The potential of mechanical recycling for post-consumer textiles.

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the technical, logistical and economic challenges and opportunities for the mechanical recycling process for post-consumer textile waste garments.

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Abstract

Currently, the amount of post-consumer textile waste is growing. Unfortunately, the European recycling infrastructure is lacking, preventing efficient recycling operations. It is still difficult to set up production lines of high-quality products with shredded textile waste fibres, yet the demand for these products is rising. The goal of this study was to find out how the mechanical recycling process for mixed post-consumer textile waste garments could be improved and integrated into circular supply chains. A literature study, semi-structured interviews and a multi-criteria analysis on Manufacture Readiness Levels were conducted to investigate the several challenges and production opportunities for recycled textile waste fibres from a technical, logistical and economic point of view. Thereafter, a roadmap for future mechanical recycling was established. The key technical challenge is a low quality and short lengths of shredded fibres. Adjusting the cutting and shredding machines per fibre type could enable change. Integrating textile waste fibres in supply chains has proven to ensure environmental benefits. From an economic perspective, the cost price of shredded textile waste fibres hinders the manufacturability, which could be resolved through the creation of new cross-sectorial open- and closed-loop production capabilities. Regarding logistics, the set-up of regional recycling hubs could scale up and map out the supply of post-consumer textiles. The evolvement of intensified collaborations could ensure the quality improvement of recycled waste fibres and extend the product applications opportunities. The potential of shredded textile waste fibres could be increased by improving manufacturing and profitability, as suggested in the roadmap proposal. However, the elaborated opportunities of this study are subject to external influences, that cannot be predicted in this study. To check the feasibility of the proposed opportunities, empirical studies on the profitability of textile waste are recommended.

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1. Introduction

In this chapter, the relevant background to comprehend the aim of this master thesis is introduced. Thereafter, the problem description, aim and research questions are presented.

1.1 Background

In a circular economy, fabrics, clothes, textiles, and fibres are upcycled and recycled to maintain a high-quality value, preventing the formation of waste. However, each year, approximately fifty-three million tonnes of fibres are produced globally for the production of garments in linear value chains. Raw materials, such as crude oil and cellulose, are extracted to manufacture synthetic and cellulosic textiles. From the total worldwide clothing production, 73% is incinerated or put at landfill at end-of-life (Ellen MacArthur Foundation, 2017). Globally, every second a garbage truck full of textile waste is thrown away, which requires land, water and fossil fuels, and leads to air, water and soil pollution (United Nations Environment Programme, 2020). When textile fabrics are incinerated, chemicals and CO_2 emissions are emitted (Cobbing & Vicaire, 2016). The textile and apparel industry are one of the world's major economic sectors and is increasing along with the worldwide population growth (Sandin & Peters, 2018). The enormous amounts of textiles production, together with a correspondent high disposal rate, are the reasons why this is the second largest polluting industry in the world (Pensupa, 2020).

Recycling textiles reduces the need for virgin fibres for the production of textiles, as the required use of water and chemicals. Textile waste management is the way forward to reduce the environmental impact of the textiles and apparel industry (Pensupa, 2020). Increasing the recycling of textile waste garments assists in the transition towards a circular economy, enabling a closed-loop circular textiles and fashion industry (Ellen MacArthur Foundation, 2017).

For this transition to be successful, it is dependent on the engagement and measures taken by stakeholders in the (circular) supply and value chains (Ellen MacArthur Foundation, 2017). A system-level change is needed. All actors from the value chain will require to share available knowledge and cooperate (Ellen MacArthur Foundation, 2019). The speed of the transition is determined by the quantity and quality of recycled textile waste fibres and their integration in production processes of new fashion and interior textiles. Fortunately, the recycling of textile waste and the use of recycled fibres is becoming a key target of the textiles industry (Euratex, 2020).

This master thesis aims to contribute to this target and increase the potential of recycled textile waste fibres, due to the improvement of mechanical recycling processes for post-consumer textile waste garments. The current technical, logistical and economic challenges of the process for textile waste were studied. Secondly, the opportunities that could enable an improvement of the mechanical recycling process and the quality level of the recycled fibres were studied, increasing the product applications for recycled fibres. Furthermore, the integration of recycled textile waste fibres in circular supply chains was investigated, as the cost-efficiency of the fibres. In the end, a roadmap of activities to enhance the product development of mechanically recycled textile waste fibres was realised for textile waste recyclers.

1.2 Company profile

This master thesis is subsidized by and in collaboration with the French company EuraMaterials. EuraMaterials functions as a cluster and network leader, that leads projects on the integration of recycling processes on a regional and intra-regional level. EuraMaterials implements circular economy paradigms in projects, some focussing on the recycling of textile waste, with the aim of stimulating innovations in recycling processes in the Northern French area (EuraMaterials, 2020a). The four-year Interreg RETEX project had the aim to investigate the set-up of circular value chains for the mechanical recycling of cotton, polyester and cotton/polyester textile waste garments. The results of the RETEX project were considered as a source of information for this study.

1.3 Problem description

The global amount of post-consumer textile waste is growing. The current linear business models of the fashion and textile industry, which have already brought negative environmental impacts and societal consequences, have led to the enormous amount of 48 million tonnes of clothing textile waste (Ellen MacArthur Foundation, 2019). Currently, throughout Europe, textiles are either exported to foreign countries (central Africa, eastern Europe), disposed at landfills or incinerated (Bartl, 2019; Ellen MacArthur Foundation, 2017). The supply of post-consumer textile waste garments is increasing, while the demand of many African countries is stagnating (Filho et al., 2019; Ljungkvist, Watson, & Elander, 2018). Besides, due to the 'fast fashion' movement, the amount pre-consumer cutting waste and unsold garments have severely increased (Koszewska, 2018). The amount of collected textile waste garments is expected to expand by 79% over the coming years across the EU. The European recycling infrastructure needs to be prepared to have the ability to recycle this incoming quantity of clothing (Bünemann & Kösegi, 2019).

Simultaneously, there is a global failure of the mechanical recycling of post-consumer textile waste, which is preventing efficient recycling operations (Ellen MacArthur Foundation, 2017). Currently, less than 1% of the European textile waste is recycled in closed-loops (Ellen MacArthur Foundation, 2019). When post-consumer textile waste garments are mechanically recycled, they are often used for the production of low-quality products such as wiping cloths and insulation materials. This is only a small range of products of the textiles industry. Besides, mechanically recycled textile waste fibres cannot yet be integrated in the production of apparel textiles, it is currently difficult to setup a closed-loop supply chain for the mechanical recycling of post-consumer textile waste garments (Jia, Yin, Chen, & Chen, 2020; Pensupa, 2020). Changes in the used-clothing market remark the need for the development of fibre-to-fibre recycling (WRAP, 2019). Textile waste recycling is currently gaining in popularity, more products are being produced from recycled textile waste fibres, however, there are still challenges that need to be overcome in the recycling of textile garments (Muthu, 2020).

1.4 Aim

The aim of this master thesis was to find out how the mechanical recycling process of post-consumer textile waste garments could be improved and integrated in circular supply chains.

During the present study, the possible technical, logistical and economic benefits of the mechanical recycling process of post-consumer textile waste garments were investigated. New methods to increase the recycling performance of mechanically recycled post-consumer textiles were examined by looking at:

- improving the quality of mechanically recycled fibres and increase the spinning and knitting/weaving possibilities.
- the influence of logistic operations on the quality level and product possibilities.

Opportunities to improve the mechanical recycling of mixed cellulosic/synthetic post-consumer textile waste garments and their integration in circular supply and value chains were studied. These opportunities for closed-loop and open-loop recycling value chains were compared regarding cost-efficiency and feasibility. The studied challenges and opportunities for improvement were examined with the hope to provide a future circular outlook of the textiles and apparel industry.

The proposed roadmap was designed for textile waste recyclers. The aim of the roadmap is to support textile waste recyclers and their network in enabling change in the textiles industry, to achieve the EU target of recycling 70% of the post-consumer textile waste in 2030 (Pensupa, 2020). Likely, the clear action steps of the roadmap might help textile waste recyclers to implement the proposed opportunities in their business operations.

1.5 Research questions

The aim of the present study resulted in the formulation of the following research question:

How can the potential of shredded textile waste fibres be increased, by looking at the current challenges and opportunities to improve the mechanical recycling process for post-consumer textile waste garments?

1. What are the current technical, logistical and economic challenges of the mechanical recycling process for post-consumer textile waste garments?
2. How could the production of products manufactured from recycled textile waste fibres be increased?
3. Which technical, logistical and economic benefits would the improvement of the mechanical recycling process for post-consumer textile waste garments generate?
4. How could mechanically recycled post-consumer textile waste fibres be integrated into circular supply chains?
5. How can the integration of mechanically recycled textile waste fibres in a circular supply chain be profitable?

2. Frame of reference

This chapter will provide a framework of relevant information on the state-of-art of the mechanical recycling process for post-consumer textiles. The present issues of the fashion and textiles industry will be explained, thereafter several methods of recycling textiles are introduced.

2.1 Circular Economy

It is becoming more and more clear that the current linear (take-make-dispose) economic model cannot be sustained any longer. Fortunately, the circular economy principles, characterized by a constant restoration and regeneration of value in the life cycle of products, are increasingly gaining interest in Europe. The circular economy model is characterized by the 3R principles: reduce, reuse, recycle, applied throughout the entire products life cycle (Prieto-Sandoval, Jaca, & Ormazabal, 2018). The circular economy is based on optimising the use of available resources and creating renewable flows of materials and products (Gardetti, 2019).

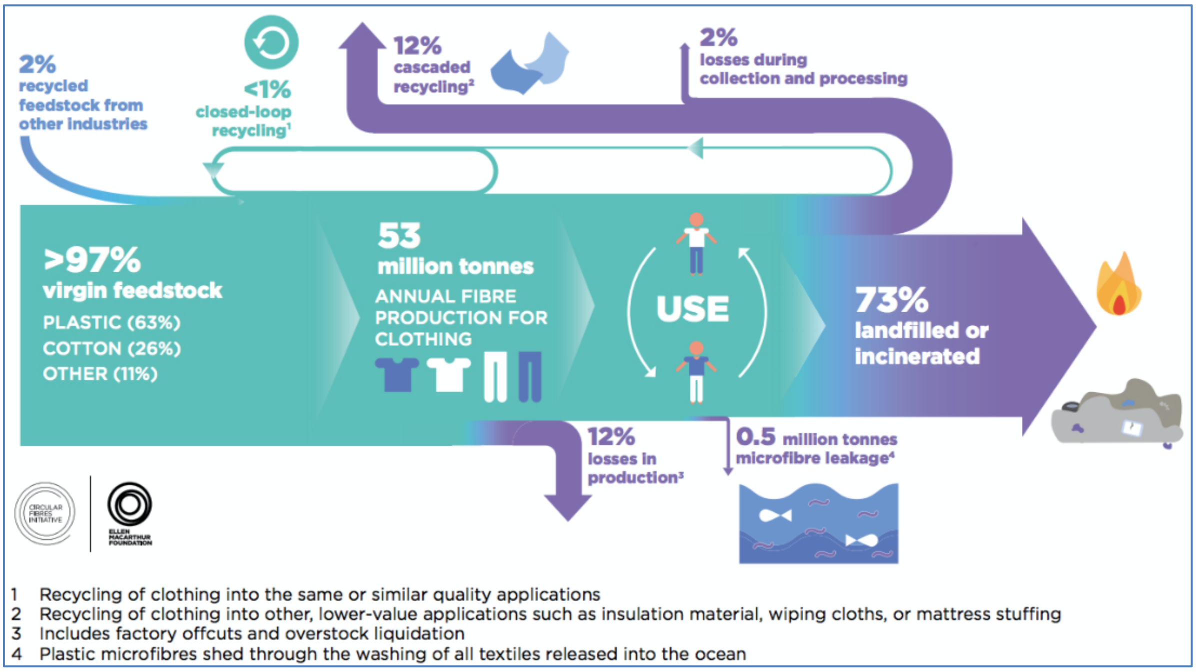
The European Union repeatedly emphasized the importance of the transition towards a circular economy. An important step in this transition is the setup of a Circular Economy Action plan in 2020 (European Commission, 2015). The implementation of textile-to-textile recycling processes was described as action step to minimise the amount of textile waste in Europe (European Commission, 2015). Besides, to raise awareness on textile waste recycling to European governments, the European Parliament included a textile waste management in the Waste Framework Directive in 2018 (Piribauer & Bartl, 2019). The plan was to recover 70% of the textile waste from landfills in 2030. The planned actions included the research for new recycling technologies and fibre sorting systems (Bukhari, Carrasco-Gallego, & Ponce-Cueto, 2018; Pensupa, 2020). It is predicted that in the new EU Strategy for Textiles, launching this month, a European recycling policy for textiles will be introduced (van Veldhoven, 2020). This new Strategy has as goal to strengthen competitiveness and innovation in the textiles sector, to encourage the reuse of textiles, and the EU market for sustainable and circular textiles (European Commission, 2020).

2.2 Fashion industry

Over the past decades, the fashion industry was characterized by rapidly changing styles and trends, responding to consumer needs. This development led to the so-called 'fast fashion', which resulted in high quantities of low-quality textiles combined with a quicker and higher disposal rate (Koszewska, 2018). This trend led to the situation that currently, post-industrial and post-consumer textile waste fabrics are mostly landfilled or incinerated. The absence of waste management facilities in Europe contributed to this situation (Dissanayake, Weerasinghe, Thebuwanage, & Bandara, 2021). It was predicted in previous research that this amount would increase to 148 million tons in 2030 (Echeverria, Handoko, Pahlevani, & Sahajwalla, 2019; Eder-Hansen et al., 2017). As seen in Figure 1, the Ellen MacArthur

Foundation estimated a percentage of 73% of the total global amount of post-consumer textile waste garments that end up at landfill or are incinerated. 12% of the collected textile waste fabrics is recycled through cascade recycling, into a lower-value application, 2% is recycled to be converted as sources for other industries and less than 1% of the total amount of textile waste is recycled in a closed-loop (Ellen MacArthur Foundation, 2017).

Figure 1. Recycling of end-of-life clothing (Ellen MacArthur Foundation, 2017).



On the other hand, the WRAP institution reported that 95% of the post-consumer textile waste garments are recyclable (Hu, Du, Pensupa, & Lin, 2018). Besides, the recycling of textile waste reduces the environmental impact of textiles, compared to landfill and incineration (Sandin & Peters, 2018).

The environmental impact of clothing production needs to be reduced, an Extend Producer Responsibility policy is necessary in Europe to diminish the virgin textiles production and increase the use of recycled post-consumer textile waste fibres (European Environment Agency, 2019). A European EPR policy will provide a sufficient supply of post-consumer textiles to the textile waste recycler, that will benefit the cost-efficiency of the shredded waste fibres and will enable the scale-up of product application opportunities on a European scale. By introducing a European recycling standard, the EU target of recycling 70% of all post-consumer textiles in 2030 can be reached (European Environment Agency, 2019). France implemented an EPR policy in 2008 (Filho et al., 2019). Producers are considered responsible by law to manage the recycling of their products. By using this framework, the recovery rate of post-consumer textile waste increased in France up to 90% (Bukhari et al., 2018).

In a recent Dutch parliament document, the Dutch circular textiles targets were presented. In 2025, the aim is to produce textiles in the Netherlands with a minimum of 25% post-consumer recycled content (INRetail, Modint, & VGT, 2019; van Veldhoven, 2020). Also, the goal is to recycle 30% of the collected post-consumer textiles on the Dutch market for the production of textiles, this percentage would increase to 50% in 2030 (van Veldhoven, 2020).

The recycling of post-consumer textile waste fabrics allows the fashion industry to move forward towards a circular economy. For this transformation to be successful, the integration of several circular supply chains is required. A circular supply chain management would need to be set in place between textile waste collecting, sorting, processing and exporting facilities of post-consumer textile waste garments (Pensupa, 2020). The Ellen MacArthur Foundation concluded that the creation of collaborations between actors is of utmost importance during this transition towards a circular textiles industry (Ellen MacArthur Foundation, 2017). The WRAP claimed that these collaborations are currently lacking (Pensupa, 2020).

2.3 Textiles

For the manufacturing of textiles and apparel garments, fibres are used that originate from natural, regenerated or manufactured sources. Natural fibres are either cellulosic fibres, such as cotton and linen, or protein fibres, such as wool and silk (Payne, 2015). Manufactured fibres are sourced from petrochemical bases, such as polyethene terephthalate (PET) (Pensupa, 2020). The manufacturing process of textiles is a chain of operations in which fibres are converted into yarns and yarn into fabrics. Textiles who are produced from different fibres materials are either mechanically twisted together to create a single yarn, or, when man-made fibres are chosen, extruded through a spinneret to create a yarn filament (Euratex, 2020a). Fibres from natural and synthetic sources are often blended to form a mix of desired qualities. The characteristics of cotton fibres, durability and wearability, are blended with the breathability and easy-care of polyester fibres. Cotton/polyester blends are the most fabricated fibre mixes in the textile and apparel industry (Dissanayake et al., 2021).

Sorting process

Pensupa (2020) concluded that the sorting process of textile waste garments is of utmost importance for the recycling of post-consumer textile waste garments. At the collection site, the textile waste garments are collected and sorted in several quality and fibre mix categories. Thereafter, labels, zippers, buttons, leather patches and metal parts need to be removed manually (Pensupa, 2020; Radhakrishnan, 2017). Currently there is a lack of a comprehensive and cost-efficient sorting system to sort textile waste garments. The diversity of fibre blends and the unstable incoming volumes of textile waste obstruct the qualitative sorting of fabrics (Euratex, 2020a).

2.4 Recycling methods

Textile waste garments can be recycled to manufacture new textile products. The textile fabric can either be upcycled or downcycled. Upcycling operations turn fabrics into high-value products, downcycling turns the fabric scraps into low-value products (Pensupa, 2020).

Besides, there are two kinds of textile waste garments. Firstly, looking at the manufacturing of fashion apparel, the cutting and sewing processes generate significant amounts of pre-consumer textile waste. Pre-consumer textiles are either off-cuts, leftovers, rejected fabrics or wasted textiles during textile production (Ellen MacArthur Foundation, 2017). The second category are post-consumer textile waste garments, that have been worn out by customers, thrown away in recycling bins or collected at collection services. Textile collectors separate these garments by the level of quality, the high-quality clothing items are put aside for resale, the lower quality items remain for recycling (Pensupa, 2020).

Both pre- and post-consumer textile waste garments can be recycled in open-loop and closed-loops. In addition, for both loops, the recycling of textiles can be distinguished between a mechanical or a chemical recycling process.

2.4.1 Open-loop recycling

In open-loop recycling, the textile waste fibres are reused for the production of different new products, hence entering new product life cycles (Curran, 2015). Open loop recycling often involves pre-consumer textile waste scraps that are transformed into fibres for the production of new non-textiles product applications. The open-loop recycling of pre-consumer textile waste has proven to have many environmental benefits (Muthu, Li, Hu, & Ze, 2012; Payne, 2015). Over the past years, open-loop recycling has proven to be feasible in the fashion industry, yet not on an industrial scale, mainly due to the downgrading of the quality of the fibres (Payne, 2015).

2.4.2 Closed-loop recycling

In closed-loop recycling, the collected textile waste fabrics are reprocessed for the production of new textiles, thus re-entering the same loop (Eder-Hansen et al., 2017). For closed-loop recycling, the cradle-to-cradle methodology is a well-known and used method, in which closed-loop recycled fibres can be recycled in the same production chain (Payne, 2015). Fiber-to-fibre recycling programs can be set up as closed-loop recycling operation for post-consumer textiles (Pensupa, 2020). Fibre-to-fibre recycling is often a downcycling operation, due to the fact that these systems are not yet scalable and cannot handle the amounts of post-consumer textile waste garments (Ellen MacArthur Foundation, 2017; Filho et al., 2019).

A major issue of closed-loop recycling operations of post-consumer textile waste is the variety of fibre blends used for the production of apparel fabrics. The diversity of fibre materials and the multiple possible fibre blends obstruct the separation of the several fibres (Payne, 2015; Pensupa, 2020). After performing a review on the current textile recycling processes, Piribauer and Bartl (2019) concluded that the multi-fibres composition of post-consumer textile waste garments make them very difficult or impossible to separate. For each fibre type of the blend a specific recycling technique needs to be optimized to accomplish fibre-to-fibre recycling (Bukhari et al., 2018).

2.4.3 Chemical recycling

Chemical recycling is a way to separate polymer-based and cellulosic fibres of a yarn by chemically breaking down the fibres. The fibres are depolymerized into monomers, which are then repolymerized into new fibres (Pensupa, 2020). The recycled yarns are known to have the same quality as virgin synthetic fibres; however, the chemical recycling process requires high amounts of energy and chemicals (Euratex, 2020a).

Cotton-polyester blended textiles can be separated through chemical recycling processes. Solvents such as NMMO or ionic liquids are used to solubilize the cellulosic fibres from the mix (Pensupa, 2020). Cellulosic fibres first need to be purified by removing remaining dye and finishes and thereafter be depolymerized (Euratex, 2020a). The dissolved cellulose and polyester fibres are then separated by filtration (Pensupa, 2020). The obtained solution resembles to the cellulosic-like pulp from the viscose or lyocell process (Euratex, 2020a). Looking at the current issue of complexity of fibre blends of post-consumer textile waste garments, textile-to-textile chemical recycling processes that can efficiently separate fibre mixes, has the potential to recycle the garments that cannot be recycled through mechanical recycling processes. The resulting cellulose pulp from the chemical recycling process was used for the production of regenerated cellulose-based fibres (such as lyocell) (Ellen MacArthur Foundation, 2019).

2.4.4 Mechanical recycling

Mechanical recycling converts a textile material into a new material, without changing its structure (Pensupa, 2020). The textile waste garments are first sorted by fibre category, then removed of metal components (zippers and buttons) and put together in bales. The fabrics are then cut into smaller pieces with a rotary blade. Thereafter, to break them apart from each other, they go through the processes of 'picking', 'pulling' or 'tearing' where they are put onto rotating spiked drum surfaces from large spikes to smaller ones. This process is referred to as shredding (Payne, 2015). The shredded fabric is in the end in a fibrous state, ready-to-use for other processes, such as re-spinning (Mishra, Behera, & Militky, 2014).

