	541,030	1,85	0,1405
Error	176	51576,0	293,046		
Total	179	53199,1			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
17,1186	3,05%	1,40%	0,00%

Means

Factor	N	Mean	StDev	95% CI
Denim (LDOW) warp	45	82,694	14,307	(77,658; 87,731)
Denim (LDOW) weft	45	83,028	18,913	(77,992; 88,064)
Denim (HDOW) warp	45	75,722	18,789	(70,686; 80,758)
Denim (HDOW) weft	45	78,833	16,024	(73,797; 83,870)

Pooled StDev = 17,1186

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
Denim (LDOW) weft	45	83,028	A
Denim (LDOW) warp	45	82,694	A
Denim (HDOW) weft	45	78,833	A
Denim (HDOW) warp	45	75,722	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
Denim (LDOW) weft-Denim (LDOW) warp	0,333	3,609	(-9,032; 9,699)	0,09	0,9997
Denim (HDOW) warp-Denim (LDOW) warp	-6,972	3,609	(-16,338; 2,393)	-1,93	0,2185
Denim (HDOW) weft-Denim (LDOW) warp	-3,861	3,609	(-13,227; 5,504)	-1,07	0,7083
Denim (HDOW) warp-Denim (LDOW) weft	-7,306	3,609	(-16,671; 2,060)	-2,02	0,1830
Denim (HDOW) weft-Denim (LDOW) weft	-4,194	3,609	(-13,560; 5,171)	-1,16	0,6514
Denim (HDOW) weft-Denim (HDOW) warp	3,111	3,609	(-6,254; 12,477)	0,86	0,8244

Individual confidence level = 98,97%

APPENDIX 6. YARN TWIST SINGLE-JERSEY

Yarn twist [twist/m]single-jersey low degree of wear				
T-shirt	Yarn	Turns	length [cm]	Twist
1	1	46	12	383
	2	49	12	408
	3	51	12	425
	4	53	12	442
	5	41	12	342
	6	45	12	375
2	7	47	12	392
	8	44	12	367
	9	48	12	400
	10	41	12	342
	11	49	12	408
	12	41	12	342
3	13	46	12	383
	14	48	12	400
	15	44	12	367
	16	44	12	367
	17	39	12	325
	18	41	12	342
4	19	33	12	275
	20	36	12	300
	21	31	12	258
	22	29	12	242
	23	34	12	283
	24	33	12	275
5	25	33	12	275
	26	30	12	250
	27	31	12	258
	28	28	12	233
	29	32	12	267
	30	25	12	208
6	31	37	12	308
	32	26	12	217
	33	31	12	258
	34	29	12	242
	35	36	12	300
	36	29	12	242
7	37	32	12	267
	38	33	12	275
	39	39	12	325
	40	32	12	267
	41	35	12	292
	42	41	12	342
8	43	27	12	225
	44	25	12	208
	45	30	12	250
	46	24	12	200
	47	32	12	267
	48	30	12	250
9	49	51	12	425
	50	51	12	425
	51	53	12	442
	52	48	12	400
	53	53	12	442
	54	50	12	417
10	55	30	12	250
	56	36	12	300
	57	29	12	242
	58	24	12	200
	59	36	12	300
	60	39	12	325

TOTAL:

n= 60
$\bar{x}$= 314
σ = 72
CV= 22,9%

Yarn twist [twist/m] single-jersey high degree of wear				
T-shirt	Yarn	Turns	length [cm]	Twist
1	1	54	12	450
	2	60	12	500
	3	59	12	492
	4	61	12	508
	5	61	12	508
	6	62	12	517
2	7	32	12	267
	8	41	12	342
	9	42	12	350
	10	31	12	258
	11	40	12	333
	12	39	12	325
3	13	33	12	275
	14	34	12	283
	15	39	12	325
	16	29	12	242
	17	31	12	258
	18	39	12	325
4	19	54	12	450
	20	33	12	275
	21	42	12	350
	22	49	12	408
	23	37	12	308
	24	45	12	375
5	25	37	12	308
	26	43	12	358
	27	36	12	300
	28	41	12	342
	29	39	12	325
	30	41	12	342
6	31	28	12	233
	32	34	12	283
	33	31	12	258
	34	26	12	217
	35	32	12	267
	36	28	12	233
7	37	66	12	550
	38	53	12	442
	39	67	12	558
	40	61	12	508
	41	60	12	500
	42	51	12	425
8	43	27	12	225
	44	30	12	250
	45	33	12	275
	46	33	12	275
	47	24	12	200
	48	21	12	175
9	49	39	12	325
	50	46	12	383
	51	37	12	308
	52	53	12	442
	53	53	12	442
	54	38	12	317
10	55	30	12	250
	56	32	12	267
	57	39	12	325
	58	41	12	342
	59	40	12	333
	60	40	12	333

