BEST BEFORE:

A SELECTIVE SERVICE LIFE ANALYSIS OF DENIM FABRICS WITH A FOCUS ON WASHING AND DRYING DEGRADATION TO OPTIMIZE THEIR RECYCLING EFFICIENCY

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Title: Best Before: A selective service life analysis of denim fabrics with a focus on washing and drying degradation to optimize their recycling efficiency

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Abstract

Purpose

Resource scarcity and increasing environmental pressure have raised the stakes for rethinking material efficiency and textile recycling potential. As current practices fail to feed a closed loop recycling system, this research aims to contribute to the improvement of prevailing practices regarding denim as one of the most popular apparel materials worldwide while focusing on the issue of increasing amounts of discarded post-consumer textiles. The superordinate objective to define the optimum point for denim recycling to retain the value of the cotton fibre as long as possible in a closed loop system, thereby elevating the recycling efficiency, can be considered a key driver for the present research.

Methodology

This investigation follows a research approach, which combines deductive and inductive features. A primer extensive literature review represents the theoretical fundament for the subsequent research. The following data acquisition is constructed and executed along a mixed method research, in which a qualitative approach based on expert interviews informs and builds up on the quantitative counter part of laboratory use simulation testing on two different denim fabrics and vice versa, leading to an embedded research design. A subjective assessment of potential alterations of the denim fabrics' visual and tactile characteristics, caused by the use simulation, provides quantitative data through an employed expert panel, which is enhanced by objectively recorded results from the conducted tear strength test and comparative weight investigation to inform changes regarding the physical properties.

Findings and Contribution

The applied research methods provide parameters to monitor the decomposition and weakening of the overall fabric structure throughout the experiment. The analysis of the data allowed to assign the number of washing and drying cycles, that a denim garment has undergone, to a corresponding degree of degradation. The presented findings are a valuable resource for developing and innovating current open-end recycling options. The maintenance of the raw material value throughout various reprocessing cycles can counteract the elevated natural fibre scarcity. The insights on the material and process level build a fundament for the successful operationalisation and management of sustainable recycling practices. Further research in this field can pave the way towards value retaining circularity.

Research limitations

The presented research is merely focussing on two denim fabrics as representative specimens. Thereby, the scope of the research is limited with regard to particular material behaviour. Furthermore, the practical applications during the experimental procedure raise the stakes for human error at multiple process stages.

Keywords: Denim, Recycling, Service Life Analysis, Material Utilisation, Use Optimisation, Circular Economy, Closed Loop Recycling, Fabric Degradation, Circularity, Recycling Efficiency

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1 Introduction

For a long time, the Aral Sea enjoyed a solid position among the largest lakes that planet earth inhabits. Meanwhile, the majority of the area it has formerly flooded has turned into desert. This has transferred the inhabitants of the surrounding regions, being dependent on the Aral Sea as a valuable source for fishing, agriculture and other purposes, into a disastrous situation (Burnett 2016). How does this critical circumstance connect to the presented discourse?

Today's consumption patterns, with special focus on textiles, have contributed a great deal to the presented critical development which is just one of many scenarios of its kind. The example of the Aral Sea is a thought-provoking situation that highlights the severe environmental impacts of natural resource depletion in connection to textile production and consumption. The constant demand for new clothes, driven by fashion trends that are ever growing in frequency, has forced the agricultural production of cotton fibres to its limits (Morgan 2015). Cotton fibres derive from cotton plants which are extraordinarily demanding in terms of irrigation. This fact comes along with the inevitably growing demand for water. In this respect, the Aral Sea has for a long time been considered an inexhaustible supplier. Yet, by 2007, only ten percent of the original lake area remained flooded with water (Burnett 2016).

According to Levin (2011) the behavioural habits of our modern society have evoked "a century of disposal". We are on a trajectory towards hitting environmental and hence planetary boundaries by exploiting natural resources excessively. With regard to cotton, the industry has already reached the capacity limit for cultivating it back in the 1980's. The amount of cotton being produced has been and still is forced to remain constant since then. This is however not in any way connected to a decline in the popularity of the fibre. The opposite is the case. The lack of potential for further cotton yield increase had to be compensated with a strong expansion in polyester fibre production (Koszewska 2018).

The situation of elevated material scarcity is up against an unparalleled growth in demand for the very same. Since our global society is facing a constantly increasing world population and irrepressible consumerism (Burnett 2016), the textile industry has to strive for new perspectives and technologies in order to advance their resource efficiency. Due to the depletion of cultivation capacity, this has shown to be especially challenging with regard to natural fibres such as cotton. Concludingly, the research on innovative ways to improve the raw material efficiency and thus become involved in quality retaining, closed loop recycling processes has evolved into a vital prerequisite for sufficient future provision of natural fibres. So far, the recovery of cotton is most commonly contextualised in a sense of downcycling, resulting in a loss of material quality and thus recycling efficiency (Payne 2015). In a long-term perspective, downcycling is not capable of providing convincing material efficiency. The challenge of maintaining the fibre quality of used textile goods on a well processable level for closed loop solutions remains and has become a motivating engine for research and development.

This discourse has narrowed its scope to the investigation of the recycling potential of particularly denim fabrics. This choice has been stimulated by denim being one of the most prevalent fabrics worldwide (Miller and Woodward 2011). Thus, its manufacturing represents a mainspring for cotton consumption since cotton represents the fundamental building block for denim production. Hence, the textile sector is pressured to increase the recycling potential for cotton to cover contemporary and prospective market demands. Taking this challenge as a framework for further research, this thesis aims at identifying the degradation behaviour of denim during its service lifetime in order to infer from these insights to the possibly altering recycling capability of denim in the course of its use phase.

Incentive for this investigation is the fact that the mechanical recycling potential of textiles is dependent on the quality of the feedstock (Schmidt et al. 2016). Consequently, the hypothesis that there is an optimum point for actively ending the use phase and initiating the recycling process of denim products has been deducted. It has been assumed that over an artificial termination of the service lifetime of a garment an elevated feedstock quality for mechanical recycling may ensue. This in turn comes along with a reduced necessity for downcycling and an intensified raw material efficiency. The approach to close the loop of the lifecycle of a denim garment in terms of quality retaining recycling processes is traded off against the unrestricted longevity of a denim product.

Especially when it comes to the employment of textile products on a daily basis during their service lifetime, very heterogeneous consumption and behavioural patterns are evident among the individual consumers. This impedes the deduction of universally valid assumptions with regard to a garment's use phase. Correspondingly, a comparable parameter was to be determined for the identification of the degree of fabric degradation. It was meant to mirror the lifetime of a garment at the best possible rate, irrespective of the general consumption behaviour of the particular user. Since washing and drying have proven to be responsible for a paramount amount of fabric degradation (Bresee et al. 1994) and are largely uniform procedures in every household, they have been determined as decisive parameters for the investigation of the textile decomposition of denim. In a laboratory experiment two different denim fabrics have hence been exposed to varying numbers of washing and drying cycles (0 to 50). Subsequently, their visual alteration as well as potential variations in tear strength have been measured and analysed. The experimental setup and the discussion of the gathered data have been informed by semi-structured expert interviews providing professional knowhow in the field of denim manufacturing and recycling. A panel validation served the purpose of triangulation and assessment authentication.

The framework of this thesis suggests the provision of an expiry date for denim products. This expiry date ought to depict the optimum point for returning a used garment into the recycling process. The challenge is the identification of the longest possible lifetime of the clothing item under the premise of avoiding over-degradation of the fabric, making it potentially less attractive for mechanical recycling processes. The longest possible use phase should not compromise the potential of the valuable cotton fibre to remain in a closed loop recycling system for the longest possible timespan. This proposal is linked to inevitable challenges and limitations which are likewise subject of debate.

The results of this research monitor the decomposition and weakening of the overall fabric structure throughout the experiment. The analysis of the data allows to assign the number of washing and drying cycles, that a denim garment has undergone, to a corresponding degree of degradation. Concludingly, this information is a valuable resource for developing and innovating current open-end recycling options. Thereby the maintenance of the raw material value throughout various reprocessing cycles can counteract the elevated natural fibre scarcity. The investigation of the material behaviour as well as the classification of a garment's recycling potential in varying conditions can drive sorting and recycling methods towards quality sensitive solutions. The insights on the process and material level build a fundament for the successful operationalisation and management of sustainable recycling processes. Further research in this field can pave the way towards circularity.

1.1 Background

1.1.1 Recycling – Current market, challenges and potential for post-consumer waste

The increasing consumption of textiles and their damaging impact on the environment require a rethinking of current consumption patterns. Due to a continuously growing world population the demand for textiles will keep on challenging the finite and infinite resources of our planet. Any measures for reducing the need of virgin material are therefore key to minimize any harmful impact of the inevitably increasing textile consumption (Schmidt et al. 2016). In order to steer both, economy and society, towards a more sustainable behaviour, the hierarchy of waste management, which will be further explained in chapter 3.2.5 (depicted in Figure 3), was introduced. Following this hierarchy, reduce and reuse should be the first options when aiming for efficient resource usage. Besides all exemplary effort, especially clothing items go out of fashion and their count of reuses is mostly limited by the volatility of trends. Eventually, these textiles turn into waste and are disposed by their consumers. At this stage recycling offers the opportunity to save raw materials and energy as well as to reduce pollution and definite disposal (Horrocks 1996). In comparison to reduction and reuse, the first two steps of the waste management hierarchy, which deal with the product, recycling is typically focused on the raw material employed (Worrell and Reuter, 2014). Recently it has developed from an issue of waste management towards a major subject of resource-efficiency.

Worrell and Reuter (2014) define recycling as "[…] the reprocessing of recovered materials at the end of product life, returning them into the supply chain" (Worrell and Reuter 2014, p. 5). It includes the reclaiming of pre-consumer and post-consumer waste, which can be distinguished further into four approaches: primary, secondary, tertiary and quaternary. (Vadicherla and Saravanan 2014). In the following, this research is concerned with recycling methods and practices of post-consumer textile waste which relates to the secondary approach. Within secondary recycling, post-consumer waste is collected and sorted according to quality, which determines further processing. Depending on the quality, it includes the option to resell besides chemical or mechanical processing of the material to reclaim or constitute fibres (Payne 2015).

Today, 49-65% of the collected textiles are reused, from which a majority of 90% are exported to East-European, Asian and African markets (Dahlbo et al. 2014) (Schmidt et al. 2016). According to data of textile collectors and sorting companies operating in European countries including Germany, Switzerland and the Netherlands the quality sorting steers 30-38% towards recycling, while 5-8% are refused (Englund et al. 2018).

The textile to textile recycling of 100% polyester already offers a closed loop method with the help of chemical recycling. Garments and textiles consisting of 100% cotton can so far only be recycled chemically to viscose or mechanically, which results in a major loss of quality. Accordingly, these materials are most commonly downcycled and used for carpets, rugs, cleaning, polishing, insulation or filling material. In order to use the recycled fibres for clothing and home textiles of higher quality, they need to be blended with virgin fibres (Schmidt et al. 2016). Downcycling can be equalized with open-loop recycling (OLR) system in which the reclaimed material is used to produce an unrelated and less valuable product than the disposed one (Payne 2015). It therefore results in little economic value and low environmental benefits (Zamani et al. 2015). In comparison, the opposing system of closed loop recycling (CLR) aims to generate a greater impact on sustainability. Align with the model of a circular economy, CLR describes a system in which a product remains in a circular stream and retains its material quality (Payne 2015). This system allows the recycling process to contribute with much greater benefits, economically and environmentally, to a more sustainable consumption and "disposal" of textiles, especially in a long-term perspective.

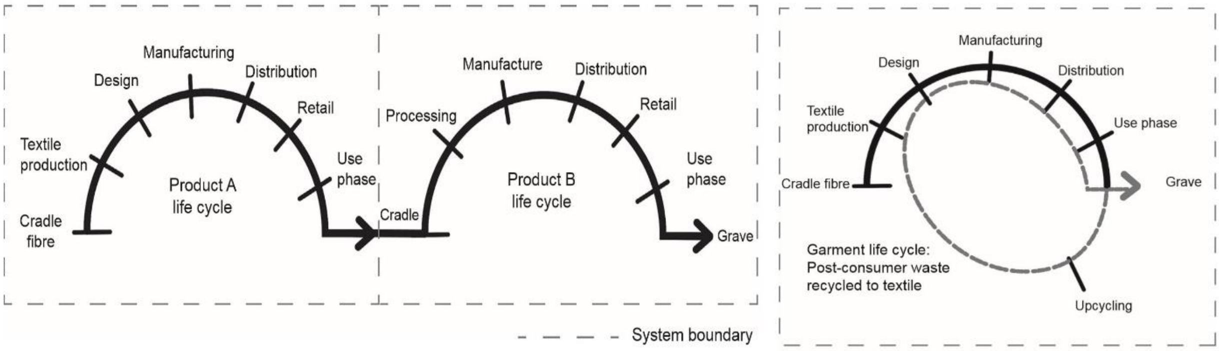


Figure 1 (l.) Open Loop Recycling, adopted from (Payne 2015), (r.) Closed Loop Recycling, adopted from (Payne 2015)

The presented discourse is focussing on the degradation of denim in order to inform industrial development of closed loop recycling processes for denim products. The challenges inherent in the process of especially cotton recycling, create obstacles in following a CLR approach. The currently available mechanical recycling processes for cotton do not deliver sufficient qualities suitable to re-enter the apparel market. Ljungkvist et al. (2018) describe a great need of recycling markets to change towards higher quality and increased value, especially with regards to current changes of the textile industry and the prominent disposal behaviour. An expected continuous increase in volume of textile donations offers great potential for the sector to develop while it simultaneously bares new challenges in building an efficient system to handle growing amounts. Additionally, to the rising volume, the last years showed a decrease in quality of the disposed items. The development of fast fashion and its impact on quality and the reuse of garments via C2C exchanges are among the mentioned reasons for the quality decrease (Ljungkvist et al. 2018).

> *"The significant increase of non-reusable textiles is a big issue for the business. From a resource point of view, it's the best way to collect as much as possible to bring textiles to a higher level of reuse and recycling. But therefore, new recycling solutions have to be established." respondent BOER Group (Ljungkvist et al. 2018, p. 32)*

In order to improve the current recycling practices Hawley (2009) points out the importance of shifting the focus from downcycling to a more holistic approach of the supply chain by integrating consumers and manufacturers into the recycling pipeline. The closing of the loop will be enhanced by a deeper understanding and integration of all actors. Accordingly, a proper incorporation of the consumer into the recycling process can support the idea and pursuit of a circular economy (Worrell and Reuter 2014). Educating consumers on recycling options and the life cycle of their clothes might be an option to help retain value within recycling process. For the nowadays mostly used OLR the quality feedstock, which refers to the condition and purity of the donated or disposed items, determines the resulting quality of the recycling process. Though, due to limitation of the mechanical recycling process used for cotton materials, it generally results in a lower fibre quality (Schmidt et al. 2016). Moreover, the shredding process causes a reduction of fibre length, which mainly determines the quality in terms of strength and evenness of the consecutive yarn and fabric production (Payne 2015). Accordingly, the recycled materials are no longer suitable for apparel production and instead are downcycled to carpets, insulation or fill material. Technical challenges within fibre separation and fibre quality are reflected in the small share of textile-to-textile recycling

(Dahlbo et al. 2014). It requires further development of sorting and recycling technologies to improve the fibre-to-fibre recycling and to use the full potential of the feedstock. Although newer systems to increase sorting efficiency and collection rates were introduced, a demand for recycling methods, that are able to preserve the input quality, remains (Elander et al. 2017a).

When Hawley (2009) points out the potential of upcycling as a value-added recycling option, the material to feed these circular businesses and practices becomes much more relevant. Quality and purity of the material itself as well as the composition of the product it originates from determine possible outputs of the recycling process (Worrell and Reuter 2014).

> *"The higher the average quality level the greater the potential size of reuse markets." (Elander et al. 2017b, p. 5)*

Hence, the management of large volumes of heterogeneous waste appears as one of the main challenges (Ljungkvist et al. 2018). Initiatives by retail companies such as the Swedish clothing brands Filippa K and Houdini, also set higher requirements for the clothes they take back. In order to achieve a greater harmonization of textile waste, these companies only collect their own products in repairable or reusable conditions. This way they do not only avoid legal problems with regards to waste collection permits, but also reduce the complexity of the collected waste as well as the high-quality variances within it (Elander et al. 2017b). Especially new business models striving for circular systems by supporting reuse and prolonging textile lifetimes face material sourcing as one of their main obstacles (Elander et al. 2017b). Additionally, consumer behaviour and lacking information on post-consumer goods can be a hurdle on the way to a more sustainable business (Schmidt et al. 2016).

While the value of used cars is industry-wide assessed along an established catalogue of parameters including driven kilometres, which indicate the level of utilization, the garment industry lacks tangible and standardized criteria to identify value and degree of degradation of textile products. Missing insights on potential alteration of fabrics during their use phase, hinders the garment sector to exploit the full potential of discarded items and decreases the efficiency of sorting processes. Hence, the rethinking of current recycling methods towards circular solutions asks to fill the gap regarding textile degradation to operationalize closed loop systems based on a clearer identification of recycling potential and value of post-consumer goods.

The idea to determine a textile's end of life stage based on a defined number of washing cycles, is already implemented for the bedding and clothing used in hospitals as they underlie strict criteria in terms of hygiene. The necessity for accuracy when counting and classifying the textiles, results in high manual effort. Therefore, Yajuan et al. (2015) present the idea to employ RFID chips in order to build a monitoring system and with it enhance the involved processes from classification to counting and allow the recording of washing, disinfection and transportation cycles as well as the usage condition. The raising technology of radiofrequency is claimed to improve work efficiency in the presented case by reducing the need for manual labour and connecting the parties within hospital logistics. (Yajuan et al. 2015)

1.1.2 Denim – Origin and current status

Over the last decades denim established itself as a wardrobe staple across countries and cultures. Especially in form of jeans, it developed to be the most popular garment worldwide today.

> *"On any given day nearly half the world's population is wearing blue jeans"*
> *(Miller and Woodward 2011)*

Once developed as a strong canvas sailcloth, the woven cotton fabric took root as durable workwear pants introduced by Levi Strauss during the gold rush in the United States (Paul 2015). The high material strength, adaptability and comfort made it popular amongst cowboys, railroad workers, farmers and gold diggers then and builds the basis for its iconic image today (Periyasamy and Militky 2017).

Traditionally, denim fabric consists out of 100% cotton, which is woven as 3/1 twill. Its properties such as weight, tightness, drape and most importantly tensile strength depend mainly on the yarn count (Paul 2015). The iconic blue colour connected with denim originates from the commonly used indigo dye. It is the specialty of this colour, which allows to create the often-desired vintage look (Chavan 2015).
Denim's adaptability allows a wide range of textile applications, and thus serves people worldwide regardless of age, sex, occasion, climate or status with a matching product. Besides its physical properties, the material and its related textile product's success is supported by a high social acceptance today. It developed from workwear to a symbol of youth rebellion to a socially fully established fashion item (Annapoorani 2017). The popularity of denim fabrics results in a significant share of 10% of the world's aggregated cotton market making it the most favourable type of fabric construction out of cotton for fashion products (Annapoorani 2017). Yet, it is one of the fastest growing segments in the apparel industry (Periyasamy and Militky 2017) and is expected to reach a market value of $56 billion in the next years (Telli and Babaarslan 2016).