Currently, the methods of mechanical recycling for post-consumer textile waste fabrics are limited. The mechanical textile recycling process is a challenging process, especially for the most frequently collected textile waste garments, fabrics made from various fibre mixes (Cobbing & Vicaire, 2016; Euratex, 2020a; Sandin & Peters, 2018; Pensupa, 2020). Mixed fabrics cannot effectively be mechanically recycled due to the variety and number of different fibre materials in the composition of one textile waste garment. The shredding process shortens the fibre lengths of the post-consumer textile waste garments. The resulting short fibres have a lower quality level and strength than virgin cotton fibres, they are often blended with virgin fibres to increase the quality level (Koszewska, 2018; Filho et al., 2019; Muthu, 2020; Pensupa, 2020; Ütebay, Çelik, & Çay, 2019). The quality of the fibres diminished after three passages in the shredding machine (Ütebay et al., 2019). For the mechanical recycling operation of both pre- and post-consumer textiles, the most important aspects that determine the quality of the shredded fibres are the blend of the fibres/polymers, the length of the fibres and the cleanliness or degree of impurities of the fabric (Payne, 2015). The quality level of mechanically recycled fibres highly depends on the homogeneity of the fibres of the textile waste category (Muthu, 2020; Pensupa, 2020; Ütebay et al., 2019). The lack of recycling technologies and infrastructure for the mechanical recycling of textile waste result in a recycled fibre of a low quality (Pensupa, 2020). Currently, mechanically recycled textile waste fibres can only be integrated in production processes of low-quality products. This is the main reason why there is currently a very low recycling rate of mixed post-consumer textile waste garments (Filho et al., 2019; Sandin & Peters, 2018). Often these products have basic functionalities, as construction bricks, insulation material, wipes, rags, non-woven textiles and paper (Pensupa, 2020). However, mechanical recycled textile fibres were used for their fibre properties; mechanical strength, moisture resistance, thermal performance, all useful for the reinforcement of materials (Pensupa, 2020).

Spinning process

Unfortunately, the recycled fibre length is a crucial characteristic to allow a new spinning process. The fibres need to go through several steps before being spun. The first step is the opening of the fibres. The fibres are pulled apart from each other, reducing the length of the fibres and removing dirt and impurities. Then the fibres go through the carding step. This is a machine that produces a web of fibres. Subsequently the drawing step, where the web becomes a sliver. Finally, the spinning step, where the sliver is stretched and twisted into a yarn. Sometimes fibre breakage can occur when the fibres are twisted, due to their short length (Klein, 2016).

The current attempts to spin mechanically recycled post-consumer recycled fibres are often performed with a rotor spinning machine. Compared to the ring spinning process, the rotor spinning machine can twist the short fibres easier, however, it is still complicated to obtain a high-quality yarn from recycled fibres (Pensupa, 2020). The quality level of the yarn is completely dependent on the textile waste material, pre-consumer scraps will result in a higher quality yarn then mixed blended post-consumer textile waste garments (Piribauer & Bartl, 2019).

2.5 RETEX project

The results of the RETEX project were the starting point of this master thesis research. The RETEX project has given a realistic and up-to-date view on the set-up of circular value chains in the Northern French area. During the RETEX project, EuraMaterials and their partners have identified streams of pre- and post-consumer textile waste. A network of textile collectors, sorters, textile manufacturers and fashion brands were set up to investigate the mechanical recycling for textile waste garments. Through the Interreg RETEX project, three successful circular supply chains were set up, investigating the recycling of cotton, polyester and cotton/polyester textile waste in open and closed-loops (EuraMaterials, 2020a).

The first value chain of the RETEX project recycled 100% pre-consumer cotton fabric scraps from the fashion brands Petit Bateau and Lemahieu. The scraps were shredded (Procotex), spun (ESG) and knitted into new children garments. One of the issues during the setup of the recycling operation was the resulting length of the cotton fibres, that came out the shredding stage as very short. Another bottleneck was the quality of the recycled fibres. The pre-consumer waste needed to be mixed with virgin cotton fibres to ensure a sufficient quality level. A mix of 25% recycled pre-consumer cotton waste and 75% virgin cotton was realised (Nm 28/1, open-end spinning). Consequently, the spinning and knitting of the cotton fibres turned out to be problematic. Finally, a fleece pullover with a 1/10 Nm and a jersey pullover with a 1/24 yarn was produced. Centexbel concluded that the homogeneity of the fibre mix of the fabric scraps was the most important factor to ensure the production of recycled cotton fibres with a sufficient quality standard. Centexbel also analysed that the textile scraps first needed to be washed before being shredded. The washing of the scraps had proven to be essential for the removal of dirt, impurities and dust, thus very important for the preservation of a sufficient quality level. Centexbel analysed that the cotton fibres were damaged due to the washing processes, both industrial and home washing. A material loss of 40% occurred during the shredding stage. The cotton fibres turn into 'dust', fibres with a length of less than 5 mm. Regarding the economic viability of the fibres, due to the setup of the value chain, the cost-efficiency of the recycled pre-consumer cotton fibres was affirmed in the price cost calculations performed by Centexbel. However, the washing step needed to be removed to ensure a positive development in the margin, the cost-efficiency of the other production tests could not be affirmed. If the textile waste scraps could be sorted automatically, instead of manually, the positive margin of the recycled cotton fibres could be increased. Centexbel also affirmed that the recycled cotton fibres could become rentable by skipping the 'hard parts' removal step. Besides, if the supply of pre-consumer textile waste scraps for the value chain could be enlarged, the positive margin of the recycled cotton fibres could be increased (EuraMaterials 2020a; EuraMaterials 2020b).

The second value chain, that recycled cotton/polyester mixed hospital waste work garments, had fewer drawbacks due to the homogeneity of the post-consumer work clothing items. In this value chain, garments were collected (van Moer), shredded (Minot Recyclage Textile), spun (Utexbel) and woven into the same garments with the same material composition (1/30 Nm, open-end spinning). All garments had the same fibre composition of cotton and polyester. Therefore, a good quality level of the recycled fibres was ensured. The shredded fibres had a sufficient length to be respun. The end composition of the new fabric resulted in a mix of 35% virgin cotton and 65% recycled polyester fibres (25% shredded post-consumer, 25% polyester industrial waste, 15% recycled polyester from bottles). An important note is the fact that the cotton fibres of the hospital garments were so damaged by the frequent industrial washing processes, that the cotton fibres mostly turned into dust during shredding and spinning and could not be used any longer (13% and 27% material loss). Thus, a bottleneck of this value chain is necessary step of mixing the recycled cotton/polyester textile waste fibres with virgin cotton fibres. Another conclusion is the fact that the elimination of 'hard parts', buttons and zippers, was essential for the retainment of a quality standard of the fibres. Due to the removal of hard parts, a gentler shredding process was chosen, which has damaged the fibres less than a normal shredding process. Regarding the cost-efficiency of the post-consumer recycled fibres, Centexbel affirmed that the recycled fibres lead towards profitable production processes. The yarn had a lower cost price compared to a yarn manufactured from virgin materials (EuraMaterials 2020a; EuraMaterials 2020b).

The third value chain investigated the thermo-mechanical recycling of 100% polyester production scraps and post-consumer fabrics for the production of polyester granulates, this is the reason why it was not taken into account in the present study (EuraMaterials 2020a; EuraMaterials 2020b).

3. Methodology

This chapter explains the research methodology of this master research. The methodology consists of two parts, in the first place an extensive literature study, second, an empirical study through the use of semi-structured interviews.

3.1 Literature study

Both the challenges and opportunities for the mechanical recycling process for post-consumer textile waste were identified based on a literature study. The literature study was conducted to understand the scope and current issues within the area of textile waste management and mechanical recycling of post-consumer textile waste garments. Articles, reports and empirical studies were analysed to investigate the most recent research findings on the topic. The several keywords that were used in databases to find relevant literature articles are, *mechanical recycling, textile recycling* and *post-consumer textile waste recycling.* The investigated databases were ScienceDirect and ResearchGate. Recent papers of independent well-known research institutes, such as the Ellen MacArthur Foundation and the WRAP, were added to the literature findings to add available up-to-date information on the topic. EuraMaterials has supported the literature study with several relevant articles and papers regarding the RETEX project and previous projects on the recycling of end-of-life textiles. The literature study was an iterative process, where additional sources were gathered throughout the master's thesis research. Since the literature on the mechanical recycling of post-consumer textiles is limited, there has not been an age restriction on the literature findings.

3.2 Empirical study

Semi-Structured Interviews

Mechanical recycling researcher, spinning experts and textile recyclers were interviewed on the topic of the mechanical recycling process for post-consumer textile waste garments through the use of semi-structured interviews, with the purpose of gaining recent insights that could not be found in literature. Semi-structured interviews were used as a qualitative research technique, which involves the conducting of an intensive individual interview, to explore someone's perspective on a particular situation (Boyce & Neale, 2006). The semi-structured individual interview is a valuable method of gaining insight into the understanding of a particular topic and contributes to the collection of in-depth data (Ryan, Coughlan, & Cronin, 2009). The semi-structured interview combines structured questions with unstructured explorations and has the possibility to ask further questions (Denscombe, 2014; Wilson, 2014). New questions were asked during the interview to continue on a particular topic. This way, if recent data on the topic missed during the literature study, these gaps of information were filled in by the in-sight information of the interviewees.

Experts in the field of the recycling of textile waste, who are known in the industry and have performed several projects and research on the topic, were contacted by email or LinkedIn. Only researchers and experts in the mechanical recycling for post-consumer textile waste were interviewed to guarantee the legitimacy of the statements. Spinners of recycled fibres and producers of textiles made from recycled fibres/yarns were interviewed, to get a clear view on the challenges and opportunities for every step of the mechanical recycling supply chain (see Table 1). The questions of the interview were prepared beforehand and guaranteed that all relevant topics were covered (Wilson, 2014). All respondents were asked the same questions and the formulation of the questions were adapted according to the given answers (see Appendix A.3). The introduction phase was performed to inform the interviewee about the research, its purpose and confidentiality of the interview (Denscombe, 2014). From the interviews a transcript was made, by writing down every word of the recorded interview. The information from the interviews were coded, by highlighting a sentence in a particular colour, corresponding to the sub-research question topics (see Appendix A.3). The interviews were analysed by comparing the coded sentences on each topic with each other.

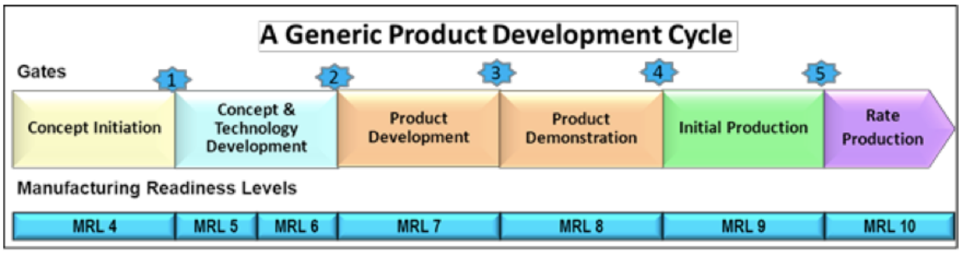
Table 1. Interviewees for the semi-structured interviews.

Name	*Field of expertise*	*Company / Institute*
1. Cathryn Anneka Hall	Mechanical recycling end-of-life textiles	University of the Arts London
2. Anita de Wit	Production of textiles with recycled fibres	ReBlend
3. Remi Veldhoven	Mechanical recycling & production textiles with recycled fibres	Wolkat
4. Anton Luiken	Mechanical recycling end-of-life textiles	Saxion University of Applied Sciences, Alcon Advies B.V.
5. Pierre van Trimpont & Daniël Verstraete	Recycling research for end-of-life textiles, economic analysis recycled fibres	Centexbel
6. Julie Lieataer	Spinning of yarn made from recycled fibres	European Spinning Group
7. Liset Pander	Spinning of yarn made from recycled fibres	Texperium
8. Carlos Rico	Mechanical recycling end-of-life textiles	Recover

Multi-criteria Analysis

After finishing the literature analysis and conducting the interviews, several recycled fibres produced from post-consumer textile waste were compared. The goal of this analysis was to research the manufacturability and cost-efficiency of mechanically recycled fibres and their integration into production processes and circular supply chains. The chosen criteria for this analysis were the Manufacturing Readiness Level criteria. The following Figure 2 shows the manufacturing stages per MRL level that were used in the assessment of each recycled textile waste fibres (see Appendix A.1) (OSD Manufacturing Technology Program, 2018). A complete Manufacturing Readiness Level assessment of all recycled textile fibres could not be effectuated, however, the criteria for each level were used as a comparison method. The focus of this research lied on 100% cotton and mixed cotton/polyester post-consumer textile waste fabrics. Therefore, the polyester value chain of the RETEX project that investigates the remelting of polyester fibres for non-textiles product applications, was not included in the research. This master thesis only researched mechanical recycling methods, preferably in closed-loops. Through the use of the multi-criteria MRL analysis the current developments of the mechanical recycling process for post-consumer textiles were researched. The MRL multi-criteria analysis showed the challenges and opportunities for improvement of the mechanically recycled textile waste fibres and how they are integrated in manufacturing productions, accordingly, answering the main research question.

Figure 2. Product Development Cycle and MRL levels (OSD Manufacturing Technology Program, 2018).



The research findings of the literature analysis and the interviews were filled in the MRL multi-criteria analysis to form the basis for the comparison between the chosen recycled fibres. Therefore, the research findings have been classified according to the MRL criteria threads. Down below a list of the MRL criteria threads (complete detailed MRL criteria in appendix):

1. Technology and industrial base thread (support development of technology)
2. Design thread (design approach)
3. Cost and Funding thread (cost reduction activities)
4. Materials thread (availability and scale-up challenges of materials)
5. Process Capabilities and Control thread (process characterization)
6. Quality management (foster quality improvement, key supply chain management structures)
7. Personnel and Facilities thread (capabilities and capacity supplier, pilot lines)
8. Manufacturing Management thread (supply chain management, translation design into integrated system.

With the results of the literature analysis, interviews and MRL multi-criteria analysis, conclusions were drawn on the way forward for mechanically recycled textile waste fibres. Future steps to increase the manufacturability and cost-efficiency of recycled waste fibres were elaborated in a roadmap. The roadmap of Centexbel (2010) functioned as example. It is likely that the roadmap will provide useful information for textile waste recyclers on the implementation of possibilities for improvement for the mechanical recycling process, thus increasing the manufacturability and cost-efficiency of mechanically recycled waste fibres.

4. Results

In this chapter, the results from the literature study and the empirical study are presented. Corresponding to the research questions, first, the challenges of the mechanical recycling process for post-consumer textile waste fibres are elaborated. Second, the opportunities for the improvement of the mechanical recycling process are proposed. Subsequently, the results of the MRL multi-criteria analysis on the recycled textile waste fibres are introduced. Thereafter, a roadmap containing future perspectives and action steps regarding the integration of mechanically recycled fibres in supply chains, is presented.

4.1 Challenges

As previously introduced, the current mechanical recycling process faces many challenges, these are further presented in this chapter. The challenges of mechanically recycling post-consumer textile waste garments are categorised from a technical, logistical and economic point of view through the several MRL threads. This chapter will answer the first sub research question; what are the current challenges of the mechanical recycling process for post-consumer waste garments?

4.1.1 Technology and Industrial base thread

The subsequent subparagraphs investigate the technical challenges of the mechanical recycling process that contribute to the downgraded quality of the recycled textile waste fibres. The Technology and Industrial base thread examine if a production operation can be supported by technical development (see Appendix A.1), it was therefore chosen as criteria to find out if the mechanical recycled fibres had the capability to support the design of a new product.

Mixed fibre blends & short fibres

The main barrier of the mechanical recycling process for post-consumer textile waste fabrics is the resulting lower quality level of the shredded fibres, due to the complexity and variety of fibre blends of fabrics and the short lengths of shredded fibres (see chapter 2.4.4).

Currently, most of the collected and sorted high-quality post-consumer textile waste fabrics are shipped abroad, resulting in the situation that mostly low-quality textiles are shredded in Europe (see chapter 2.2). When collected, post-consumer mixed-blended fabrics are often severely damaged by extensive use and many washing cycles, which implicates that the low-quality level is further decreased (Pensupa, 2020). The RETEX project showed that fabrics that were washed many times were so damaged, that during shredding they turned into 'dust' (fibres <5mm) (see chapter 2.5). The homogeneity of the fibre mix of fabrics cannot be guaranteed, the composition of the fibre materials is often unknown, meaning that the shredded fibres have an unpredictable resulting quality level and fibre lengths after shredding (Bukhari et al., 2018; Pensupa, 2020). The mechanical recycling researcher Cathryn Anneka Hall stated in the interview that, due to the unknown fibre blends, the sorting of textile waste into categories is still difficult (see Appendix A.3.1). Besides, the material composition of post-consumer textiles that were treated with a finish or are composed of several material layers is often unknown, which makes it difficult to sort these fabrics in a specific category to guarantee the homogeneity of fibres mix (Echeverria et al., 2019; European Recycling Industries' Confederation, 2021; Ütebay et al., 2019). Consequently, the uncertainty of the fibre composition and the resulting differences in shredded fibre lengths result in the situation that the mechanically recycled post-consumer recycled fibres cannot easily be integrated into a production line, because there isn't a clear view on the quality level of the end product outcome (Bukhari et al., 2018; Pensupa, 2020). Therefore, looking at the Technology and Industrial MRL thread, the mechanically recycled textile waste fibres cannot support the design of (many) new products yet.

Lack of technical recycling technologies and infrastructure

Second, due to the lack of mechanical recycling technologies and infrastructures for post-consumer textile waste garments, the quality level of shredded textile waste fibres is downgraded and the possibility to be integrated into a production process is minimised.

The lack of mechanical recycling technologies is demonstrated in the fact that the cutting and shredding process cannot be adapted to a specific fibre sort. All post-consumer textiles are shredded the same way, the decreasing level of quality of the fibres cannot be controlled (Muthu, 2020). The development of a mechanical recycling process that could result in shredded fibres that have a high-quality level and could replace virgin cotton fibres, was proven over the past years to be difficult, due to the mixed fibre blends of post-consumer textiles (Filho et al., 2019; Muthu, 2020). Consequently, due to the lack of mechanical recycling technologies and infrastructure, and the mixed blends of post-consumer garments, not all textile waste fabrics are recyclable (Freise & Seuring, 2015; Jia et al., 2020; Kazancoglu et al., 2020a; Ljungkvist & Elander, 2016). According to the study of Kazancoglu et al. (2020b), the lack of technical recycling knowledge was the main barrier for the set-up of a circular supply chain for textile companies. Besides, there is a lack of theoretical information on textile waste materials, which hinders the development of recycling technologies (Govindan & Hasanagic, 2018; Kazancoglu, Kazancoglu, Yarimoglu, & Kahraman, 2020a). The mechanical recycling expert Anton Luiken stated in the interview that the lack of recycling technologies is the main reason why fibre-to-fibre recycling is not yet possible with the mechanical recycling process (see Appendix A.3.4). This is the reason why the founder of the ReBlend brand, Anita de Wit, thought the mechanical recycling infrastructure was at a starting pilot phase level in the Netherlands (see Appendix A.3.2). Therefore, due to the lack of mechanical recycling technologies, the development of a production line with recycled waste fibres cannot be supported.

4.1.2 Design thread

The following subparagraph investigates the technical challenges of designing a product manufactured from shredded textile waste fibres. The Design thread examines the design approach of a product when researching the development of a pilot production line (see Appendix A.1), it was therefore chosen as criteria to investigate the product design possibilities for shredded textile waste fibres.

Difficulty to design a product

Currently, the end-of-life stage of clothing garments is not considered in clothing design (Ellen MacArthur Foundation, 2017). Fibres are blended to obtain functional and aesthetic characteristics, that cannot be separated at end-of-life (see chapter 2.3 and 2.4.4). The uncertainty of composition of fibre blends, the presence of non-textile materials (zippers and buttons) that need to be removed and the presence of dyes, hinder the design possibilities of post-consumer fibres (see chapter 2.4.4).

The research of Kazancoglu et al. (2020a) concluded that design challenges were one of the main barriers when setting up a circular textiles supply chain. Several research articles designated the difficulty of designing a product manufactured from recycled fibres as a main technological barrier to integrating circular economy principles in supply chains (Franco, 2017; Govindan & Hasanagic, 2018; Rathinamoorthy, 2019). Therefore, looking at the MRL design thread, it is currently still difficult to design a product with shredded textile waste fibres.

4.1.3 Cost and Funding thread

The following subparagraph investigates the economic challenges of the mechanical recycling process when researching the production possibilities for textile waste fibres. The Cost and Funding thread examines the cost reduction activities and early manufacturing involvement for the development of a production line (see Appendix A.1), it was therefore chosen as criteria to investigate the possibilities of shredded fibres to be integrated in production processes.

Cost of the mechanical recycling process

The main economic challenge of the integration of shredded textile waste fibres is, in most cases, the cost price being more expensive than virgin fibre materials (Filho et al., 2019; Pensupa, 2020). This is because the operations of collection, sorting, shredding and shipment between the facilities are included in the production costs of the recycled textile waste fibres (Kazancoglu et al., 2020a; Koszewska, 2018; Filho et al., 2019; Pensupa, 2020; Rathinamoorthy, 2019).

The collection and sorting of post-consumer textile waste garments is a costly and labour-intensive operation (see chapter 2.4.4), thus, it isn't economically interesting for apparel and interior textile companies to set up a mechanical recycling operation with a textile recycling company while using leftover textiles (Ljungkvist et al., 2018; Muthu, 2020). Being dependent on human capital while operating a labour-intensive operation can cause a reduction of benefit if there is a lack of experience (Govindan & Hasanagic, 2018; Kazancoglu et al., 2020a). Besides, due to investments in the mechanical recycling process, the margin of profit of shredded fibres is quite low for the textile recycling company compared to virgin cotton fibres (Berg et al., 2020; Huang et al., 2021; Jia et al., 2020; Hole & Hole, 2020). According to mechanical recycling researcher Remi Veldhoven, who stated in the interview, that this is the main reason why textile manufacturers do not integrate textile waste fibres in production processes on an industrial scale (see Appendix A.3.3). Currently, textile waste collectors and shredders are dealing with a competitive environment, which obstructs the margin of profit of shredded fibres (Neto et al., 2021). As a result, the textile recycling company cannot invest in technical recycling technologies (see chapter 4.1.1). The sales margin from low-quality products manufactured from mechanically recycled fibres does not ensure the cost-efficiency of these fibres (Ljungkvist & Elander, 2016; Pensupa, 2017).