TOTAL:

n= 60
$\bar{x}$= 344
σ = 96
CV= 27,9%

APPENDIX 6. YARN TWIST SINGLE-JERSEY

Statistical analysis yarn twist [twist/m], single-jersey low and high degree of wear

One-Way ANOVA: Single-jersey (LDOW); Single-jersey (HDOW)

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	Single-jersey (LDOW); Single-jersey (HDOW)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	27090	27090,1	3,78	0,0544
Error	118	846669	7175,2		
Total	119	873759			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
84,7063	3,10%	2,28%	0,00%

Means

Factor	N	Mean	StDev	95% CI
Single-jersey (LDOW)	60	313,950	71,862	(292,295; 335,605)
Single-jersey (HDOW)	60	344,00	95,84	(322,34; 365,66)

Pooled StDev = 84,7063

APPENDIX 6. YARN TWIST DENIM

Yarn twist denim: low degree of wear [twist/m]

Denim	Yarn	Count	Turns	Length [m]	Twist
1	Warp	1	51	0,12	425
		2	56	0,12	467
		3	68	0,12	567
	Weft	4	16	0,07	229
		5	15	0,07	214
		6	15	0,07	214
2	Warp	7	47	0,12	392
		8	48	0,12	400
		9	49	0,12	408
	Weft	10	19	0,07	271
		11	16	0,07	229
		12	21	0,07	300
3	Warp	13	47	0,12	392
		14	48	0,12	400
		15	49	0,12	408
	Weft	16	18	0,07	257
		17	17	0,07	243
		18	16	0,07	229
4	Warp	19	20	0,12	167
		20	19	0,12	158
		21	29	0,12	242
	Weft	22	11	0,07	157
		23	20	0,07	286
		24	12	0,07	171
5	Warp	25	59	0,12	492
		26	53	0,12	442
		27	40	0,12	333
	Weft	28	20	0,07	286
		29	24	0,07	343
		30	25	0,07	357
6	Warp	31	32	0,12	267
		32	42	0,12	350
		33	37	0,12	308
	Weft	34	25	0,07	357
		35	28	0,07	400
		36	32	0,07	457
7	Warp	37	32	0,12	267
		38	29	0,12	242
		39	35	0,12	292
	Weft	40	10	0,07	143
		41	12	0,07	171
		42	11	0,07	157
8	Warp	43	67	0,12	558
		44	68	0,12	567
		45	71	0,12	592
	Weft	46	12	0,07	171
		47	16	0,07	229
		48	23	0,07	329
9	Warp	49	31	0,12	258
		50	33	0,12	275
		51	46	0,12	383
	Weft	52	13	0,07	186
		53	16	0,07	229
		54	9	0,07	129
10	Warp	55	37	0,12	308
		56	30	0,12	250
		57	43	0,12	358
	Weft	58	11	0,07	157
		59	15	0,07	214
		60	19	0,07	271
11	Warp	61	32	0,12	267
		62	31	0,12	258
		63	28	0,12	233
	Weft	64	10	0,07	143
		65	14	0,07	200
		66	14	0,07	200
12	Warp	67	44	0,12	367
		68	31	0,12	258
		69	41	0,12	342
	Weft	70	11	0,07	157
		71	16	0,07	229
		72	10	0,07	143
13	Warp	73	59	0,12	492
		74	46	0,12	383
		75	47	0,12	392
	Weft	76	11	0,07	157
		77	10	0,07	143
		78	14	0,07	200
14	Warp	79	67	0,12	558
		80	69	0,12	575
		81	43	0,12	358
	Weft	82	23	0,07	329
		83	22	0,07	314
		84	25	0,07	357
15	Warp	85	54	0,12	450
		86	50	0,12	417
		87	60	0,12	500
	Weft	88	17	0,07	243
		89	12	0,07	171
		90	17	0,07	243

TOTAL:

n=	90
x̄=	305
σ =	119
CV=	39,06%

Yarn twist denim: low degree of wear [twist/m]