The success of this universally used fabric comes with environmental downsides. By looking at the consumption of resources including water, energy, chemicals and land and the occurring emissions to air, water and land the extent of a product's environmental impact can be assessed (Fletcher 2013). Denim production consumes great amounts of fresh water and energy and applies harmful chemicals, altogether contributing to pollution and climate change (Szmydke-Cacciapalle 2018). Especially the growing of the raw material cotton as well as the dyeing and washing processes have severe environmental impacts (Paul 2015).

From the very beginning of denim production, cotton growing already consumes approximately 3800 litres of water per kg (Turley 2009). Even the denim brand Levi's, who states to be eager to reduce the water consumption of their production, cumulates 2912 litres from fibre to packaging for one pair of jeans (Levi Strauss & Co 2015). Besides high water consumption, the production also occupies broad landscapes, summing up to 10,3 m^2 land per year and product. A life-cycle analysis by Levis in 2015 further identified the emission of 20kg CO_2 and 37,4g PO_4 with the production of a jeans (Levi Strauss & Co 2015). Both of these chemicals are related to air and water pollution.

The low fastness of the characteristic indigo dye, which is the key property to achieve the desired used look of denim, is also responsible for water pollution due to effluents during the process. Although, research in the field of dyeing techniques already offers more environmentally friendly alternatives such as sulphur dyeing, indigo holds its ground as denim's standard dye and continuous to pollute rivers and surroundings of the respective factories (Paul 2015). The demand, with the denim market as its mainspring, amounts to a production of 66,000 tons of indigo dye every year (Szmydke-Cacciapalle 2018).

Another cause for pollution are the applied washing techniques, which are essential to transform the naturally stiff cotton fabric into a suitable leisure product. Methods like the commonly employed stone washing add to the chemical effluents of the dyeing process. Though, new dry treatments are developed to offer an environmentally friendly alternative to traditional wet treatments (Paul 2015).

Additionally, the high demand and growth in production is accompanied by an increasing amount of waste from both pre-consumer stages as well as post-consumer disposal of used garments. Especially the prevailing fashion trends, which are asking for already distressed and used looks, initiate increasingly environmental harmful chemical or mechanical treatments and impact the lifetime of the end product (Card et al. 2006). As discussed previously, denim as a cotton fabric, is no exception, when it comes to its recycling practices. Accordingly, most denim waste today is downcycled and used for insulation (Telli & Babaarslan 2016).

The key characteristic of denim, which Spevack describes as the "[…] ability to change with every social and cultural evolution" (Spevack 1997, p. 7), will sustain denim's presence in fashion and closets worldwide. Thus, its consumption initiates a relevant issue within the recycling discussion now and in the future. Furthermore, the mentioned properties including durability and longevity offer an interesting potential for value recapturing or retaining. The high quality and strengths of the fabric appears as potentially suitable feedstock for CLR. Most importantly, the sheer amount of denim waste and its expected increase demand for an improvement of its current recycling options (Szmydke-Cacciapalle 2018). Ideally this research can contribute to the optimisation of the recycling process while retaining the emotional and physical value of the fabric.

2 Problem Presentment and Research Questions

As discussed in the previous chapter, the textile industry faces various challenges with regards to the finiteness of its (natural) raw materials and the end-of life stage of their products. Growing consumption and changing consumer behaviours increase the pressure on all actors within the industry considering especially resource scarcity. Accordingly, this research focuses on the handling of post-consumer waste as a result of a society of disposal and more specifically its recycling, which yet remains beneath its potential (Szmydke-Cacciapalle 2018). In the following, this research aims to contribute to improve current recycling practices of denim as one of the most popular apparel materials worldwide.

The motivation of this research is initiated by the aim to optimize denim recycling towards a quality retaining closed loop process. Nowadays most textiles including denim are being downcycled after their use phase (Luiken and Bouwhuis 2015), which results in huge amounts of textile waste in landfill. Based on the concept of circular economy it gains global importance to support a closed loop recycling, in order to recreate or retain the material value of denim products and eventually improve resource utilisation. The topic of closed loop recycling is especially challenged with an existing literature gap in the case of denim degradation. Hence, a material focused approach to the topic is required rather than a management perspective, in order to connect circular business models with operations and further support the realisation of CLR concepts.

As the material going into the recycling process impacts the output quality, this research aims to investigate how fabric intrinsic characteristics change under selective influences of usage, more specifically looking at the impact of washing and drying procedures, and how a potential change relates to the fabric recyclability. The examination of the alteration of denim in accordance to washing and drying delivers important insights regarding the weakening of the fabric. The gathered insights can have an influence on the adjustment of mechanical recycling processes for instance with regard to opening aggressiveness, thereby potentially prolonging the overall lifespan of the raw material. Accordingly, the following research questions were formulated:

1. **How are the characteristics of denim fabrics influenced by an increasing number of laundering and drying cycles, which represent the textiles' service lifetime?**
2. **How does a potential fabric degradation resulting from laundering and drying processes influence the recycling potential of denim?**

3 Literature Review

3.1 Service lifetime – how to assess the use phase of a garment

The recycling process of denim has been investigated in the context of fibre recovery with regard to available post-consumer waste that is sorted and allocated to fitting recycling processes (Miller and Woodward 2011). Yet, the literature lacks investigation with a focus on influencing the quality of post-consumer waste actively by collaborating with and educating the consumer. In order to do so it is a fundamental requirement to conduct research in the field of fabric degradation and correspondingly investigate a change in quality of fabric and fibre throughout the service lifetime of a clothing item. The acquisition of this data builds an important cornerstone for future developments. The provision of information about desirable recycling qualities and the maintenance of the raw material value in a closed loop system can be informed by this discourse.

Following the approach of determining the optimum point for returning worn denim jeans to recycling after their effective "service lifetime" requires a differentiated definition of the term as well as of its underlying parameters relevant for this thesis. The service lifetime of a garment can be translated into the time a garment services its user after it has been purchased and until it is disposed. In this discourse the terms "service lifetime", "use phase" and "utilisation period" are employed interchangeably. The use phase is independent of the further processing of the textile post-consumer waste (Payne 2011). However, it encompasses a very individual and heterogeneous treatment of the clothes, depending on the consumer behaviour (McQueen et al. 2017). Daily routines and behavioural patterns determine the velocity of degradation of the fabric as well as the environmental impact a garment is subject to during its service lifetime. According to van der Velden et al. (2014) the most influential processes can be considered washing, drying and ironing. This assumption is supported by Jack (2013), who underlines the challenges that these habitual routines pose to sustainable and environmentally friendly utilisation. Correspondingly, the composition and duration of an apparel's service lifetime is strongly dependent on the private decisions and implementations of the individual consumer (Allwood 2006).

With regard to the difficulty of comparing the service lifetime of garments due to the strongly diverging consumer treatment it is critical to create significant, homogeneous data for the purpose of defining an optimum point for denim recycling. Laundering retains a central role in the utilisation period of a garment since the process is in average advancing in frequency. Washed clothes inhabit the image of elevated hygiene, which has driven consumer behaviour to laundering their clothes after they have been worn only one or two times due to societal conventions rather than soiling or odours (Jack 2013). From a sustainable point of view, this is a critical development owed to the fact that laundering is the key driving force for denim degradation. Bresee et al. (1994) have conducted laboratory research, revealing that 50% of the deconstruction of fabrics is generated by the exposure to abrasion during the laundering process. In their studies Agarwal et al. (2011) could even prove washing to be responsible for around 90% of the total damage in a garment's use phase. They concluded that "that's why the period of life cycle of a garment during use can be represented by the number of laundry cycles which a garment can be withstand in a usable condition" (Agarwal et al. 2011, p. 671).

The washing process causes the fabric to alter structurally by initiating fibre transfer. This translates into the relocation, detachment and release of single fibres composing the garment. However, the degree of damage and fibre transfer caused by washing is varying according to the fabric structure and physical properties (Bresee et al. 1994). Besides the resulting fibre loss and relocation, the deconstruction of particularly denim during laundering shows in the phenomenon of edge abrasion. To a certain extent this form of scratch appears in all kinds of garments and fabrics. Nevertheless, especially denim trousers are prone to edge abrasion due to the occurrence of extraordinarily rigid areas, exemplarily found in seams and cuffs. Above all, these sections of the garment are firmer due to their layered construction and tend to not move as much while laundering. This inflexible, static position leads to an increased abrasion potential (Morris and Prato 2016). Accordingly, McQueen et al. (2017) outlined the negative impact by hinting at the thinning of the fabric, the loss of tensile strength in warp direction as well as the fade of colour. They introduced the fact that wet cotton fibres are even more prone to abrasive forces, which yet again highlights the paramount influence of washing on the fabric.

Regarding the impact of laundering on the fibre level reveals that the above stated fibre transfer and edge abrasion cause severe damage to the fibre structure. Breakage and a corresponding loss in fibre length have been proven to result from domestic washing and drying habits (McQueen et al. 2017). This in turn encourages the deterioration of the denim fabric and reduces the quality of the employed cotton fibres, which simultaneously lowers their recycling potential. Generally, McQueen et al.'s (2017) research has revealed that laundering frequency comes along with a negative correlation to the tensile strength of the fabric. Increased washing lowers the stability of the fabric due to fibre loss and their structural degradation, leading to lower forces required to destroy the denim fabric.

In correspondence with these assumptions they have concluded that the education and encouragement of customers to reconsider and reduce their laundering impact in terms of frequency is vital for the extension of the useful life of a garment. Bresee et al. (1994) confirm this deduction by underlining the benefits in terms of water and energy consumption as well as postponed material fatigue and disposal. Due to the tremendous impact of laundering and drying on the ageing and decomposition process of a garment, it can be considered a cornerstone for determining the service lifetime of a clothing item in terms of washing cycles.

In order to assess the degree of potential fabric degradation in response to the increasing number of washes, the alteration of tear strength of the denim fabric is investigated. Even though it can be considered "difficult to correlate directly the results of laboratory [tear] tests with service performance" (Hu 2008, p. 97), the results can illuminate the fabrics behaviour with regard to the "catastrophic growth of a cut on application of a force" (Hu 2008, p. 97). The investigation of a fabrics tear strength potentially allows to draw inferences about the performance of the textile when being subject to high forces during the mechanical processing. Furthermore, the tear strength testing can enlighten the determination of the degree of the estimated increase in denim degradation as a response to a rising number of washing and drying cycles. As depicted by Mc Queen et al. (2017), washing causes the tensile strength of the fabric to decline. This assumption is supported by the fact that the "Tearing of a fabric [...] is involved in fatigue and abrasion processes" (Hu 2008, p. 97) as they admittedly occur during washing and laundering.

3.2 Fabric properties and structure of denim/cotton

The quality of denim fabrics is strongly dependent on the underlying material characteristics. Critical attributes encompass the raw material, particularly the textile fibre, as well as the yarn and fabric construction and production. The following section is presenting the preferable parameters for denim production and sheds a light on the properties of the cotton fibre as being the backbone of the denim fabric.

3.2.1 Properties of Cotton Fibres

Cotton as a raw material builds the cornerstones for denim production. The fibre itself is of regenerative, natural origin and consists to around 96% of pure cellulose. During the industrial processing of the fibre, nearly all non-cellulosic components are removed from the structure, resulting in a score of up to 99% cellulose (Cook 2012). Due to the high crystallinity of the polymer chains composing the fibre, cotton can convince with high strength and paramount molecular weight among plant fibres (Gordon and Hsieh 2007). These properties have shaped cotton to become one of the premier materials for fabric construction within the textile industry (Cook 2012). During the 20th century cotton has occupied the position of the unchallenged market leader. Meanwhile it has been superseded by polyester in terms of production volume (Gordon and Hsieh 2007). This development has however not been initiated by a decline with regard to the popularity of cotton, but by the circumstance that cotton production has reached its capacity limit. The agricultural scope for cotton is exhausted whereas polyester, as a chemical man-made fibre is in comparison not limited in growth. Figure 2 depicts this development, underlining that the production of cotton remained and is projected to remain moderately constant since the early 1990s (Koszewska 2018).

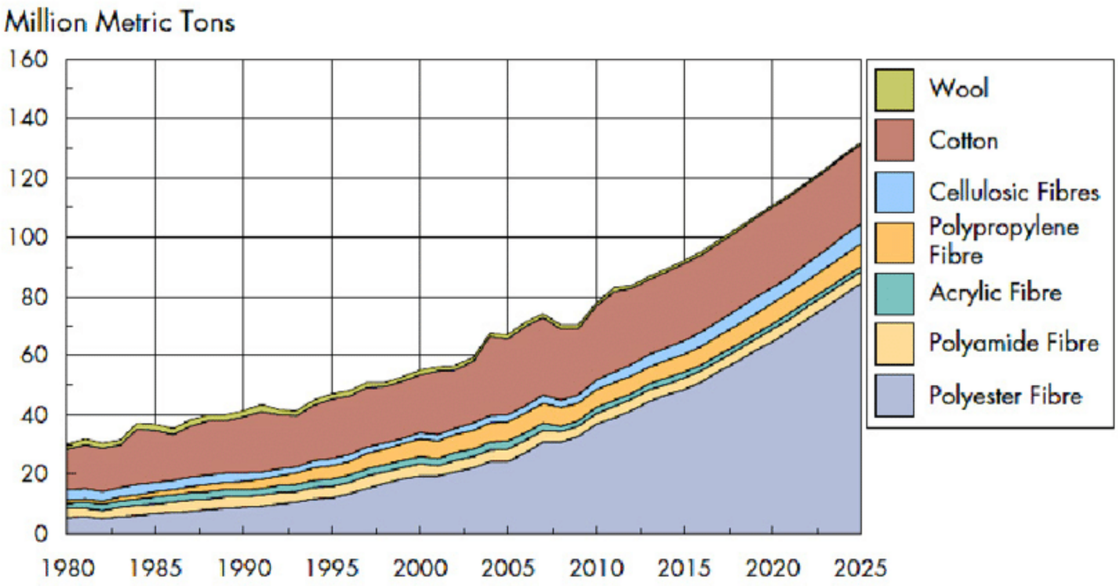


Figure 2 Development of the Global Fibre Production (Koszewska 2018)

The physical properties of cotton are strongly dependent on the breed of the crop as well as the growing region and the cultivation conditions. Exemplarily, the tenacity of the fibres grown in India diverges with a value of 0.185 N/tex noticeably from cotton grown at Sea Island reaching values around 0.452 N/tex. This fluctuation comes along with diverse finesses as well as fibre lengths. Besides the genetically determined heterogeneous fibre occurrence, the condition of the fibre plays a central role for its physical properties and performance. This can refer to the age, maturity or humidity of the fibre (Gordon and Hsieh 2007).

Denim fabrics rely on cotton for being resistant to several environmental influences while providing high wearing comfort. Cook (2012) points out that the fibre has the significant ability to resist degradation when being exposed to heat. This aptitude makes denim fabrics less prone to potential heat damages caused by tumble drying. Nevertheless, temperatures around 120°C instigate the fibre to alter structurally and superficially as they turn yellow after hours. Hence, the influence of sunlight decreases the strength of the material gradually while triggering the process of yellowing. This effect is amplified by the combination of high temperatures and humidity. Heat of 150°C and above causes decomposition due to the initiation of oxidation processes. When it comes to natural ageing of the fibre, cotton remains high in strength when being stored judiciously. Several years of storage cause only very slight structural changes. These characteristics have qualified cotton as the fundamental building block for the most popular garment in the world. Yet, the successful transformation of cotton fibres into a denim fabric is tied to defined parameters and conditions presented in the following.

3.2.2 Fibre Properties for Denim Production

With the aim of producing denim of a consistent quality that ensures longevity and a certain resistance to the environmental influences occurring in its daily use, the quality of its fundamental building block – the cotton fibre - plays a vital role. An essential parameter is the fibre length. Cotton is a natural staple fibre and grows, as underlined previously, in different qualities under varying conditions. The diverging measurements of the fibres can be assigned to three categories. The longest fibres vary between 25 to 65 mm, forming the first group. These are followed by medium sized fibres with a length of 13 to 35mm. The shortest fibres range in their staple length between 10 and 20 mm. Correspondingly, cotton fibres vary in size from 10 to 65 mm with a fineness of 1-3 dtex. In general, it can be stated that longer staple fibres produce softer fabrics in comparison to shorter ones (McLoughlin et al. 2015).

The length of the fibre has a central influence on the properties and performance of a fabric (Miller and Woodward 2011). With regard to the impact it has on the production of denim fabrics it can be stated that a fine denim warp yarn requires fine and long fibres to support smooth drape and haptics. Additionally, the final product will profit from increased evenness, longevity and wearing comfort. As a rule, denim should be composed of fibres with a minimum length of 28mm while the yarn must not contain more than 40% of fibres that are classified as short in order to guarantee sufficient quality (McLoughlin et al. 2015).

Generally, the cotton fibre has qualified itself as the raw material for denim by offering essential performance advantages. Cotton has the rare attribute that its strength increases when being wet (Cook 2012). This motivates improved processing and fabric manufacturing. Due to its crystalline polymer structure it does however also provide high strength in a dry state while inhabiting low elasticity (McLoughlin et al. 2015).

3.2.3 Yarn Construction for Denim Production

As its core element yarn production inhabits a spinning process. This process may vary according to the fibre properties and the desired yarn characteristics and performance. Dominant requirements for denim yarns are “high yarn strength, pilling resistance, compactness and less hairiness besides evenness and uniformity” (Raina et al. 2015, p. 162). To ensure the desired quality, the industry relies on ring spinning, compact spinning and rotor spinning as adequate technologies or denim production. Correspondingly, Table 1 highlights the differences and limitations concerning the process parameters and yarn qualities with focus on the employment of ring- and rotor spinning methods.

Generally, it can be stated that spinning is the most critical process parameter for the reprocessing of recycled materials. Most recycled fibres do not provide the sufficient properties that are required for the technologies presented in the following. Therefore, recycled fibres are reliant on a predominant share of virgin material, which carries the shorter recycled fibres and embeds them in the yarn structure due to higher fibre-fibre friction (Muthu 2018). After the employment of one of the three technologies presented below, Raina et al. (2015) suggest that the fineness of the created yarn should typically lay between 50 tex and 150 tex for the production of denim. “Denim warp yarns usually have a metric twist factor of 140 and weft yarns a factor of 130” (McQueen et al. 2017, p. 31). The length of the fibres exposed to any spinning process are considered a parameter of paramount importance for the quality of the resulting yarn.

Ring Spinning

The ring spinning process enjoys industry wide, superior popularity due to its flexibility and adaptability in terms of yarn density and processible fibre types. Furthermore, ring spun yarns inhabit exclusive quality due to decent fibre control encouraging parallelisation. However, a limiting factor is represented by the restriction in productivity combined with a high energy consumption (Gordon and Hsieh 2007). Generally, the ring spinning process is composed of a drawing phase, to reduce the thickness of the roving and to parallelise the fibres, the twist insertion as a central stage of the yarn formation, and the winding phase which is essential for the creation of yarn packages (McLoughlin et al. 2015). The suitable twist insertion is dependent on the intended application as well as the fibre properties. A vital decisive factor here is again the fibre length. For the spinning of a warp yarn the twist varies from around 3260 αtex for long fibres up to 4790 αtex for short fibres. The variation in required twist is determined by the compensation of the decreasing fibre-fibre friction in correspondence to the decreasing fibre length. Length and uniformity can be considered the most critical parameters for high-quality ring and compact spinning (Gordon and Hsieh 2007).