During the interview with spinning expert Carlos Rico of Recover, he confirmed the difficulty of obtaining profitable yarns, because the spinning process is expensive. Multiple spinning tests need to be performed according to the several mixed blends and the volumes of post-consumer textiles are small, therefore, textile waste sorts are accumulated to ensure a profitable yarn (see Appendix A.3.8). Besides, the mechanical recycling experts Pierre van Trimpont and Daniël Verstraete of Centexbel mentioned that the costs of logistics have a share of 3% to 5% of the total cost price, which is quite significant (see Appendix A.3.5). The difference in cost price between mechanically shredded fibres and virgin fibres will be shown in the results of the MRL analysis (see chapter 4.3). Subsequently, the existing mechanical recycling infrastructure cannot effectively recycle post-consumer textiles (see chapter 4.1.1). Therefore, looking at the MRL criteria of the Cost and Funding thread, the low sales margins for shredded fibres and the high investment costs for the mechanical recycling process result in the situation that an end-product manufactured from shredded textile waste fibres is not profitable yet.

4.1.4 Materials thread

The sequent subparagraph investigates the logistical challenges of the mechanical recycling process when researching the possibilities to set up production processes with shredded textile waste fibres. The Materials thread examines the availability of post-consumer textile waste fabrics as raw material source (see Appendix A.1), it was therefore chosen to research the possibility to scale up the use of shredded fibres as material source.

Collection and sorting of textile waste garments

As previously introduced, currently, there is a lack of a rentable sorting system for post-consumer textile waste garments. As a result, the shredded textile waste fibres cannot easily be integrated into supply chains, which is seen in the Materials thread MRL criteria as a material availability risk (see Appendix A.1) (Pensupa, 2020; Ütebay et al., 2019).

One of the challenges that hinder the development of an efficient sorting process is the unstable incoming volumes of textile waste garments (see chapter 2.4.4). There is limited availability of recyclable post-consumer textiles (Filho et al., 2019; Kumar & Suganya, 2019; Kazancoglu et al., 2020a). Poor distribution of information and collaboration between actors contribute to this problem (Jia et al., 2020; Pensupa, 2017). Thereafter, the integration of recycled fibres in production processes cannot be scaled up to an industrial scale (Koszewska, 2018; Rathinamoorthy, 2019; Ütebay et al., 2019; Pensupa, 2020). Besides, the majority of the collected post-consumer textile waste fabrics is unsuitable for mechanical recycling because they are completely worn out and have lost all quality (see chapter 2.4.4). There is also a lack of awareness on the importance of an accurate sorting and classification of the post-consumer textile waste garments at the collection and sorting sites (Ütebay et al., 2019). In the interviews of Cathryn Anneka Hall and Anita de Wit, both stated the necessity of sorting post-consumer textiles according to colour and dye to guarantee the shredded fibres' quality level (see Appendix A.3.1 and A.3.2). There is a lack of traceability to investigate the volumes and sources of post-consumer textiles (Jia et al., 2020; Kazancoglu et al., 2020a; Kumar & Suganya, 2019). During the interview with Carlos Rico, he emphasised the fact that because at Recover they sort the fabrics in multiple colour categories and the incoming volumes of textiles are quite small, they cannot produce stable quantities of recycled yarns of each colour (see Appendix A.3.8). Therefore, looking at the Materials MRL criteria thread, there is a lack of a stable supply of recyclable post-consumer textile waste garments to enable an efficient collection and sorting system on an industrial scale (Huang et al., 2021).

4.1.5 Process Capability and Control thread

The upcoming subparagraph investigates the technical challenges of the mechanical recycling process when researching the production capabilities for shredded textile waste fibres. The Process capability and Control thread examines the characterization of the set-up of a production process (see Appendix A.1), therefore it was chosen as criteria for the research of manufacturing processes capabilities for shredded fibres.

Spinnability of shredded fibres

A major technical challenge that hinders the process capabilities of mechanically recycled fibres is the situation that the fibres can currently only be integrated into the manufacturing processes of low-quality products (see chapter 2.4.4). The unravelling and shredding processes are causing the decrease of the fibres lengths of the post-consumer textile waste fabrics, which results in the incapability of the shredded fibres to be integrated into a spinning process (see chapter 2.4.4).

During the interview with the spinning researcher Liset Pander from Texperium, she mentioned the challenge of spinning shredded textile waste fibres due to the difference in lengths, openness and density. Also, she stated that due to the pollution between the fibres they would easily break, therefore an extra pre-treatment step was required to filter out impurities (see Appendix A.3.7). In the interview with Carlos Rico, he demonstrated the difficulty of spinning post-consumer textile fibres, due to the necessity of performing spinning tests for each specific fibre sort/mix (Appendix A.3.8). There is a lack of available processes that can complement the mechanical recycling process, which is negatively affecting the production process capabilities of shredded fibres (Jia et al., 2020; Kazancoglu et al., 2020a). Therefore, looking at the Process capability and control thread of the MRL criteria, the production capabilities of shredded post-consumer textile waste fibres are not yet used to their full extension.

4.1.6 Quality Management thread

The following subparagraph investigates the logistical and technical challenges of the mechanical recycling process when researching the quality improvement of recycled textile waste fibres. The Quality management thread examines the management of efforts to control the quality of the resulting product and set up of key supply chain management structures (see Appendix A.1), therefore it was chosen as criteria to research the quality improvement possibilities for shredded fibres and supply chain management capabilities.

Collaboration between recycling actors

Currently, the lack of collaboration between actors in the supply chain is resulting in the inefficiency of the mechanical recycling process for post-consumer textiles (see chapter 2.4.4). The framework for the collection, sorting and shredding of textiles is uncoordinated and unintegrated (Payne, 2015). The interests of the several actors differ, which hinders effective collaboration (Filho et al., 2019). There is a lack of collaborative innovation between the supply chain partners (Huang et al., 2021). Besides, there is currently a competitive textile recycling environment (see chapter 4.1.3). Also, there is a lack of transparency on the material flows of the actors in the mechanical recycling network and the unwillingness of suppliers and distributors to provide support (Jia et al., 2020; Paras, Pal, & Ekwall, 2017; WRAP, 2019). There is a lack of a shared vision, support and willingness to collaborate in the textile recycling supply chain (Kazancoglu et al., 2020a). However, there is an interdependence between the actors involved in the mechanical recycling process, which implicates that failures at one stage lead to issues at the next recycling step (Todeschini, Cortimiglia, & Medeiros, 2020). There is a lack of a performance evaluation system that investigates the quality level of shredded fibres (Bianchini, Rossi, & Pellegrini, 2019; Jia et al., 2020; Kazancoglu et al., 2020a). Therefore, it is difficult to foster the quality improvement of shredded textile waste fibres due to the lack of collaboration between actors in the current supply chain structures.

The conflicting interests of the actors in the supply chain for textile waste fibres need to change, Filho et al. (2019) suggests that centralising the operations could enable the development of more unified policies and regulations for shredded fibres, which could lead to improved collaborations between actors. Furthermore, to start researching the possibilities for improving the quality level of shredded fibres, the actors in the supply chain need to be convinced that the gross margin of the fibres will increase (Filho et al., 2019). Either the mechanical recycling process steps need to be improved to obtain a higher quality level, an increased margin and reduced cost price of the shredded fibres, or the sales growth of shredded fibres need to be increased (Ellen MacArthur Foundation, 2017). Therefore, looking at the Quality management thread of the MRL criteria, the research on quality improvement of textile waste fibres cannot yet be effectuated due to supply chain management challenges.

4.1.7 Personnel and Facilities thread

The following subparagraph investigates the logistical challenges of the mechanical recycling process when researching the facilities capacities in the set-up of the supply chains. The Personnel and Facilities thread examines the capabilities of the suppliers to foresee the demand of supply of post-consumer textile waste fabrics (see Appendix A.1), therefore it was chosen as criteria to research the possibilities to set up a pilot line and supply chain including the mechanical recycling process for post-consumer textile waste fabrics.

To set up a pilot production line for products manufactured from mechanically recycled textile waste fibres, the supply/cost balance is considered by the several actors of the mechanical recycling supply chain. For most textile waste recyclers, the supply of a homogenic group of post-consumers textiles needs to be of a sufficient volume to outweigh the fixed costs of the mechanical recycling process and to meet the criteria for delivering cost-efficient shredded fibres (Guide & van Wassenhove, 2009; Huang et al., 2021; Jia et al., 2020). This matter is confirmed by the interview with Julie Lietaer, director of the European Spinning Group (see Appendix A.3.6). The current production volumes of products manufactured from shredded fibres are low, which prevents the involved companies in the supply chain to benefit from the profit of scaling up production processes (Baltussen, 2019; Kazancoglu et al., 2020a; Rathinamoorthy, 2019). As previously discussed, the mechanical recycling activities are costly (see chapter 4.1.3), there is a lack of stable supply of homogenic post-consumer textile waste fabrics (see chapter 4.1.4) and the cost-efficiency of mechanically shredded fibres cannot be guaranteed. Therefore, looking at the MRL Personnel and Facilities thread, it is currently not yet profitable to set up a pilot production line while using shredded textile waste fibres.

4.1.8 Manufacturing Management thread

The following subparagraph investigates the logistical and economic challenges of the mechanical recycling process when researching the capability to set up a supply chain management and manufacturing plan with textile waste garments. The Manufacturing management thread analyses the orchestration of all elements needed to translate the design of a product with a specific material source into an integrated system (see Appendix A.1), it was therefore chosen as criteria to research the maturity of a manufacturing plan while using shredded textile waste fibres.

As previously introduced, it is currently difficult to deliver high-quality products manufactured from shredded post-consumer textile waste fibres, because they have an unpredictable quality level and fibre lengths. The batch post-consumer textiles need to be homogenic in material composition, colour and quality, which cannot yet be guaranteed (see chapter 4.1.1). The set-up of a manufacturing plan for the production of a high-quality product manufactured from shredded textile waste fibres is, therefore, a troublesome operation. To enable change, the availability and quality of post-consumer textile waste fibres need to be secured (Huang et al., 2021; Majumdar & Sinha, 2019; Rathinamoorthy, 2019). If the cost-efficiency of the shredded fibres could be assured, a profitable manufacturing plan could be created, which would result in a market demand growth for shredded textile waste fibres (Filho et al., 2019; Hole & Hole, 2020; Huang et al., 2021). In the interview with Anita de Wit, she emphasised this challenge as a problem of economies of scale. She believed that the market for textile waste fibres cannot change if the textile waste fibres are still more expensive than its virgin competitor. She thought that the market demand for textile waste fibres is currently not yet large enough to scale up production processes with these fibres (see Appendix A.3.2). Only if the uncertainty of cost-effectiveness of the fibres could be taken away, textile waste recyclers would have the certitude to make investments, despite their lack of capital (Baltussen, 2019; Kazancoglu et al., 2020a; Rizos et al., 2016). Therefore, looking at the MRL Manufacturing management thread, it is currently not yet profitable and manufacturable to set up the manufacturing planning and supply chain management for the production of high-quality products from post-consumer textile waste fibres.

4.2 Opportunities

The current mechanical recycling process has shown many complexities. In the following chapter, the opportunities for improving the mechanical recycling process for post-consumer textile waste garments will be presented. The opportunities are categorised from a technical, logistical and economic point of view through the several MRL threads. This chapter fulfils the aim of this master thesis, finding out how the mechanical recycling process for post-consumer textile waste fabrics could be improved and integrated in supply chains.

4.2.1 Technology and Industrial base thread

The subsequent subparagraphs investigate the technical opportunities for the improvement of the mechanical recycling process. These technical opportunities are either improvements of the process or improvements of the quality of shredded textile waste fibres. The Technology and Industrial base thread examine if a production operation can be supported by technical development (see Appendix A.1), it was therefore chosen as criteria to find out if the mechanical recycled fibres had the capability to support the design of a new product.

Improvement mechanical recycling process

Adapting the machines of the mechanical recycling process to post-consumer textiles, the cutting, shredding and carding machine, is a needed development to lengthen the shredded fibres (see chapter 4.1.1). The machines need to have the capability to handle mixed blended fabrics because these are the most represented collected textiles (see chapter 2.3 and 2.4.4). The parameters of the cutting and shredding machine thus need to be regulated according to the material composition of the textiles (Filho et al., 2019; Euratex, 2020a; Pensupa, 2020; Ütebay et al., 2019). Fibres from natural or synthetic sources are affected differently by the shredding machine, as the construction of the textile (Roos et al., 2019b).

Several textile waste recyclers are currently changing the parameters of shredding and carding machines to investigate the effect on the shredded fibres lengths. The French textile waste recycler Minot stated that, due to adaptions of the parameters of the shredding and carding machine, the length of the post-consumer shredded fibres was elongated. One of the possible options is to lower the speed of the cutting machine (Dussart, 2020). Another possible change would be to shift to spiked drums of the shredding machine with an inferior number of spikes, to ensure a less harsh shredding process with minor damage and shortening of the fibres (Roos et al., 2019b). During the interview with Pierre van Trimpont and Daniël Verstraete, they confirmed that by reducing the speed and the number of spikes on the drums of the shredders, a less aggressive shredding process was obtained (see Appendix A.3.5). Carlos Rico mentioned that at Recover, they are currently investigating to change the angle of the drum onto the fabrics (see Appendix A.3.8). The innovative textiles research centre CETI tried another modification to the mechanical recycling process, placing the several machines of the process one after the other in the same hall. The output of one process step was the feedstock for the next step, this way, the material loss between each process step was diminished. CETI concluded that the new mechanical recycling line resulted in an improved quality level of the shredded fibres (Poggio, 2019). In the interview with Julie Lietaer, she mentioned the need for pilot scale shredding machines, for which the parameters could be adapted to each post-consumer fibre mix. This way, small volumes of wasted fabrics were shredded, which would result in higher quality fibres (see Appendix A.3.6). Therefore, looking at the MRL Technology and Industrial base thread, adapting the parameters of the mechanical recycling process machines could increase the length and quality of shredded textile waste fibres.

Chemical recycling process

The recycling of 100% post-consumer textile waste garments is impossible with the mechanical recycling process (see chapter 2.4.4). To ameliorate the quality level and to lengthen the shredded textile waste fibres lengths, the chemical recycling process could complement the mechanical recycling process for textile waste fibres. When the textile waste fabrics are that damaged that when shredded they turn into 'dust' (lengths lesser than 5 mm), the fibres could go through the chemical recycling process and be transformed into new textile fibres with product application possibilities.

Many research projects have researched the chemical recycling of mixed post-consumer textile waste fibres (Linnenkoper, 2019; Liu et al., 2019; SaXcell B.V., 2020; Yousef et al., 2019; Yousef et al., 2020). The chemical recycling processes have the potential to efficiently separate cellulosic from synthetic fibres of textile waste fibres, thus increasing the product application possibilities of the fibres that would have been incinerated or sent to landfill (European Clothing Action Plan, 2019; Textile Exchange, 2019). In the interview with Cathryn Anneka Hall, she believed that efficient recycling of post-consumer textiles could be obtained if both mechanical and chemical processes could be aligned (see Appendix A.3.1). According to the interview with Anton Luiken, the chemical recycling process will generate Tencel/lyocell fibres from shredded textile waste fibres that can be used for the production of new textiles (see Appendix A.3.4). The research of Yousef et al. (2019) demonstrated that the chemical recycling of post-consumer cotton/polyester wasted jeans could result in cost-efficient fibres that could be respun into yarns. Therefore, looking at the MRL Technology and Industrial base thread, the chemical recycling process can support the design of a new product manufactured from recycled fibres, in case the mechanical recycling process cannot do so.

4.2.2 Design thread

The following subparagraph investigates the technical, environmental and economic benefits of designing a product manufactured from shredded textile waste fibres. The Design thread examines the design approach of a new product when setting up a pilot production line (see Appendix A.1), it was therefore chosen as criteria to investigate the product design possibilities for shredded textile waste fibres.

Environmental impact benefits

Designing new products manufactured from shredded textile waste fibres contributes to the transformation of the textiles industry towards a circular economy, as one principle is to design out of waste (Ellen MacArthur Foundation, 2017). Mixed blended shredded fibres can be combined with high-quality fibres, such as recycled cotton, to ensure desired fabric properties and increase the content of recycled fibres in textiles (Ljungkvist & Elander, 2016).

According to a Mistra Future of Fashion research, replacing virgin cotton fibres with post-consumer textile fibres enables the reduction of environmental issues, namely, the use of freshwater, pesticides, chemicals and soil depletion (Roos et al., 2019a). Also, the fibre production processes of spinning, knitting and weaving, causes environmental impacts that can be avoided by recycling textile waste fabrics (Pensupa, 2020; Sandin et al., 2019; Sandin & Peters, 2018). However, recycled textile waste fibres lead to increased energy costs of cutting and shredding processes compared to virgin fibres. But overall, the use of recycled cotton fibres is beneficial for the environment and leading to economic benefits, due to the reduction of cultivation costs (Esteve-Turrillas & de la Guardia, 2017). The research of Liu et al. (2020) confirms the economic viability of recycled cotton fibres compared to virgin cotton fibres. Therefore, looking at the MRL Design thread, the shredded post-consumer textile fibres should be chosen while designing a new textile product, due to reduced environmental impacts and economic viability.

4.2.3 Cost and Funding thread

The subsequent subparagraph investigates the economic opportunities for the post-consumer textile waste fibres, due to the improvement of the mechanical recycling process (as discussed in the Technology and Industrial base thread). The Cost and Funding thread examines the cost reduction activities and early manufacturing involvement for the development of a production line (see Appendix A.1), it was therefore chosen as criteria to investigates the cost-efficiency of shredded fibres and the possibilities for integration in productions.

Profitable process

As previously discussed, the mechanical recycling process does not yet result in recycled fibres with a cost price that is comparable to virgin fibres, due to the several needed labour-intensive process steps and high investment costs (see chapter 4.1.3). Yet, if the quality level of the shredded textile waste fibres could be increased and the cost price could be lowered, the cost-effectiveness of the fibres could be ensured.

Filho et al. (2019) stated, after reviewing the socio-economic advantages of textile waste recycling, that the mechanical recycling process leads to a reduction of production costs due to the use of low-cost textile waste fabrics as raw materials. Even though shredded post-consumer textile waste fibres cannot be used as yet for the manufacturing of new textiles, they are of added value as a material source for open-loop product applications. Due to their specifics, the end product gains in quality level and can be sold at a higher sales price, which could compensate the initial higher cost price of the shredded fibres (Roos et al., 2019b). Jia et al. (2020) emphasised a current paradigm shift by companies who integrate recycled fibres in their production processes to cost-effectively improve value, which might provide a competitive advantage. However, the added value of post-consumer textile waste fibres is completely dependent on an efficient collection and sorting of the garments in specific colour/fibre categories. Otherwise, the costs of collection, transport and sorting, cannot be outweighed by the manufactured products value (Filho et al., 2019). Pierre van Trimpont and Daniël Verstraete had concluded during the RETEX project that the influence of logistics costs on the cost price was quite high (see chapter 4.1.3). In the interview they mentioned the mechanical recycling process set-up at the research centre CETI, aligning the machines one after the other in one room and thus reducing the costs of logistics, could result in a gross margin of 7,5% (see Appendix A.3.5).

Several costs are involved for recycling textile waste fabrics with the mechanical recycling process, but these costs are comparable with the costs for incineration and landfill that fashion and interior companies would otherwise have to pay (Hole & Hole, 2020). To promote the recycling of wasted fabrics, governments could impose environmental taxes, to push the fashion and interior textiles industry to start implementing the mechanical recycling process in the supply chains (Hole & Hole, 2020). A possible measure could be to introduce an EPR policy scheme, as a cost allocation mechanism, to hold the textile manufacturer accountable for the recycling of its textile waste (Atasu, 2018; Micheaux & Aggeri, 2021).

Furthermore, the research of Wanassi, Azzouz, & Hassen (2016) has demonstrated that a 50% virgin cotton 50% recycled pre-consumer cotton waste could have a lower cost price compared to a 100% virgin cotton yarn, with similar physical and mechanical properties. More recently, the spinning machine producer Rieter stated that a rotor spun yarn, with mechanically opened high short-fibres content up to 75%, were produced and proven to be economically viable. The economic analysis of Rieter was based on the assumption that the raw material price of recycled post-consumer textiles was slightly cheaper compared to virgin cotton (Schwippl, 2020). Rieter stated that the cost price of the yarn was reduced by choosing post-consumer textiles as raw material source (Schwippl, 2020; Spatafora & Schwippl, 2020). Remi Veldhoven stated during the interview that the recycled textiles manufacturer Wolkat can currently not foresee the market demand for interior textiles with a high post-consumer recycled content (see Appendix A.3.3 and chapter 4.3). Therefore, looking at the MRL Cost and Funding thread, the shredded post-consumer textile waste fibres are becoming more and more attractive from a cost perspective.

4.2.4 Materials thread

The subsequent subparagraph investigates the logistical opportunities for the mechanical recycling process when researching the production line possibilities of shredded textile waste fibres. The Materials thread examines the availability of post-consumer textile waste fabrics as raw material source (see Appendix A.1), it was therefore chosen to research the possibility to scale up the use of shredded fibres as material source.

Automated sorting

An automated sorting machine that can sort post-consumer textile waste garments by fibre type, material composition and colour, scanning high volumes of low-quality textiles at a high speed, could potentially replace the manual sorting process (Ljungkvist, Watson, & Elander, 2018). Investing in an automated sorting machine is expensive, but more efficient, more precise and faster than manual sorting, resulting in lower sorting costs (Ljungkvist et al., 2018; Rathinamoorthy, 2019).