Denim	Yarn	Count	Turns	Length [m]	Twist
1	Warp	1	49	0,12	408
		2	32	0,12	267
		3	39	0,12	325
	Weft	4	25	0,07	357
		5	24	0,07	343
		6	20	0,07	286
2	Warp	7	20	0,12	167
		8	11	0,12	92
		9	9	0,12	75
	Weft	10	9	0,07	129
		11	9	0,07	129
		12	10	0,07	143
3	Warp	13	32	0,12	267
		14	20	0,12	167
		15	19	0,12	158
	Weft	16	9	0,07	129
		17	12	0,07	171
		18	9	0,07	129
4	Warp	19	22	0,12	183
		20	16	0,12	133
		21	14	0,12	117
	Weft	22	8	0,07	114
		23	13	0,07	186
		24	11	0,07	157
5	Warp	25	55	0,12	458
		26	46	0,12	383
		27	49	0,12	408
	Weft	28	33	0,07	471
		29	28	0,07	400
		30	23	0,07	329
6	Warp	31	16	0,12	133
		32	21	0,12	175
		33	13	0,12	108
	Weft	34	14	0,07	200
		35	11	0,07	157
		36	19	0,07	271
7	Warp	37	28	0,12	233
		38	20	0,12	167
		39	19	0,12	158
	Weft	40	15	0,07	214
		41	16	0,07	229
		42	22	0,07	314
8	Warp	43	35	0,12	292
		44	48	0,12	400
		45	35	0,12	292
	Weft	46	13	0,07	186
		47	13	0,07	186
		48	19	0,07	271
9	Warp	49	23	0,12	192
		50	19	0,12	158
		51	27	0,12	225
	Weft	52	21	0,07	300
		53	10	0,07	143
		54	15	0,07	214
10	Warp	55	14	0,12	117
		56	24	0,12	200
		57	18	0,12	150
	Weft	58	19	0,07	271
		59	17	0,07	243
		60	21	0,07	300
11	Warp	61	16	0,12	133
		62	17	0,12	142
		63	18	0,12	150
	Weft	64	16	0,07	229
		65	10	0,07	143
		66	13	0,07	186
12	Warp	67	29	0,12	242
		68	34	0,12	283
		69	35	0,12	292
	Weft	70	18	0,07	257
		71	11	0,07	157
		72	9	0,07	129
13	Warp	73	16	0,12	133
		74	14	0,12	117
		75	19	0,12	158
	Weft	76	17	0,07	243
		77	15	0,07	214
		78	16	0,07	229
14	Warp	79	29	0,12	242
		80	24	0,12	200
		81	18	0,12	150
	Weft	82	15	0,07	214
		83	14	0,07	200
		84	14	0,07	200
15	Warp	85	59	0,12	492
		86	60	0,12	500
		87	57	0,12	475
	Weft	88	17	0,07	243
		89	21	0,07	300
		90	26	0,07	371

TOTAL:

n=	90
x̄=	229
σ =	100
CV=	43,76%

APPENDIX 6. YARN TWIST DENIM

Statistical analysis yarn twist [twist/m], denim low and high degree of wear

One-Way ANOVA: Denim (LDOW) warp; Denim (LDOW) weft; Denim (HDOW) warp; Denim (HDOW) weft

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	4	Denim (LDOW) warp; Denim (LDOW) weft; Denim (HDOW) warp; Denim (HDOW) weft

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	3	686619	228873	23,33	<0,0001
Error	176	1726809	9811		
Total	179	2413428			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
99,0526	28,45%	27,23%	25,16%

Means

Factor	N	Mean	StDev	95% CI
Denim (LDOW) warp	45	373,73	113,37	(344,59; 402,87)
Denim (LDOW) weft	45	235,89	78,18	(206,75; 265,03)
Denim (HDOW) warp	45	229,27	116,54	(200,13; 258,41)
Denim (HDOW) weft	45	228,60	81,85	(199,46; 257,74)

Pooled StDev = 99,0526

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping	
Denim (LDOW) warp	45	373,73	A	
Denim (LDOW) weft	45	235,89		B
Denim (HDOW) warp	45	229,27		B
Denim (HDOW) weft	45	228,60		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
Denim (LDOW) weft-Denim (LDOW) warp	-137,84	20,88	(-192,04; -83,65)	-6,60	<0,0001
Denim (HDOW) warp-Denim (LDOW) warp	-144,47	20,88	(-198,66; -90,28)	-6,92	<0,0001
Denim (HDOW) weft-Denim (LDOW) warp	-145,13	20,88	(-199,32; -90,94)	-6,95	<0,0001
Denim (HDOW) warp-Denim (LDOW) weft	-6,62	20,88	(-60,81; 47,57)	-0,32	0,9889
Denim (HDOW) weft-Denim (LDOW) weft	-7,29	20,88	(-61,48; 46,90)	-0,35	0,9854
Denim (HDOW) weft-Denim (HDOW) warp	-0,67	20,88	(-54,86; 53,52)	-0,03	1,0000

Individual confidence level = 98,97%

APPENDIX 7. TWIST FACTOR SINGLE-JERSEY

Statistical analysis twist factor [twist m^{-1} $tex^{1/2}$], single-jersey low and high degree of wear

One-Way ANOVA: Single-jersey (LDOW); Single-jersey (HDOW)

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	Single-jersey (LDOW); Single-jersey (HDOW)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	1032864	1032864	5,23	0,0240
Error	118	23306136	197510		
Total	119	24339000			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
444,421	4,24%	3,43%	0,97%