Compact Spinning

The compact spinning technology generally inhabits the same setup and process steps as ring spinning. The fundamental difference is the installation of an additional compacting zone which is meant to guide the fibres from the roving closer together in order to increase the quality and evenness of the resulting product. The compacting zone appears in form of a suction device that is designed to control floating fibres and guide them to remain a central position in the fibre strand. This in turn avoids the occurrence of unoriented and unparalleled fibres in the structure of the yarn. The compact spinning technology is however not capable of elevating the overall productivity of the process. Therefore, the output efficiency remains equal. In corresponding research, that dealt with the comparison of ring spinning and compact spinning, “it [has been] concluded that woven fabrics produced from compact spun yarns have higher breaking strength, breaking extension, tear strength, pilling resistance and abrasion resistance.” (Kaynak et al. 2017, p. 197)

Rotor Spinning

Rotor spinning is “generally referred to as open-end (OE) spinning, since there is a definite break (discontinuity or open end) in the fibre flow prior to yarn formation” (Gordon and Hsieh 2007, p. 262). It represents the technology with the second-largest market share within the realm of short staple yarn production. The process convinces with high productivity and the possibility of handling the twisting and the winding process individually. Hence, the process is, unlike ring spinning, much less limited by the bobbin size and does require bobbin changes less frequently (McLoughlin et al. 2015). Yet, compared to ring and especially compact spun products, rotor spun yarn offers respectively lower strength and a lower degree of parallelisation. This is partly owed to the presence of wrapper fibres circumvoluting the core fibres of the yarn in an almost 90° angle. These fibres represent one of the major shortcomings of the rotor spinning technology since they influence the yarn quality negatively. The strength of the single fibre fed to the rotor represents the most critical factor for high-quality rotor spun yarn (Gordon and Hsieh 2007).

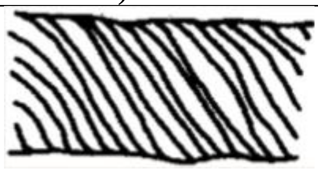
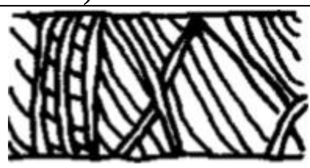
CHARACTERISTICS	RING SPINNING	ROTOR SPINNING
Required fibre length	• Minimum required fibre length is longer than for rotor spinning • Short fibre content (10-20mm) should not exceed 40% • Maximum fibre length is limited by distance of the drafting elements (space between rollers must exceed fibre length, otherwise fibres are torn apart and break) • The longer the fibres, the higher the yarn quality incl. higher strength and less hairiness	• Suitable for short fibres (<20mm), in this case recommended use of around 20% carrier fibres (>20mm) to improve yarn quality and strength • Even waste fibres [9-12mm] may be spun, requires more carrier fibres • Rotor radius needs to be at least equal to maximum fibre length • Spinning stability depends on fibre length relative to rotor circumference
Fibre input	Roving	Open-end
Twist-insertion rate/min	15,000-25,000	80,000-150,000
Delivery Speed m/min	20-30	100-300
Tensile Strength	Good	Lower than ring-spun yarn
Strength variation	Higher than rotor-spun yarns	Low
Evenness	Good	Very good to good
Hairiness	High	Very Low
Stiffness	Low	Higher than ring-spun yarn
Abrasion resistance	Low	Higher than ring-spun yarn
Twist structure	Homogeneous across the length and cross-section	Homogeneous except for the presence of systematically formed wrapper fibres
Importance of fibre properties for process (1 = most critical)	1. Length and length uniformity 2. Strength 3. Fineness	1. Strength 2. Fineness 3. Length and length uniformity
Appearance	Less uniform (due to high hairiness)	Very uniform (due to wrapper fibres)
Graphical Comparison of yarn structure		
Denim fabric properties	Very fine and smooth	Thicker and coarser than ring-spun

Table 1 Comparison of process characteristics for ring spinning and rotor spinning (Gordon and Hsieh 2007; McLoughlin et al. 2015; Raina et al. 2015; Lawrence 2010)

3.2.4 Fabric Construction for Denim Production

Raina et al. (2015) have closely examined the requirements and properties of denim fabrics. Accordingly, denim is classically inhabiting a twill weave structure. This structure allows to respond with resistance to rough environmental influences such as abrasion. Finer fabrics, that are less likely to be exposed to rough conditions might be constructed with a plain weave, that is however not the rule for the traditional denim, which is crafted to withstand the burden of hard physical work. Twill weaves offer the processing advantage that they can be constructed very densely “resulting in a very firm and long-wearing fabric that was originally used for farmer and worker pants in the US” (Raina et al. 2015, p. 169). Habitually, denim fabrics are woven as 3/1 or 2/1 twills besides 3/1 or 2/2 broken twills (Wulfhorst et al. 2006). The dense structure and the short floats are consistent with a high number of interlaces, which strengthens the fabric and protects fibres from being abraded or erected by external stimuli. Considering the weaving technology, mainly rapier or air jet weaving are utilised (Muthu 2018).

For most denim fabrics yarn dyeing is the processing method of choice. Correspondingly, the weft yarns are generally white whereas the warp yarn is characterised by the distinctive indigo colour. The interlacing of these phenotypically diverging yarns in the generally warp faced fabric provides denim with its unique, traditional appearance (Muthu 2018).

3.2.5 Recycling of Cotton

The recycling of cotton can happen on multiple levels and scales along the premises of the four presented recycling stages: primary, secondary, tertiary and quaternary. The following section presents available options for the further processing of used cotton and correspondingly denim fabrics. Generally, the optimal recycling method ensures a value retaining process in terms of a closed loop system. Hence, the need for downcycling due to a crucial reduction of the quality of the raw material becomes void. However, closed loop systems remain very challenging for the textile industry and are rarely developed thus established (Schmidt et al. 2016). This thesis focuses on mechanical recycling processes as a method of choice, as it is most common for the reprocessing of cotton materials. However, closed loop recycling processes are not evident for this technology, yet. All applicable recycling methods in the case of denim are briefly outlined in the following.

Reuse

The reuse of products is being forcefully encouraged by governmental and private initiatives, who promote reuse along the aspect of energy and resource savings. Especially industrialised countries have adapted to this approach and offer a broad scope of consumer touchpoints for donating or selling second-hand garments and textiles. Second-hand-, thrift-, or consignment stores represent a public platform for the exchange of used products. Furthermore, non-profit organisations such as charity foundations strive for textile donations to resell them in domestic or global market environments. However, the amount of textile waste emerging on a post-consumer level exceeds the volume of garments or fabrics that these platforms can handle. Hence, instead of being resold, some garments are being recycled or disposed (Gordon and Hsieh 2007).

Remanufacturing

Remanufacturing claims to be of great potential as recycling and resource recovery option (Lazlo 2010). In order to reduce the need for virgin material, the process of remanufacturing reintroduces used products as “raw material” into the production cycle. Thus, the concept is based on used or retired products or components, which are if necessary repaired or reconditioned to consecutively be turned into a product of similar or even higher quality than the input material (Haynsworth and Lyons 1987). Included in the process are disassembling, cleaning, inspecting, restoring, replacing, and reassembling (Lazlo 2010). The restoration to like-new condition is also the key characteristic to distinguish remanufacturing from the other disassembly recycling processes including repairing and reconditioning (Matsumoto and Ijomah 2013). Matsumoto and Ijoma (2013) identify the major advantages of remanufacturing in the combination of low raw material costs and a high-quality output.

Though, the process requires a stable core product with relatively high market value to be efficient. If life cycles are prolonged irrespective of market demand the effort of a remanufacturing process may be counterproductive (Matsumoto and Ijomah 2013). Currently, the automotive sector is the predominant industry commercialising this resource recovery method, while the textile industry is launching first projects to exploit the ecological and economic benefits for suitable products.

Disposal

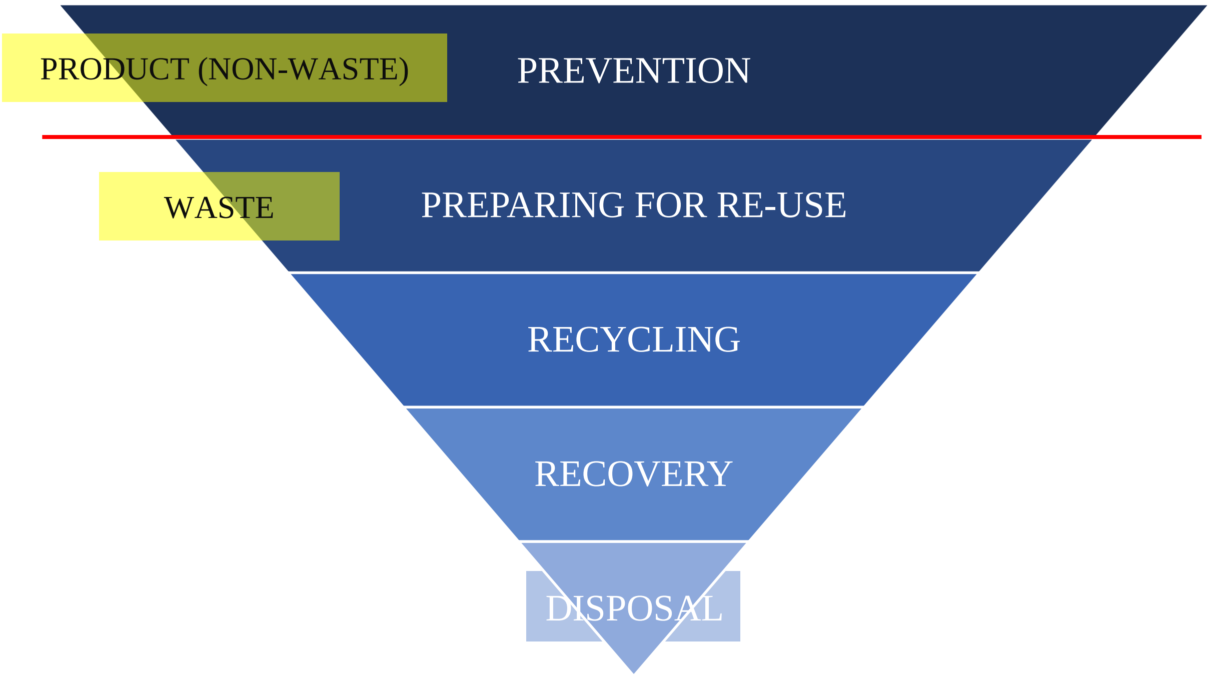


Figure 3 Waste Management Hierarchy (adapted from European Commission 2016)

The processing of textile waste in form of disposal is the environmentally least preferable option. Respectively, the waste management hierarchy presented in Figure 3 highlights the favourability of waste management applications in relation to their sustainable impact. Accordingly, disposal builds the bottom of the inverted pyramid as it implies textiles ending up in landfill (Gordon and Hsieh 2007). Not only does their decomposition take a very long time, if applicable at all, but their degrading process also releases toxic gases and substances into air and soil (Morgan 2015). Nevertheless, cotton is characterised by being a biodegradable fibre which allows its natural decomposition once ending up in landfill. Yet, todays amount of disposal exceeds the natural decomposition rate by far, resulting in vast waste volumes. Consumers dispose their garments much faster than the ecosystem manages to biologically degenerate (Gordon and Hsieh 2007).

Energy Recovery

Energy recovery outperforms disposal according to the waste management hierarchy since it produces a transformable energetic outcome. The underlying principle is mainly incineration. By burning textile waste, the heat can be converted into energy and thereby recover parts of the energy that had been required during the production of the garments and fabrics (Gordon and Hsieh 2007). This form of textile waste management builds the fundament for quaternary recycling (Vadicherla and Saravanan 2014). Yet, the amount of generated energy is fairly low and volatile compared to the energy invested in textile manufacturing processes, which is why this approach is surpassed by the other three recycling stages in terms of environmental impact (European Commission 2016).

Mechanical Processing

The method of mechanical recycling inhabits two central processes: sorting of the waste material as well as the mechanical decomposition of the fabric. Primarily, the reclaimed material needs to be sorted according to fibre type, colour, quality etc. This is particularly convenient if the textile waste originates from post-industrial sources. For these waste streams the fibre content as well as the precise quality and properties of the fibres is known. Accordingly, sorting can be executed very accurately and with a diminishingly small risk of uncertainty (Gordon and Hsieh 2007). The inhouse reprocessing of manufacturing related waste represents recycling on the primary level (Gulich and Wang 2006).

However, the sorting of post-consumer waste represents a much more complex challenge. This is owed to the heterogeneity of the garments and textiles that are returned. In the majority of cases the fibre content of the product is not known and can hardly, if applicable at all, be determined due to missing or unreadable care labels. Furthermore, the products are generally of strongly diverging quality and state. This symbolises a burden for the creation of recycled products inhabiting consistent or even a known quality. The reprocessing of post-consumer waste is classified as secondary recycling (Gulich and Wang 2006).

Once the garments and textiles have been sorted, they can undergo varying mechanical recycling processes. For the recycling of natural fibres, the most popular method for fibre recovery is shredding. The exposure to the shredding machine causes the fabrics to be torn apart and separated into single fibres by needle equipped cylinders (Gordon and Hsieh 2007). This translates into a very rough treatment of the fibres and causes severe material damages besides fibre breakages. Hence, corresponding to a tremendous loss in fibre length, the material quality decreases significantly (Gulich and Wang 2006). Nonetheless, albeit the drawbacks coming along with shredding, this technology "has shown promise [for the] reprocessing of denim fabric and garments. These are usually recognisable and can be separated fairly easily during sorting" (Gordon and Hsieh 2007, p. 490).

Chemical Recycling

The chemical recycling of cotton fibres, on behalf of tertiary recycling, has enjoyed increased attention from industry and research entities. The chemical fibre recovery of cellulose fibres can be compared to the procedure of melting PET bottles in order to create new fibres by reintroducing this dope to the spinning process. For cellulose based fibres, such as cotton, the dissolved material is classified as regenerated cellulose. Popular examples for regenerated cellulose fibres are viscose and lyocell (Gordon and Hsieh 2007). Since chemical recycling is only to a very limited degree dependent on the quality of the processed waste and decomposes fibres down to the polymeric level, this procedure is less relevant and applicable for this discourse.

One criterion influencing, which of the above-mentioned recycling options to choose for a disposed product is its disposing condition which is determining its recyclability. The sorting process of the heterogeneous post-consumer waste identifies as one of the main challenges within all recycling process (Dahlbo et al. 2014). Once disposed, it’s the task of rag sorters to grade the textiles according to fabric, style, brand and condition. Especially the last factor determines the variety of recycling options. The higher the degree of use, which is reflected in highly damaged post-consumer waste, the more limited are the recycling options (Hawley 2006). If recyclability is described as “The ability of a product to be recycled […] through an established process” (Kubba 2016) the degradation of a fabric caused by e.g. wearing and washing reduces the recycling possibilities due to technological limitations at the end of its use phase and thus influences its recyclability.

While focusing on a value retaining or recreating recycling process, a closed loop recycling, as it is the case for this thesis, the quality of the feedstock for the recycling process is of high importance. Table 2 underlines the potential of mechanical and chemical recycling as well as remanufacturing for a closed loop process. As fibre-to-fibre recycling methods and their output quality rely on the same factors as the general spinning processes of virgin material (elaborated in chapter 3.2.3), the recycled feedstock has to meet the requirements for these yarn production processes. Aaronson (2017) investigated the currently available mechanical recycling method and found that it seems to reduce the quality of input material independent of its initial (pre-processed) condition to an extent, which makes the output fibres unable to meet the existing spinning requirements.

METHOD	INDUSTRIALISED PROCESSES	POTENTIAL FOR CLOSED LOOP RECYCLING
Mechanical	**Shredding process**. Comminution of fibre material until single fibres are separated again.	Contemporary versions of the process are too aggressive to retain fibre quality. Mixture with virgin material for spinning processes is inevitable. Heterogeneity of post-consumer waste exacerbates constant quality retention.
Chemical	**Viscose process**. Dissolution of cellulosic fibres in solvent. Cellulose solution is re-spun into filament or staple fibres	The viscose process influences the polymeric structure of the fibre. This changes the physical and aesthetic properties of the material (not fibre-to-fibre). The fibre degradation occurring during the service lifetime of a product cannot be levelled out by the spinning process without the addition of supplementary material of better polymeric quality. Hence, the process cannot be repeated in a close loop.
Remanufacturing	Reintroduction of used and pre-processed raw material into the production cycle.	The quality of the material is not improved or recovered, only products which previously inhabit a good quality can be employed for remanufacturing. Demands selection of processible and non-processible garments. Major share cannot be employed for remanufacturing. Resulting product can have comparable quality to feedstock. Heterogeneity of post-consumer waste exacerbates constant quality retention. Reduces scalability.

Table 2 Comparison of the potential for circularity along different recycling options (Gordon and Hsieh 2007)

4 Methodology

Figure 4 Sequential presentment of the stages of the research process (own presentment)

Methodologically the research process of this thesis is constructed and executed along a rather deductive research approach, as the discourse refers to a basic fundament of theoretical knowledge. Since the topic, however, lacks a solid and differentiated literature, the aim is to contribute to the development of innovative theory regarding the scientific field of denim deconstruction and recycling. Hence a combination of induction and deduction is used to "[assess] the validity of conclusions about observable events" (Blumberg et al. 2008, p. 27). This aligns with the purpose of monitoring the gradual decomposition of denim, concentrating on laundering as a decisive factor for fabric fragmentation in its service lifetime with the help of empirical data (Blumberg et al. 2008). The superordinate objective to define the optimum point for denim recycling to retain the value of the cotton fibre as long as possible in a closed loop system, thereby elevating the recycling efficiency, can be considered a key driver for the investigation process.

The sequential structure of the research process is depicted in Figure 4. The investigation is initiated by an extensive literature review that represents the theoretical fundament for the subsequent research. It encompasses an examination of the historical, cultural and industrial background of denim. Besides, it elaborates on the state of the art with regard to existing recycling options and habits for denim and presents the key terms and processes that are related to the understanding and analysis of existing methods. Furthermore, technological conditions and developments are depicted which delve deeper into the manufacturing parameters and attributes for denim fabric manufacturing.

The theoretical outline serves as a cornerstone for the data acquisition, which happens along two different research methods. Primarily, a qualitative approach (Bryman and Bell 2015) is followed by conducting expert interviews. Professionals, who qualified themselves with expertise and know-how in the field of denim manufacturing, quality testing and recycling, contribute with their experience to the discussion of the experimental results. The interviewees have been selected on the background of purposive sampling. Their positions and research fields address and complement the identified literature gap with regard to denim recycling and the influence of the fabric degradation on the process. The selection process resulted in the consultancy of a quality manager for an established trouser manufacturer. Her knowledge encompasses valuable information with regard to industry practises for the service life simulation of denim fabrics, as well as general expertise in the field of fabric processing and customer collaboration. Furthermore, a project leader specialised on smart textiles, recycling and remanufacturing has been interviewed who could contribute with detailed insights in post-consumer waste handling, material and garment flows along the textile value chain and use phase besides emerging business models and recycling approaches in the textile industry. Moreover, a professor with research focus on spinning technologies and yarn optimisation for mechanical recycling processes added value to this thesis by supplying knowledge regarding the technical parameters and constraints of the shredding and spinning of recycled fibres. Finally, a doctoral student who investigates the optimisation of shredding processes with regard to material quality retention delivered insights concerning the innovation potential and current developments in the field of mechanical recycling. Table 3 provides an overview of the backgrounds of the interviewed professionals. It further depicts how the participants have been coded for anonymity reasons.