Both the Textiles 4 Textiles and the Fibresort projects developed automated sorting machines for post-consumer textiles, using near-infrared spectroscopy technology to categorise the textile fabrics by colour and fibre material composition (Linnenkoper, 2019; Pensupa, 2020). The fabrics go through an optical detection system that scans the fibre mix of each item, then passing onto a belt that automatically sorts the items with a pressurised air system (Linnenkoper, 2019; Riba et al., 2021). The machine ensures the creation of homogenic groups of fabrics, resulting in fibres of a higher quality level when shredded, thus increasing the product applications possibilities for the textile waste fibres (Pensupa, 2020). Cathryn

Hall confirmed this matter during the interview (see Appendix A.3.1). Remi Veldhoven mentioned in the interview that the Fibresort machine can efficiently sort post-consumer textiles into 40 colour categories has some problems with mixed blends (see Appendix A.3.3). Recently, the Sysav Group launched an automated sorting plant for post-consumer textile waste garments on an industrial scale (Abdullah, 2020; Filho et al., 2019). Therefore, looking at the MRL Materials thread, the automated sorting machine has the potential to increase the amount of post-consumer textiles that are suited for the mechanical recycling process.

4.2.5 Process Capability and Control thread

The upcoming subparagraphs investigate the technical opportunities for shredded post-consumer waste fibres to be integrated in new production processes. The Process capability and Control thread examines the manufacturing processes capabilities (see Appendix A.1), it was therefore chosen as criteria to research the process capabilities of shredded fibres, during the set-up of manufacturing processes.

Spinnability of shredded fibres

As discussed in the previous Cost and Funding chapter, Rieter had developed a Recycling Spinning System that can spin post-consumer textile waste fibres with high short-fibre content, for both rotor and ring spinning (Schwippl, 2020; Spatafora & Schwippl, 2020). The resulting quality of the yarn is of a sufficient level to be used for apparel and interior textiles production, it has thus the opportunity to enable a closed-loop recycling process for post-consumer textile waste garments.

Several companies have developed yarns manufactured from recycled pre-and post-consumer textile waste fibres over the past years. The Spanish brand Recover has set up the production of multiple spinning lines, including yarns produced from 100% cotton textiles, mixed post-consumer textiles and post-consumer denim fabrics (Recover Textile Systems S.L., 2020; Textile Exchange, 2019). Carlos Rico mentioned in the interview that spinning research is required on the adaptations of the several fibre mixes and fibre requirements for the spinning machines. He stated that Recover is now able to spin a yarn with a recycled post-consumer content of up to 75% (see Appendix A.3.8). Besides, recent research investigated the treatment of textile waste fibres before shredding, which could lead to less short-fibre contents. The treatment enabled a less damaging opening phase, which resulted in longer shredded fibre lengths, enabling the rotor spinning of 100% shredded fibres (Kuppen, 2019; Lindström et al., 2020). Both Liset Pander and Anton Luiken stated during the interview the necessity of an extra pre-treatment process step before spinning post-consumer fibres to filter impurities (see Appendix A.3.7 and A.3.4). Therefore, looking at the MRL Process capability and Control thread, the post-consumer textiles waste fibres can be spun, thus increasing the end-product application possibilities of the shredded fibres.

New textiles

Several companies already integrated these yarns for the manufacturing of interior textiles, such as mattress covers and furniture seating's (Shirvanimoghaddam et al., 2020). The Dutch brand's ReBlend and Wolkat successfully produce interior and apparel textiles, with a content of 70% and 80% recycled post-consumer textile waste, combined with recycled polyester or wool yarn (see chapter 4.3) (Pensupa, 2020; Stichting ReBlend, 2020).

Product applications capabilities

Currently, the possibilities for post-consumer textile waste fibres to be integrated into the production processes of several industries are increasing. The market for products manufactured from recycled textile waste fibres is predicted to grow soon (Senthil Kumar & Femina Carolin, 2019).

Denim

Post-consumer denim fabrics are often used as a material source for the production of new textiles because they are easily sorted and retain a high-quality value (WRAP, 2018). Shredded denim fibres are particularly known for their sound-absorbing properties, thermal properties, compressive and flexural strength characteristics (Luiken & Bouwhuis, 2015; Raj et al., 2020; Shirvanimoghaddam et al., 2020). This is why denim fibres are used for the production of insulation material and reinforcement material for concrete (Peña-Pichardo et al., 2018). Recently, shredded denim fibres were used for the production of tent fabric (25% denim fibres, 25% pre-consumer cotton, 50% recycled polyester) (Hoff, 2020). Recent research concluded that resin-bounded denim composites had great acoustical properties, as well as being an environmentally friendly and economically viable product (Hassani et al., 2021). The Dutch brand Planq fabricates chairs, tables and closets from these composites (Planq, 2020). The French brand Pierreplume also manufactures these panels, as the Danish brand Kvadrat with their Really collection (Pierreplume, 2020; Kvadrat, 2020).

Building sector

Post-consumer textile waste fibres are often used for lower-value product applications in the building sector due to their thermal and acoustical properties (Islam & Bhat, 2019). Mixed fibre blended post-consumer textiles could replace the use of wood in panel sheets in the future, due to the mechanical properties of textile fibres reinforced composites namely, good moisture absorption, fire resistance and load-bearing properties (Lacoste et al., 2018; Pensupa, 2020). Producing building applications with textile waste fibres could have great long-term economic benefits (Echeverria et al., 2019). Recent research investigated the use of a nonwoven manufactured from post-consumer textile waste, as reinforcement for cement-based matrixes in non-structural applications. The results showed an improvement in toughness and post-cracking stress-bearing capacity due to the textile waste reinforcement layers (Balea et al., 2021). Earlier in 2016, Avelar et al. (2016) had proven that cotton industrial waste was used for the manufacturing of briquettes for building purposes. The French start-up Fab.brick developed the production of bricks manufactured from 100% post-consumer textile waste fibres, used for non-building interior decoration (Merlet, 2020).

Felt material

Over the past years, shredded post-consumer textile waste fibres were needle punched for the manufacturing of felt materials for the automotive and building sectors. Felt made from textile waste fibres has great thermal and acoustical properties (Bhatia et al., 2014; Shirvanimoghaddam et al., 2020). The Dutch brand I-did manufactures bags, cases, wall covers and acoustical panels from post-consumer textiles felt (I-did, 2020).

Dust recycling

In the past, when shredding damaged cotton/polyester garments, a large percentage of the fibres turned into 'dust' fibres (<5 mm length). These 'dust' fibres were incinerated because they could not be integrated into new value chains. Yet, these dust fibres can be used in the non-woven and paper manufacturing industries (Bhatia et al., 2014; Sadrolodabaee et al., 2021; Shirvanimoghaddam et al., 2020). As such, shredded denim fibres are used for the production of paper (Travers, 2017).

Therefore, looking at the MRL Process capability and Control thread, post-consumer textiles waste fibres can be integrated into several product manufacturing processes, which could lead to increased use of shredded fibres soon.

4.2.6 Quality Management thread

The following subparagraph investigates the logistical opportunities of the mechanical recycling process when researching the quality management of shredded textile waste fibres. The Quality management thread examines the management of efforts to foster quality improvement of the resulting product and set up of key supply chain management structures (see Appendix A.1), therefore it was chosen as criteria to research the production possibilities for shredded fibres due to quality improvement and key supply chain management capabilities.

Partnerships

When setting up a supply chain for post-consumer textile waste garments, the partnerships and collaborations between actors determine the demand, supply and resulting quality of the textile waste fibres. Partnerships need to be set up between fashion and interior brands, textile waste managers, collectors, recyclers, spinners, weavers, recycling machine manufacturers, logistics, transport and regional government parties (Boiten et al., 2019; Euratex, 2020a; Farooque et al., 2019).

Stakeholders need to discuss their specialized knowledge, intensify the collaborations and start the development of improvements and innovations in the several processes, to create open- and closed-loop value chains across multiple clusters (Neto et al., 2021; Watson et al., 2017). Due to these collaborations, a steady and increased supply of post-consumer textile waste can be established, as the reduction of several production costs (Bridgens et al., 2018; Dissanayake & Sinha, 2015; Dissanayake et al., 2021; Singh et al., 2019). Thereafter, projects on a pilot scale can be established (Euratex, 2020a). The set-up of reverse logistics supply chain structures enables the textile actors to close the loop and efficiently recycle textile waste (Jia et al., 2020; Lippman, 2001). Therefore, looking at the MRL Quality management thread, due to intensified collaborative relationships and interaction with circular supply chain execution, actors in the mechanical recycling processes could foster the quality improvement of the shredded fibres which could subsequently result in new product applications possibilities.

4.2.7 Personnel and Facilities thread

The following subparagraph investigates the logistical opportunities of the mechanical recycling process when researching the scaling up of facilities capacities, during the set-up supply chains with shredded textile waste fibres. The Personnel and Facilities thread examines the capabilities of the suppliers to foresee the demand of supply of post-consumer textile waste fabrics (see Appendix A.1), therefore it was chosen as criteria to research the logistics when setting up a pilot production line with mechanically recycled textile waste fibres.

Recycling hub

The first required step when setting up a pilot production line with shredded textile waste fibres is to chart the location, activities, material sorts and amount of supply of the several actors. During this investigation, it will become clear which actors are located in the same region and could work together in a supply chain to set up a pilot production line, thus forming regional recycling centres (Euratex, 2020b; Siderius & Poldner, 2021). These recycling centres can be aligned with the EU Strategy for Textiles (see chapter 2.1). Recently, the European organization Euratex translated this thought into the idea of creating ReHubs, regional recycling hubs with coordinated large-scale recycling value chains (Euratex, 2020b).

In the Netherlands, the Dutch Circular Textile Valley set up networks of recyclers, manufacturers and knowledge institutions to form several recycling hubs, each with its specialisation and circular supply chains (Dutch Circular Textile Valley, 2019). Besides creating intensified collaborations, the recycling hubs have the benefit of a geographical concentration, which optimises logistics and goods flows. This way, the transport emissions of the logistics could be reduced (Oelze, 2017). It is predicted that this development could result in cross-value chain collaborations on a regional level, which would increase the integration of shredded textile waste fibres in value chains (Boiten et al., 2019). Sharing knowledge on textile recycling innovations and collecting data on material flows between the partners, is stated by Huang et al. (2021) to be essential when setting up the infrastructure of a recycling hub. Julie Lietaer mentioned in the interview the need for a digital platform where the multiple sorts of textiles supply could be aligned with the demand of partners, thus facilitating the set-up of supply chains (see Appendix A.3.6). Due to the formation of recycling hubs, the supply of post-consumer textile waste garments and capacities of facilities of the mechanical recycling process can be scaled up. Besides, the increased use of shredded textile waste fibres in new production processes would simultaneously stimulate investments in the development of the mechanical recycling process, thus enabling improvement of the shredded fibres' quality (Euratex, 2020b).

The VTT Technical Research Centre of Finland's Circular Economy of Textiles project 'Telaketju – Towards Circularity of Textiles' successfully resulted in the formation of regional circular value chains, whereby a circular textiles 'ecosystem' was created, providing business possibilities for the recycling of textile waste fabrics (Heikkilä et al., 2019). Another European project, the Resyntex project, established the cooperation of several regional hubs and the set-up of European circular supply chains for the mechanical recycling of post-consumer textile waste garments (Ellen MacArthur Foundation & McKinsey & Company, 2014). Anton Luiken mentioned in the interview the wool recycling hub in Prato, which functions as an example of a recycling hub with successful supply chains on an industrial scale (see Appendix A.3.4). Therefore, looking at the MRL Personnel and Facilities thread, the set-up of recycling hubs could stimulate and scale up the integration of shredded textile waste fibres in pilot productions lines.

4.2.8 Manufacturing Management thread

The following subparagraph investigates the economic opportunities for the mechanical recycling process when researching the capability to set up a supply chain management and manufacturing plan with shredded textile waste fibres. The Manufacturing management thread analyses the orchestration of all elements needed to translate the design of a new product manufactured with a specific material source into an integrated system (see Appendix A.1), it was therefore chosen as criteria to research the maturity of a manufacturing plan while using shredded textile waste fibres.

Scaling up production

If all elements required to set up pilot production lines for products using shredded textile waste fibres are set in place; the formation of collaborative relationships between actors, transparency and availability of supply of post-consumer textiles waste garments, demand for shredded fibres, product application possibilities in multiple sectors, circular supply chain execution and the certainty of manufacturability and cost-efficiency of textile waste fibres, subsequently, the way forward for scaling up production processes on an industrial scale is the creation of agreements (Euratex, 2020a; Pinheiro, de Francisco, Piekarski, & de Souza, 2019). Long-term business plans can be developed, which could result in the reduction of production costs and increased profits (Jia et al., 2020; Pinheiro et al., 2019). If the recycling cluster is prepared for scaling up production, if the shredding and spinning machines could handle greater volumes, for example, the production line scale could be increased. Naturally, testing the performance and quality level of the shredded post-consumer textile waste fibres at the spinning and weaving/knitting processes is required to investigate the fibre/yarn properties at a full commercial scale (Roos et al., 2019a; Roos et al., 2019b). Liset Pander mentioned in the interview the need for a European quality standard for post-consumer textile waste fibres, to standardize the quality level on a European or worldwide level. She believed that, only if this standard would be applied, the production processes of products manufactured from shredded textile waste fibres could be scaled up on an industrial scale (see Appendix A.3.7). Remi Veldhoven stated this thought in her interview as well and added that a European EPR recycling law system would enable the reduction of the cost price of textile waste fibres (see Appendix A.3.3). Besides, Carlos Rico emphasized in the interview that, if an EPR scheme would be entered on a national level, they would receive a greater supply of post-consumer textiles at Recover and could soon scale up the production of recycled yarns on an industrial scale (see Appendix A.3.8). Therefore, looking at the MRL Manufacturing management thread, developing long-term business plans and agreements could be the way forward for scaling up the production of products manufactured from shredded textile waste fibres.

4.3 Multi-criteria analysis

After investigating the challenges and possible opportunities to improve the mechanical recycling process for post-consumer textile waste fabrics, through the use of the Manufacture Readiness Level threads classification, the manufacturability of several shredded textile waste fibres is assessed. Both the literature analysis (see chapter 4.1 and 4.2), semi-structured interviews (see Appendix A.3.2, A.3.3 and A.3.5) and the internal RETEX documents (see Appendix A.2) form the basis for the MRL comparison. The production process of the recycled cotton RETEX fibres, the recycled cotton/polyester RETEX fibres (see chapter 2.5 for full description), the recycled mixed waste fibres of ReBlend and the recycled mixed waste fibres of Wolkat were compared with each other, to research the cost-efficiency and feasibility of the fibres to be integrated in circular supply chains and production processes.

The following Table 2, the manufacturability challenges of the recycled fibres are shown, thereafter in Table 3, the possibilities for improvement are presented. Subsequently, the fibres are compared with each other in a separate sub-paragraph.

Table 2. Multi-criteria Manufacture Readiness Level analysis of the challenges of shredded textile waste fibres.

MRL thread	*Challenges*	*Textile fibre*	*Description*
1. Technology and Industrial base thread	Mixed fibres blends & short fibres	RETEX 100% cotton	The resulting lengths of the shredded fibres after shredding were very short. The quality level of the fibres was insufficient, the pre-consumer textile waste scraps needed to be mixed with virgin cotton fibres. The cotton scraps did not go through any washing processes, still, the decreasing quality level could not be controlled.
		RETEX cotton/polyester	The resulting lengths of the fibres were very short. It was necessary to mix the shredded hospital work wear fibres with virgin cotton fibres to ensure a sufficient quality level.
		ReBlend & Wolkat cotton/polyester	It is necessary to add recycled polyester fibres to the shredded post-consumer textile waste fibres of ReBlend and Wolkat to obtain a sufficient yarn quality level. ReBlend is researching the addition of Tencel/lyocell fibres to replace the recycled polyester content.
	Lack of recycling technologies and infrastructure	RETEX cotton/polyester	The textile fabrics were that damaged by multiple industrial washing processes, that the cotton fibres content turned completely into dust during the shredding process (fibres <5 mm length). The dust formation of the cotton fibres could not be controlled. A material loss of 13% of the fibres occurred during the opening phase and a material loss of 15% occurred during the shredding stage. The 'dust' fibres were seen as 'waste' material and could not be used. There was a lack of processes that could complement the shredding stage (pre-treatment, after treatment).

2. Cost and Funding thread	Cost of the mechanical recycling process	RETEX 100% cotton	Regarding the economic viability of the fibres, the cost-efficiency of the recycled pre-consumer cotton fibres was affirmed with the price cost calculations of Centexbel (1,57 euro per kilo compared to 1,65 euro/kilo virgin). However, the washing step needed to be removed to ensure a positive development in the margin, the profitability of the other production tests could not be affirmed. Both the collection and sorting costs were not taken into account, because the scraps were collected at manufacturer.
		RETEX cotton/polyester	Regarding the economic viability of the fibres, the cost-efficiency of the recycled cotton/polyester fibres was affirmed with the price cost calculations of Centexbel (1,25 euro/kilo compared to 1,35 euro/kilo virgin). Both the collection and sorting costs were not taken into account, because the textiles were collected at the industrial washer.
		ReBlend & Wolkat cotton/polyester	For both ReBlend and Wolkat mechanical recycling processes, the cost-efficiency of the fibres was affirmed. However, the collecting and sorting processes are costly processes, the cost price of the recycled fibres is pricey compared to virgin cotton fibres and the margins of the fibres are quite small.
3. Design thread	Difficulty to design a product	RETEX 100% cotton & RETEX cotton/polyester	Both supply chains were set-up with a specific new product in mind, for the cotton fibres a children's jumper and for the cotton/polyester fibres new hospital work garments, therefore there was no difficulty to design a new product with the shredded textile waste fibres.
4. Materials thread	Collection and sorting of textile waste garments	RETEX 100% cotton	Centexbel analysed that the textile scraps first needed to be washed before being shredded. The washing process had proven to be essential for the removal of dirt, impurities and dust, thus very important for the preservation of a sufficient quality level. This step is most often required for post-consumer textiles, the RETEX project has shown the necessity of washing pre-consumer scraps. The sample batch of fabric scraps was small (200kg), it was difficult to scale up the available fabric materials.
		RETEX cotton/polyester	The sample batch of hospital work garments was small, however, the scaling up of available fabrics is not predicted to be a challenge, due to the fact that the batch was collected at a washing site with other cotton/polyester textile waste sorts.
		ReBlend & Wolkat cotton/polyester	For both the ReBlend and Wolkat shredded textile waste fibres, the sorting process to determine a homogenic category of post-consumer textile waste garments are essential for the end-quality of shredded fibres. ReBlend and Wolkat both collect and sorts their clothing items into more than 250 categories, per fibre type and colour. The challenge with these groups of textiles is that it is not easy to scale up the availability of the fabrics.

5. Process capability and Control thread	Spinnability of shredded fibres	RETEX 100% cotton	Consequently, due to the short fibre lengths, the spinning and knitting of the cotton fibres turned out to be problematic. A material loss of 40% of the cotton fibres occurred during the spinning process.
		RETEX cotton/polyester	The elimination of 'hard parts', buttons and zippers, was essential for the retainment of a quality standard of the fibres. Just as during the shredding process, a material loss of 27% occurred during the spinning stage.
6. Quality management thread	Collaboration between recycling actors	RETEX 100% cotton & RETEX cotton/polyester	For both value chains, the interdependence between actors in the value chain resulted in a negative chain reaction. Due to the lack of quality of shredded fibres, the spinning process could not be effectuated effectively. Therefore, it was proven to be difficult to foster the quality improvement of the new yarns due to supply chain challenges.
7. Personnel and Facilities thread	Enough supply / Cost price balance	RETEX 100% cotton	The pilot production scale was low, only a small number of children's garments was produced. The supply / cost price balance could not be outweighed, the pilot production line was not profitable yet (and could not easily be scaled up).
		RETEX cotton/polyester	The supply of work garments was enough to set up a pilot production line, however, the production costs could not be outweighed. The pilot production line was not profitable yet.
8. Manufacturing management thread	Manufacturability	RETEX 100% cotton	The unpredictable quality of the shredded cotton fibres resulted in the difficulty to set-up a production line. The availability of the pre-consumer scraps and the cost-efficiency of the shredded fibres could not be secured to scale up the production line to a semi-industrial scale. The new children's garments were not manufacturable yet for a scaled-up production line.
		RETEX cotton/polyester	The pilot line of new hospital work wear garments could not yet be scaled up to a semi-industrial scale during the RETEX project, because the production line was not manufacturable and profitable yet.
		ReBlend cotton/polyester	The production line of ReBlend is not yet on a semi-industrial production line. The upscaling of the production line is dependent on the market demand from brands and customers and the B2B collaborations with brands.

Note: see Appendix A.1 for complete Manufacture Readiness Level threads.

Table 3. Multi-criteria Manufacture Readiness Level analysis of the opportunities of shredded textile waste fibres.

MRL thread	*Opportunities*	*Textile fibre*	*Description*
1.Technology and Industrial base thread	Improvement mechanical recycling process	RETEX 100% cotton	From the cotton textile waste scraps, a yarn of sufficient quality was manufactured, that was used for the production of knitted children's garments.
		RETEX cotton/polyester	From the cotton/polyester hospital waste work garments sample, a yarn with a sufficient quality level was manufactured, due to the homogeneity of the textile items (all the same fibre composition of cotton/polyester mix and colour). The fibres had a sufficient length to be respun.
		ReBlend & Wolkat cotton/polyester	Both the ReBlend and Wolkat post-consumer textile waste fibres, when mixed with recycled polyester fibres, have a sufficient quality level to be spun. ReBlend is investigating the replacement of the recycled polyester fibres by lyocell/Tencel fibres, that could originate from the chemical recycling process.
2. Design thread	Sustainable option	RETEX 100% cotton & RETEX cotton/polyester	Both the RETEX supply chains resulted in the reduction of environmental impacts of the partners involved in the production lines (Petit Bateau, Lemahieu, Van Moer).
3. Cost and Funding thread	Profitable process	RETEX 100% cotton	Centexbel calculated that the positive margin of the recycled cotton fibres would increase if the step of 'hard parts' removal could be skipped. Compared to the sliver cost price of 1,65 euro/kilo for virgin cotton fibres, the best-case scenario cost price for the recycled cotton supply chain was calculated at 1,57 euro/kilo, thus profitable.
		RETEX cotton/polyester	Centexbel affirmed that the post-consumer cotton/polyester fibres could be cost-efficient (1,25 euro/kilo for recycled fibres compared to 1,35 euro/kilo for virgin fibres) with a gross margin of 7,49%. If the mechanical recycling process could be aligned in the same room, as at the CETI research centre, the margin of the cotton/polyester fibres could increase to 11% due to the reduction of logistics costs. According to Centexbel, the homogenous industrial scraps thus yield to positive margins.
		ReBlend cotton/polyester	The cost price of the recycled post-consumer textile waste fibres of ReBlend was not known, however, the current mechanical recycling process had proven to be profitable.
		Wolkat cotton/polyester	The cost price of the recycled post-consumer textile waste fibres of Wolkat was unknown, however, the current mechanical recycling process had proven to be profitable.
		RETEX 100% cotton	Centexbel concluded that the homogeneity of the pre-consumer textile fabric scraps sample was the most important factor to obtain a sufficient quality standard of shredded fibres.