Means

Factor	N	Mean	StDev	95% CI
Single-jersey (LDOW)	60	1457,90	435,89	(1344,28; 1571,52)
Single-jersey (HDOW)	60	1643,45	452,79	(1529,83; 1757,07)

Pooled StDev = 444,421

APPENDIX 7. TWIST FACTOR DENIM

Statistical analysis twist factor [twist m^{-1} $tex^{1/2}$], denim low and high degree of wear

One-Way ANOVA: Denim (LDOW) warp; Denim (LDOW) weft; Denim (HDOW) warp; Denim (HDOW) weft

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	4	Denim (LDOW) warp; Denim (LDOW) weft; Denim (HDOW) warp; Denim (HDOW) weft

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	3	60490932	20163644	21,19	<0,0001
Error	176	167454321	951445		
Total	179	227945254			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
975,420	26,54%	25,29%	23,16%

Means

Factor	N	Mean	StDev	95% CI
Denim (LDOW) warp	45	3402,4	1093,8	(3115,4; 3689,3)
Denim (LDOW) weft	45	2148,0	798,8	(1861,1; 2435,0)
Denim (HDOW) warp	45	2049,3	1208,7	(1762,3; 2336,2)
Denim (HDOW) weft	45	2008,8	714,3	(1721,8; 2295,8)

Pooled StDev = 975,420

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping	
Denim (LDOW) warp	45	3402,4	A	
Denim (LDOW) weft	45	2148,0		B
Denim (HDOW) warp	45	2049,3		B
Denim (HDOW) weft	45	2008,8		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
Denim (LDOW) weft-Denim (LDOW) warp	-1254,3	205,6	(-1788,0; -720,7)	-6,10	<0,0001
Denim (HDOW) warp-Denim (LDOW) warp	-1353,1	205,6	(-1886,7; -819,4)	-6,58	<0,0001
Denim (HDOW) weft-Denim (LDOW) warp	-1393,6	205,6	(-1927,2; -859,9)	-6,78	<0,0001
Denim (HDOW) warp-Denim (LDOW) weft	-98,8	205,6	(-632,4; 434,9)	-0,48	0,9634
Denim (HDOW) weft-Denim (LDOW) weft	-139,2	205,6	(-672,9; 394,4)	-0,68	0,9057
Denim (HDOW) weft-Denim (HDOW) warp	-40,5	205,6	(-574,1; 493,2)	-0,20	0,9973

Individual confidence level = 98,97%

APPENDIX 8. FIBRE WIDTH

Fibre width [αm]

Single-jersey		
Count	Low	High
1	24,87	20,3
2	20,25	22,69
3	20,37	16,41
4	21,38	22,75
5	23,84	20,05
6	22,21	22,26
7	20,2	24,8
8	20,46	29,98
9	21,29	19,29
10	20,68	19,95
11	20,62	19,29
12	17,11	22,64
13	19,17	19,87
14	18,27	17,05
15	22,6	20,25
16	14,39	16,22
17	18,99	17,31
18	19,66	22,93
19	14,61	16,99
20	21,96	22,21
21	17,53	16,99
22	16,02	17,42
23	16,08	17,56
24	14,7	27,49
25	19,34	20,66
26	26,29	18,08
27	21,92	16,41
28	18,07	17,11
29	19,6	18,71
30	25,13	22,86
31	15,49	19,66
32	24,55	20,37
33	18,14	14,55
34	19,66	27,76
35	18,04	18,62
36	18,3	20,3
37	20,25	14,98
38	21,48	19,73
39	24,1	21,19
40	16,22	16,99
$\bar{x}$=	19,8	20,0
σ =	3,0	3,4
CV=	15,2%	17,1%