INTERVIEWEE	PROFESSION	ORGANISATION	COUNTRY
A	*Quality Management*	Established trouser manufacturer	Germany
B	*Project leader* in the field of smart textiles, remanufacturing and recycling	University	Sweden
C	*Professor* in the field of spinning, currently researching on yarn optimisation for mechanical recycling processes	University	Germany
D	*Doctoral student* researching in the field of process optimisation for mechanical recycling	University	Sweden

Table 3 Overview of the Interviewees and their professional background

Their practical knowledge considering the state of the art as well as process opportunities and limitations in the field of use simulation and textile testing is a valuable tool to enhance and contextualise the practical experimental phase of this research from a management perspective. Conducting the semi-structured expert interviews partly simultaneously to the testing process helps to create a feedback loop and to eliminate errors and process barriers due to the access to professional insights resulting from practical industrial experience. The choice of semi-structured interviews supports the evolvement of new perspectives and inspiring content with regard to the process setup and execution. The interviewee has the chance to add personal experiences and impressions. Therefore, the experimental design can benefit from the differentiated elaborations evoked during the conversation.

The laboratory use simulation testing is executed with two different denim fabrics for the option of comparative analysis and is subdivided into two separate tests generating quantitative data output. In order to ensure the sampled fabrics to fit the scope of this research a purposive sampling design is employed. This sampling method allows the researchers to select samples "conform to certain criteria" (Blumberg et al. 2008, p. 253). The fabrics were chosen based on criterions gathered during the literature review and thus are able to represent commonly used types of denim regarding their way of construction, the material composition as well as the colour way. The exact fabric specifications can be found in chapter 5, table 4.

First, samples of both fabrics undergo laundering processes at varying cycle quantities. All specimens are being weighed to determine potential alterations in the weight per area of the fabrics during the process. Six samples per fabric type are assigned to each washing stage. Afterwards their visual and tactile degradation is assessed subjectively based on the standard SS-EN ISO 15487:2018. In order to increase the internal validity of the subjective assessment is conducted by an independent panel. The panel consists of nine experts in the field of textiles and clothing and evaluates the degradation of the fabric along provided standardised instructions and parameters with the help of a numerical Likert scale to ensure comparability. The underlying framework for the panel study is defined further during the presentment of the experimental setup in chapter 5.1.2.

Once the decomposition of the fabric has been evaluated on a visual and tactile level, the development of the fabrics' tear strength in relation to their laundering frequency will be measured employing the tear strengths test according to the ASTM D2261-13. Fabric tearing in general is connected to fatigue and abrasion of fabrics and therefore proofs to be a suitable testing method when evaluating the degradation of fabrics. Tear strength tests are usually applied to determine the resistance of especially woven fabrics towards tearing caused by tensile forces (Hu 2008). In line with the ASTM D2261-13 the tests are conducted on a constant-rate-extension (CRE) machine. The standard further specifies the use of a so-called tongue method, in which "a rectangular specimen is cut in the centre of the shorter edge to form two 'tongues'" (Hu 2008 p. 99). It implies a destructive testing method since the CRE machine tears the specimen along the cut to simulate a rip. Based on the readings, the test delivers data on the force required to continue and propagate the tear (Hu 2008). Employing this method enables the acquisition of numerical data as well as the graphical grading of the values in order to visualise the fabric degradation in relation to increased laundering along the measuring scope of tear strength. A detailed description of the experimental setup is delivered in chapter 5.2.

The fact that qualitative and quantitative methods are employed classifies the presented discourse as a mixed method research. Since both practices are informing and building upon each other, an embedded research design is being utilised (Bryman and Bell 2015). The employment of diverse data generation practises allows to enhance the validity and reliability of the results due to triangulation. Triangulation "implies that the results of an investigation employing a method associated with one research strategy are cross-checked against the results of using a method associated with the other research strategy" (Bryman and Bell 2015, p. 647). This benefit is substantiated by the inclusion of the opinions and expertise of professionals related to the field.

Once the necessary data has been gathered and generated, the outcomes are subject to analysis and discussion. Correspondingly, the values and assessments are contextualised and interpreted respecting existing process limitations. In the final section of this thesis, the results are introduced to and embedded in the context of existing theory and their contribution to existing knowledge in the field of denim recycling is evaluated and outlined. The determination of an 'expiry date' for denim serves as an overarching approach for driving the research process towards the optimisation of the recycling potential of denim products.

4.1 Limitations

The previously outlaid methodology of this research causes inevitable limitations impacting the interpretation of the findings. Since only two different denim fabrics are examined within the scope of this research the external validity of the findings is moderate. Though, laundering as the chosen use-simulation test delivers reliable results, due to controllable and standardised conditions, and can thus be generalised and transferred to household practices. Additionally, the reasons for choosing laundering refer to the literature review in chapter 3.1, stating it as central parameter for determining the service lifetime of a clothing item. Although, washing can be held responsible for a majority of fabric deconstruction, which ranges between 50% to 90% according to findings of previous studies, it is not the only force causing degradation and thus cannot fully recreate a garment's use phase. Due to resource limitations this research remains focused on the most destructive influence on the garment during its active life. The measures were chosen according to previous research which clearly states washing as main reason for the degradation of denim fabric and therefore supports the external validity of the findings with regards to the purpose of this research.

Furthermore, the degradation of the fabric over the testing process is limited to observation of overall weakening of the fabric and therefore disregards selective destruction in form of smaller holes or similar. Should the fabric at one point tear into two or more parts before all predetermined stages of the laundering test are executed, it will mark the final stage and end the testing for this fabric. This limitation has yet not affected the presented discourse. The subjective evaluation of the denim fabric implies a risk for the internal validity of this study. In order to support the integrity of conclusions made and with it improve the internal validity the subjective assessment is conducted by external experts in form of a panel (Bryman and Bell 2015). However, the evaluation done by the employed assessment panel underlies the limitations of subjective assessment and is affected by age, gender, as well as their level of experience. Due to the spatial proximity of panel members and a common connection via the University of Borås, the panellists represent a homogeneous group in relation to influential factors like climate and cultural background. Further, a scale is adopted from the SS-EN ISO 15487:2018 *(Textiles – Method for assessing appearance of apparel and other textile end products after domestic washing and drying)* to allow categorisation and comparison of subjective data.

In addition to the subjective fabric assessment, the applied tear test as well as the weighing procedures produce objective and quantitative data to contribute to the findings on fabric degradation by assessing the development of the fabrics' tear strengths and tracking potential fibre loss. Further, it is important to mention, that due to the manual sample cutting and the high degree of manual handling of the CRE machine, the tear strength as well as the weight evaluation underly the risk of human error.

The reliability of findings derived from the employed measures is ensured by the guidance of the following standards employed during the testing procedures:

- SS-EN ISO 6330:2012 *(Textiles – Domestic washing and drying procedures for textile testing)*
- SS-EN ISO 15487:2018 *(Textiles – Method for assessing appearance of apparel and other textile end products after domestic washing and drying)*
- ASTM D2261-13 *(Standard Test Method for Tearing Strength of Fabrics by the Tongue (Single Rip) Procedure)*

Additionally, the same educational background as well as a spatial proximity of the researchers during the work process allow a high inter-rater reliability.

5 Experimental Setup

As depicted in the description of the methodological framework of this discourse, two different representative denim fabrics are each exposed to two separate tests. The purposively chosen denim samples have been provided by the online agency Rekotex (Borås, Sweden). Table 4 summarises the fabric specifications according to the manufacturers (Bossa Denim 2017, Berto Industria Tessile, n.a.):

CHARACTERISTICS	**FABRIC A** **"BERTO COMFORT STRETCH"**	**FABRIC B** **"BOSSA DAVID"**
Composition	98% Cotton, 2% Elastane	100% Organic Cotton
Construction	3/1 Z (Twill weave)*	3/1 Z (Twill weave)
Weight g/m²	350	420
Washing instructions	40°C	40°C
Drying instructions	Tumble Dry	Tumble Dry

*Table 4 Fabric Specifications according to manufacturers (Bossa Denim, 2017, Berto Industria Tessile, n.a.) *identified during this research, not included in manufacturer's description*

5.1 Washing and Drying Fastness

5.1.1 Testing Process

Primarily the two fabrics are exposed to laundering and drying in different frequencies in order to determine their degradation in response to domestic washing and drying. The samples are washed as one fabric cloth each. The examination of the fabric happens at the stages of 0-10-20-30-40-45-50 washing and drying cycles. A reduction to five washes between each measurement stage from 40 cycles onwards (inspection at 45 cycles) has been introduced according to the assumption that more significant alterations in fabric degradation are expected in response to a higher number of cycles. "Each washing procedure represents a single domestic wash" (SS-EN ISO 6330:2012). "A complete test consists of a washing and drying procedure" (ibid.). At the end of each washing stage a number of six specimen is cut in the shape and size required for the subsequent tear strength test according to ASTM D2261-13 *(Standard Test Method for Tearing Strength of Fabrics by the Tongue (Single Rip) Procedure)*. Six samples are assigned to each washing stage, including five specimens for the tear strength test and one to keep as reference for the visual assessment. This enables comparison, allows the identification of outliers and the avoidance of coincidental results. The charge of each cycle amounts to two kilogram in total. The varying load in terms of fabric weight per washing cycle stage is being compensated with a corresponding amount of ballast fabric, which consists of one of the sample fabrics. The equipment employed for laundering and drying is classified according to SS-EN ISO 6330:2012 *(Textiles – Domestic washing and drying procedures for textile testing)*. This standard is utilized by a broad range of textile quality and performance evaluations. It references to the type of washing machine, dryer, detergent as well as the resultant method employed. Correspondingly, the following classifications apply to this experimental design:

Washing machine:	Type A: Horizontal axis, front-loading type
Wash programme:	4N (40°C, ~41 min)
Drying Procedure:	Type F: Tumble drying (70°C, 25 min)
Tumble Dryer:	Type A3
Detergent:	Reference detergent 2 (without optical brightener) Tvättmedel Kulörtvätt Parfymfri Miljömärkt ICA Skona*

*Used in washing process according to reference detergent 2
Ingredients: 15-30% Zeolite, 5-15% Anionic Tensides, <5% Soap, Polycarboxylates, Enzymes (Subtilisin, Amylase, Pectate lyase, Mannanase, Cellulase, Lipase)
Additional Ingredients: Sodium carbonate, Sodium Chloride, Cellulose Gum, Sodium Silicate, Polyether/Polyester-copolymer, PVPI)
PH: 10.5

5.1.2 Evaluation Process

In accordance to the standard, the samples are being weighed at their initial stage (0) and after each subsequent washing and drying cycle stage (10-20-30-40-45-50) in order to identify potential fibre loss. To determine the average weight of an unwashed sample with the measurements 75 x 200 mm (required sample size for tear strength testing according to ASTM D2261-13) 48 samples of each fabric are being weighed. Accordingly, the average weight of an unwashed sample is specified as well as the underlying standard deviation. These reference values are fundamental for the examination of potential fibre loss in relation to the increasing number of washing cycles. By weighing the washed samples after cutting them from the fabric cloth at the defined stages, weight differences, compared to the determined reference average, and thereby the potential reduction of the fibre content of the samples can be identified.
In order to evaluate the degree of degradation a subjective assessment method is being employed that is designed and structured in accordance to SS-EN ISO 15487:2018 *(Textiles – Method for assessing appearance of apparel and other textile end products after domestic washing and drying).* Some adaptations underlie the employment of this standard since it has been conceptualised for clothing and diverging textile end products and not for fabrics. Furthermore, the referenced washing machine is a Type B machine which deviates from the Type A machine employed in this research. Nonetheless, the standard represents a normative fundament for a uniform assessment of the denim degradation. The rating of the visual decomposition of the fabric is executed along a scale adapted from SS-EN ISO 15487:2018. This form of assessment results, according to the standard, in a qualitative hence subjective method. The following classification applies:

Grade	Description
5	**No** change
4	**Slight** change
3	**Moderate** change
2	**Distinct** change
1	**Outstanding** change

Table 5 Grading Scale for the classification of fabric degradation after visual assessment based on SS-EN ISO 15487:2018.

The washed samples undergo assessment by an expert panel, who assign grades to the specimens according to the presented scale. The categories for grading are colour, hairiness, appearance of abrasion as well as flexibility and softness. To ensure interrater reliability, the evaluation underlaid standardised conditions and happened simultaneously in a closed environment. Within this setup, the specimens' appearance has been captured photographically under the same conditions with regard to light, temperature and humidity. The camera settings for all shots were the following:

Camera model:	Canon PowerShot G7 X
Aperture:	F/8
Exposure Time:	1/125 Sec.
ISO speed:	ISO-800
Flash modus:	No flash
Specimen distance:	35 cm
Lighting:	Daylight (no artificial light influence)
Background:	White

The panel assessment

The sensory evaluation of the fabric specimens is conducted by a group triangulation process with a panel of experts, which consisted out of one male and eight female members, including undergraduate and graduate students of the textile department of Borås University. Information about age, gender as well as the textile background of the group members have been documented. The panel study took place in a closed room with all nine penal members simultaneously. The participants were introduced to the research scope and experimental setup. Questions were answered in the whole group and the terminology has been clarified.

Furthermore, they received detailed instruction on how to assess the fabrics according to the four requested categories which were:

colour, hairiness, appearance of abrasion as well as flexibility and softness.

These attributes were chosen according to the fabric relevant surface changes specified in the SS EN ISO 15487:2018. All the terms used during the evaluation procedure are established vocabulary for the presented purpose. They are defined and used in the mentioned standard and should be well known by the panel members as suggested in the case of sensory studies to avoid any misinterpretation by individuals (Agarwal et al. 2011).

During the test, each panellist has been given two sets of samples - one of each fabric - consisting out of seven specimens each. All the samples were conditioned for 24 hours under standard atmospheric conditions (21 ± 1°C temperature, 65 ± 2% relative humidity). It can therefore be assumed that the textiles were not influenced by environmental differences regarding their physical properties. The panel was provided with the background information that the two batches of fabric samples were washed and dried between 10 and 50 times (10-20-30-40-45-50). One sample in each stack represented the grey fabric (X), which demonstrated the unwashed initial condition. This was the only sample where the number of washing and drying cycles it has been exposed to (zero) was known to the observer, serving the purpose of referencing it to the remaining specimens. Each inspector was asked to grade the six remaining specimens A-F, which represented the different numbers of washing and drying cycles from 10-50.

The letters on the samples (A-F) have only served the purpose of documentation and data assessment. In order to avoid any bias, they were assigned randomly to the samples and did not indicate the number of washes a specimen had undergone. Hence, they were not informing the panel about their relationship to each other. The number of laundering and drying cycles each sample has been exposed to remained unknown to the panellists throughout the whole procedure. Moreover, the participants were not allowed to interact during the process to avoid outside influences and biased interpretations.

A sensory evaluation scale was deducted in accordance to Sülar and Okur (2007) in order to enhance the comparability of the evaluation done by each individual panellist. The grading of each individual sample was executed in relation to the specimen of the grey fabric. Grades between one and five were available to be assigned through visual and tactile investigation, referring to the grading scale adapted from SS EN ISO 15487:2018 depicted above. The scale has been subject of discussion with the participants prior to the evaluation process, to prevent from misunderstandings and erroneous grading. Additionally, the panellists are asked about the wearability and processability of each specimen, in order to reflect on the overall changes in quality with regards to potential processing and moreover recycling possibilities.

5.2 Tear Strength Test - CRE Tensile Testing Machine

5.2.1 Testing Process

The ASTM D2261-13 outlines the method of the tongue (single rip) procedure for the determination of tear force of textile fabrics. It describes the measurement of the tear force required to continue and propagate a single-rip tear from a cut in a fabric by using a constant-rate-of-extension-type (CRE) machine.

> *"A rectangular specimen, cut in the center of a short edge to form a two-tongued (trouser shaped) specimen, in which one tongue of the specimen is gripped in the upper jaw and the other tongue is gripped in the lower jaw of a tensile testing machine. The separation of the jaws is continuously increased to apply a force to propagate the tear. At the same time, the force developed is recorded. The force to continue the tear is calculated from autographic chart recorders or microprocessor data collection systems." (ASTM D2261-13, p. 2)*

As the tear is started by a cut before conducting the actual test, the force required to initiate a tear cannot directly be obtained through this method. Due to its stated applicability for a variety of fabrics including woven fabrics, knit fabrics or layered fabrics as well as coated or otherwise treated ones, this tensile test offers a suitable method regarding the purpose and objects of interest for the present research.

Within the scope of this study the practical investigations include tests on warp tear strengths as the thinning and abrasion of fabric caused by e.g. laundering mainly influences the tensile strength in warp direction. Based on the findings of McQueen et al. (2017), who could not identify any effect on the tensile strength in weft direction, which is explained with the protected position of weft yarns on the inside of a jeans minimizing the abrasion effect on them, this research disregards the weft tear strengths. Accordingly, a number of five specimens is tested on tear strength across warp direction only.

After the completion of the defined washing cycles per stage, these five specimens are cut out of the two sample fabrics to meet the required measurements of 75 x 200 mm according to ASTM D2261-13. Subsequently, the specimens are prepared with the initial cut and conditioned as stated in the followed standard. All samples were tested in dry condition only after being conditioned for 24 hours under standard atmospheric conditions (21 ± 1 °C temperature, 65 ±

2% relative humidity). For the testing procedure each specimen was clamped individually into the CRE machine (MESDAN LAB, 100 N, Typ S2) and elongated with a clamp speed of 300 mm/min along a maximum of 150 mm cross head travel. Thereby a set of manual clamps with an initial load of 5 N/kg was used.

5.2.2 Evaluation Process

With a total number of seven tests (one for each washing stage from 0-50), information on the development of the fabrics' tear strength across the different number of washing cycles is acquired. The data generated by the tear strength tests was recorded with the Tensolab Vol. 2.2.18.0 software developed by MESDAN S.p.A. and the evaluation method "Option 1". The chosen method calculates the average of the five highest peak forces for each of the five specimens per test as described in ASTM D2261-13.

Included in the software created report are the tear strength mean across all five specimens as well as the individual specimen data on tear strength across the peaks and the number of peaks. In order to support the evaluation of the quantitative data and the comparison between the different tests as representatives of the different number of washing cycles, a set of descriptive statistics is employed. Additionally, it was manually recorded if a specimen occurred not to tear lengthwise (across warp) as intended. These notes were used subsequently to interpret the data with regards to comparability and the intended testing of strength across the warp of the fabrics. According to the depicted experimental setup Table 6 provides a summarised overview considering the key characteristics underlying each testing procedure.

CHARACTERISTICS	DOMESTIC WASHING AND DRYING PROCEDURES	TEAR STRENGTH TESTING
Standards	**SS-EN ISO 6330:2012** *Textiles – Domestic washing and drying procedures for textile testing* **SS-EN ISO 15487:2018** *Textiles – Method for assessing appearance of apparel and other textile end products after domestic washing and drying*	**ASTM D2261-13** *Standard Test Method for Tearing Strength of Fabrics by the Tongue (Single Rip) Procedure*
Samples	6 Samples (75 x 200 mm) per defined washing cycle stage (0-10-20-30-40-45-50) **Total:** 42 Samples	5 Samples (75 x 200 mm) per defined washing cycle stage (0-10-20-30-40-45-50) **Total:** 35 Samples
Employed Equipment	**Washing machine:** Type A **Wash programme:** 4N **Drying Procedure:** Type F **Tumble Dryer:** Type A3 **Detergent:** Reference detergent 2	**Machine type:** constant-rate-of-extension-type (CRE) machine **Specification:** Instron 5900 Series

Table 6 Comparison of applied testing methods

6 Results

6.1 Visible Degradation (sensory assessment)

The degree of occurring fabric degradation has been examined along different methods within this discourse. One of them was the subjective evaluation of the visible degradation on the basis of sensory assessment, including visual and tactile investigation. Figure 5 and 6 show one representative sample for each washing stage conducted with both fabrics tested. The left field shows the grey fabric, which serves as a reference to compare the degree of degradation of each specimen to the initial condition before being washed. The images reveal an alteration in appearance of both fabrics. With an increasing number of laundering and drying cycles, the colour has faded, and surface abrasion has caused the white weft yarns to become more apparent in the warp faced fabric structure.