4. Materials thread	Automated sorting	RETEX cotton/polyester	The homogeneity of the textile waste sample, all fabrics were the same, was the most important factor to obtain a sufficient quality standard of shredded fibres.
		ReBlend cotton/polyester	Post-consumer textile waste garments were hand-picked at the Sympany collection site, sorted by type of material and colour, thereafter, garments with a high percentage of cotton are put aside for shredding. By sorting homogenic groups of textiles, the end product applications of the fibres are increased.
		Wolkat cotton/polyester	Wolkat emphasised on keeping a high-quality value of the recycled textile waste fibres, by sorting the post-consumer textile waste garments into forty different colours. Therefore, only homogenic group of textiles were shredded.
5. Process capability and Control thread	Spinnability of shredded fibres	RETEX 100% cotton	A yarn made from 75% virgin cotton and 25% recycled cotton yarn was manufactured (Nm 28/1, open-end). A fleece pullover (1/10 Nm) and a jersey pullover (1/24 Nm) was produced.
		RETEX cotton/polyester	The composition of the fabric resulted in a mix of 35% virgin cotton and 65% recycled polyester fibres (25% shredded post-consumer, 25% pre-consumer cotton waste, 15% recycled polyester). A closed-loop textile-to-textile production with the same fibre material composition (1/30 Nm, open-end spinning) was produced.
		ReBlend cotton/polyester	The ReBlend textiles are composed of 70% post-consumer textile waste garments and 30% rPET.
		Wolkat cotton/polyester	The Wolkat yarns consist of 80% post-consumer textile waste fibres and 20% recycled polyester yarn. The production site succeeded in the manufacturing of recycled yarns of 15Nm.
	Product applications capabilities	RETEX cotton/polyester	The cotton fibres that turned into dust in the shredding process, could have been used for the production of paper or nonwovens, because fibres with lengths of <5 mm are suited for production lines in these industries.
		ReBlend cotton/polyester	The ReBlend yarns are suitable for production line of interior and apparel textiles and applicable for new product applications such as towels, linen and denim.
		Wolkat cotton/polyester	The recycled textile waste fibres of Wolkat are suitable for other textile production, as denim and other apparel fabrics. The product applications opportunities for the yarn could be increased.
		RETEX 100% cotton	During the RETEX project, a successful collaboration between the fashion brands Petit Bateau and Lemahieu, textile waste recycler Procotex, and spinning mill European Spinning Group was established.
		RETEX cotton/polyester	During the RETEX project, a successful collaboration between the fabric's collector Van Moer, textile waste recycler Minot, and spinning mill Utexbel was established.

6. Quality management thread	Partnerships	ReBlend cotton/polyester	ReBlend has successful collaborations with textile waste shredders and spinners in Spain and Portugal. They share knowledge together on how to improve the shredding and spinning of post-consumer textile waste fibres, thus beneficial for the end textiles.
		Wolkat cotton/polyester	Wolkat has set-up a supply chain for the mechanical recycling process in Morocco. The post-consumer textiles are collected and sorted in the Netherlands. thereafter shipped to Tangier, where the garments were undone from zippers and buttons, sorted by colour and sorted by fibre materials. Several categories are formed whereby denim fabrics, acryl fabrics and knitted fabrics are put aside. The fabrics are then shredded, spun and woven into new fabrics. Because the supply chain is at one place, the costs of transports and logistics are reduced.
7. Personnel and Facilities thread	Recycling hubs	RETEX 100% cotton	During the RETEX project a regional supply chain was set-up. Materials were located, facilities connected through logistics. The regional supply chain resulted in low logistics costs.
		RETEX cotton/polyester	During the RETEX project a regional supply chain was set-up. Materials were located, facilities connected through logistics. The regional supply chain resulted in low logistics costs.
		ReBlend cotton/polyester	ReBlend has successfully set-up a circular supply chain for the production of interior and apparel textiles. Taking part in a recycling hub could enable ReBlend to scale up productions, due to increased demand.
		Wolkat cotton/polyester	Cross-sector value chain collaborations with the Wolkat yarns could become possible in the near future. Taking part in a recycling hub could increase the product application opportunities for Wolkat.
8. Manufacturing management thread	Scaled-up production	RETEX 100% cotton	Centexbel stated that, if the supply of pre-consumer textile waste scraps for the value chain could be enlarged during the project, the positive margin of the recycled cotton fibres could be increased. A circular supply chain was set up, a small production of new fleece garments was effectuated. The production line was on a pilot scale, therefore an MRL level 8 was chosen, supporting a Low-Rate Production (LRP).
		RETEX cotton/polyester	The RETEX recycled cotton/polyester yarn was estimated at a MRL level of 8, because the recycled cotton/polyester yarn was validated by the Centexbel experiments and adequate to support a Low-Rate Initial Production (LRIP).
		ReBlend cotton/polyester	ReBlend had thus set-up an international production line, integrating recycled textile waste fibres as raw material source. Miss de Wit estimated during the interview the fact that her production line could be scaled up on a semi-industrial scale. The ReBlend yarns would accord to the MRL level 9, however, production line is not yet on an industrial scale, therefore the MRL level 8 is adequate.

		Wolkat cotton/polyester	Wolkat had thus succeeded in the set-up of a circular supply chain in Morocco. Currently, the production of new textiles was at a semi-industrial scale and will soon be upscaled to an industrial scale production, by expanding the production site. New collaborations were established, which would increase the product applications opportunities for the recycled waste fibres. As Pierre van Trimpont and Daniël Verstraete suggested that the logistics costs had an influence on the cost price of the fibres, the cost price of the Wolkat fibres could compete with virgin cotton fibres. Wolkat has proven the manufacturability and cost-efficiency of shredded post-consumer textile waste fibres, when producing new textiles, because they could adapt the shredding and spinning machines to their sorted textile waste fabrics.

Note: see Appendix A.1 for complete Manufacture Readiness Level threads.

Comparison of manufacturability fibres

Quality

The several textile waste fibres all decreased in fibre lengths and quality during the shredding process. The difference in quality became clear between the pre-consumer RETEX cotton fibres and post-consumer RETEX cotton/polyester fibres, the several (industrially) washing cycles damaged the cotton/polyester fibres whereafter they turned into 'dust' during shredding. The problem of significant fibre loss did not occur at both ReBlend and Wolkat shredding sites, because they recycled sorted homogenic groups of post-consumer textiles (by colour and fibre sorts). The RETEX cotton pre-consumer scraps needed to be washed to ensure a sufficient level of quality, which is different from the ReBlend and Wolkat post-consumer fibres who do not wash the mixed post-consumer fibres before shredding. For both the RETEX cotton and cotton/polyester fibres, the spinning stage was problematic, material losses of 40% and 27% occurred. For both the spinning processes of ReBlend, at Recover, and Wolkat at the Moroccan site, the spinning process was successful. Eventually, yarns with good quality levels could be manufactured for both RETEX supply chains on small pilot scales. The supply chains of both ReBlend and Wolkat obtain yarns with a good quality level on semi- and industrial scales.

To retain shredded textile waste fibres with a good quality standard, the homogeneity of the textiles sample was proven by both RETEX supply chains and the ReBlend and Wolkat supply chains to be the key for success. The manufacturability of the textile waste fibres thereafter depended on the volume of supply. The automated sorting machine could help increase the supply of textiles soon for the supply chains of ReBlend and Wolkat.

The knitting stage of the RETEX cotton supply chain turned out to be problematic, but in the end, children's jumper could be manufactured. The RETEX cotton/polyester supply successfully manufactured hospital workwear textiles. Both the supply chains of ReBlend and Wolkat produce interior and apparel textiles, on semi- and industrial scales without problems. The partnerships and intensified collaborations between actors in the supply chain were proven by the supply chains to be beneficial for the end-product. By sharing knowledge on improvements of the sorting stage and shredding and spinning machines, the fibres and end-products quality level will increase. Both RETEX supply chains setup collaborations between actors during the RETEX project and could share knowledge spinning and knitting improvements.

Cost price

Surprisingly, the RETEX cotton and cotton/polyester fibres resulted in reduced cost prices compared to virgin competitors. However, the costs of collection and sorting, which were proven in the literature and interviews to be costly, were not taken into account in the calculation. For the RETEX cotton fibres the costs of washing needed to be removed to ensure the cost-efficiency of the fibres. For the cost price calculations of the ReBlend and Wolkat fibres, the sorting and collection costs were taken into account, this is the reason why both cost prices were more expensive than virgin fibres. The sorting costs are thus important for the resulting cost price of both the ReBlend and the Wolkat fibres. For all fibres, the gross margin was quite small. Both the RETEX cotton and cotton/polyester supply chains were small pilot production processes, the supply/cost balance could not yet be outweighed.

Both the RETEX cotton, RETEX cotton/polyester, ReBlend and Wolkat supply chains proved to be profitable. The positive margin of the RETEX cotton supply chain could further be increased in the future by skipping the step of 'hard parts' removal, predicted Centexbel. For the cotton/polyester RETEX supply chain, the gross margin could be increased by setting up the mechanical recycling just as in the CETI research centre, one machine directly feeding the other, thus reducing the costs of logistics. The profitability of the RETEX supply chains lied in the reduction of production costs, due to the low-cost textile waste fabrics. RETEX supply chains were on a regional level, decreasing the costs of transport. Both ReBlend and Wolkat supply chains are at a European level, whereby logistics is an important influencer on the gross margin.

Availability

Due to negative chain reactions between shredding and spinning, the RETEX cotton and cotton/polyester supply chains could not foster quality improvement. This problem did not occur for the supply chains of the ReBlend and Wolkat fibres. Due to the uncertainty of availability of textile waste garments and profitability of the RETEX cotton and cotton/polyester fibres, the new products were not manufacturable yet on a semi-industrial scale. The availability of specific groups of textiles and the market demand for recycled textiles determine the scale-up of the production line of ReBlend. For both the RETEX cotton scraps batch and the sorted post-consumer textiles for Wolkat and ReBlend, it was proven difficult to scale up the availability of fabrics. For both the RETEX cotton and cotton/polyester supply chains, Centexbel affirmed that if the supply of textiles could be increased, the cost-efficiency of the fibres would increase. If regional recycling hubs would be created in a near future, the possibilities of scale-up production could become possible for ReBlend and Wolkat. New cross-sectoral value chains could thereafter be set up. This could not be achieved during the RETEX project due to time limitations.

For both the RETEX cotton and cotton/polyester supply chains, an MRL level 8 was estimated because it could support a Low-Rate Production scale. The ReBlend supply chain could be increased to a semi-industrial scale, but because this is not yet the case, an MRL level 8 was estimated. The Wolkat supply chain is already at a semi-industrial scale, the manufacturability and profitability of the fibres were proven in several production collaborations, therefore, an MRL level 9 was estimated.

Discussion

The present study has analysed the current mechanical recycling process for post-consumer textile waste garments. Throughout this chapter, the results of this master thesis are discussed on feasibility. Furthermore, a roadmap for the future of textile waste fibres is presented.

The multi-criteria comparison showed that the cotton/polyester fibres from the RETEX project, the ReBlend and the Wolkat fibres could be cost-efficient. This cost-efficiency could be further increased through the scale-up of production processes to a semi- or industrial scale. Today, production scale-up is however completely dependent on the retail price of the fibres and the willingness of B2B partners and customers to pay for the end-product. To guarantee these sales, the difference in cost and selling price between the recycled product and its virgin competitor needs to be as small as possible. This possibility has been demonstrated by Pierre van Trimpont and Daniël Verstraete from Centexbel in the RETEX project, which confirmed that the economic cost price analysis of the recycled cotton/polyester fibres and the recycled cotton fibres were favourable compared to virgin cotton/polyester and cotton fibres. Another factor that could increase the cost-efficiency of post-consumer fibres, is the set-up of a recycling hub, which would lower the costs of logistics (see chapter 4.3, Appendix A.2., A.3.4. and A.3.5).

The cotton/polyester textiles sample of the RETEX project showed that the most important contributor to cost efficiency is the homogeneity in the composition of the fibres. The sorting of homogenic categories of textile waste is thus of utmost importance for the manufacturability of mixed textile waste garments. Another contributor to the cost-efficiency is the fact that the textiles were picked up at the industrial washer, thus, the costs of sorting could be avoided. It is to be noted that the 'hard parts' removal process needed to be skipped to guarantee the cost-efficiency of the fibres. As seen in the Appendix, the cost price calculation of these garments performed by Centexbel, came to 1,25 euro/kg compared to 1,35 euro/kg for virgin cotton/polyester fibres (see Appendix 2.2). We can see the difference in cost price as a promising development.

The introduction of an EPR scheme on textiles in Europe could be a contributing factor to the future reduction of the cost price of post-consumer textile waste fibres (see chapter 2.1 and 2.2). Fashion and interior brands will realise that mechanical recycling could be more cost-effective, compared to incineration costs of their textile waste scraps and unsold garments (EuraMaterials 2020b). The introduction of a tax on textile waste incineration could be a further incentive to persuade them towards mechanical recycling. LCAs on the environmental benefits of the mechanical recycling process of post-consumer textiles, compared to landfill and incineration, needs to be researched in future studies. The following roadmap will show key action steps to increase the mechanical recycling of post-consumer textile waste, this will enable the textiles industry to comply with the EPR scheme.

An EPR scheme on a European scale could also lead to the introduction of a European, or global, recycling standard (see Appendix A.3.3). A standard for shredded textile waste fibres could enable mechanical recycling supply chains on a European scale. It would bring clarity on the standard characteristics of shredded textile waste fibres, in terms of length, strength or composition, for all companies involved in the recycling supply chain. This could positively influence the integration of shredded fibres in production processes. There is already a global recycling standard for textiles, but it does not have a clear category for textiles manufactured from post-consumer textile waste fibres (Textile Exchange, 2015).

The, in the roadmap proposed, recycling hubs could enable the development of bringing back the production of textiles to Europe (see Appendix A.3.4). This development will be determined by the cost-efficiency of textile production processes, the availability of textile waste supply, mechanical recycling infrastructure (collection, shredding and spinning) and the market demand for European textiles. Some textile production sites in Europe have successfully integrated the use of post-consumer cotton, denim or polyester in their production. These production sites are mostly situated in Turkey, Spain and Portugal, because of their low labour costs (Textile Exchange, 2015).

The study shows that there are opportunities for new product applications, both open- and closed-loop. Unfortunately, the open-loop interior applications, whereby shredded textile waste fibres are compressed with bio-resins, cannot easily be recycled as yet (Franco, 2019; Vanegas et al., 2018). The recyclability of products manufactured from shredded textile waste fibres needs to be researched in future studies.

In the present study, the challenge of microfibres could not be investigated. There is no data available yet on the release of microfibres when textiles manufactured from post-consumer textile waste fibres are washed (see Appendix A.3.1). Furthermore, the influence of the washing process on the quality of the textile waste fibres could not yet be investigated. The Dutch parliament has recently started a research project on this matter (van Veldhoven, 2020).

The roadmap was based on an analysis of the current challenges and opportunities for the mechanical recycling of post-consumer textiles. The feasibility of the roadmap is difficult at this stage to guarantee because it needs all partners to be convinced of the opportunities and the added value it will offer them. It is to be noted that the economic circumstances of the partners and the European market for recycled fibres are not well predictable and will have an impact on the proposed roadmap. Nevertheless, it is predicted that the textiles industry will start to accept the slightly higher cost price for recycled waste fibres and implement them in production processes on an industrial scale (Euratex, 2020b; Schwippl, 2020).

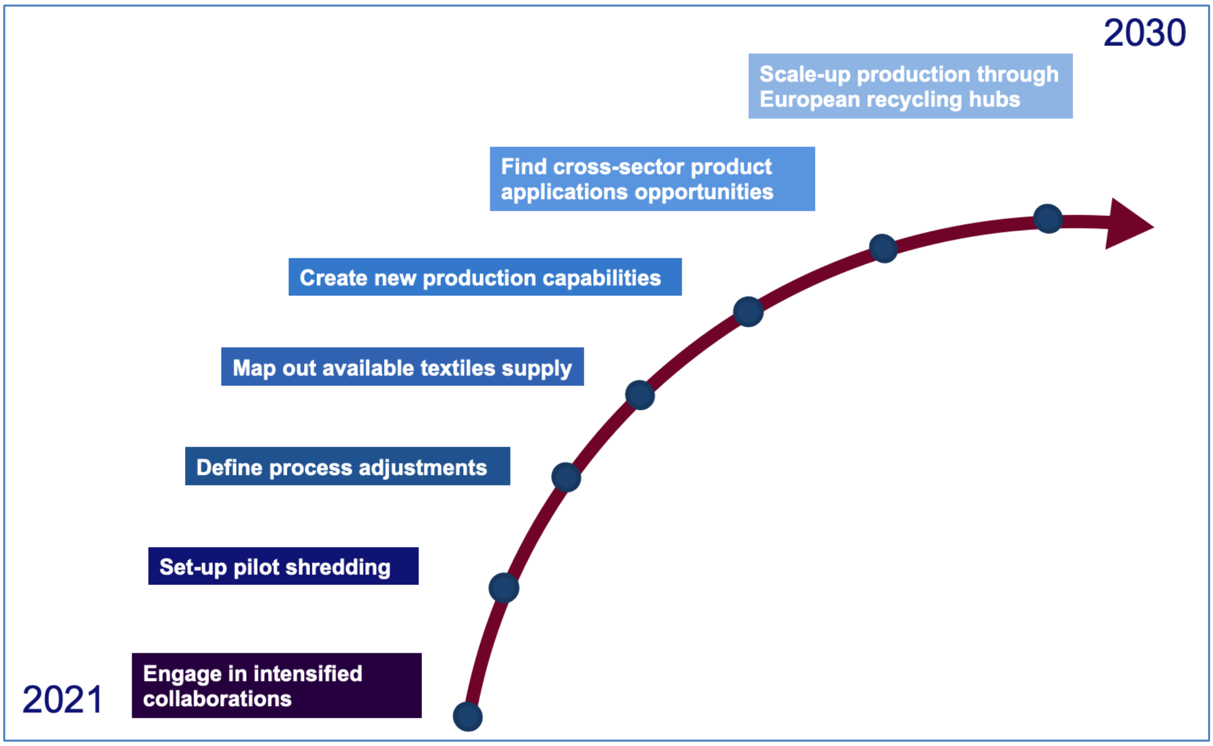
Roadmap

After looking at the results of this master thesis, a roadmap proposal with clear action steps to implement the investigated opportunities for the mechanical recycling process for post-consumer textile waste fabrics is developed. The goal of this outlook is to advise textile waste recyclers on how to create new product application opportunities by improving the manufacturability and cost-efficiency of shredded textile waste fibres.

Today, less than 1% of post-consumer textile waste garments is recycled into high-quality fibres and used for the production of new textiles. This pile of waste fabrics is expected to grow (see chapter 1.3). Unfortunately, the mechanical recycling infrastructure cannot foresee this growth. The mechanical recycling process damages the fibres, a closed-loop textile-to-textile production using shredded textile waste fibres is currently almost impossible (see chapter 4.1.1). However, adaptations to the cutting and shredding machines are being investigated and lead to spinnable, value-adding and cost-efficient fibres (see chapters 4.2.1, 4.2.2 and 4.4.4).

The following action steps are designed to enable textile waste recyclers to reach the EU target of recycling 70% of all post-consumer textiles in Europe in 2030 (see chapter 2.2, 4.2.8 and Appendix A.3.8). The French EPR policy and Dutch post-consumer textiles recycling targets will form the framework of this roadmap (see chapter 2.1 and 2.2 and Appendix A.3.3). The action steps (see Figure 3) are elaborated in the following paragraphs.

Figure 3. Roadmap towards recycling of 70% post-consumer textile waste in compliance to EU target 2030.



1. Engage in intensified collaborations.

The current lack of collaboration and coordination between actors in the mechanical recycling supply chains (see chapter 4.1.6) could be resolved by the formation of intensified collaborations (see chapter 4.2.6 and 4.3). The various partners could share knowledge on their latest innovations to find out which production lines could be set in place for which sectors/industries (see chapter 4.2.6 and Appendix A.3.7). In case the profitability of these new products could be confirmed, which was demonstrated in the MRL comparison (see chapter 4.3), the competitive environment and different interests of actors could be put aside (see chapter 4.1.6) to come up with new products manufactured from shredded textile waste fibres. A roundtable discussion can be set up by the textile waste recycler, where the shredded fibres' quality, is determined, to align the characteristics and quality expectations of the customer, with the quality of the fibres from the textile waste supplier.

2. Set-up pilot shredding

To investigate the shredded fibres' potential quality, the textile waste recycler needs to invest in the set-up of a pilot shredding line. A pilot shredding machine can demonstrate required process adjustments to increase the shredded fibres' lengths and test the needed adaptations to each fibre type/mix (see chapter 4.1.1 and Appendix A.3.6 and A.3.8). The pilot shredding machine will be of added value in the lacking mechanical recycling technologies and infrastructure (see chapters 4.1.1 and 4.1.3). The unpredictable quality of shredded textile waste fibres will no longer be an issue (see chapter 4.1.8 and Appendix A.3.5). More importantly, when the intensified collaborations will be initiated, the pilot shredding machine can shred small volumes of textile waste fabrics. In this way, the benefits of the collaborations will be demonstrated for the textile waste recycler, and it can be used as a promotor for new partnerships and projects (see chapter 4.1.6). With the pilot shredding machine, the calculations of the supply/cost price can be calculated before investigating the new production capabilities (see chapter 4.1.7). As seen in the MRL comparison, setting up the pilot mechanical recycling process as the CETI research centre in one hall will also improve the cost-efficiency of the fibres which is economically beneficial for the textile waste recycler (see chapter 4.2.3 and 4.3 and Appendix A.3.5).