Denim				
	Low		High	
Count	Warp	Weft	Warp	Weft
1	18,26	18,07	20,58	21,07
2	23,57	16,03	27,27	25,32
3	15,77	19,66	27,49	17,42
4	17,59	22,82	20,25	22,92
5	22,5	22,21	19,04	19,29
6	18,14	21,29	18,71	20,5
7	18,99	23,2	21,57	18,72
8	20,89	15,63	24,55	22,5
9	17,77	19,84	23,7	22,18
10	21,71	16,94	23,52	24,14
11	14,62	19,28	21,89	17,24
12	21,29	23,75	25,9	16,41
13	19,11	24,28	21,71	30,99
14	16,13	26,18	18,04	19
15	17,36	27,49	26,29	19,87
16	17,19	21,48	19,28	16,56
17	19	17,66	19,72	20,93
18	18,85	18,48	21,57	23,24
19	26,29	26,22	21,07	17,66
20	24,83	22,55	20,46	20,46
21	30,11	17,42	20,34	19,87
22	14,03	18,08	19,93	16,22
23	20,15	23,84	17,66	18,62
24	16,65	24,1	19,84	22,69
25	23,3	28,52	26,1	21,57
26	18,04	32,34	21,89	21,69
27	17,11	25,51	24,81	23,24
28	16,94	14,68	19,72	17,42
29	16,22	24,5	21,89	17,59
30	23,96	22,21	25,93	18,59
31	18,43	21,89	20,79	24,71
32	28,94	24,87	18,07	22,65
33	19,17	21,23	15,25	16,07
34	19,6	22,55	20,91	25,82
35	23,52	20,67	23,42	16,56
36	23,33	21,92	14,4	19,77
37	20,5	27,03	26,38	27,65
38	17,83	26,13	15,35	18,43
39	18,14	27,96	17,66	18,78
40	26,78	19	18,59	19,65
$\bar{x}$=	20,1	22,2	21,3	20,6
σ =	3,8	3,9	3,3	3,4
CV=	18,8%	17,8%	15,6%	16,3%

APPENDIX 8. FIBRE WIDTH

Statistical analysis fibre width [αm] – single-jersey and denim, low and high degree of wear respectively

One-Way ANOVA: Single-jersey (LDOW); Single-jersey (HDOW)

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	Single-jersey (LDOW); Single-jersey (HDOW)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	0,585	0,5848	0,06	0,8134
Error	78	812,770	10,4201		
Total	79	813,355			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3,22802	0,07%	0,00%	0,00%

Means

Factor	N	Mean	StDev	95% CI
Single-jersey (LDOW)	40	19,8460	3,0194	(18,8299; 20,8621)
Single-jersey (HDOW)	40	20,0170	3,4240	(19,0009; 21,0331)

Pooled StDev = 3,22802

One-Way ANOVA: Denim warp (LDOW); Denim weft (LDOW); Denim warp (HDOW); Denim weft (HDOW)

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	4	Denim warp (LDOW); Denim weft (LDOW); Denim warp (HDOW); Denim weft (HDOW)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	3	100,90	33,6336	2,58	0,0557
Error	156	2034,41	13,0411		
Total	159	2135,31			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3,61124	4,73%	2,89%	0,00%

Means

Factor	N	Mean	StDev	95% CI
Denim warp (LDOW)	40	20,0653	3,7819	(18,9374; 21,1931)
Denim weft (LDOW)	40	22,1878	3,9389	(21,0599; 23,3156)
Denim warp (HDOW)	40	21,2885	3,3315	(20,1606; 22,4164)
Denim weft (HDOW)	40	20,6003	3,3538	(19,4724; 21,7281)

Pooled StDev = 3,61124

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping	
Denim weft (LDOW)	40	22,1878	A	
Denim warp (HDOW)	40	21,2885	A	B
Denim weft (HDOW)	40	20,6003	A	B
Denim warp (LDOW)	40	20,0653		B

Means that do not share a letter are significantly different.

APPENDIX 9. INPUT FIBRE LENGTH SINGLE-JERSEY

Single-jersey	
Low degree of wear	
Zone 1	
Fiber length [mm]	Frequence
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	2
11	2
12	5
13	6
14	1
15	14
16	15
17	10
18	14
19	23
20	17
21	29
22	16
23	20
24	18
25	27
26	19
27	21
28	9
29	8
30	11
31	5
32	5
33	1
34	
35	1
36	
37	1
38	
39	
40	

TOTAL:

n= 300
$\bar{x}$= 22
σ = 5
CV= 22,73%

Single-jersey	
Low degree of wear	
Zone 2	
Fiber length [mm]	Frequence
1	
2	
3	
4	
5	
6	
7	
8	1
9	
10	1
11	5
12	11
13	4
14	6
15	14
16	11
17	11
18	13
19	10
20	18
21	37
22	18
23	23
24	22
25	23
26	16
27	17
28	12
29	10
30	10
31	3
32	3
33	1
34	
35	
36	
37	
38	
39	
40	

TOTAL:

n= 300
$\bar{x}$= 22
σ = 5
CV= 22,73%

APPENDIX 9. INPUT FIBRE LENGTH SINGLE-JERSEY

Single-jersey	
High degree of wear	
Zone 1	
Fiber length [mm]	Frequence
1	
2	
3	
4	
5	
6	1
7	6
8	4
9	9
10	12
11	18
12	8
13	16
14	14
15	20
16	18
17	15
18	13
19	20
20	19
21	21
22	9
23	13
24	10
25	14
26	11
27	7
28	6
29	5
30	3
31	1
32	3
33	2
34	
35	2
36	
37	
38	
39	
40	