Fabric A, which consists of 98% cotton and 2% elastane shows signs of creasing from 30 washing and drying cycles onwards. Furthermore, the colour of this fabric has not only faded, but also transformed with regard to the colour tone. While the grey fabric inhabits a dark grey colour, it turns more and more into a brighter indigo tone that can be considered typical for classical denim. This development could already be examined to a slight extent after ten washes. Generally, the appearance changed gradually in correspondence to the increasing number of cycles. Fabric B has reacted similarly to the diverging washing and drying frequencies. The colour of the fabric has likewise been fading gradually. Yet, fabric B originally inhabits a dark indigo shade. Therefore, no transformation considering the colour tone occured. Furthermore, the 100% cotton fabric did not show signs of creasing. This information could be deducted by visually examining the specimens.

Analysing the samples purely visually comes along with limitations concerning the amount of data as well as their validity. Hence, tactile evaluation has additionally been implemented. The following data has evolved from the assessment of a nine-headed panel of textile experts. The investigation and grading of all specimens happened under standardised conditions as depicted previously. The following charts represent the mean of the grades that have been assigned to the fabric specimens, representing the varying laundering and drying frequency, according to the predetermined categories. The grades ranged from five, indicating no change, to one, indicating outstanding change in comparison to the grey sample.

Figure 5 Representative Samples of Fabric A for each washing and drying stage.

Figure 6 Representative Samples of Fabric B for each washing and drying stage.

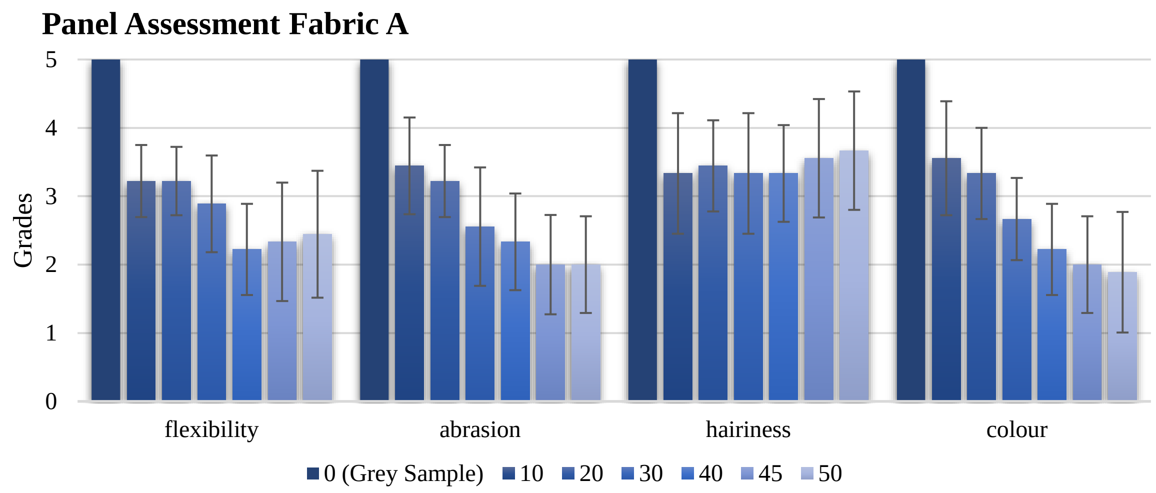


Figure 7 Presentment of the results of the results of the panel assessment for Fabric A.

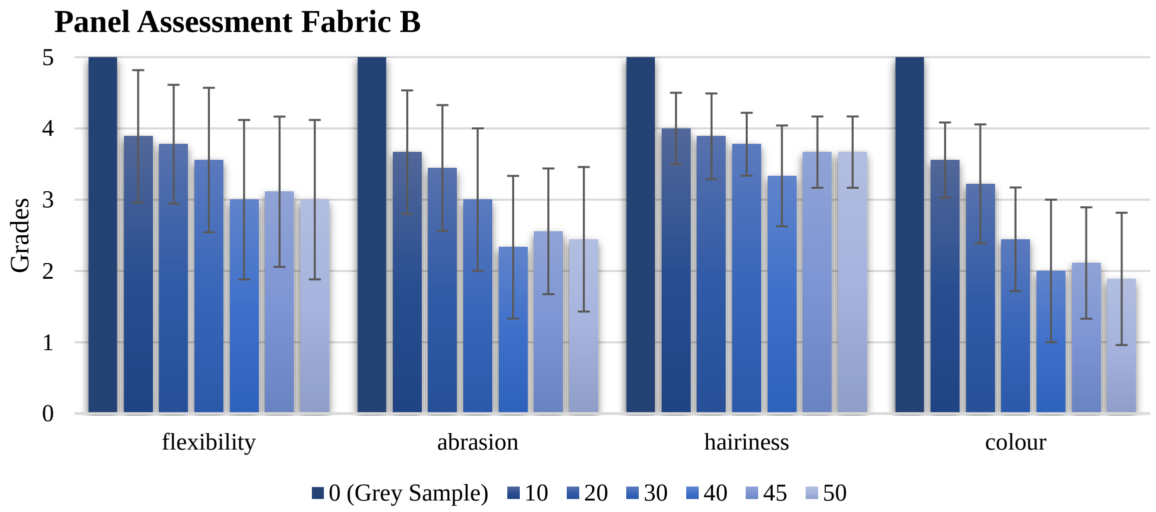


Figure 8 Presentment of the results of the results of the panel assessment for Fabric B.

The visualisation highlights the average grade that has been assigned to the samples. The data depicted in one bar is segregated by category and the number of undergone cycles. With regard to flexibility, the assessment of both fabrics results in a similar graphical progression. After 10 and 20 washing and drying cycles, the specimens were graded corresponding to slight or moderate change. Fabric A was considered to alter slightly more from the grey specimen in terms of flexibility, showing in an average grade of 3.22 for both, 10 and 20 cycles. With a mean of 3.89 and 3.78 fabric B was ranked closer to the original state. For both textiles, the grades declined slightly after 30 washes. After 40 washes, the average grades go down by approximately half a grade compared to the previous stage. Fabric A sinks to a grade of 2.22, while fabric B drops to 3.0. The last two stages were ranked slightly higher or at least equal to the value for 40 washes. No further decline in varying flexibility could thus be detected among the last three stages. The values only fluctuated around 0.22 (A) and 0.11 (B) grades between 40, 45 and 50 cycles. The overall decline happens along a strong negative correlation with a correlation coefficient of -0.91 (A) respectively -0.96 (B). This indicates a high strength of the linear relationship between the alteration of flexibility and the washing cycles.

With regard to the appearance of abrasion, the grading declines even more linearly. The correlation coefficients of -0.98 (A) and -0.95 (B) suggest that an increasing number of washes coherently evokes a higher alteration of abrasion appearance. Again, fabric B starts off with slightly higher grades amounting to 3.67 in average for 10 washes. Fabric B was ranked 3.44 at equal stage. Fabric A then shows a clear linear decline in grades apart from the last two stages, 45 and 50, which are generally graded equally with grade two, corresponding to distinct change. The grades for fabric B were likewise lowered linearly, yet the samples that have been exposed to 45 and 50 washes were assessed marginally higher than after 40 cycles. Consequently, those samples show an abrasion appearance that is slightly closer to the original state of the fabric.

The investigation of the hairiness delivers less distinct results in terms of declining grades with a growing number of cycles. With values of 0,67 (A) and -0.74 (B), the coefficients of correlation suggest a less linear relationship when compared to the first two categories. For Fabric A, the samples for 10, 30 and 40 washes were ranked equally with a 3.33 in average. 20 washes were generally just graded 0.22 higher. The specimens that had undergone 45 and 50 cycles were assessed as being closer to the original state again with the corresponding values 3.56 and 3.67. With all values laying between 3.33 and 3.67, the properties were ranked very similarly in a dense field. Likewise, fabric B was evaluated in a very narrowed scope. The values range from 3.33 to 4.0. However, sample B shows more fluctuation. After 10 cycles the sample were ranked closest to the grey sample. 40 cycles have caused the highest alteration in that sense with a value of 3.33. The remaining values lay very closely to each other.

The final criterium, the colour, has already been addressed previously when describing the images that have been taken of the specimens, showing the gradual fade in colour in correspondence to rising cycle frequency. Among the panel participants, this category shows the most distinct results in terms of grade decline at higher washing stages. For fabric A, the linear relationship can be defined by the coefficient -0.99. Respectively, fabric B has linearly altered in colour along the coefficient -0.97. Both values are very close to a perfect negative linear correlation (-1). For both fabrics, the first three samples (10, 20, 30) deliver comparable results. The grades decrease rapidly in this range and drop from 3.56 (A/B, 10) to 2.67 (A, 30) respectively 2.44 (B, 30). In both cases, the last three samples were ranked closely together again with values going down to a minimum of 1.89 after 50 cycles in both cases.

The standard deviations for the grades assigned to fabric A range between 0.5 and 0.93 (range= 0.43) with a median of 0.71. The median shows that the deviations are evenly distributed within the range. The average amounts to a deviation of 0.74 grades. For fabric B the standard deviations ranged between 0.5 and 1.12 (range= 0.62). The median lays with 0.82 at a very central point of the range again and indicates even value distribution. The average standard deviation is represented by the value 0.87. Therefore, the deviations for the assessment of fabric B are slightly higher, mirroring slightly larger discrepancies in the grades assigned to the specimens by each panellist.

Along with the grading procedure, the participants were asked two questions to close the assessment. Primarily, they were asked whether they consider the fabric sample still wearable in case it mirrors the quality of a denim garment. The term ‘wearable’ is defined as indicating a quality state in which the garment would not yet be discarded in the eyes of the observer. Secondly, the final question was directed towards the processability of the fabric. This encompasses whether the fabric, if discarded by the consumer in the presented stage, does still show potential for further processing such as for instance recycling or remanufacturing. Both questions could either be answered with ‘yes’ or ‘no’. Table 7 shows the answers of the participants in relation to the number of washing cycles. The results show that both fabrics are considered wearable and processible in any of the presented stages by the majority of participants. Nevertheless, a decline of positive answers in relation to a higher number of washing cycles can be observed in case of both fabrics. For fabric A the coefficients of correlation suggest a solid negative linear correlation with values of -0.89 for wearability and -0.78 for processability. The same pattern occurs for fabric B with correlation coefficients of -0.72 for both questions. The strongest decline can be identified with regard to the processability of fabric A. While generally all panellists consider the fabric processible after the first 30 washes, only two thirds do stick to this opinion after 45 and 50 cycles. For fabric B wearability and processability have been assessed to decline simultaneously. The data shows a slight drop to seven positive answers after 40 washes, but for 45 and 50 cycles, only one participant sees wearability and processability endangered. For the wearability of fabric A, clear cut can be documented after 40, 45 and 50 washes when 22% of participant estimated the quality of the fabric to be too poor for being worn.

WASHING CYCLES	**WEARABLE**				**PROCESSIBLE**			
	Fabric A		**Fabric B**		**Fabric A**		**Fabric B**	
	Yes	No	Yes	No	Yes	No	Yes	No
10	9	0	9	0	8	1	9	0
20	9	0	9	0	9	0	9	0
30	9	0	9	0	9	0	9	0
40	7	2	7	2	7	2	7	2
45	7	2	8	1	6	3	8	1
50	7	2	8	1	6	3	8	1

Table 7 Panel assessment of wearability and processability of both fabrics

6.2 Physical degradation (tear strength testing)

In addition to the subjective assessment of visual and tactile changes, the influence of increasing amount of washing cycles on the physical properties of the fabric was examined. Exemplarily, the fabrics were subject to a tear strength test, which delivers quantitative data on the tearing strength across the warp of the denim materials. For each one of the seven washing stages, from 0 to 50 wash cycles, a group of five specimens was tested and their results are combined in the analysis.

While the testing setup intends to tear the fabric lengthwise as initiated by the pre-cut test-specimen, the majority of fabric A samples, which had undergone 0 to 20 washing and drying cycles, tore across the weft of the fabric. Especially, among the unwashed grey fabric all five test specimens followed this behaviour. The images below show a correctly torn specimen of fabric A (torn lengthwise) (Figure 9) and one of the incorrectly torn specimens (torn across the weft of the fabric) (Figure 10) in the machine set-up.

Figure 9 correctly (lengthwise) torn specimen

Figure 10 incorrectly (across weft) torn specimen

The individual samples, which occurred to tear not substantially lengthwise (across warp) as intended by the testing method, were recorded and are marked in Blue in the following documentation as required by the employed testing standard (ASTM D2261-13).

In order to avoid the risk of result falsification through an incorrect tearing behaviour the results are analysed in two ways, one including and one excluding the weft torn specimens. Accordingly, the graph displaying the tear strength of fabric A includes two separate lines, one including all tested specimens and one excluding the incorrectly torn ones (Figure 11). By comparing the two graphs, a slight difference of tear strength development can be detected. This is mainly influenced by the noticeable difference in force calculated for the test in which the fabric specimens, which had undergone 10 washing and drying cycles, have been torn. In the case of this test, the average of the tear strength differs by 13.5N, so that the exclusion of weft torn specimens results in a distinctly higher tear strength value. Additionally, the high standard deviation of 13.79N stands out from the overall average of 5.13N and is reduced to 3.54N by excluding the weft torn specimens, which represents more homogeneous testing results. The elimination of the incorrectly performing specimens reduces the range for most of the tests, which can also be depicted in lower standard deviations. Across the seven deducted tests the generated values lay within a range of 13.29N (including all samples) and 5.83N (excluding the weft torn specimens). Although, there is a relatively wide spread of values in comparison to the average difference of ~4.5N between the consecutive tested stages, which compare a difference of 10 washing and drying cycles, the respective t-test shows a significant difference for all stages, besides the one representing 20 washing and drying cycles (p-value = 0.124), when compared to the results of the unwashed fabric. The t-test was calculated with the data sets including all samples, also incorrectly torn ones, as otherwise there is no sufficient data for the samples of the grey fabric and the first washing stages.

Both of the graphs (including and excluding the weft torn samples) sketch a decrease in tear strength from 83N of the grey fabric to 55N after 50 washes. The significance of the change from 0 to 50 wash cycles can be supported by performing a t-test to evaluate the statistical significance of the mean values, resulting in a p-value < 0.001. According to the calculated p-value H_0 can be rejected and it is assumed, that the results deriving from the specimens of the grey fabric and the ones of the most frequently washed specimens are significantly different.

With a decrease of 28N the fabric lost 33.7% of its tear strength. A slight increase between the washing stage 40 and 45 does not change the appearance of the overall course. Additionally, the decreasing tear strength follows a linear development with a high negative correlation of -0.760, when including all specimens, and an even higher negative correlation of -0.943, when excluding the incorrectly specimens as potential source of falsification.

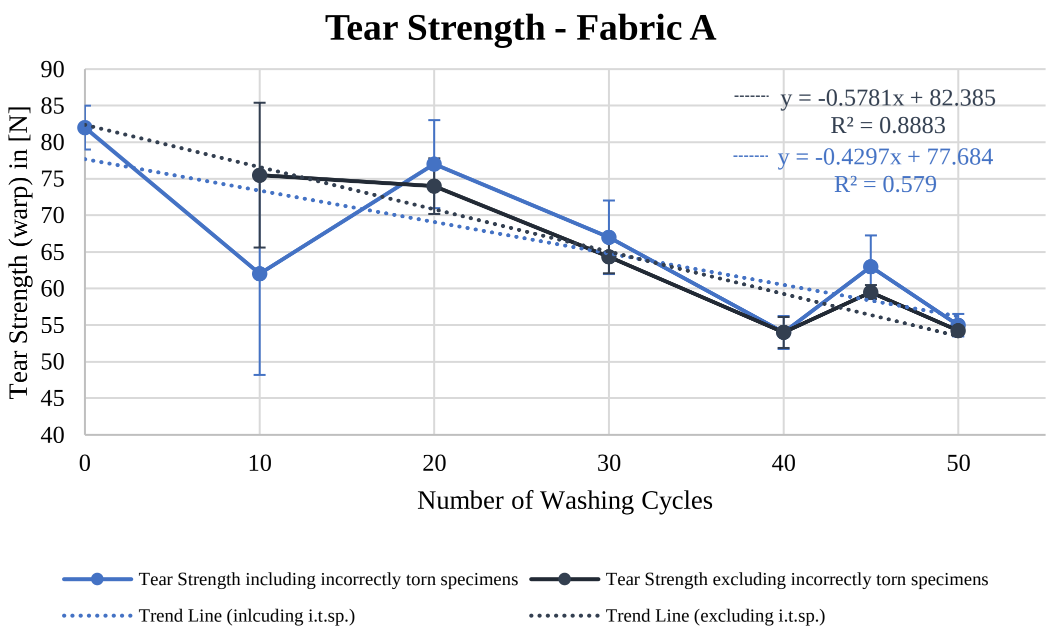


Figure 11 Visual presentment of the alteration of tear strength of fabric A in the course of washing and drying

WASHING STAGE	TEAR STRENGTH [N]					MEAN ± STDEV [N]	
	S1	S2	S3	S4	S5	INCLUDING INCORRECTLY TORN SPECIMENS	EXCLUDING INCORRECTLY TORN SPECIMENS
00	83	77	85	82	83	82 ± 3.00	-
10	73	51	46	78	59	62 ± 13.79	75.5 ± 3.54
20	67	78	82	81	75	77 ± 6.02	74.0 ± 9.90
30	67	71	60	66	73	67 ± 5.03	64.3 ± 3.79
40	56	53	50	53	57	54 ± 2.27	54.0 ± 2.27
45	71	58	61	64	61	63 ± 4.25	59.5 ± 2.12
50	55	55	58	53	54	55 ± 1.55	54.2 ± 0.96

Table 8 Descriptive statistics for the tear strength test of Fabric A

When testing the samples of the 100% cotton fabric all specimens could be torn as initiated by the machinery and experimental set up. Hence, the recorded data seems to deliver unfalsified data on the tearing strength of fabric B and its development across the different washing stages. The report shows an initial tear strength of 75Nfor the grey fabric. With a standard deviation of 3.2N and a range of 9N the fabric samples of the unwashed and untreated stage lay above the average standard deviation of 2.3N and the average range of 5.43N calculate across all test conducted with samples of fabric B.