3. Define process adjustments

To improve the manufacturability and cost-efficiency of shredded textile waste fibres, the cutting and shredding process need to be adjusted to each fibre sort, to obtain longer fibre lengths' and increased quality levels (see chapter 4.1.1). A slower cutting process and a less harsh shredding process was suggested by multiple interviews as a priority to be researched (see Appendix A.3.4, A.3.5 and A.3.8). At the same time, the textile waste recycler can look for spinning partners that research the spinnability of shredded textile waste fibres, to increase the manufacturability of the fibres (see chapter 4.2.5, 4.3 and Appendix A.3.3, A.3.4., A.3.8). Also, textile waste recyclers can contact partners who investigate the automated sorting of textile waste garments, to investigate the creation of homogenic groups of textiles, that will increase the manufacturability and profitability of the fibres (see chapter 4.2.4, 4.3 and Appendix A.3.1 and A.3.3).

4. Map out available textiles supply

When the mechanical recycling process can guarantee a sufficient quality level of shredded textile waste fibres, the available textiles supply (in a region or country) can be mapped out (see chapter 4.2.7). If all partners investigate their available textiles, both pre-and post-consumer, manufacturing plans can be set up for the production of new products (see chapter 4.2.6). Through the obtained information, it will become clear where partners are situated and what their activities are. New product applications possibilities and business opportunities will emerge, which will increase the economic benefits of the textile waste recycler (see chapter 4.1.4, 4.2.7 and 4.2.8). Currently, the European Spinning Group is setting up a B2B platform with this purpose (see Appendix A.3.6).

5. Create new production capabilities

Thereafter, manufacturing plans can be set up for these new product application opportunities (both open- and closed-loop) (see chapter 4.2.7 and 4.2.8). The expected characteristics of the end product will be matched to the available textile waste supplies. Within the recycling network, a chain of required processes for the manufacturing of the end product can be set up, thereafter the logistics operations can be initiated (see chapter 4.2.5). The several actors can introduce cost-sharing agreements to strengthen the collaborations and invest in process innovations (see chapter 4.2.7 and 4.2.8). If the spinnability of textile waste fibres could be improved, closed-loop production of textiles made from textile waste fibres could become possible on a greater scale, which was proven in the MRL comparison (see chapter 4.3 and Appendix A.3.1). These new production capabilities will economically benefit the textile waste recycler and strengthen its position in the recycling network, as it is the supplier of the raw materials needed for the product application opportunities (see Appendix A.3.4).

6. Find cross-sector product application opportunities

Subsequently, new cross-sector product application opportunities will emerge (see chapter 4.2.7). Textile waste fibres can be integrated into many manufacturing processes, for example, construction, building or interior industries, creating value-added open-loop products (see chapter 4.2.3 and 4.2.5). These broadened operations will result in higher margins, which will enable the scale-up of production capabilities and stimulate investments, business partnerships/opportunities and process improvements (see chapter 4.2.7, 4.3 and 4.2.8).

7. Scale-up production through European recycling hubs

Due to its proximity, the established mechanical recycling network will develop into a regional recycling hub (see chapter 2.4.7 and 4.3). New business partners will see the advantage of connecting with not only one partner, but with the full network. Also, supply chain and logistics costs are reduced (see chapter 4.2.7, 4.3 and Appendix A.3.5). This development will allow scale-up productions, towards semi- and industrial scale, enabling the increased recycling of post-consumer textiles for textile waste recyclers to meet the EU 2030 target and at increased profitability (see chapter 4.2.8, 4.3 and Appendix A.3.4). The MRL comparison showed the possibilities to set up a regional recycling hub, enabling the production of textiles manufactured from recycled waste fibres and possibilities for scaling-up (see chapter 4.3). This increased cost-efficiency will convince fashion and interior textiles manufacturers to opt for the recycling route, instead of incinerating their textile waste garments.

Conclusion

This master thesis has researched the potential for the mechanical recycling process for post-consumer textile waste fibres. The results are promising, with a feasible roadmap for implementation for partners in the mechanical recycling chain. In answer to the research question, how can the potential of shredded textile waste fibres be increased, the set-up of pilot cutting/shredding lines and the intensified collaborations between partners in the supply chain would be the two most contributing factors.

Through the use of literary analysis and semi-structured interviews, the current challenges and opportunities for the improvement of the mechanical recycling process for post-consumer textile waste fabrics were investigated. These findings were filled in a multi-criteria analysis, that assessed the Manufacture Readiness Level of multiple shredded textile waste fibres. The most important bottleneck that hinders the manufacturability of the fibres, is low quality, high short-fibre content and uncertainty of material composition of shredded fibres. Next to this, post-consumer textiles are often damaged, that a high material loss occurs during shredding. By lowering the speed of the cutting machine and enabling a gentler shredding process, the fibre lengths could be elongated. The lack of mechanical recycling technologies and infrastructure on a pilot-scale prevents these process adjustments per fibre type. Shredded textile waste fibres have proven to reduce the supply chains' environmental impacts, therefore, designing a product with the fibres will become more attractive. An important economic bottleneck for the integration of shredded post-consumer fibres in production processes is the cost price, which could be compensated by scaled up productions or by using the fibres in end-products with a higher sales price. Furthermore, the collection and sorting costs constitute a large part of the cost price. The investment in an automated sorting machine could lower these costs. Besides, the new sorting process could ensure a stable supply of homogenic groups of textiles, for which more product applications could then likely be found. The problematic spinnability of shredded textile waste fibres is currently improved through new spinning techniques. Where formerly only production processes of low-quality products for post-consumer fibres were set up, actually, new cross-sectorial production capabilities enable also the manufacturing of high-quality products. Subsequently, the set-up of regional recycling hubs could scale up the supply of post-consumer textiles and the capabilities for new production processes. The sharing of knowledge through intensified collaborations could enable the, now difficult to foster, quality improvement of shredded textile waste fibres and map out the availability of textile waste materials. Thereafter, increased demand for shredded fibres from the market could be foreseen, as the possibility to bring back textiles production to Europe. Thus, improved manufacturability and profitability are the most important factors to increase the potential of mechanical recycling for post-consumer textile waste fibres.

The roadmap is a proposal to achieve an increase in the recycling rate of post-consumer textiles and to improve the profitability of the commercialization of recycled textile waste fibres.

Reflection and recommendations

The present study has contributed to the field of mechanical recycling research, by performing a study that combines the use of a literature analysis, semi-structured interviews and a multi-criteria analysis on Manufacture Readiness Levels. The chosen approach of dividing the challenges and opportunities of the mechanical recycling process for post-consumer textile waste garments on technical, logistical and economic aspects, has enabled a multi-perspective view on the topic.

With the present study, I tried to examine a complete perspective on the circular supply chain for recycled textile waste fibres, including the opinions of mechanical recycling experts and researchers. I tried to obtain information through the use of semi-structured interviews to obtain up-to-date and unpublished information on each topic. For the topics of setting up a supply chain and potential mechanical process solutions, this was performed successfully, however, for the topics of weaving and knitting recycled waste fibres, there was a lack of information. The interviewees were all experts with knowledge about a particular topic of expertise. This resulted in the fact that not all topics were covered in the present study. For a future study I would recommend searching for experts working on each particular process step of the circular supply chain. For example, this could be performed by setting up a work group of several actors of the circular supply chain that could discuss possible product application opportunities and possible improvements of the mechanical recycling process.

Lastly, while researching the present literature, the lacking information was completed with recent insights from reports and interviews. However, these reports were not peer-reviewed. Naturally, this is due to the fact that this is a relatively new topic. Therefore, I could recommend in a future study to perform empirical studies on the profitability of mechanically recycled textile waste fibres and the feasibility of new mechanical recycling technologies/adaptations. For example, shredding tests could be performed to seek for changes in the cutting and shredding processes, creating the collection of data while keeping the thought in mind to retain a high-quality product.

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Appendix

A.1 Detailed MRL Criteria

Acquisition Phase		Pre-Materiel Development Decision (Pre-MDD)			Materiel Solution Analysis (MSA)	Technology Maturation and Risk Reduction (TMRR)		Engineering & Manufacturing Development (EMD)		Low-Rate Initial Production (LRIP)	Full-Rate Production (FRP)
Technical Reviews				MDD	ASR A	SRR/SFR	PDR B	CDR	PRR/SVR C	PCA FRP	
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
	Technology Maturity	Should be assessed at TRL 1.	Should be assessed at TRL 2.	Should be assessed at TRL 3.	Should be assessed at TRL 4.	Should be assessed at TRL 5.	Should be assessed at TRL 6.	Should be assessed at TRL 7	Should be assessed at TRL 7 or TRL 8.	Should be assessed at TRL 8 or TRL 9.	Should be assessed at TRL 9.
A - Technology and Industrial Base	A.1 Industrial Base			Potential sources identified to address technology needs. Understand state of the art.	Industrial base capabilities surveyed and known gaps/risks/issues identified for preferred concept, key technologies, components, and/or key processes.	Industrial base capabilities assessment initiated to identify potential manufacturing sources. Sole/single/ foreign source vendors and vendors of technologies with potential obsolescence issues identified and planning initiated to minimize risks.	Industrial base capabilities assessment for MS B completed. Industrial capability in place to support manufacturing of development articles. Plans to minimize sole/single/foreign sources and obsolescence issues complete. Need for sole/single/foreign sources justified. Potential alternative sources identified.	Industrial capability to support production analyzed. Sole/single/foreign sources, source stability, and obsolescence issues are assessed/monitored. Potential alternate sources developed if necessary.	Industrial base capability assessment for MS C completed. Industrial capability is in place to support LRIP. Sources are available, including multi-sourcing where cost-effective or necessary to mitigate risk.	Industrial capability assessment for FRP has been completed and capability is in place to support start of FRP.	Industrial capability supports FRP and is assessed to support modifications, upgrades, surge and other potential manufacturing requirements.
	A.2 Manufacturing Technology Development		New manufacturing concepts and potential solutions identified.	Manufacturing technology concepts identified through experiments/ models.	Manufacturing Science & Advanced Manufacturing Technology requirements identified.	Required manufacturing technology development efforts initiated.	Manufacturing technology efforts continuing. Required manufacturing technology development solutions demonstrated in a production relevant environment.	Manufacturing technology efforts continuing. Required manufacturing technology development solutions demonstrated in a production representative environment.	Primary manufacturing technology efforts concluding. Improvement efforts continuing. Required manufacturing technology solutions validated on a pilot line.	Manufacturing technology process improvements efforts initiated for FRP.	Manufacturing technology continuous process improvements ongoing.

Figure 4. Manufacturing Readiness Levels for the Technology and Industrial Base Thread (OSD Manufacturing Technology Program & The Joint Service/Industry MRL Working Group, 2018).

Acquisition Phase		Pre-Materiel Development Decision (Pre-MDD)			Materiel Solution Analysis (MSA)	Technology Maturation and Risk Reduction (TMRR)		Engineering & Manufacturing Development (EMD)		Low-Rate Initial Production (LRIP)	Full-Rate Production (FRP)
Technical Reviews				MDD	ASR	A SRR/SFR	PDR	B CDR	PRR/SVR	C PCA	FRP
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
B - Design	B.1 Producibility Program			Relevant materials/processes evaluated for manufacturability using experiments/ models.	Initial producibility and manufacturability assessment of preferred systems concepts completed. Results considered in selection of preferred design concepts and reflected in AS key components/ technologies.	Producibility and manufacturability assessments of key technologies and components initiated. Ongoing design trades consider manufacturing processes and industrial base capability constraints. Manufacturing processes assessed for capability to be tested and verified in production. Manufacturing processes assessed for influence on O&S.	Producibility assessments and producibility trade studies (performance vs. producibility) of key technologies/components completed. Results used to shape AS, SEP, manufacturing and producibility plans, and planning for EMD or technology insertion programs. Preliminary design choices assessed against manufacturing processes and industrial base capability constraints. Producibility enhancement efforts (i.e., DFM, DFA, etc.) initiated.	Detailed producibility trade studies using knowledge of key design characteristics and related manufacturing process capability completed. Producibility enhancement efforts (i.e., DFM, DFA, etc.) ongoing for optimized integrated system. Manufacturing processes re-assessed as needed for capability to be tested and verified. Manufacturing processes re-assessed as needed for potential influence on O&S.	Producibility improvements implemented on system. Known producibility risks and issues managed for LRIP.	Prior producibility improvements analyzed for effectiveness during LRIP. Producibility risks and issues discovered in LRIP managed for FRP.	Design producibility improvements demonstrated in FRP. Process producibility improvements ongoing. All modifications, upgrades, DMSMS and other changes assessed for producibility.
	B.2 Design Maturity	Manufacturing research opportunities identified.	Applications defined. Broad performance goals identified that may drive manufacturing options.	Top level performance requirements defined. Trade-offs in design options assessed based on experiments. Product lifecycle and technical requirements evaluated.	SEP and T&E Strategy recognize the need for the establishment/validation of manufacturing capability and management of manufacturing risk for the product lifecycle. Initial KPPs identified for preferred systems concept. System characteristics and measures to support required capabilities identified. Form, fit, and function constraints, and manufacturing capabilities identified for preferred systems concept.	Lower level performance requirements sufficient to proceed to preliminary design. All enabling/critical technologies and components identified and the product lifecycle considered. Evaluation of the design for KCs initiated. Product data required for prototype component manufacturing released.	System allocated baseline established. Product requirements and features are well enough defined to support PDR. Product data essential for subsystem/ system prototyping has been released, and all enabling/critical components have been prototyped. Preliminary KCs for the design identified and mitigation plans initiated.	Product design and features are well enough defined to support CDR, even though design change traffic may be significant. All product data essential for component manufacturing released. Potential KC risks and issues identified with mitigation plans in place.	Detailed design of product features and interfaces completed. All product data essential for system manufacturing released. Design change traffic does not significantly impact LRIP. KCs are attainable based upon pilot line demonstrations.	Major product design features and configuration are stable. System design has been validated through operational testing of LRIP items. PCA or equivalent complete as necessary. Design change traffic is limited. All KCs are controlled in LRIP to appropriate quality levels.	Product design is stable. Design changes are few and generally limited to those required for continuous improvement or in reaction to obsolescence. All KCs are controlled in FRP to appropriate quality levels.

Figure 5. Manufacturing Readiness Levels for the Design Thread (OSD Manufacturing Technology Program & The Joint Service/Industry MRL Working Group, 2018).

Acquisition Phase		Pre-Materiel Development Decision (Pre-MDD)			Materiel Solution Analysis (MSA)	Technology Maturation and Risk Reduction (TMRR)		Engineering & Manufacturing Development (EMD)		Low-Rate Initial Production (LRIP)	Full-Rate Production (FRP)
Technical Reviews				MDD	ASR	A SRR/SFR	PDR	B CDR	PRR/SVR	C PCA	FRP
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
C - Cost & Funding	C.1 Production Cost Knowledge (Cost modeling)		Cost model approach defined.	Initial cost targets and risks identified. High level process chart model developed. Technology cost models developed for new process steps and materials based on experiments.	Manufacturing, material and special requirement cost drivers identified. Detailed process chart cost models driven by process variables. Cost driver uncertainty quantified.	Prototype components produced in a production relevant environment, or simulations drive end-to-end cost models. Cost model includes materials, labor, equipment, tooling/STE/SIE, setup, yield/scrap/rework, WIP, and capability/capacity constraints.	Cost model updated with design requirements, material specifications, tolerances, IMS, results of system/subsystem simulations and production relevant prototype demonstrations.	Cost model updated with the results of systems/sub-systems produced in a production representative environment, production plant layout and design, and obsolescence solutions.	Cost model updated with results of pilot line build.	FRP cost model updated with result of LRIP build.	Cost model validated against actual FRP cost.
	C.2 Cost Analysis	Identify any manufacturing cost implications.	Cost elements identified.	Sensitivity analysis conducted to define cost drivers and production development strategy (i.e. lab to pilot to factory).	Producibility cost risks and issues assessed. Initial cost model supports AoA and ASR.	Costs analyzed using prototype component actuals to ensure target costs are achievable. Decisions regarding design choices, make/buy, capacity, process capability, sources, quality, KCs, yield/rate, and variability influenced by cost models.	Costs analyzed using prototype system/sub-system actuals to ensure target costs are achievable. Cost targets allocated to subsystems. Cost reduction and avoidance strategies developed. Manufacturing cost drivers for "Should-Cost" model provided.	Manufacturing costs rolled up to system/sub-system level and tracked against targets. Detailed trade studies and engineering change requests supported by cost estimates. Cost reduction and avoidance strategies underway. Manufacturing cost drivers for "Should-Cost" model updated.	Costs analyzed using pilot line actuals to ensure target costs are achievable. Manufacturing cost analysis supports proposed changes to requirements or configuration. Cost reduction initiatives ongoing. Manufacturing cost drivers for "Should-Cost" model updated.	LRIP cost goals met and learning curves analyzed with actual data. Cost reduction initiatives ongoing. Touch labor efficiency analyzed to meet production rates and elements of inefficiency are identified with plans in place for reduction.	FRP cost goals met. Cost reduction initiatives ongoing.
	C.3 Manufacturing Investment Budget	Potential investments identified.	Program/ projects have reasonable budget estimates for reaching MRL 3 through experiment.	Program/ projects have reasonable budget estimates for reaching MRL 4 by MS A.	Manufacturing technology initiatives identified to reduce costs. Program has reasonable budget estimate for reaching MRL 6 by MS B. Estimate includes capital investment for production-relevant equipment. All outstanding MRL 4 risks and issues understood with approved mitigation plans in place.	Program has updated budget estimate for reaching MRL 6 by MS B. All outstanding MRL 5 risks and issues understood with approved mitigation plans in place.	Program has reasonable budget estimate for reaching MRL 8 by MS C. Estimate includes capital investment for production-representative equipment by CDR and pilot line equipment by MS C. All outstanding MRL 6 risks and issues understood with approved mitigation plans in place.	Program has updated budget estimate for reaching MRL 8 by MS C. All outstanding MRL 7 risks and issues understood with approved mitigation plans in place.	Program has reasonable budget estimate for reaching MRL 9 by the FRP decision point. Estimate includes investment for LRIP and FRP. All outstanding MRL 8 risks and issues understood with approved mitigation plans in place.	Program has reasonable budget estimate for FRP. All outstanding MRL 9 risks and issues understood with approved mitigation plans in place.	Production budgets sufficient for production at required rates and schedule to support funded program.

Figure 6. Manufacturing Readiness Levels for the Cost and Funding Thread (OSD Manufacturing Technology Program & The Joint Service/Industry MRL Working Group, 2018).

Acquisition Phase		Pre-Materiel Development Decision (Pre-MDD)			Materiel Solution Analysis (MSA)	Technology Maturation and Risk Reduction (TMRR)		Engineering & Manufacturing Development (EMD)		Low-Rate Initial Production (LRIP)	Full-Rate Production (FRP)
Technical Reviews					MDD ASR	A SRR/SFR	PDR	B CDR	PRR/SVR	C PCA	FRP
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
D - Materials (Raw Materials, Components, Sub-assemblies and Sub-systems)	D.1 Maturity	Material properties identified for research.	Material properties and characteristics predicted.	Material properties validated and assessed for basic manufacturability using experiments.	Projected materials produced in a laboratory environment.	Materials manufactured or produced in a prototype environment (may be in a similar application/program). Maturation efforts in place to address new material production risks for technology demonstration.	Material maturity verified through technology demonstration articles. Preliminary material specifications in place. Material properties adequately characterized.	Material maturity sufficient for pilot line build. Material specifications approved.	Materials proven and validated during EMD as adequate to support LRIP. Material specifications stable.	Materials controlled to specifications in LRIP. Materials proven and validated as adequate to support FRP.	Materials controlled to specifications in FRP.
	D.2 Availability		Material availability assessed.	Material scale-up issues identified.	Projected lead times identified for all difficult to obtain, difficult to process, or hazardous materials. Quantities and lead times estimated.	Availability risks and issues addressed for prototype build. Significant material risks identified for all materials. Planning initiated to address scale-up issues.	Availability risks and issues addressed to meet EMD build. Long-lead items identified. Potential obsolescence issues identified. Components assessed for future DMSMS risk.	Availability risks and issues addressed to meet LRIP builds. Long lead procurements identified and mitigated. Obsolescence plan in place. DMSMS mitigation strategies for components in place.	Availability risks and issues managed for LRIP. Long lead procurement initiated for LRIP. Availability issues addressed to meet FRP builds.	Long lead procurement initiated for FRP. Availability risks and issues managed for FRP.	All material availability risks and issues managed.
	D.3 Supply Chain Management			Initial assessment of potential supply chain capability.	Survey for potential supply chain sources completed.	Potential supply chain sources identified and evaluated as able to support prototype build.	Lifecycle Supply Chain requirements updated. Critical suppliers list updated. Supply chain plans in place (e.g. teaming agreements, etc.) supporting an EMD contract award.	Effective supply chain management processes defined, documented, and in place. Plan developed for predictive indicators. Assessment of critical first tier supply chain completed (i.e., capability, capacity, etc.).	Assessment of critical second and lower tier supply chain completed. Robust requirements flow down processes in place and verified. Supplier compliance with program requirements and changes validated. Plan for predictive indicators for use in production updated. Supply chain adequate to support LRIP.	Long term agreements in place where practical. Prime's supplier management metrics (including thresholds and goals) in place and used to manage risks. Predictive indicators to manage suppliers in place. Supply chain is stable and adequate to support FRP.	Supply chain proven and supports FRP requirements.
	D.4 Special Handling (i.e. GFP, shelf life, security, hazardous materials, storage environment, ESH, etc.)		Initial evaluation of potential regulatory requirements and special handling concerns.	ESH compliance risk identified. List of hazardous materials identified and alternatives evaluated. Special handling procedures applied in the lab. Special handling concerns assessed.	ESH compliance risk mitigated in lab environment. List of hazardous materials updated and alternatives assessed. Special handling procedures applied and disposal procedures evaluated. Special handling requirements identified and analyzed.	ESH requirements and special handling procedures applied in production relevant environment. Special handling requirement gaps identified. New special handling processes demonstrated in lab environment.	ESH requirements addressed and documented. Special handling procedures demonstrated in production relevant environment. Plans to address special handling requirement gaps, risks, and issues complete. Manufacturing assessed for material storage and waste handling risks.	ESH compliance demonstrated in production representative environment. Special handling procedures applied in production representative environment. Special handling procedures developed and annotated on work instructions for pilot line. Hazardous material storage and disposal plan in place for the pilot line.	ESH compliance demonstrated in pilot line production. Special handling procedures applied in pilot line environment and demonstrated in EMD or technology insertion programs. Special handling risks and issues managed for LRIP. All work instructions contain special handling provisions as required. Hazardous material storage and disposal plan evaluated and in place for LRIP.	ESH compliance demonstrated in LRIP. Special handling, and hazardous material storage and disposal procedures demonstrated in LRIP environment. Special handling, and hazardous material storage and disposal risks and issues managed for FRP.	ESH compliance demonstrated in FRP. Special handling and hazardous material storage and disposal procedures effectively implemented in FRP.