TOTAL:

n= 300
x̄= 18
σ = 6
CV= 32,82%

Single-jersey	
High degree of wear	
Zone 2	
Fiber length [mm]	Frequence
1	
2	
3	
4	
5	
6	1
7	5
8	3
9	7
10	9
11	12
12	11
13	9
14	22
15	14
16	19
17	15
18	13
19	27
20	22
21	23
22	16
23	16
24	11
25	14
26	10
27	3
28	6
29	3
30	5
31	1
32	1
33	1
34	
35	1
36	
37	
38	
39	
40	

TOTAL:

n= 300
x̄= 19
σ = 6
CV= 32,39%

APPENDIX 9. INPUT FIBRE LENGTH SINGLE-JERSEY

Statistical analysis input fibre length [mm], single-jersey low and high degree of wear in conjunction with zone 1-2

One-Way ANOVA: Single-jersey 1 (LDOW); Single-jersey 2 (LDOW); Single-jersey 1 (HDOW); Single-jersey 2 (HDOW)

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	4	Single-jersey 1 (LDOW); Single-jersey 2 (LDOW); Single-jersey 1 (HDOW); Single-jersey 2 (HDOW)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	3	3893,4	1297,80	43,13	<0,0001
Error	1196	35987,0	30,09		
Total	1199	39880,4			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
5,48538	9,76%	9,54%	9,16%

Means

Factor	N	Mean	StDev	95% CI
Single-jersey 1 (LDOW)	300	22,2200	5,0328	(21,5987; 22,8413)
Single-jersey 2 (LDOW)	300	21,7533	5,0825	(21,1320; 22,3747)
Single-jersey 1 (HDOW)	300	18,2833	6,1467	(17,6620; 18,9047)
Single-jersey 2 (HDOW)	300	18,5233	5,6048	(17,9020; 19,1447)

Pooled StDev = 5,48538

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping	
Single-jersey 1 (LDOW)	300	22,2200	A	
Single-jersey 2 (LDOW)	300	21,7533	A	
Single-jersey 2 (HDOW)	300	18,5233		B
Single-jersey 1 (HDOW)	300	18,2833		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
Single-jersey 2 (LDOW)-Single-jersey 1 (LDOW)	-0,4667	0,4479	(-1,6163; 0,6830)	-1,04	0,7247
Single-jersey 1 (HDOW)-Single-jersey 1 (LDOW)	-3,9367	0,4479	(-5,0863; -2,7870)	-8,79	<0,0001
Single-jersey 2 (HDOW)-Single-jersey 1 (LDOW)	-3,6967	0,4479	(-4,8463; -2,5470)	-8,25	<0,0001
Single-jersey 1 (HDOW)-Single-jersey 2 (LDOW)	-3,4700	0,4479	(-4,6196; -2,3204)	-7,75	<0,0001
Single-jersey 2 (HDOW)-Single-jersey 2 (LDOW)	-3,2300	0,4479	(-4,3796; -2,0804)	-7,21	<0,0001
Single-jersey 2 (HDOW)-Single-jersey 1 (HDOW)	0,2400	0,4479	(-0,9096; 1,3896)	0,54	0,9503

Individual confidence level = 98,96%

APPENDIX 10. INPUT FIBRE LENGTH DENIM

Denim high degree of wear	
Warp	
Fibre length [mm]	Frequence
1	
2	
3	
4	
5	
6	3
7	1
8	8
9	20
10	21
11	26
12	26
13	23
14	26
15	28
16	37
17	29
18	23
19	35
20	29
21	18
22	19
23	13
24	12
25	12
26	12
27	4
28	6
29	7
30	4
31	3
32	1
33	2
34	1
35	1
36	
37	
38	
39	
40	
TOTAL:	
n=	450
$\bar{x}$=	17
σ =	6
CV=	35,3%

Denim low degree of wear	
Warp	
Fibre length [mm]	Frequence
1	
2	
3	
4	
5	
6	
7	1
8	
9	1
10	2
11	9
12	14
13	13
14	14
15	22
16	27
17	20
18	13
19	24
20	30
21	31
22	31
23	19
24	22
25	45
26	23
27	16
28	16
29	16
30	12
31	12
32	10
33	2
34	
35	5
36	
37	
38	
39	
40	
TOTAL:	
n=	450
$\bar{x}$=	22
σ =	6
CV=	27,27%

APPENDIX 10. INPUT FIBRE LENGTH DENIM

Denim high degree of wear	
Weft	
Fibre length [mm]	Frequence
1	
2	
3	
4	
5	
6	
7	3
8	1
9	6
10	9
11	17
12	16
13	16
14	20
15	30
16	22
17	27
18	20
19	29
20	28
21	28
22	21
23	28
24	22
25	21
26	19
27	19
28	8
29	8
30	13
31	7
32	7
33	3
34	1
35	
36	
37	
38	1
39	
40	
TOTAL:	
n=	450
$\bar{x}$=	20
σ =	6
CV=	30,0%