Similarly, to the course detected in the case of fabric A, the graph for the 100% cotton fabric displays a decrease of tear strength with an increasing number of washing and drying cycles. Moreover, the values fall constantly without any intermediate increases. When regarding the difference between the tear strength values of two subsequent washing stages, the decrease ranges between 2N and 8N for the samples washed and dried up to 40 times, while the value almost stagnates at 53/52N from stage 5 (40 wash cycles) to 7 (50 wash cycles). Thereby, it is important to state, that washing stage 6 and 7 only differ by 5 washing and drying cycles, while all the other stages were defined with an interval of 10 washing and drying cycles. The calculated correlation also depicts a linear trend of the tear strength with a high negative correlation of -0.982. This linear development can be detected when comparing two specimen sets with a difference of 20 wash cycles in between, which show a decrease of around 10N in average. A calculated statistically significant difference underlines the visible results. The calculated p-values proof a significant difference for all stages from 10-50 when compared to the results of the unwashed samples. The decrease from an initial tear strength of 75N, assigned to the unwashed fabric, results in an overall loss of tear strength by 23N (30.67%) after 50 washing and drying cycles.

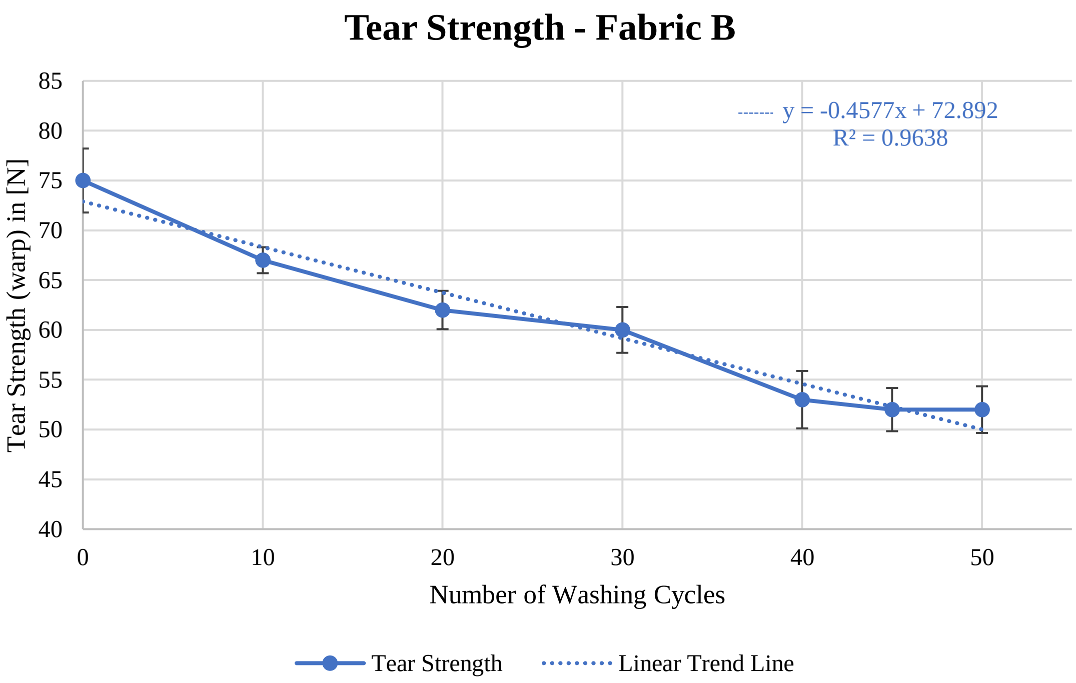


Figure 12 Visual presentment of the alteration of tear strength of fabric B in the course of washing and drying.

WASHING STAGE	TEAR STRENGTH [N]					MEAN ± STDEV [N]		
	S1	S2	S3	S4	S5			
00	70	74	79	75	75	75	±	3.21
10	69	66	66	67	66	67	±	1.30
20	64	63	63	62	59	62	±	1.92
30	58	61	62	63	58	60	±	2.30
40	56	51	50	56	55	53	±	2.88
45	53	50	55	51	50	52	±	2.16
50	50	54	51	50	55	52	±	2.34

Table 9 Descriptive statistics for the tear strength test of Fabric B

6.3 Weight differences

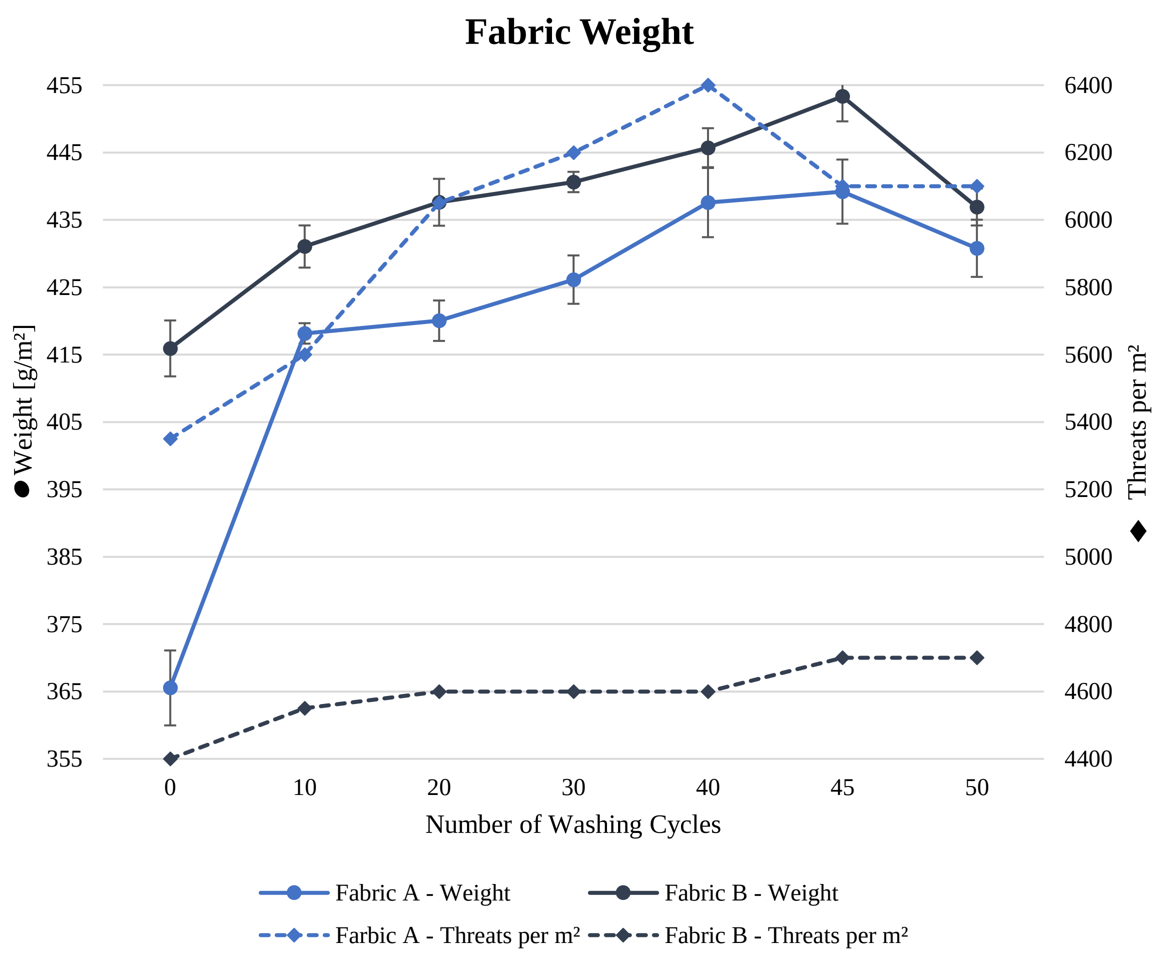


Figure 13 Visual presentment of the alteration of the fabric weight in the course of washing and drying.

The initial weight of the grey fabric was determined by cutting 48 samples in the shape required for the tear strength testing (200mm x 75mm) and weighing with an accuracy of 0.001g (1mg). The average of these values served as a reference for potential weight alterations in the course of washing. Both fabric cloths were washed in one piece. After each predetermined washing stage, six samples were cut out in the same shape (200mm x 75mm) and were weighed after being conditioned under standard atmospheric conditions for at least 24 hours. Concludingly, 36 samples (six per washing stage) were weighed and compared. For the purpose of comparability, the recorded data is followingly presented as areal weight in [g/m²]. The average values of each cycle stage are shown in Figure 13.

For both fabrics a constant increase in weight can be identified up to 45 laundering and drying cycles. The steepest slope occurs between the initial fabric and the weight of the specimens after ten washes. The weight of fabric A changes from 365.53g/m² in average to 418.14g/m². This amounts to an increase of 14.4%. Fabric B shows an increase as well at that point, yet not as steep as for fabric A. The values for B rise from 415.92g/m² to 431.04g/m² corresponding to a plus of 3.6%. Afterwards the weight gain proceeds gradually but less intensely. The weight of fabric A reaches its peak at 439.19g/m² which signifies a difference of 20.2% compared to the original state. Fabric B culminates in 453.32g/m², showing a relative growth of 9% compared to the initial weight. Further t-tests, which compare each stage with the previous one, can clarify a significant difference in weight at least when comparing the results of two stages with an interval of 10 wash cycles in between. The only exception regarding significance can be seen from 40 to 45 washing cycles and only for Fabric A.

Motivated by the observed primary growth in weight, the results are compared to a potential shrinkage behaviour of the fabrics. In order to identify any changes regarding the density of the fabric construction, the individual samples of each stage were investigated with the help of a digital microscope. The microscopic pictures in Figure 14 and Figure 15 show the fabric backsides with constant magnification and are thus able to visualize the shrinkage behaviour of both denim materials. By analysing the thread count, an increase in picks and ends per m² can be identified for both fabrics until the stage of 40 washes for A and until 45 washes for B, which allows to conclude a higher weight per m² resulting from fabric shrinkage. The close-up microscopic images for stage 0 and 50 of both fabrics in Figure 16 and Figure 17 emphasize this contrast and highlight the alteration of areal density of the textiles (the microscopic close-ups for all stages can be examined in the appendix). A positive correlation for the means of both fabrics from stage 10 to 40/45 of weight and threats per m² suggests a dependency between these characteristics.

For the final stage (50 cycles) the weight declines for both textiles as the graphs indicate by dropping at that point. Fabric A scaled 430.78g/m², indicating a decrease of 2.3% in comparison to 45 cycles. A conducted t-test with a calculated p-value of 0.0092 confirms the statistical significance of the weight loss between these two stages. This substantial decrease reduces the weight difference of the samples to the original fabric to 17.9%. For fabric B 436.91g/m² were measured at the termination stage, amounting to a reduction of 3.9% compared to the previous stage. The disparity to the grey sample average dropped to 5%. Likewise, a conducted t-test verifies the statistical significance between the initial and final stage of the test (p-value <0.001). The weight loss, however, does not correlate with the observed changes of thread count per m². While both fabrics lose in weight, their thread count does not change between the last two stages. The calculated correlation coefficient for the values between 40 and 50 washing and drying cycles (0.34 for Fabric A; -0.04 for Fabric B) cannot indicate a dependency between the two characteristics. The calculated standard deviations for the values measured for fabric A range between 1.52g/m² and 5.56g/m². For fabric B the range of deviations encompasses values between 1.51g/m² and 4.15g/m².

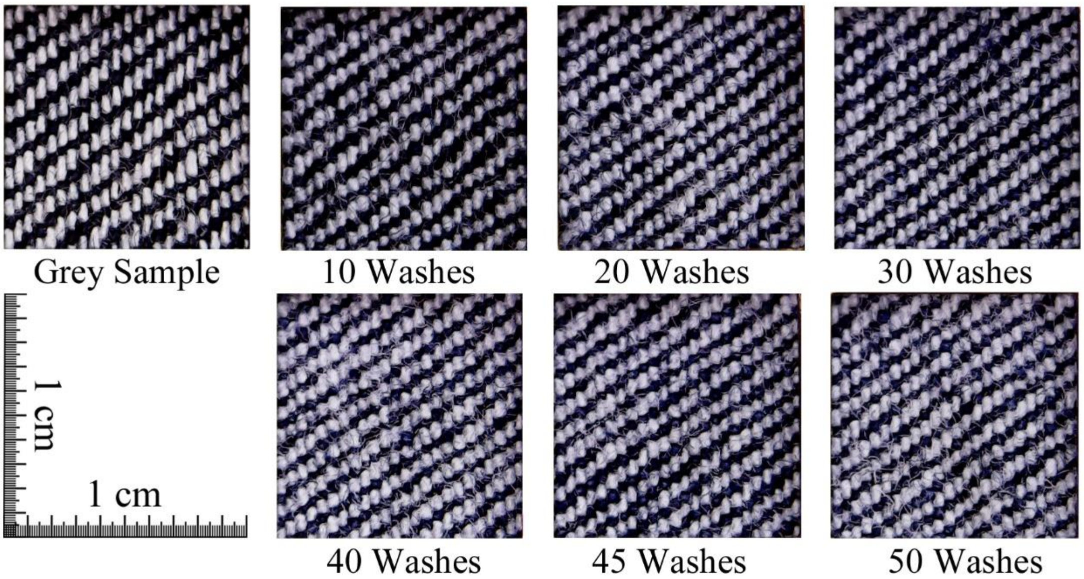


Figure 14 Microscopic images of the backside of fabric A along all washing stages to determine the yarn count per cm².

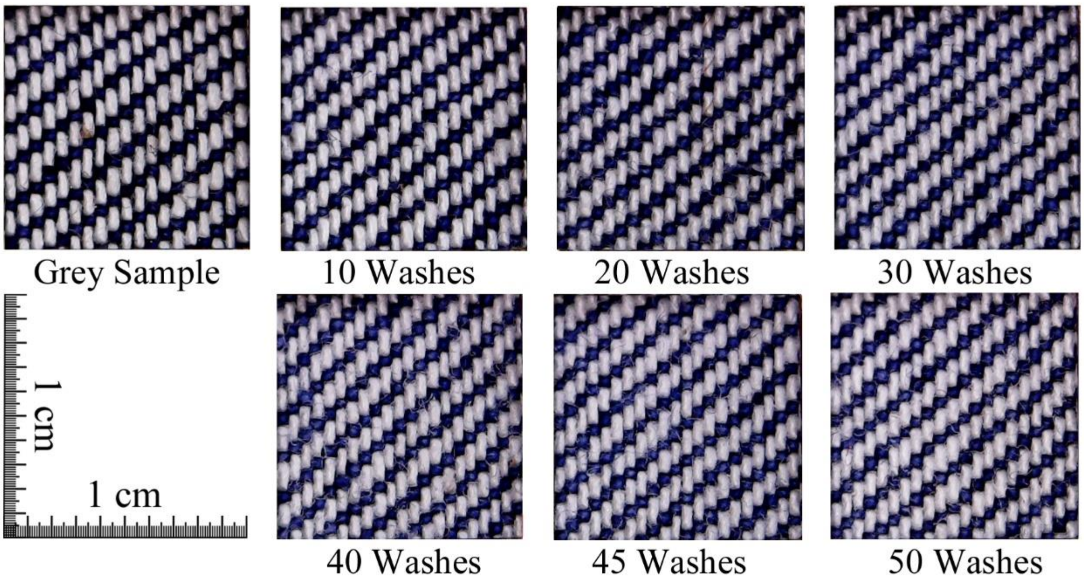


Figure 15 Microscopic images of the backside of fabric B along all washing stages to determine the yarn count per cm².

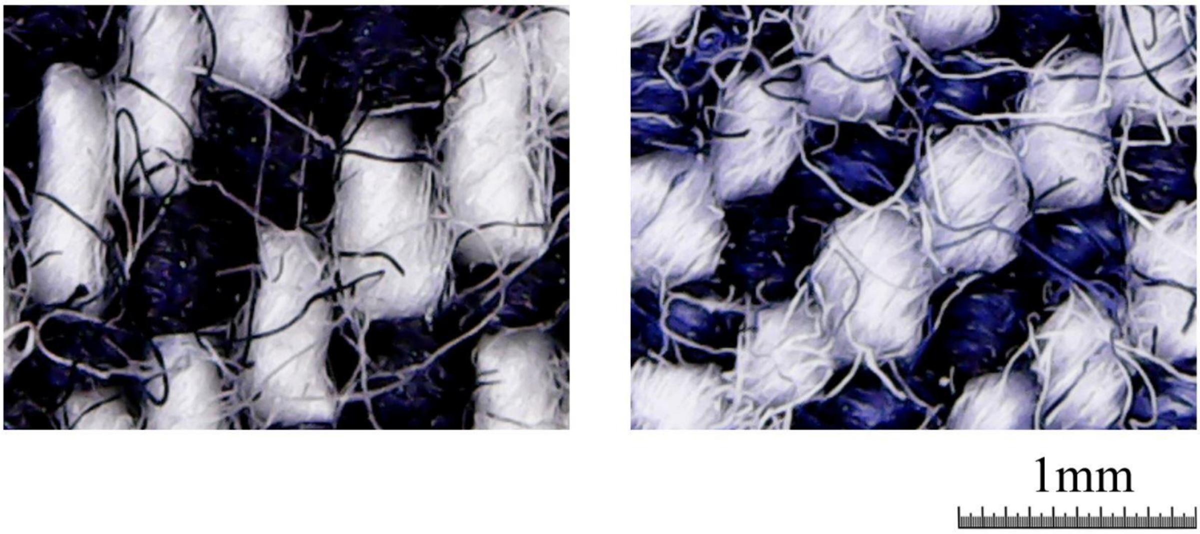


Figure 16 Microscopic close-ups of backside of fabric A after 0 (l.) and 50 (r.) cycles

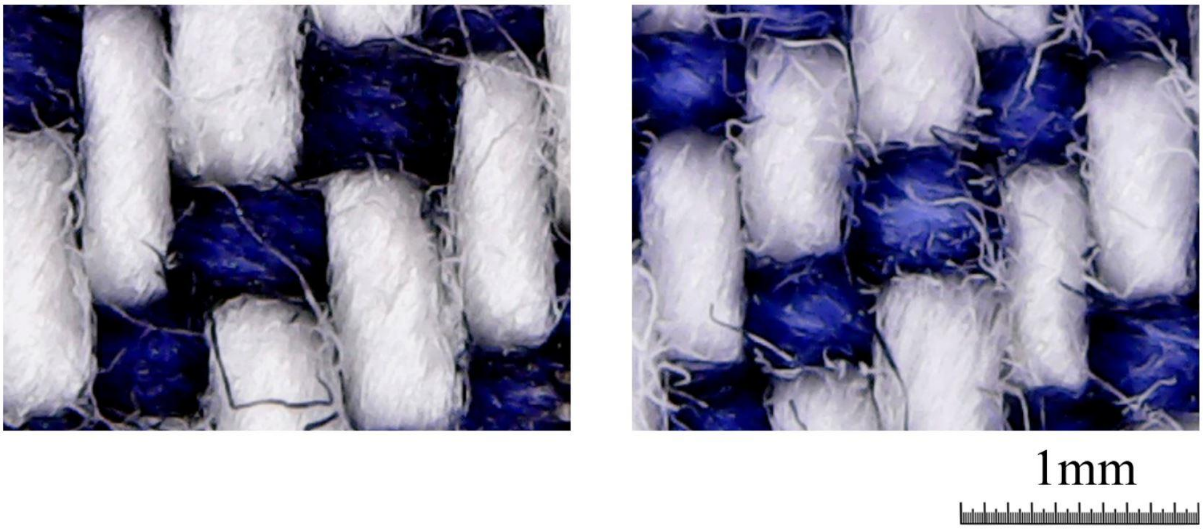


Figure 17 Microscopic close-ups of backside of fabric B after 0 (l.) and 50 (r.) cycles

6.4 Interview Findings

As part of the primer qualitative approach included in this research expert interviews were conducted. Among the interviewees are researchers in the field of textile spinning and reprocessing as well as industry professionals, who contribute with their know-how in the area of denim manufacturing and quality testing and shared their experience from pilot projects in garment remanufacturing. The professional background as well as the coding of the interviewees in the following section has been depicted in Table 3 in chapter 4. It highlights the experts' profession and field of research as well as the organisation they work for and in which country it is situated. The choice for this data collection method is mainly motivated by the literature gap in the present research field, which required external data and new perspectives on the challenges and limitations, which denim recycling is currently facing, especially with regards to closed-loop systems.