Figure 7. Manufacturing Readiness Levels for the Materials Thread (OSD Manufacturing Technology Program & The Joint Service/Industry MRL Working Group, 2018).

Acquisition Phase		Pre-Materiel Development Decision (Pre-MDD)			Materiel Solution Analysis (MSA)	Technology Maturation and Risk Reduction (TMRR)		Engineering & Manufacturing Development (EMD)		Low-Rate Initial Production (LRIP)	Full-Rate Production (FRP)
Technical Reviews				MDD	ASR	A SRR/SFR	PDR	B CDR	PRR/SVR	C PCA	FRP
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
E - Process Capability & Control	E.1 Modeling & Simulation (Product & Process)		Initial models developed, if applicable.	Identification of proposed manufacturing concepts or producibility needs based on high-level process flow chart models.	Production modeling & simulation approaches for process or product are identified.	Initial modeling & simulations (product or process) developed at the component level and used to determine constraints.	Initial modeling & simulations developed at the sub-system or system level, and used to determine system constraints.	Modeling & simulations used to determine system constraints and to identify improvement opportunities.	Modeling & simulations verified by pilot line build. Results used to improve process and demonstrate that LRIP requirements can be met.	Modeling & simulations verified by LRIP build, assist in management of LRIP, and demonstrate that FRP requirements can be met.	Modeling & simulations verified by FRP build. Production simulation models used as tools to assist in management of FRP.
	E.2 Manufacturing Process Maturity		Identification of material and/or process approaches.	Document high level manufacturing processes. Critical manufacturing processes identified through experimentation.	Survey to determine the current state of critical processes completed.	Process Maturity assessed on similar processes in production. Process capability requirements identified for pilot line, LRIP and FRP.	Manufacturing processes demonstrated in production relevant environment. Collection or estimation of process capability data from prototype build and refinement of process capability requirements initiated.	Manufacturing processes demonstrated in a production representative environment. Collection and/or estimation of process capability data and refinement of process capability requirements ongoing.	Manufacturing processes for LRIP verified on a pilot line. Process Capability data from pilot line meets target. Process capability requirements for LRIP and FRP refined based upon pilot line data.	Manufacturing processes are stable, adequately controlled, capable, and have achieved program LRIP objectives. Variability experiments conducted to show FRP impact and potential for continuous improvement.	Manufacturing processes are stable, adequately controlled, capable, and have achieved program FRP objectives.
	E.3 Process Yields and Rates			Initial estimates of yields and rates based on experiments or state of the art.	Yield and rate assessments on proposed/similar processes complete and applied within the AoA.	Target yields and rates established for pilot line, LRIP, and FRP. Yield and rate issues identified. Improvement plans developed/initiated.	Yields and rates from production relevant environment evaluated against targets and the results feed improvement plan.	Yields and rates from production representative environment evaluated against pilot line targets and the results feed improvement plans.	Pilot line targets achieved. Yields and rates required to begin LRIP refined using pilot line results. Improvement plans ongoing and updated.	LRIP yield and rate targets achieved. Yields and rates required to begin FRP refined using LRIP results. Yield improvements on-going.	FRP yield and rate targets achieved. Yield improvements on-going.

Figure 8. Manufacturing Readiness Levels for the Process Capability and Control Thread (OSD Manufacturing Technology Program & The Joint Service/Industry MRL Working Group, 2018).

Acquisition Phase		Pre-Materiel Development Decision (Pre-MDD)			Materiel Solution Analysis (MSA)	Technology Maturation and Risk Reduction (TMRR)		Engineering & Manufacturing Development (EMD)		Low-Rate Initial Production (LRIP)	Full-Rate Production (FRP)
Technical Reviews					MDD ASR A	SRR/SFR	PDR B	CDR	PRR/SVR C	PCA FRP	
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
F - Quality	F.1 Quality Management				Quality strategy identified as part of the AS and included in SEP.	Quality strategy updated to reflect KC identification activities.	Initial Quality Plan and QMS are in place. Quality risks, issues, and metrics have been identified and improvement plans initiated.	Quality targets established. QMS elements (i.e., control of nonconforming material, corrective action, etc.) meet requirements of appropriate industry standards. Program-specific Quality Program Plan developed.	Program-specific Quality Program Plan established. Program Quality Manager assigned. Quality targets assessed against pilot line, results feed continuous quality improvements.	Quality targets verified on LRIP line. Continuous quality improvement on-going. Management review of Quality measures conducted on regular basis and appropriate actions taken.	Quality targets verified on FRP line. Continuous quality improvement on-going. Statistical controls applied where appropriate.
	F.2 Product Quality				Product inspection and acceptance testing strategy identified as part of the AS and included in SEP.	Roles and responsibilities identified for acceptance test procedures, in-process and final inspections, and statistical process controls for prototype units.	KC management approach defined. Initial requirements identified for acceptance test procedures and in-process and final inspection requirements for EMD units. Appropriate inspection and acceptance test procedures identified for prototype units.	Quality data from the production representative environment collected and analyzed and results used to shape improvement plans. Control plans completed for management of KCs. Test and Inspection plans being developed for EMD units.	KCs managed. Measurement procedures and controls in place (e.g. SPC, FRACAS, audits, customer satisfaction, etc.). Pilot line data meets capability requirements for all KCs. Test and Inspection plans complete and validated for production units.	Data from LRIP demonstrates production processes, for all KCs and other manufacturing processes critical to quality, are capable and under control for FRP.	KCs controlled at rate. Results achieve targeted statistical level on all KCs. Results reflect continuous improvement.
	F.3 Supplier Quality/ Management				Potential supplier base quality capabilities and risks identified, including subtier supplier quality management.	Supply base quality capabilities and risks identified, including subtier supplier quality management.	Supply base quality improvement initiatives identified addressing supplier QMS shortfalls, including subtier supplier quality management.	Key supplier QMSs meet appropriate industry standards. Supplier quality data from production representative units collected and analyzed. Strategy for audits of critical supplier processes outlined.	Supplier program-specific QMSs adequate. Supplier products qualification testing and first article inspection completed. Acceptance testing of supplier products adequate to begin LRIP. Plan for subcontractor process audits in place and implemented by prime contractor.	Supplier quality management of KCs and other critical manufacturing processes demonstrates capability and control for FRP. Acceptance testing of supplier products reflects control of quality adequate to begin FRP. Subcontractor quality audits performed as necessary to ensure subcontractor specification compliance.	Supplier quality data reflects adequate management of KCs and control of critical manufacturing processes, including quality management down to subtier suppliers. Results achieve high statistical level (e.g., 6-sigma) on all critical dimensions. Subcontractor quality audits performed as necessary to ensure subcontractor specification compliance.

Figure 9. Manufacturing Readiness Levels for the Quality Management Thread (OSD Manufacturing Technology Program & The Joint Service/Industry MRL Working Group, 2018).

Acquisition Phase		Pre-Materiel Development Decision (Pre-MDD)			Materiel Solution Analysis (MSA)	Technology Maturation and Risk Reduction (TMRR)		Engineering & Manufacturing Development (EMD)		Low-Rate Initial Production (LRIP)	Full-Rate Production (FRP)
Technical Reviews				MDD	ASR	A SRR/SFR	PDR	B CDR	PRR/SVR	C PCA	FRP
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
G - Manufacturing Workforce (Engineering & Production)	G.1 Manufacturing Workforce (Engineering & Production)			New manufacturing skills identified.	Manufacturing skill sets identified and production workforce requirements (technical and operational) evaluated as part of AoA. Availability of process development workforce for TMRR Phase determined.	Skill sets identified and plans developed to meet prototype and production needs. Special skills certification and training requirements established.	Manufacturing workforce skills available for the production relevant environment. Resources (quantities and skill sets) identified and initial plans developed to achieve requirements for pilot line and production.	Manufacturing workforce resource requirements identified and plans developed to achieve pilot line requirements. Plans to achieve LRIP workforce requirements updated. Pilot line workforce trained in production representative environment.	Manufacturing workforce resource requirements identified and plans developed to achieve LRIP requirements. LRIP personnel trained on pilot line where possible. Plans to achieve FRP workforce requirements initiated based on pilot line.	LRIP personnel requirements met. Plan to achieve FRP workforce requirements implemented.	FRP personnel requirements met. Production workforce skill sets maintained in spite of workforce attrition.
H - Facilities	H.1 Tooling/STE/SIE				Tooling/STE/SIE requirements are considered as part of AoA.	Tooling and STE/SIE requirements identified with supporting rationale and schedule.	Prototype tooling and STE/SIE concepts demonstrated in production relevant environment. Requirements development efforts for production tooling and STE/SIE complete.	Design and development efforts for production tooling and STE/SIE initiated with STE/SIE validation plans complete. Manufacturing equipment maintenance strategy developed.	Tooling, test and inspection equipment proven on pilot line and additional requirements identified for LRIP. STE/SIE validated as part of pilot line validation IAW validation plan. Manufacturing equipment maintenance demonstrated on pilot line.	All tooling, test and inspection equipment proven in LRIP and additional requirements identified for FRP. Manufacturing equipment maintenance schedule demonstrated. STE/SIE validation maintained as necessary.	Proven tooling, test and inspection equipment in place to support maximum FRP. Planned equipment maintenance schedule achieved. STE/SIE validation maintained as necessary.
	H.2 Facilities			Specialized facility requirements/needs identified.	Availability of manufacturing facilities for prototype development and production evaluated as part of AoA. Human factors & ergonomics and safety requirements for manufacturing (personnel, processes & equipment) identified.	Manufacturing facilities identified and plans developed to produce prototypes. Human factors & ergonomics and safety requirements for manufacturing (personnel, processes & equipment) assessed.	Manufacturing facilities identified and plans developed to produce pilot line build. Human factors & ergonomics and safety requirements for manufacturing (personnel, processes & equipment) verified in a production relevant environment.	Manufacturing facilities identified and plans developed to produce LRIP build. Human factors & ergonomics and safety practices for manufacturing (personnel, processes & equipment) validated in a production representative environment.	Pilot line facilities demonstrated. Manufacturing facilities adequate to begin LRIP. Plans in place to support transition to FRP. Workplace safety is adequate. Human factors & ergonomics and safety practices for manufacturing (personnel, processes & equipment) demonstrated on a pilot line.	Manufacturing facilities in place and demonstrated in LRIP. Capacity plans adequate to support FRP. Human factors & ergonomics and safety practices for manufacturing (personnel, processes & equipment) demonstrated in LRIP .	Production facilities in place and capacity demonstrated to meet maximum FRP requirements. Human factors & ergonomics and safety requirements for manufacturing (personnel, processes & equipment) demonstrated in FRP.

Figure 10. Manufacturing Readiness Levels for the Manufacturing Personnel and Facilities Threads (OSD Manufacturing Technology Program & The Joint Service/Industry MRL Working Group, 2018).

Acquisition Phase		Pre-Materiel Development Decision (Pre-MDD)			Materiel Solution Analysis (MSA)	Technology Maturation and Risk Reduction (TMRR)		Engineering & Manufacturing Development (EMD)		Low-Rate Initial Production (LRIP)	Full-Rate Production (FRP)
Technical Reviews				MDD	ASR A	SRR/SFR	PDR B	CDR	PRR/SVR C	PCA FRP	
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
I - Manufacturing Management	I.1 Manufacturing Planning & Scheduling				Manufacturing strategy developed and integrated with the AS. Prototype schedule risk mitigation efforts incorporated into the AS.	Manufacturing strategy refined based upon preferred concept. Prototype schedule risk mitigation efforts initiated.	Initial manufacturing approach developed. All system design related manufacturing events included in IMP/IMS. Manufacturing risk, and issue mitigation approach for pilot line and/or technology insertion programs defined.	Initial Manufacturing Plan developed and included in IMP/IMS. Manufacturing risks and issues integrated into mitigation plans. Initial work instructions developed. Effective production control system in place to support pilot line.	Manufacturing Plan updated for LRIP. All manufacturing risks and issues identified and assessed with approved mitigation plans in place. Work instructions finalized. Effective production control system in place to support LRIP.	Manufacturing plan updated for FRP. All manufacturing risks and issues managed. Effective production control system in place to support FRP.	All manufacturing risks and issues managed.
	I.2 Materials Planning				Technology development article component list developed with associated lead time estimates.	Make/buy evaluations initiated and include production considerations for pilot line, LRIP, and FRP needs. Lead times and other materials risks and issues identified.	Most material make/buy decisions complete, material risks and issues identified, and mitigation plans developed. BOM initiated.	Make/Buy decisions and BOM complete for pilot line build. Material planning systems in place for pilot line build.	Make/Buy decisions and BOM complete to support LRIP. Material planning systems proven on pilot line for LRIP build.	Make/Buy decisions and BOM complete to support FRP. Material planning systems proven in LRIP and sufficient for FRP.	Material planning systems validated on FRP build.

Figure 11. Manufacturing Readiness Levels for the Manufacturing Management Thread (OSD Manufacturing Technology Program & The Joint Service/Industry MRL Working Group, 2018).

A.2 Detailed cost price analysis

Chaine de valeur Polyester - Coton : route RECYCLAGE MECANIQUE — HOSP_OPTI_2 — CV2

TENUES HOSPITALIERES FIN DE VIE PROVENANCE: LAVOIRS INDUSTRIELS	coût/kg	matière vierge euro/kg	in kg	out kg	perte matière	coût total	
fibre vierge en 100% PES en balle		1,05 €					matière vierge est la fibre polyester à 100%
fibre vierge en 100% COTON en balle		1,50 €					coton normal, pas de biocoton
tenue hospitalière en fin de vie	**0,00 €**						prix à l'enlèvement du déchet
mise en balle/manipulation	0,10 €						pas de collecte ni tri , enlèvement matière lavoir industriel
tri	0,00 €						pas de collecte ni tri , enlèvement matière lavoir industriel
transport > délissage	0,05 €		100,00	100,00		15,00 €	
délissage	0,32 €		100,00	87,00	-13,00%	32,00 €	rythme de délissage au prix carcéral
transport > effilochage	0,05 €		87,00	87,00		4,35 €	
éffilochage	0,25 €		87,00	73,95	-15,00%	21,75 €	offre effilochage industriel; Laroche indique une perte en matière de 15% lors de l'effilochage
transport > filature	0,05 €		73,95	73,95		3,70 €	
cardage/épuration	0,15 €	0,15 €	73,95	53,98	-27,00%	11,09 €	perte de matière due à la réduction en poussière du coton (67 kg sur 246 kg = 27 %)
						87,89 €	la matière zffilochée continet quasiment que du polyester
valeur entrée filature OE/ kg	100% PES vierge	1,20 €				1,63 €	car il appert que la portion de coton après éffilochage est minimale
	100% coton vierge	1,65 €					avec des propriétés techniques quasi nulles
							donc on rajoute exclusivement du coton vierge en filature

	25,00%	RETEX effiloché	1,63 €	25,00%	RETEX effiloché	1,63 €
	25,00%	IW PES	€ 0,30	25,00%	RPET	€ 1,30
	17,00%	R-Pet	€ 1,30	17,00%	RPET	€ 1,30
	33,00%	virgin coton	1,65 €	33,00%	virgin coton	1,65 €
recycled fiber cost price		**1,25**	**euro/kg**		**€ 1,50**	**euro/kg**
virgin cost price		**1,35 €**	**euro/kg**		**€ 1,35**	**euro/kg**
DELTA		**7,49%**	**euro/kg**		**-11,05%**	**euro/kg**

enlèvement à euro/tonne	DELTA IW PES	DELTA RPET	prix fibre RPET euro/tonne	DELTA IW PES	DELTA RPET
-300,00 €	17,79%	0,75%	800,00 €	13,79%	4,52%
-100,00 €	10,92%	-7,62%	1.000,00 €	11,27%	-1,71%
0,00 €	7,49%	-11,05%	1.300,00 €	7,49%	-11,05%
100,00 €	4,05%	-14,49%	1.500,00 €	4,97%	-17,28%
300,00 €	-2,81%	-21,35%	1.900,00 €	-0,08%	-29,74%

je dédie ma redevance au recyclage et pas à l'incinération			
VL	170,00 €	13,33%	-5,21%
WAL	165,00 €	13,15%	-5,38%
FR	115,00 €	11,44%	-7,10%

Figure 12. Cost price analysis end-of-life hospital work clothes (Centexbel, 2020).

Chaine de valeur 100% Coton : route RECYCLAGE MECANIQUE CV4

DECHETS INDUSTRIELS

	coût/kg	matière vierge euro/kg	in kg	out kg	perte matière	coût total	
fibre vierge en 100% COTON		1,50 €					
déchets industriels	0,10 €		100,00	100,00		10,00 €	prix enlèvement déchets ex salle de coupe , non lavés
collecte	0,00 €		100,00	100,00		0,00 €	
tri/manipulation/emballage	0,10 €		100,00	100,00		10,00 €	manipulation et emballage des déchets industriels
transport > délissage	0,00 €		100,00	100,00		0,00 €	il n'y pas de délissage
délissage	0,00 €		100,00	100,00	0,00%	0,00 €	il n'y pas de délissage
transport > effilochage	0,05 €		100,00	100,00		5,00 €	
éffilochage	0,25 €		100,00	85,00	-15,00%	25,00 €	perte matière optimale: Laroche indique 15% lors de l'effilochage
transport > filature	0,05 €		85,00	85,00		4,25 €	
cardage/épuration	0,15 €	0,15 €	85,00	51,00	-40,00%	12,75 €	40% de perte de matière lors de l'épuration, basés sur tests RETEX 100%CO
						67,00 €	
valeur entrée filature OE/ kg						1,31 €	
	100% coton vierge	1,65 €					

25,00%	RETEX effiloché	1,31 €
0,00%	IW PES	€ 0,00
0,00%	R-Pet	€ 0,00
75,00%	virgin coton	1,65 €

mixed fiber cost price	**1,57**	**euro/kg**
virgin cost price	**1,65**	**euro/kg**
DELTA	**5,10%**	

enlévement à euro/tonne	DELTA %	prix coton vierge euro/kg	DELTA %
-300,00 €	16,98%	0,80 €	-9,57%
-100,00 €	11,04%	1,00 €	-3,56%
0,00 €	8,70%	1,20 €	0,67%
100,00 €	5,10%	1,50 €	5,10%

Figure 13. Cost price analysis of pre-consumer cotton textiles (Centexbel, 2020).

A.3 Interview guide

1. Description of the master's thesis

This interview is part of a master's thesis for the master Innovative Textile Development at the Saxion University of Applied Sciences. I am researching the mechanical recycling of post-consumer textile waste garments, particularly the cotton/polyester mixed textile waste. First, I am researching the current challenges that hinder the mechanical recycling processes of post-consumer textile waste. More importantly I am seeking for new innovations/solutions/opportunities that could enable a more efficient closed-loop mechanical recycling of mixed textile waste. I am looking at the technical ameliorations, for example the different machines used in the recycling processes, the logistical solutions, for example the set-up of a circular supply chain management, and economical and environmental benefits due to the amelioration of the mechanical recycling processes. This master's thesis' research has started by looking at the results of the Interreg RETEX project, where EuraMaterials has been one of the leading partners. After looking at the results of the RETEX project, this master thesis researches the bottlenecks of mechanical recycling that could not yet be integrated during the project. This master thesis investigates how the results of the RETEX project could were ameliorated, what could be done differently when a new mechanical process project would be started.

1.1. Aim of the master's thesis

I am investigating the challenges that hinder the improvement of the closed-loop mechanical recycling processes of post-consumer textile waste and the possible innovations/changes that could possibly help overcome these barriers and enable a higher recycling rate of mixed post-consumer waste fabrics.

2. General questions

- Would you have a problem with me publishing the content of this interview in my master's thesis?
- Would you want me to put some parts of this interview as confidential?
- What is your current function?
- For which company do you work for or research for?
- What is the current project or research on mechanical recycling of textile waste that you are working on?

3. Discussion on challenges and solutions

- Based on your work or research work, which challenges do you see hindering the mechanical recycling processes of post-consumer textile waste?
- Do you see any technical, logistical, economical or environmental challenges?
- What are the most important factors to achieve an efficient mechanical recycling of post-consumer textile waste?
- How could we ensure a 100% recycling of cotton/polyester mixed textile waste garments?
- Which changes/solutions do you think would be suited to improve these recycling processes and the separation of cotton/polyester blended textiles?
- How could we ameliorate the mechanical recycling process of post-consumer textile waste, looking at technical, logistical, economic and environmental point of view?

4. Discussion on the setup of a circular supply chain for the production of circular textiles

- How would you start the set-up of a supply chain with shredded textile waste fibres?

The colour coding that has been used for the analysis of the interviews:

xxxxxxxx Challenges

xxxxxxxx Opportunities

xxxxxxxx Roadmap

A.3.1 Interview Cathryn Anneka Hall

Function: Founder of Anneka Textiles and PhD researcher in the field of Textile Recycling.

Company: University of the Arts London.

Date: September 21, 2020.

After introducing myself, the master thesis and the description of the master thesis:

… (Margot) I have heard you speak at the webinar Design for mechanical textile recycling on the 20/04/2020.