Denim low degree of wear	
Weft	
Fibre length [mm]	Frequence
1	
2	
3	
4	
5	
6	
7	1
8	1
9	2
10	4
11	10
12	10
13	14
14	6
15	13
16	21
17	21
18	18
19	15
20	25
21	39
22	30
23	32
24	31
25	29
26	19
27	28
28	25
29	12
30	15
31	9
32	8
33	5
34	3
35	2
36	1
37	1
38	
39	
40	
TOTAL:	
n=	450
$\bar{x}$=	21
σ =	6
CV=	28,57%

APPENDIX 10. INPUT FIBRE LENGTH DENIM

Statistical analysis fibre length [mm], denim low and high degree of wear in conjunction with warp and weft

One-Way ANOVA: Denim warp (LDOW); Denim weft (LDOW); Denim warp (HDOW); Denim weft (HDOW)

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	4	Denim warp (LDOW); Denim weft (LDOW); Denim warp (HDOW); Denim weft (HDOW)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	3	6460,0	2153,33	64,82	<0,0001
Error	1796	59666,8	33,22		
Total	1799	66126,8			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
5,76386	9,77%	9,62%	9,37%

Means

Factor	N	Mean	StDev	95% CI
Denim warp (LDOW)	450	21,5956	5,7098	(21,0627; 22,1285)
Denim weft (LDOW)	450	22,0956	5,7282	(21,5627; 22,6285)
Denim warp (HDOW)	450	17,2400	5,6753	(16,7071; 17,7729)
Denim weft (HDOW)	450	19,9644	5,9383	(19,4315; 20,4973)

Pooled StDev = 5,76386

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping		
Denim weft (LDOW)	450	22,0956	A		
Denim warp (LDOW)	450	21,5956	A		
Denim weft (HDOW)	450	19,9644		B	
Denim warp (HDOW)	450	17,2400			C

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
Denim weft (LDOW)-Denim warp (LDOW)	0,5000	0,3843	(-0,4863; 1,4863)	1,30	0,5621
Denim warp (HDOW)-Denim warp (LDOW)	-4,3556	0,3843	(-5,3419; -3,3692)	-11,34	<0,0001
Denim weft (HDOW)-Denim warp (LDOW)	-1,6311	0,3843	(-2,6174; -0,6448)	-4,24	0,0001
Denim warp (HDOW)-Denim weft (LDOW)	-4,8556	0,3843	(-5,8419; -3,8692)	-12,64	<0,0001
Denim weft (HDOW)-Denim weft (LDOW)	-2,1311	0,3843	(-3,1174; -1,1448)	-5,55	<0,0001
Denim weft (HDOW)-Denim warp (HDOW)	2,7244	0,3843	(1,7381; 3,7108)	7,09	<0,0001

Individual confidence level = 98,97%

APPENDIX 11. OUTPUT FIBRE LENGTH SINGLE-JERSEY

Single-jersey	
Low degree of wear	
Fiber length [mm]	Frequence
1	8
2	20
3	30
4	29
5	30
6	41
7	44
8	22
9	18
10	30
11	33
12	27
13	24
14	16
15	24
16	30
17	11
18	6
19	11
20	9
21	13
22	7
23	5
24	4
25	2
26	1
27	1
28	2
29	1
30	1
31	
32	
33	
34	
35	

TOTAL:

n= 500
$\bar{x}$= 10
σ = 6
CV= 58%

Single-jersey	
Mixture	
Fiber length [mm]	Frequence
1	11
2	24
3	35
4	41
5	32
6	34
7	36
8	20
9	26
10	29
11	22
12	22
13	19
14	18
15	18
16	17
17	7
18	13
19	18
20	13
21	7
22	11
23	6
24	5
25	3
26	6
27	3
28	2
29	1
30	
31	1
32	
33	
34	
35	

TOTAL:

n= 500
$\bar{x}$= 10
σ = 7
CV= 67%

Single-jersey	
High degree of wear	
Fiber length [mm]	Frequence
1	11
2	17
3	32
4	37
5	32
6	26
7	29
8	22
9	19
10	18
11	24
12	17
13	24
14	18
15	19
16	20
17	17
18	13
19	11
20	17
21	20
22	19
23	4
24	3
25	4
26	11
27	5
28	2
29	1
30	3
31	2
32	
33	2
34	
35	1

TOTAL:

n= 500
$\bar{x}$= 12
σ = 7
CV= 59%

APPENDIX 11. OUTPUT FIBRE LENGTH SINGLE-JERSEY

Statistical analysis fibre length [mm], single-jersey low and high degree of wear and mixture