Within the review of existing literature, it has already been stated, that current recycling practices for denim fabrics, fail to feed a circular system, due to the fact that the majority of discarded clothing items is downcycled. Findings from the interview with interviewee C (Interview C 2019), an expert within the scope of spinning and mechanical recycling, can provide further reasoning for the current situation. According to C the shredding process, which is most commonly employed for the recycling of cotton materials, exposes fabrics to enormous forces when being processed. The currently available mechanical recycling method underlies the limitations of its kinetic aggressiveness, which causes a great loss in fibre length. Eventually, this aggressive process harms important parameters impacting the quality of the recycling output. As relevant parameters for a quality retaining recycling process, he emphasizes fibre length, the ability to separate a yarn into single fibres again and the colour purity. The latter does not result in a challenge in the exclusive case of denim, as also heterogenous waste of denim products will always remain within a range of blue shades, which can therefore easily be reprocessed into new denim products. However, the spinning expert especially points out the challenge of recycling processes with regards to fibre length, which decreases independently of the feedstock quality to an insufficient length for spinning. Accordingly, a 100% recycled cotton yarn based of the material output from the shredding process is not possible. Instead the recycled fibres can only be mixed with virgin material to generate a sufficient yarn quality. (Interview C 2019) Additionally, interviewee D (Interview D 2019), who is currently researching in the field of process innovation for mechanical recycling, points out that, in case of processing shredded fibres with a significantly shorter length than virgin cotton fibres, rotor spinning should be the method of choice, as it is less dependent on the fibre length in comparison to the other available spinning options.

However, it can be observed that the textile industry has begun to dedicate attention to this challenge. Modern research aims to improve the present recycling options (Interview C 2019). Across the industry, the necessity for recycling methods, that are able to preserve the input quality is recognizes and underlined by several interviewees (Interview C 2019; Interview D 2019). Especially, interviewee B (Interview B 2019), who is responsible for the remanufacturing project of Re:Textile and Cheap Monday, pointed out the importance of optimized recycling methods when striving for a CLR. Within the Re:Textile collaboration with clothing retailer Cheap Monday, in which B was involved, the potential of remanufacturing was used to support a circular economy approach. As part of the collaboration of the two a collection from used and disposed workwear was created and successfully sold through the channels of the fashion retailer.

Besides this exemplary industry project, the interviewees C and D, both independently dedicate their research to the challenge of the mechanical recycling process (Interview C 2019; Interview D 2019). One approach focuses on yarn modifications to support the opening process of fabrics in the recycling stage. With the help of alterations made already in the initial spinning process of the yarn, the fabric structure can be loosened just before the shredding process by activating the integrated yarns, so that the fibre separation requires less aggressive mechanical treatment. Concludingly, the fibre quality suffers less during the mechanical recycling process. Likewise, current university research lead by interviewee D could successfully optimize the shredding process with additional lubricants, which support the fibre separation and enable a less aggressive procedure (Interview D 2019). Accordingly, the both innovative approaches lead to higher ability to sustain the fibre quality throughout the recycling process.

Besides the technological limitations, the recycling industry has to cope with further challenges which were among others discussed in the interview with an established trouser manufacture. Interviewee A, who is responsible for the quality assurance of denim materials, has highlighted the variety of influencing factors during the use phase enthusiastically. She underlined aspects such as varying physical activity level, varying detergents, employment of softeners or the habit of tumble- or air drying (Interview A 2019). A's statement aligns with the heterogeneity of post-consumer waste, which B (Interview B 2019) experienced during remanufacturing projects. Further, the industry expert sees a demand to improve the sorting process as initial step to drive closed loop systems. Especially, the great manual effort can be seen as a major challenge and is therefore limiting the efficiency of current recycling processes. Interviewee B (Interview B 2019) agrees that additional information, which could be provided with the help of tracking tools to record for example the number of washing cycles a garment has undergone and thus indicate a garments condition, can support the sorting process. Moreover, in combination with more insight on fabric degradation and its impact on a garment's functionality, he sees such as a beneficial management tool for sorting companies as well as textile leasing services (Interview B 2019). Interviewee A (Interview A 2019) has however asserted the reasonable doubt regarding this concept as long as it requires high engagement and accuracy from the consumer side in order to be a valuable tool.

Throughout all the interviews, the interest in new solutions and demand to improve the current recycling processes is vividly expressed. According to interviewee D (Interview D 2019), reuse and the maximal prolonging of a garment's service lifetime would provide the most resource saving option. However, B (Interview B 2019) and C (Interview C 2019) are concerned with the present consumer behaviour, which in times of fast fashion and shorter product life cycles, challenges a sustainable textile consumption (Interview C 2019). Since the discarding of garments cannot be prohibited, D agrees with the statement of interviewee C, who states that in comparison to the cultivation of virgin cotton any recycling method offers a less resource consuming manufacturing process due to saving raw material, energy and water.

7 Discussion and Outlook

7.1 How are the characteristics of denim fabrics influenced by an increasing number of laundering and drying cycles, which represent the textiles' service lifetime?

The following section refers to research question one and summarizes as well as discusses the results with regard to their impact on the alteration and degradation of the denim fabrics in relation to an increasing exposure to laundering and drying cycles.

7.1.1 Visible degradation (sensory assessment)

The visual assessment of the fabric alteration corresponding to increasing laundering and drying cycles has revealed clear patterns. Signs of degradation have proven to become apparent within a scope of fifty standardised domestic washing cycles. The images in Figures 5 and 6 have already been revealing a fade of colour as well as an indication of structural variation. The grading process executed by a panel of textile experts has underlined these assumptions and mirrors the development in numerical values, allowing quantitative analysis of the subjective visual and tactile assessment.

In terms of flexibility, both fabrics have been ranked in between slight and moderate change for 10 to 30 cycles. With a rising number of cycles, it can be observed that the grading tendency clearly declines as indicated by the strongly negative linear correlations. For 40, 45 and 50 cycles, the samples of fabric A were assigned between distinct and moderate change (grade 2 to 3) change, with a tendency towards distinct, whereas the samples of fabric B have clearly been rated to moderately (grade 3) differ from the grey sample. The careful inspection of the samples has shown that the grading corresponds to an elevated flexibility, the more the fabric has been washed. The higher flexibility can be considered as a sign of fabric degradation since the fibres lose steadfastness. From the loss of steadfastness, a weakening of the fibre structure has been inferred. This aligns with the assumptions of Bresee et al. (1994), who have highlighted the severe impact of laundering on the structural integrity of the fibre. Furthermore, it relates to the presentment of Mc Queen et al. (2017), who identified laundering as the main responsible process for fibre breakage and a corresponding loss in length.

Likewise, the increase of abrasion appearance in correspondence to higher laundering frequency can be deducted from the constantly decreasing grades. This has again been underlined by significant coefficients for a negative linear correlation. The samples of fabric A that have undergone 40 to 50 cycles have been ranked to show distinct changes in comparison to the grey fabric. For Fabric B the values lay between distinct and moderate, yet with a slight tendency towards distinct (grade 2). Again, this investigation compares to Bresee et al. (1994) who have shed a light on the occurrence of fibre transfer and edge abrasion as a result of domestic laundering. Accordingly, the abrasion becomes apparent due to the surface friction of the washed items. Moreover, it can be assumed that by the surface fibre transfer, analysed by Bresee et al. (1994), the core fibres lose protection with an increasing number of laundering and drying cycles. Therefore, the overall fabric structure may show further signs of abrasion in an extended form of this study.

With regard to the hairiness, all fabric samples have been graded according to a moderate to slight change. However, a slightly higher difference of the specimens of fabric A to their original state can be observed in comparison to fabric B which shows less alteration. The higher concentration of the data does also show in less distinctive and complementary coefficients of correlation. The relationships are less linear than the dependency of abrasion and flexibility on the number of undergone washing cycles. As a result, the grade values do not tend to absent themselves remarkably from the grey fabric. This can be related to the fact that denim is a very densely woven fabric owed to its particular weave construction. According to Raina et al. (2015) its twill weave structure provides resistance to rough environmental influences as presented in the literature review (3.2.4). One possible explanation is that a dense fabric protects fibres from being erected, resulting in lower hairiness. The panel study has however shown that for both fabrics the investigators tended to give higher grades for the specimens that have been washed and dried the most (45, 50). This can be related to the fact that once single fibres became detached from the yarn structure, they were exposed to the burden of abrasion presented above. This again corresponds to Bresee et al.'s (1994) findings regarding fibre transfer as a common result of laundering. This hypothesis is supported by the fact that the collecting sieve of the washing machine comprised detached cotton fibres of the laundered denim material after each cycle.

As depicted in the images of the fabric as well as mirrored in the grading of the participants, the final criterium of colour has undergone a linear alteration. This does also mirror in the highest coefficients of correlation reached for both fabrics. Generally, it can be stated that the fabrics have changed their colour remarkably after 50 washes when compared to the grey sample. Yet, this does not necessarily indicate fabric degradation, but rather relates to the quality of the dyestuff. It can however be stated that the appearance of the fabrics might have become lighter in correspondence to the appearance of abrasion, which likewise had a strong negative correlation. As highlighted by Raina et al. (2015) denim is a warp-faced fabric. Therefore, the indigo-dyed warp yarns determine the dark colour and the surface appearance of the textile. Once the surface yarns are exposed to abrasion, the white weft yarns show through the structure and can cause the fabric to appear lighter. In this case one could deduct an increase in fabric degradation.

The grades that have been assigned by each participant deviated within an average range of 0.74 grades for fabric A and 0.87 grades for fabric B. This corresponds to less than one grade difference to the average value between the single assessments. Accordingly, the provenly linearly correlated results demonstrate the alteration of both fabrics in the course of washing as well as the common perception of the appearance of increasing degradation. The evaluation has revealed a weakening of the overall fabric structure as well as signs of abrasion. The results harmonise with the research of Bresee et al. (1994), who highlighted fibre transfer and edge abrasion as predominantly apparent when laundering denim. The data shows accurately that the exposure to 50 washes causes a significant decline of quality of the fabric.

This deduction has likewise been supported by the investigation of the panellists' opinions with regard to wearability and processability of the samples. The research has shown that the quality is diminishing which causes a growing number of participants to rate wearability and processability as being insufficient with an increasing number of laundering and dying cycles. Especially fabric A, consisting of 2% elastane, has shown a clearly reduced potential for processability after 45 and 50 washes, yet the majority rated the quality as remaining sufficient. Generally, it has to be taken into consideration that the panel consisted of only nine members which allows the opinion of one single panellist to have a large impact on the statistical analysis of the results due to a relative share of 11.1%. Furthermore, the questions demand a very subjective assessment and relate to individual consumption behaviours in relation to clothing.

Nevertheless, it can be deducted that both wearability and processability underlie signs of degradation. Within this study, both properties did not decline significantly, yet a tendency for their decrease could be determined. This can reveal a correlation between degradation and recycling efficiency which will be discussed further in connection to the second research question.

7.1.2 Physical Degradation - Tear Strength (Warp)

Denim fabrics demonstrate their popularity as most favourable material construction out of cotton, due to its quintessential characteristics as stated in the background and literature review of this study. Among these characteristics, strength and durability mark important physical properties to support the success of this fabric type. In relation to these distinct characteristics the observed development of the fabrics' tear strength with increasing number of wash and drying cycles, shows impacts on the overall quality of the fabrics over the course of a simulated service lifetime.

During the testing conducted on Fabric A, it could be observed, that especially the fabric samples, which represent the early washing stages from 0 to 20, had a high tendency to tear across the weft of the fabric instead of lengthwise along the prepared cut. Reasonable cause for this behaviour could be a comparably weaker weft yarn and the additional fabric component of 2% Elastane, which provides an obvious distinguishing factor between the two tested denim fabrics. The thinning and abrasion caused by laundering, which was described by McQueen et al. (2017) to mainly affect the tensile strength in warp direction, can further explain, why later washing stages with 30 plus washing and drying cycles were less prone to a weft tear. While the weft yarns were protected from weakening caused by abrasion, the warp of the fabric lost strength, which resulted in a generally lower required machine force to propagate the cross-warp tear. Correspondingly, the warp strength adapted to or got even lower than the strength of the weft and thereby reduced the force applied to the weft yarns.

Independently of the incorrectly torn specimens in case of Fabric A, both of the denim fabrics, examined in the practical evaluation of this researched, show a similar trend for the analysed tear strength. The initial tear strength of the unwashed fabric decreased by 33.7% for Fabric A and 30.67% for Fabric B after 50 washing cycles. Concludingly, these results show a loss of 1/3 of the strength of the warp yarns, which were subject to tear strength investigations. Likewise, a linear progression of the decrease in strength can be observed and hints at general trend of degradation with regards to the fabrics' tear strength, if the number of wash cycles would increase further. A high negative correlation for the results of both fabrics, depicts a continuous and steady loss in strength. As Raina et al. (2015) mentions high yarn strength among others as dominant requirement for denim production, the results of this research describe a significant change of one of the physical properties, which frame durability as a substantial characteristic of denim. Once more, it shows the vital impact of laundering in terms of frequency on the useful life of a garment similar to what Bresee et al. (1994) concluded from their findings. For the purpose of this study the fabrics were washed and dried up to 50 times over a short period of time. When translating the number of 50 washes into an actual service life of a garment, it would represent the cumulation of bi-weekly washes within a two-year span. This appears as a realistic time span taking into consideration, that the current societal development drives a frequent washing behaviour after only one to two wears (Jack 2013). Within this washing frequency and the respective time span the degradation did not yet mark an end of lifetime in the sense of its initiated purpose as the subjective assessment likewise states the fabric at the final stage to provide sufficient quality as a "wearable" garment. Especially, due to the previously described characteristic including durability and longevity, resulting from densely woven twill construction, the denim fabrics were expected to withstand the mechanical stress caused by washing machine and dryer to a certain extent. However, a loss of more than 30% of a major physical property, which was detectable for both fabrics, proofs an undeniable quality deficit.

As mentioned in the limitations of this study, the results on tear strength were derived from only two different denim fabrics and the manual operating of the CRE machine might have influenced the data collection. Nevertheless, a clear trend and correlation of increasing washing cycles and decreasing tear strength can be drawn from the results.

7.1.3 Weight differences

The weight of the specimens has been determined with the intention of documenting potential weight differences after an increasing number of laundering and drying cycles. It has been speculated that after a certain point, the weight of the specimens will decline as a result of fibre transfer and surface abrasion which have been acquainted as common side effects of domestic laundering on the basis of Bresee et al.'s (1994) research. A loss of weight was predetermined as a potential indicator for fabric degradation since it suggests a loss of material and hence a thinning of the textile. It was chosen as an additional signifier for fabric alteration in relation to an elevated washing frequency.

The responsible manager for the quality assurance of fabrics at an established trouser manufacturer in Germany (Interview A 2019) has underlined the circumstance that denim initially tends to gain weight after it has been washed. She presented this phenomenon as a result of fabric shrinkage. The material gains density during the first washing and laundering processes since the yarns react with contraction to the procedure. This increase in density influences the amount of fibre material per area and hence causes the textile to become heavier with regard to weight per square metre. An additional investigation of thread counts per m² on the tested samples could confirm this behaviour for the fabrics included in this study.

The collected data on thread count, indicating fabric shrinkage, are taken into consideration when analysing the initial increase in weight of both fabrics. Since the fabric has been washed as a whole piece of cloth and the specimens have been cut after each determined washing stage into the same size of 200mm x 75mm, the shrinkage did influence the amount of material allocated within the sample area. Increasing numbers of threads per m² support the present effect, which is monitored in Figure 16 and 17.

As can be deducted from the graphical presentment of the weight differences in chapter 6.3, the weight of both fabrics keeps increasing up to 45 washes. This implies that the shrinkage predominantly influences the measured weight differences of the specimens in comparison to the grey sample. Consequently, potential fibre loss has not become apparent in the weighing results until that point since it did not exceed the gain in weight that occurred due to the contraction of the textile. However, after 50 washes the fabric has stopped to become heavier and in contrast lost weight compared to the previous stage. This loss in weight has shown to have high statistical significance for both fabrics, resulting from very low p-values in the t-test against the results of the previous stage (45). Furthermore, all previous stages show a decent correlation between alteration in weight and increase in thread count. Yet, this correlation is no longer evident for the last two stages, suggesting that the thread count is no longer responsible for the differences in weight at those stages.

Accordingly, the weight reduction can be assigned to a loss of fibre material. A reversal of shrinkage in the course of washing has not been taken into consideration as it is lacking scientific or practical evidence and has not become visible in the microscopic images in Figure 14 to 17. Furthermore, especially Figure 16 and 17 serve as an indicator for the roughening of the yarn structure. Single fibres got erected with increasing washes and can thus be easier detached and separated from the yarn- thus fabric structure. Fibre transfer is likely to be encouraged. Henceforth, it can be stated that the fabric has lost material and related to that mass. This can be contextualised with the occurrence of fabric degradation since it implies an overall weakening of the fabric structure. In this case, the fibre loss has only become evident after 50 washes due to the mentioned shrinkage. In further research, the shrinkage could be calculated, and its mass could hence be subtracted from the weighing results so that potential fibre loss can be identified at earlier stages of the process. Within this discourse it remains unclear to what exact extent shrinkage and fibre loss influence the final weighing result. Nonetheless, the measurements recorded after 50 washes prove a degradation process as being evident.

7.1.4 Generalisation

In general, the testing and investigation of both fabrics along versatile methods have enabled inferences on the degradation and alteration of the fabric in the course of drying and laundering. Generally, it can be stated that 50 washes might not fully cover the active service lifetime of a denim garment. Yet, especially with regard to fast fashion, the use-phase of garments has shortened, and clothes are regularly disposed earlier than their actual end of life in terms of degradation (Interview B 2019). Therefore, the analysis of 50 washes has solid potential to represent a large share of a denim item's active service life in "a century of disposal" (Levin 2011).

The evident degree of degradation of both fabrics tested is limited. However, it has to be considered that denim is an extraordinarily durable fabric that has been designed for rough environmental conditions as revealed in the literature review (Paul 2015). Therefore, the fabric is not as prone to physical decomposition than other fabrics might be. Hence it can be assumed that an extension of this research with a broader variety of textiles can enlighten the influence of laundering and drying on the alteration of textiles further. Nevertheless, denim is one of the world's most prevalent textiles, which makes it a very valuable source for raw material regeneration (Miller and Woodward 2011). It can thus be declared that an investigation of the degradation of denim fabrics throughout their service lifetime can help to create deeper insights into the recycling potential of the material at varying laundering stages. This in turn can have a large impact on future management processes. The investigation of the material behaviour can help to deduct valuable information for process optimisation as well operationalisation of recycling practises. Concludingly, the analysis of the properties of the most essential component of recycling - the raw material - paves the way to develop innovative technical and managerial solutions. The following section will further discuss the impact of the laboratory findings of this research on the recycling efficiency of denim.

7.2 How does a potential fabric degradation resulting from laundering and drying processes influence the recycling potential of denim?