One-Way ANOVA: LDOW; HDOW; MIXTURE

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	3	LDOW; HDOW; MIXTURE

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	2	660,9	330,429	7,38	0,0006
Error	1497	66991,1	44,750		
Total	1499	67651,9			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
6,68956	0,98%	0,84%	0,58%

Means

Factor	N	Mean	StDev	95% CI
LDOW	500	10,3980	5,9879	(9,8112; 10,9848)
HDOW	500	11,8120	7,3931	(11,2252; 12,3988)
MIXTURE	500	10,4100	6,6134	(9,8232; 10,9968)

Pooled StDev = 6,68956

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping	
HDOW	500	11,8120	A	
MIXTURE	500	10,4100		B
LDOW	500	10,3980		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
HDOW-LDOW	1,4140	0,4231	(0,4238; 2,4042)	3,34	0,0024
MIXTURE-LDOW	0,0120	0,4231	(-0,9782; 1,0022)	0,03	0,9996
MIXTURE-HDOW	-1,4020	0,4231	(-2,3922; -0,4118)	-3,31	0,0026

Individual confidence level = 98,06%

APPENDIX 12. OUTPUT FIBRE LENGTH DENIM

Denim	
Low degree of wear	
Fiber length [mm]	Frequence
1	10
2	14
3	18
4	26
5	26
6	36
7	32
8	13
9	12
10	22
11	23
12	26
13	17
14	21
15	17
16	24
17	28
18	14
19	16
20	18
21	22
22	11
23	12
24	10
25	7
26	4
27	6
28	7
29	3
30	3
31	
32	
33	2
34	
35	

TOTAL:
n= 500
x̄= 13
σ = 7
CV= 55%

Denim	
Mixture	
Fiber length [mm]	Frequence
1	9
2	16
3	35
4	18
5	28
6	29
7	28
8	26
9	19
10	27
11	32
12	25
13	15
14	13
15	19
16	26
17	22
18	20
19	9
20	12
21	18
22	7
23	11
24	4
25	10
26	7
27	7
28	2
29	1
30	1
31	1
32	2
33	
34	
35	1

TOTAL:
n= 500
x̄= 12
σ = 7
CV= 59,2%

Denim	
High degree of wear	
Fiber length [mm]	Frequence
1	5
2	17
3	18
4	23
5	28
6	30
7	29
8	11
9	15
10	22
11	20
12	27
13	22
14	20
15	20
16	25
17	21
18	19
19	22
20	13
21	17
22	13
23	14
24	15
25	10
26	6
27	2
28	6
29	2
30	4
31	
32	2
33	1
34	1
35	

TOTAL:
n= 500
x̄= 13
σ = 7
CV= 53%

APPENDIX 12. OUTPUT FIBRE LENGTH DENIM

Statistical analysis fibre length [mm], denim low and high degree of wear and mixture

One-Way ANOVA: LDOW; HDOW; MIXTURE

Method

Null hypothesis	H_0: All means are equal
Alternative hypothesis	H_1: At least one mean is different

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	3	LDOW; HDOW; MIXTURE

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	2	377,2	188,594	3,59	0,0278
Error	1497	78639,4	52,531		
Total	1499	79016,6			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
7,24785	0,48%	0,34%	0,08%

Means

Factor	N	Mean	StDev	95% CI
LDOW	500	12,8180	7,2979	(12,1822; 13,4538)
HDOW	500	13,2000	7,3414	(12,5642; 13,8358)
MIXTURE	500	11,9980	7,1020	(11,3622; 12,6338)

Pooled StDev = 7,24785

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping	
HDOW	500	13,2000	A	
LDOW	500	12,8180	A	B
MIXTURE	500	11,9980		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
HDOW-LDOW	0,3820	0,4584	(-0,6909; 1,4549)	0,83	0,6823
MIXTURE-LDOW	-0,8200	0,4584	(-1,8929; 0,2529)	-1,79	0,1733
MIXTURE-HDOW	-1,2020	0,4584	(-2,2749; -0,1291)	-2,62	0,0237

Individual confidence level = 98,06%

APPENDIX 13.

Frequency table of measured fibre length [mm] – 50% single-jersey and 50% denim

Single-jersey + denim	
Mixture	
Fibre length [mm]	Frequence
1	5
2	16
3	39
4	31
5	43
6	32
7	33
8	17
9	16
10	25
11	17
12	29
13	20
14	18
15	19
16	17
17	18
18	13
19	13
20	21
21	12
22	15
23	5
24	5
25	6
26	1
27	2
28	3
29	
30	5
31	1
32	2
33	
34	
35	1

TOTAL:

n= 500

$\bar{x}$= 11

σ = 7

CV= 62,13%