7.2.1 Influences from the process perspective

Generally, laboratory tests on fabric specimens can be difficult to compare with the actual service performance of a garment due to several unpredictably interacting influences (Hu 2008). However, the presented results provide a clear indication of fabric degradation as well as the resulting change of important physical properties. These properties are not only relevant during the use phase but might likewise influence the textile's recyclability. According to interviewee C (Interview C 2019), an expert within the scope of spinning and mechanical recycling, fabrics are being exposed to enormous forces when being shredded. Hence, the fabrics' tear strength potentially impacts the performance of the textile during mechanical processing.

Especially with a focus on closed loop recycling, the feedstock quality is of importance. Schmidt, Watson & Roos (2016) stated a dependency of recycling potential and the quality of feedstock. Since the fibre-to-fibre processes essentially refer to the same spinning processes used for virgin material, the output quality also depends on the same factors. Further, interviewee C (Interview C 2019) emphasizes the fibre length, the ability to separate a yarn back into single fibres and the colour purity as important parameters representing the main challenges for the (mechanical) recycling process. This does correspond to the presented parameter hierarchy for ring spinning depicted in Table 1, which highlights the importance of especially fibre length for the production of quality ring spun yarns. Interviewee D (Interview D 2019), who is currently researching in the field of process innovation for mechanical recycling, has emphasised that shredded fibres are therefore preferably rotor spun, since this process is less dependent on the length than on the strength of the fibres, which has equally been demonstrated in the tabular comparison (Table 1).In relation to the mentioned parameters for quality retaining fibre to fibre recycling, among which colour purity is mentioned, denim fabrics provide a general basis potential for pursuing such a recycling strategy. When recycling denim fabrics, the output material will appear in a blue shade, which compared to the recycling of other types of heterogeneous waste does not cause any problems and instead provides a suitable colour to be reprocessed into a new denim product (Interview C 2019). Accordingly, this parameter does not challenge denim recycling specifically, but moreover increases its potential for CLR.

The currently available mechanical recycling method shredding underlies the limitations of its kinetic aggressiveness, which causes a great loss in fibre length. Strong shredding machines tear the fabric apart, so that the separated fibres are highly damaged and cannot compete with virgin material (Interview C 2019). Accordingly, the input quality, which is supposed to be steered with a "best before date", is not as important as assumed in the motivation of this research with regards to the currently employed shredding procedure. Independent of the feedstock quality, the output material can anyways only be used to complement virgin fibres with a small percentage, when it is further spun into yarns of sufficient quality for textile production, in order to stretch the available amount of cotton material.

However, it can be observed that the textile industry has begun to dedicate attention to this challenge. The demand for recycling methods, that are able to preserve the input quality is not only present in literature as previously discussed (Elander et al. 2017b) but drives researchers from different institutions to seek for new solutions (Interview C 2019; Interview D 2019). Especially, when aiming for a circular system the necessity to find optimized solutions within the recycling of clothes remains as underlined by the B and C (Interview B 2019; Interview C 2019).

Experts in the field of textile spinning and reprocessing aim to improve the present recycling options with different approaches as the conducted interviews with industry experts revealed. For example, the yarn modifications within the initial production are supposed to enable an easier and less aggressive opening process of fabrics once they reached the end of their service life and are introduced into the recycling procedure (Interview C 2019). Another approach, which directly focuses on optimizing the shredding process with the help of lubricants, could name first successes in producing a higher quality of recycled fibres (Interview D 2019). According to the increasing potential to sustain a higher fibre quality, both of these methods and their results seem more sensitive to the quality of the feedstock, which corresponds with the findings of the literature review. Here it states, that the output quality in general is influenced by ingoing condition and purity of the material. Concludingly, a "best before date", which gives more specific indications on foreseeable degradation, could be beneficial, when striving for closed loop recycling with these innovations. The signs of degradation observed on the two denim fabrics subject to this study can already indicate a significant loss in strength as well as visible colour fading and surface structure changes reducing the overall quality of the fibres and the one of potentially recycled fibres. This degradation data can serve as a basis for further studies with regard to the optimisation of the shredding process, which has not been subject to this work. The information about the reaction of denim fabrics to an increased number of washes can for example allow an informed adjustment of opening aggressiveness according to the remaining strength of the fabric.

Apart from the feedstock quality and the technically limiting process parameters, the question whether the process can actually be considered economically rewarding remains. Are the additional process and energy costs outperformed by the value addition owed to recycling? Interviewee D (Interview D 2019) has pointed out that the option to wear a garment until its physical end of life can be considered superior in terms of material and product efficiency. This implies a prolonging of the use-phase until a point of degradation that compromises the functionality of a garment. Nevertheless, she underlines the option of recycling as being far less resource and energy consuming than manufacturing a product from virgin material whose impact reaches back to the growing of the cotton fibre. As presented in the introduction of this thesis, especially cotton poses an environmental burden to its growing areas and hence the ecosystem since it is extraordinarily demanding with regard to water and pesticides (Burnett 2016). Therefore, recycling of cotton raises the material efficiency and thus the resource efficiency of the components required for growing the fibre. This has likewise been highlighted by interviewee C who has stressed this advantage even further. He clearly stated that recycling is a beneficial and inevitable process for the resource situation the textile industry finds itself in (Interview C 2019; Koszewska 2018).

Interviewee B (Interview B 2019), who has been responsible for remanufacturing processes in collaboration with established retailers and workwear providers, has pointed out that the idea of consumers wearing their garments until they fall apart is not contemporary with regard to the omnipresence of fast fashion. The lifetime of garments has shortened, and garments are mainly disposed due to the fact that they lost their fashionability as well as for the sake of following new, ever evolving trends. Consequently, the textile industry needs to find efficient ways, such as closed loop recycling methods, to deal with this vast amount of post-consumer waste. Two aims drive this responsibility: First, the avoidance of garments ending up in landfill, which is as suggested by the waste hierarchy in chapter 3.2.5 the least favourable option. Second, the increase of material efficiency as an answer to an increasing scarcity of natural resources which is opposed to constantly growing demand for the very same (Schmidt et al. 2016).

Literature as well as the interviewed experts name the sorting procedure as a major challenge for CLR (Interview B 2019). In the case of this very first step when regarding the holistic recycling process, the quality of feedstock also refers to its homogeneity. Technical challenges and high manual effort are among the reasons which hinder to use the full potential of discarded textiles. Interviewee B (Interview B 2019) clearly emphasized that the effective operationalisation and innovative development of recycling processes are fundamentally reliant on an improved information supply with regard to the heterogeneous masses of post-consumer waste. This information is vital for adequate sorting processes which in turn are essential for retaining the highest possible value from the garments disposed.

7.2.2 Influences from the managerial perspective

The presented research focuses on the identification of fabric degradation as a driver for managerial process optimisation. The identification of the degree of denim degradation after a defined number of washing and drying cycles is a valuable tool for the retention of material quality. According to the number of cycles that a denim product has undergone during its active service lifetime, the optimum recycling solution can be selected. A garment that has for instance been discarded after only a small amount of laundering cycles has thus not degraded significantly and can be resold or remanufactured before being recycled mechanically even though the material value is still high. The ‘best before date’, hence the date when it should no longer be reused but recycled in order to retain the optimum material value, could not be determined within the scope of this research but instead requires an additional investigation of the shredding process on denim fabrics in varying degradation stages.

Generally, the outcome of this study serves as reference data for the potential that a discarded garment still inhabits, defining how it can be processed further in the most efficient way. This principle follows existing practices in other industrial fields such as the car sector. When a used car is meant to be resold, the number of kilometres it has been driven for has an enormous influence on the market value of the car. It can influence whether the car still has potential to be reused and thus be sold second-hand or whether the end of its active service life is reached, resulting in scrapping of the car. Concludingly, the examination of a garments' maximum number of washing cycles before it is meant to be recycled, offers the potential to influence the selection processes of sorting services as well as second-hand businesses in terms of quality sensitivity and pricing.

However, even if the data for the degradation of a fabric after a defined number of washes is available, the tracking of the number of cycles in a domestic surrounding remains challenging. This represents a critical aspect of implementing and operationalising the presented concept for elevated recycling efficiency. The hypothetical proposal to introduce a tool that tracks the number of washing and drying cycles that a garment undergoes in its active service lifetime has evoked a positive reaction. Information about the potential degradation stage of a garment can help to assign it to the best suitable recycling option. Products that are still in a very good conditions and have not been exposed to laundering frequently could thus be employed for remanufacturing processes whereas further decomposed clothes can undergo mechanical or chemical recycling. Furthermore, as indicated above, the tool could represent a valuable management tool for garment leasing services, who could monitor the current stage of the garment in terms of washing and drying cycles after it is being returned from a lease. Consequently, the leasing and recycling conditions can be individually adjusted to the degree of degradation of the particular article (Interview B 2019).

The tracking of the washes could practically be implemented along the employment of RFID (Radio Frequency Identification) technology, which documents the cycle times electronically on a chip. For this purpose, the chip however needs to receive data from the washing machine as well as the dryer and vice versa. The technological basis for this communication is not yet established in the domestic environment and is hence not scalable so far. Large institutions such as hospitals are already employing RFID technology as a technological instrument to sort their laundry and process it in accordance to the implied laundering specifications. The hard- and software is available on an industrialised scale yet requires the technological framework to process and modify the digital data (Yajuan et al. 2015). Hence, further innovation in the field of domestic washing machinery in collaboration with RFID developers is mandatory for the broad establishment of this tool in private households.

A second approach would be a washing tag, which is manually maintained by the consumer. It implies that the consumer keeps track of the number of washes a garment is exposed to by ticking each wash for instance on a provided care label attached to the item. By this, sorting facilities would receive valuable information for sorting and could deduct the physical condition of the textile and thus the further proceeding. For this purpose, this research would have to be expanded to a broader scope of textiles again in order to contextualise the information and deliver a frame of reference for the degradation stage after a certain amount of cycles.

With regard to the washing tag, interviewee A (Interview A 2019) has however asserted the reasonable doubt that this requires high engagement and accuracy by the consumer which poses a burden to the successful implementation of this concept. Nevertheless, a decent educational framework and storytelling could encourage dedication in favour of this approach. The fact that environmental and societal conflicts have gained elevated importance on the global agenda has likewise risen the awareness of individual consumers (Fletcher 2013). In a long-term perspective there is significant potential for technological developments, for instance in the presented field of RFID, which allow an automatization of this documentation. This would instigate easy operationalisation, reduce human error and enhance standardisation of the data, enumerating essential parameters for large scale high-precision sorting and recycling. For the successful application such technology and further research on the material level is inevitable since this data, as exemplarily presented in this discourse, builds the cornerstone for closing the loop towards the choice of the most suitable and efficient recycling option.

8 Contribution

Denim fabrics are ubiquitous in the contemporary society (Miller and Woodward 2011). Hence the development of current practices towards closed loop recycling methods for denim represents a cornerstone for exhausting the full potential of the raw material employed, encouraging quality retaining circularity. Cotton has happened to become a scarce natural resource, facing an ever-growing global demand. Therefore, this research contributes to the rethinking and innovation of currently existing recycling procedures for denim. The investigation of the degradation of denim fabrics during their active service lifetime, represented by laundering and drying cycles, provides the possibility of assigning the number of washes the textile has been exposed to a corresponding degradation stage. Henceforth, this can contribute to enhancing the sensitivity as well as the accuracy of currently existing mechanical recycling processes in the future.

The research has not allowed to assign a defined expiry date to denim garment due to a lack of information regarding how the fabric reacts to being shredded in different degradation stages. The quality of the fibre outcome of mechanical recycling after different cycle times represents a vital indicator for further inferences within this scope. However, it serves as a reference for further research in this field. The gathered data allows deductions concerning the development of fabric strength and can thus lead to a targeted and informed adjustment of opening aggressiveness as an instrument for further investigation.

Employing modern technology such as for instance RFID opens new possibilities for sorting and individualised processing. As a result, discarded garments can receive a treatment that is tailored to their state of disposal. This in turn enhances the maximisation of material exploitation. Current research aims at reducing the aggressiveness of momentarily existing mechanical recycling options, thereby steering the process towards elevated quality dependency. Correspondingly, the material data gathered within the scope of this research adds value to the process optimisation of denim recycling. The optimum point for actively terminating the service lifetime of a garment to maintain its full processing potential can potentially become a focus of industrial attention in the future.

The examined degradation represents a set of data that can inform management decisions as well as technological adaptation to the feedstock quality, for example in terms of accurately adjustable opening aggressiveness during shredding. In order to deduct the adequate process measures from these findings, further research is to be conducted. The influence of the shredding process on the denim fabrics at different degradation levels has not yet been analysed. Likewise, for the improvement of sorting and processing efficiency, further textiles have to be investigated in terms of their decomposing behaviour so as to generate an extended database for efficient material handling. This is especially mandatory considering the heterogeneity of post-consumer waste, owed to the vast diversity of textiles and garments disposed.

Solutions to deal with the enormous variety of discarded post-consumer textiles find their roots in understanding the very structure and condition of them. The acquisition of fabric degradation data in combination with the development of mechanical recycling processes towards a higher sensitivity for feedstock quality represent the trailblazers for closed-loop recycling solutions. Without an investigation of the alteration of fabric characteristics at varying stages of the service lifetime of a garment, the successful operationalisation, innovation and management of recycling processes is jeopardised. Generally, this thesis contributes to the existing body of theory in the field of textile recycling by presenting novel correlations between washing stage and denim degradation resulting from standardised practical testing procedures. Thereby, the outcome is addressing an evident literature gap.

9 Conclusion

The presented research has investigated the alteration and corresponding degradation of two representative denim fabrics while being exposed to an increasing number of laundering and drying cycles. From the results, according to the physical and aesthetic discrepancies of the fabric at different process stages, insights with regard to the recycling potential and further processing of discarded denim products have been inferred.

Referring back to the initial idea of introducing a "best before date" for denim products, it needs to be considered that the expert interviews as well as the literature review have revealed contemporary process insufficiencies which pose a burden to the efficiency of the intended concept. This includes the previously mentioned aggressiveness of the shredding process and thus its insensitivity towards the quality and degradation stage of the feedstock. Nevertheless, research within the scope of process optimisation in order to improve the shredding process with regard to fibre breakage is evident. These developments promise to enhance the significance of the degradation stage in which the garments are entering the recycling procedure, resulting in an elevated necessity for an optimisation of the service lifetime of a clothing item as to exhaust its full recycling potential. Consequently, an optimum point for feeding a used garment back into a value retaining process is to be determined.

In this context the presented research gains relevance by providing information on the material alteration in the course of washing and laundering. These insights can serve as a framework for further investigations regarding the influence of the identified degradation stages on the mechanical recycling process. So far, the information does not allow deductions considering an differentiation of recycling behaviour at different stages. However, the results allow to infer from the number of launderings to a denim garments' evident degradation. This can drive the management of sorting and reselling businesses towards elevated quality- thus processing and pricing sensitivity.

The tear strength testing has revealed that the stability of the fabric is declining linearly in relation to an increased number of laundering and drying cycles. This is underlined by the investigated weight reduction owed to the phenomenon of fibre loss and a corresponding textile thinning. A general decline in the strength of the warp threads as well as in the weight of the denim can suggest that the textile structure might open up more easily during the shredding process owed to a reduced stability of the weave construction. Therefore, the energy and aggressiveness required to separate single fibres recedes. Yet, it does also imply a reduced stability of the fibre structure itself which jeopardises the spinnability of the fibres into value retaining yarns. Thus, it is essential to initiate further investigations in the field of material degradation to allow more precise prognoses concerning an optimum point for value retaining recycling.

The panel study embedded in this discourse allows to deduct a first tendency for a best before date. The question referring to the wearability as well as the processability of both fabrics after each washing stage has disclosed that from 30 washes onwards single participants started to question and negate the adequacy of fabric A and B with regard to both categories. This indicates that the fabrics have started to show severe appearance of fatigue and alteration after 30 cycles. Yet, as mentioned above, it does not allow to deduct the fabrics' behaviour during a shredding process as well as the quality of the connected outcome from these assumptions. Consequently, it has become evident that further research concerning material degradation as well as its influence on the quality of shredded material has to be conducted. It is inevitable, that the ever-growing demand for natural fibres cannot be covered by the current cultivation capacity of cotton which has been exhausted from the beginning of the 1990's onwards. Hence, recycling processes need to be optimised in collaboration with material experts as well as professionals for the subsequent process steps such as spinning. The industry needs to become engaged on an interdisciplinary level and must regard recycling from a holistic process perspective to close the loop towards material value retention. Accordingly, the presented research represents a potential link for material- and process informed management decisions.

This discourse has contributed to the existing theory by developing insights with regard to the degradation and alteration of denim in response to washing and drying throughout its active service lifetime. It has investigated and analysed the impact of an increasing number of cycles on the physical and aesthetic properties of the fabric and has drawn conclusions considering the influence of these findings on the recycling potential and quality sensitive handling of denim. The narrow scope of the research, being that it has merely focused on one type of fabric, has nevertheless the potential to have a large impact on the scientific realm of textile degradation and recycling since denim, as the textile in focus, is one of the most prevalent ones worldwide. Further research in this field can help to steer the management of post-consumer waste towards exalted efficiency and allows more suitable, individualised treatment of garments according to their stage of degradation. A standardised employment of the washing stage as an indicator for fabric degradation may potentially have wide-ranging influence on the level of sorting, recycling, pricing and thus the circularity of denim garments. This standardisation is driven by material data as exemplarily presented in this thesis. Thereby, the chance for exhausting a denim fabrics' full potential towards utmost utilisation is elevated.

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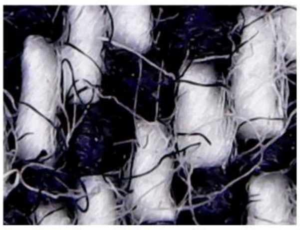
11 Appendix

11.1 Whole series of microscopic close-ups for fabric A and B

A

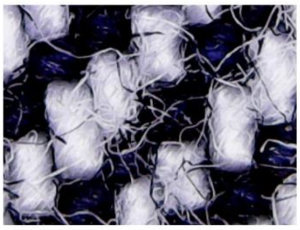
B

1mm



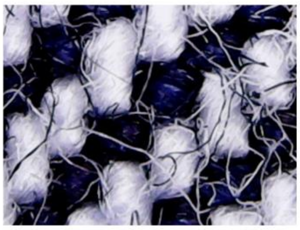
0 Washes

0 Washes



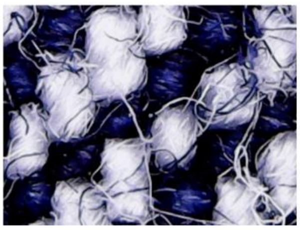
10 Washes

10 Washes



20 Washes

20 Washes



30 Washes

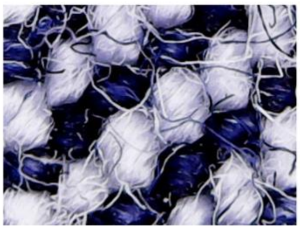
30 Washes

40 Washes

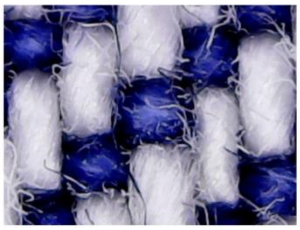
40 Washes

45 Washes

45 Washes



50 Washes



50 Washes

THE SWEDISH SCHOOL
OF TEXTILES
UNIVERSITY OF BORÅS

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