(Cathryn) I will run over the most important conclusions of the webinar once more. The post-consumer textile waste is sorted depending on whether it is to be reused, re-made/manufactured, or recycled. Re-use is just the re-use of the garment in its original form. Re-making/manufacturing can be done in a number of ways but usually the outcome (in textiles) is only a one-time use before disposal such as such as creating new products like a wiper cloth from the garments. Recycling, this is my area of expertise specifically mechanical recycling. Generally, there are three routes of mechanical recycling it can take:

1. Recycling into high-value product applications, such as wool recycling in Prato, Italy.
2. Recycled into mid/low value product application, such as aid/relief blankets (India).
3. Recycled in low value applications such as insulation material and moving sheets (examples in the UK and across Europe).

I will give you an insight in my PhD work. I have done field research in Prato Italy where I have investigated wool recycling. The recycled wool is often certified that it is produced in Prato, contains a minimum of 65% recycled wool and is evaluated while performing an LCA analysis.

(Margot) How does the mechanical recycling supply chain look like?

(Cathryn) The post-consumer textile wool waste fabrics are sorted, mutilated and pulled (shredded). The recycled wool fibres are then blended, carded and spun. The manufacturing of yarn is thereafter possible, by knitting and weaving the recycled fibres into a fabric. The sorting process is as follows: The input of textile waste garments is sorted into woven and knitted fabrics, then sorted by colour, then sorted by shades of colour, thereafter, sorted in fine knits or ordinary knits. In the end, the sorters look if the garments are clean before shredding. The colour separation is very important to ensure a high-quality recycled fibre. The colour of the fabrics is investigated, to see if overdyeing is needed. Then the blending is done for the recycled fibres. The recycled wool fibres can be mixed with acrylic fibres, or the colours can be blended to obtain new colour ranges. Then the fibres are spun and knitted to obtain a fabric. Weaving has proven to be a better option to integrate short fibres in a tight fabric than knitting.

(Margot) How do you see the future for circular textiles?

(Cathryn) We could apply a Design for Recycling. When Design for Recycling we currently have two options retaining mono material or design for disassembly. However, it is very difficult to obtain a closed-loop recycling process when we consider the types of materials entering our recycling systems which are formed of blend and require a lot of sorting and cleaning. We could cascade our textiles into a variety of different uses. If recycling is to be a vital part of the circular economy, it is very important to understand these systems and process so we can design for them. Design for

recyclability is vital when designing new product applications this is even more important when designing using mechanically recycled textile waste fibres. In the future, I can see a time when both mechanical and chemical recycling process could work together to create efficient recycling of post-consumer textile waste garments.
(Margot) Which challenges do you currently see for the mechanical recycling process for post-consumer textile waste garments?
(Cathryn) Microfibres are a great challenge when it comes to the mechanical recycling of post-consumer textile waste garments, we do not know how much microfibres are released when a new textile is manufactured from recycled textile waste fibres and washed. We do not know what to do with this problem when producing post-consumer textile waste yarn. Blending the mechanically recycled fibres with virgin fibres needs to be done to obtain a good quality level, mechanically recycled fibres cannot be used as mono material in a new recycled yarn. The biggest challenge of mechanical recycling is the fact that we do not know the composition of the fibre materials of the textiles.
(Margot) And which new opportunities would you consider if the mechanical recycling of post-consumer textile waste would be improved?
(Cathryn) To enable a more efficient mechanical recycling process, an automated sorting process is needed. The more precise the textile waste garments are categorized during the sorting process, the higher the quality of the recycled fibres will be, due to the fact that the textile waste garments will be categorized into mono-materials categories. Currently this technology is being developed but, in the future, this could be the reality of sorting textiles for recycling. In addition to good sorting, we could also start recycling the blended fibres together. There is no reason this cannot be done we just need to be able to design the fibres that are produced into useful products. The challenge is to keep the quality of the recycled fibres high and to increase the quality. We have seen lots of small projects which demonstrate that recycling with the tricky post-consumer waste is possible but these need to be scaled up. One of the solutions for the future is considering how the mechanical and chemical recycling systems could work together. For example, blending the mechanically recycled cotton fibres with virgin cotton, or with recycled polyester or Tencel or lyocell. Cotton is a cellulosic material that has the advantage of the possibility of being mechanically and chemically recycled. This is similar to a lyocell or Tencel material. A future yarn could be manufactured from a mix of recycled post-consumer cotton and chemically recycled material. This way the mechanical and chemical recycling processes would be combined to obtain a new recycled waste yarn.

A.3.2 Interview Anita de Wit

Function: Founder.
Company: ReBlend.
Date: September 29, 2020.

After introducing myself, the master thesis and the description of the master thesis:

… (Anita) I have had many troubles while starting with the production of interior textiles using mechanically recycled textile waste fibres. The interior textiles market is difficult to enter.
(Margot). Tell me more about your textiles production.
(Anita) I have started the production of circular interior textiles by looking at the collected post-consumer textile waste garments in the Netherlands. I looked up the Dutch spinning factories and started the discussion on spinning textiles made from recycled textile waste fibres. I see the interest in circular textiles growing in the Netherlands. We were able to realise an interior textile manufactured from 70% recycled post-consumer textile waste garments from Dutch

households, combined with 30% recycled polyester yarn.

(Margot) How is your supply chain set-up?

(Anita) The post-consumer textile waste garments are sorted into several colour categories, hand sorted at the sorting facility of Sympany. Mostly cotton wasted garments are sorted; a high percentage of cotton material is needed to ensure a good quality level. Then the garments are shredded in a factory in Spain. Thereafter, the mechanically recycled fibres are mixed with recycled polyester yarn. They are mixed in a blowing room. Then they are spun at the Spanish Hilaturas Ferau factory.

(Margot) What do you think about the current integration of mechanically recycled fibres?

(Anita) The Dutch textiles and apparel market is not ready yet for an integration of mechanically recycled textile fibres. The mechanical recycling process is currently at a starting pilot phase in the Netherlands. The production of circular textiles could be scaled up to industrial scale, as the sorting process. Currently the market demand for mechanically recycled fibres is not big enough to scale up the production. The Dutch government should have more focus to support the market development. Just supporting technology is not enough. There will always be a problem of economies of scale. The market itself will not change as long as prices for recycled fibres are more expensive since the market is not comparable.

(Margot) Tell me more about your current projects

(Anita) I am currently researching the production of textiles manufactured from 70% post-consumer textile waste, combined with 30% Tencel or lyocell instead of recycled polyester. This is a very soft yarn that can be used for the manufacturing of denim fabric and towels.

A.3.3 Interview Remi Veldhoven

Function: mechanical recycling supply chain manager, textile engineer.

Company: Wolkat.

Date: October 1, 2020.

After introducing myself, the master thesis and the description of the master thesis:

… (Margot) Tell me more about how the circular supply chain of Wolkat is set-up and how your mechanical recycling process looks like.

(Remi) We have a site in Tilburg, but the production site is in Morocco. The post-consumer textiles are collected and sorted. Thereafter, the waste garments are sent to the production site in Morocco where they are shredded, and respun in yarn to produce new textiles manufactured from mechanically recycled post-consumer textile waste garments.

(Margot What is according to you the current state of the mechanical recycling process?

(Remi) The mechanical recycling process is further developed than chemical recycling. We have seen that the challenge of the Fibresort machine is the fact that it can only recognise the textile fabrics that are made out of 1 kind of fibre material. It is not very accurate for mixed textile waste garments.

(Margot) What are according to you the current challenges of the mechanical recycling process for post-consumer textile waste garments?

(Remi) The challenge of mechanically recycling post-consumer garments is the required steps of removing the zippers and the fact that the textiles than need to be sorted by colour. The textile waste garments are sorted by fibre material type. The garments in Morocco are shredded, spun into yarns and woven into new textiles. The several kind of fibre categories are knitted garments, fabrics with high a percentage of acrylic and denim garments. A major challenge of mechanically recycling post-consumer textile waste garments is the fact that the fabrics result in short fibres that are difficult to respun. Another challenge is the fact that the sorting process of textile waste garments happens manually, thus increasing the price of the mechanically recycled fibres.

(Margot) And what could be new opportunities for the mechanical recycling process?

(Remi) The entire mechanical recycling supply chain could be made more efficient by using an automatic sorting machine that categorises the textile waste garments into fibre type material. At Wolkat we are successfully producing interior fabrics manufactured from mechanically recycled textile waste fibres. We need to ameliorate the spinning machines that can spin more effectively mechanically recycled short textile waste fibres. We need to be able to spin fine yarns manufactured from mechanically recycled textile waste yarns. Thus, we need to improve the technical process of mechanically recycling post-consumer textile waste garments. What we would need is a European law system as the Extended Producer Responsibility. We would also need to have a global recycling standard. We need measures that would enable mechanical recycling supply chains on a European scale. It needs to be less expensive for textile manufacturers to integrate mechanically recycled textile waste fibres in their supply chain. We can currently not produce enough textiles manufactured from mechanically recycled textile fibres to foresee the demand for circular textiles.

A.3.4 Interview Anton Luiken

Function: mechanical recycling expert, owner of Alcon Advies B.V., co-founder REMOkey, member of the knowledge circle of the professorship Sustainable and Functional Materials (Professor Jan Mahy)
Company: Alcon Advies BV., Saxion University of Applied Sciences.
Date: October 2, 2020.

After introducing myself, the master thesis and the description of the master thesis:

… (Margot) What are your thoughts on the current available yarns manufactured from mechanically recycled post-consumer textile waste fibres.

(Anton) The new mix of ReBlend for example, could be a solution for manufacturing a new yarn with these fibres. I see that it is difficult to find a market for the bulk of mixed cotton/polyester textile waste garments.

(Margot) What needs to be achieved to enlarge this potential market?

(Anton) An automated sorting machine is needed to improve the sorting process of post-consumer textiles. A good sorting process is essential to be able to get high-quality recycled fibres in the end. The Fibresort machine needs to be improved. We need to sort textiles by fibres material and colour, but also by structure and type of finish. Secondly, we need to look at the spinning mills in the Netherlands and Europe, look at their spinning skills and together look at how to spin recycled fibres. The shredding or unravelling process is also important in keeping a high-quality standard. We should need to improve the process, that it does not damage the quality too much. Denim is now mostly used as material source for the mechanical recycling process, due to the fact that the quality of the fibres can be sustained. Denim is a relatively easy source of material due to the fact that you can sort it quite easily from other textile fabrics at the collection site. Besides, the shredding can be adapted to the characteristics of the denim garment, we are not able to do that for other kinds of garments as these are not so uniform compared to denim. Another important factor is the fact that the mechanically shredded post-consumer waste fibres need to correspond to the fibres that can be spun at the spinning mill. This is why, we need an extra process step between the shredding and spinning stage (what that step could be is not clear), or we need an extra step at the spinning mill to prepare the fibres to be spun. Thus, the logistics between the several partners is of utmost importance. The coordination between the different steps is key to ensure an effective mechanical recycling process. In Prato, they have shown a very good example of an effective circular supply chain management. The recycled wool fibres can effectively be integrated in new production lines and the recycled fibres have proven to be profitable. The wool recycling hub of Prato had proven to be successful in the set-up of the mechanical recycling process on an industrial scale. To be able to set-up such a circular supply chain management for cotton and polyester clothing is much more difficult. I do not think that it is presently possible to effectively recycle polyester garments into new polyester garments. The process has not proven to be effective yet, this is why they use polyester bottles to manufacture recycled polyester yarns. The process of polyester textile recycling could become reality with the use of a chemical recycling process. Such a production line could be set-up for wasted cotton garments, if the price of virgin (organic) cotton is quite high, the price of mechanically recycled cotton fibres could level this cost price. We should set-up mechanical recycling processes for post-consumer textile waste garments where possible. We should focus on improving the several mechanical recycling steps to obtain higher quality fibres that can effectively be integrated into production lines of the textiles industry. The new SaXcell chemical recycling process and the Tencel/Refibra & lyocell fibres can complement the use of mechanical recycling fibres.

(Margot) How do you think the improvements of a circular supply chain can have an influence on this development?

(Anton) The set-up of a network is crucial for an effective mechanical recycling process. Circular supply chains need to be set-up, whereby the logistics costs need to be calculated. The sorting process needs to be improved as well as an improvement in the shredding process. If we could achieve those improvements the mechanically recycled fibres can be profitable. If, for instance, Frankenhuis and Minot could obtain a higher quality shredded fibre, new opportunities will emerge. We need to sort better, shred better and enable a greater capacity of the machines. To obtain a better-quality level of the mechanically recycled post-consumer textile waste fibres we need to look at technical changes to be able to obtain the same quality as pre-consumer waste fibres. We need to change the mechanical recycling processes into the cycle: sorting, cutting, sorting, shredding, spinning, weaving. If the quality of the new yarn can be ensured, then there will be no problems with the weaving, thus much more product applications will emerge. Spinning is thus the crucial process step for the level of quality. Only then we could enable a fully closed-loop mechanical recycling process. I have seen that the market is ready for the integration of the recycled fibres. The demand from consumers will only grow in the near future. We need to look for ways to get the production of textiles back to the Netherlands or France.

A.3.5 Interview Pierre van Trimpont & Daniël Verstraete

Function: mechanical recycling experts, researchers in the field of textile waste recycling.

Company: Centexbel.

Date: October 8, 2020.

After introducing myself, the master thesis and the description of the master thesis:

… (Margot) What were your thoughts on the results of the RETEX project?

(Pierre & Daniël) The success of the RETEX project lies in the set-up of three different circular supply chains. Through these value chains we could investigate the benefits for the textiles industry by looking at the technical project results. The profitability of the fibres haven been researched after performing many tests to improve the mechanical recycled fibres. Utexbel could spin yarn while using the mechanically recycled fibres (end-of-life clothing from hospitals).

While performing the mechanical recycling processes and analysing the mechanically recycled fibres by performing several tests, we can conclude the most important factor to obtain high-quality mechanically recycled fibres is the sorting process of wasted fabrics by colour and the homogeneity of the textile waste fabrics in fibre materials. We have seen that the shredding machine performed during the mechanical recycling process is often too aggressive to maintain long and high-quality fibres (they result in very short fibres). Improvements of the machines of the several mechanical recycling processes is needed to be able to obtain longer fibres after shredding. The spinning stage is crucial for the resulting quality of the recycled fibres yarns. A solution would be to, during the shredding process, to shred less aggressively and less fast. Thus, important factor for the recycled fibres quality is the length of the recycled fibres, important for the spinnability of the fibres. Second, the sorting process of textile waste garments at the sorting site is very important for the resulting quality of recycled fibres, the fabrics need to be sorted by colour, structure/texture and fibre material. This process could be completely automated.

(Margot) How did the mechanical recycling processes go during the RETEX project

(Pierre & Daniël) In the RETEX project we had a homogenic material source of mixed cotton/polyester clothing fabrics, coming from hospitals. Besides, we see that tons of textile waste garments come from the industrial washing laundries which could be exploited in the same way. Regarding the rentability of the mechanical recycled fibres, the profitability of the industrial waste scraps (pre-consumer) has a higher potential in becoming rentable compared to post-consumer mixed cotton/polyester garments. In the near future the garments manufactured for the fashion industry should need to become homogenic in fibres materials, in best cases mono-materials, to be designed for disassembly and recyclability. Currently the unsold garments of big retailers are thrown away at landfill, there is a huge potential for new material sources for the mechanical recycling process. To obtain good quality 100% cotton fibres we should need to start with industrial textile waste scraps, because they have the best quality, they are unwashed cotton (and have almost the same quality as virgin cotton fibres). The garments that come from the industrial washing have been damaged due to the aggressive washing processes. When these garments have been washed multiple times, the present cotton turns into dust in the shredding stage. There is thus a huge material loss when shredded. The hospitals work garments used during the RETEX project, had a composition of 33% cotton and 66 % polyester, and the cotton part turns completely into dust. Due to the fact that the mechanical recycling process is not completely closed loop, it severely diminishes the rentability of the recycled fibres. The cotton that is so severely damaged by the industrial washing processes, now recycled by Frankenhuis into briquettes, could be chemically recycled by projects like SaXcell because the lengths of the fibres are so short.

(Margot) What about the profitability of the mechanically recycled waste fibres, for the 100% cotton and the cotton/polyester supply chains?

(Pierre & Daniël and information from latest RETEX results added to this information) Regarding the cotton/polyester supply chain, the sliver cost price containing 67% recycled polyester fibres ends up at 1,25 euro/kg. The influence of the logistic costs is quite high, 3 to 5%. This is due to the fact the several mechanical recycling processes are all at different sites. These costs have been calculated through the use of several economical modulation programs, where economical business models have been added. The cost price for the virgin cotton/polyester sliver would be 1,35 euro/kg, compared to its recycled cotton/polyester fibres of 1,25 euro and thus rentable in a new production line with a gross margin of 7,49%. If all the mechanical recycling machines of the several processes could be aligned in the same room, in an ideal situation, the marge of the recycled cotton/polyester fibre could improve from 7 % to 11%, which would thus increase the profitability of the mechanical recycling. One of the major conclusions of the RETEX project regarding the profitability of the recycled fibres, is the fact that the price that the fashion brands need to pay for the process of incinerating the end-of-life garments, are potentially higher than the price that the company needs to pay for the costs of mechanical recycling. Thus, this could enable the fact that the mechanical recycling process is profitable for a fashion or interior brand that has left-over material, unsold garments but also industrial waste scraps, instead of bringing the fabrics to incineration. This due to this rentability, new markets could emerge for mechanically recycled textile waste fibres. The recycling of homogenous industrial textile waste scraps or end-of-life garments from industrial laundries thus yield to positive margins and the profitability of the recycled waste fibres. Second, looking at the profitability of the mechanically recycled fibres from the 100% cotton production scraps, they proven to be profitable. The sliver cost price containing recycled cotton fibres, with the analyse of several economic models, lies between 1,57 and 1,87 euro/kg. Compared to the sliver cost price containing only virgin cotton fibres of 1,65 euro/kg, the best-case scenario of having a cost price of 1,57 euro would thus make the recycled cotton fibres originating from industrial scrap material profitable. The recycled fibres would have a gross margin of 5,1 %. Same as for the cotton/polyester fibres, if the fashion and interior textiles companies would send their left-over fabrics to the recycler instead of incineration, the marge of the recycled cotton/polyester fibres would be enlarged, thus increasing the rentability of the fibres. The fashion or interior brand needs to pay around 150 euro per ton for their fabrics to go to incineration, the costs of the mechanical recycling process is near 300 euro for one ton of unsold garments. The mechanical recycling process is thus feasible, profitable and more importantly, could be applied in the industry right now.

A.3.6 Interview Julie Lietaer

Function: researcher in spinning post-consumer textile waste fibres, co-CEO.
Company: European Spinning Group.
Date: February 17, 2021.

After introducing myself, the master thesis and the description of the master thesis:

… (Margot) What are your current developments on spinning post-consumer textile waste fibres?
(Julie) It is difficult to spin yarns with fibres of short lengths. For the open-end spinning process, we need to have a minimum of 30 – 40 mm lengths.
(Margot) What are your current biggest challenges?
(Julie) We now face the challenge that there is a lack of recyclable textile waste garments. We use pre-consumer textile waste fabrics. The sorting of colours of garments is not a problem, the shredding machine is the problem. We need a flexible shredding machine that can adapt to the several sorts of textile waste fibres, which would improve the quality of the fibres that we can thereafter spin. In the supply chain we need to look at the availability of the several machines. We need to go to a system where we can shred smaller volumes of textile waste garments. Just like at the CETI pilot scale mechanical recycling process, where they have pilot scale to semi-industrial scale machines that can effectively shred small volumes of textile waste garments. More flexibility with the shredding and carding machine results in better quality fibres and profitable fibres. Or we need to go to a system just like Recover does, they sort and shred the garments at one site by themselves, thus they control the quality of the fibres by sorting themselves.
(Margot) What do you think about the recycling hubs idea?
(Julie) What would help is, what we are doing right now, setting up a b2b platform where you could connect distributors, spinners, partners from all around the industry to set-up together supply chains. You could say on the platform that you have 2000 pieces of clothing leftover and see who could do and want to do something with it. This automatic matchmaking tool could be used in a recycling hub.

A.3.7 Interview Liset Pander

Function: spinning researcher post-consumer textile waste fibres.

Company: Texperium.

Date: February 25, 2021.

After introducing myself, the master thesis and the description of the master thesis:

… (Margot) What are your current developments on spinning post-consumer textile waste fibres?

(Liset) We are currently open-end spinning post-consumer textile waste fibres. We see the biggest challenge during the spinning process is the differences between the fibres, there is difference in short/long, opened/unopened, fine/coarse fibres. Due to pollution between the fibres, they break easily. We need to have an extra pre-treatment step to filter the impurities of the fibres. The sorting phase is very important for the quality of the fibres. It depends on the machine, but we with suction we can filter the fibres shorter than 5 mm.

(Margot) What would you advise to do with 5 mm too short fibres?

(Liset) They go to the paper industry and nonwoven industry. But when they are shorter than 0,5 cm they are sometimes incinerated.

(Margot) What do you think about the idea of a recycling hub?

(Liset) We need to standardize the European quality level for post-consumer shredded textile waste fibres. Only then the European market for textile production could compete with the Chinese market. The European textiles market is getting stronger. The Dutch market is too small to handle a lot of post-consumer textile waste garments. And we do not have enough post-consumer textile waste garments. We are in a phase where knowledge sharing is more important, because we are in a starting phase, but you will still get competition in cost price.

(Margot) What would you do in a roadmap for the future?

(Liset) We are talking too much; we need more action! We need new business models to help the market. We need a shredder machine that can provide shredded fibres of an improved quality. To be able to scale up the production of spinning mills that can spin post-consumer textile waste garments. If you give a good example, more people will follow, so we need more spinners of post-consumer textile waste garments that give an example. The difference in quality of shredded textile waste fibres is too big, we need to align the quality of the fibres.

A.3.8 Interview Carlos Rico

Function: Shredding expert post-consumer textile waste garments.

Company: Recover.

Date: February 19, 2021.

After introducing myself, the master thesis and the description of the master thesis:

… (Margot) What are your current developments on spinning post-consumer textile waste fibres?

(Carlos) In the spinning mill of Hilaturas Ferau we are able to spin post-industrial waste fibres but also post-consumer textile waste fibres. We are looking at improving the quality of the post-consumer textile waste yarn. We have a new spinning machine that increases the possibilities for post-consumer textile waste fibres because we can make adjustments with the machine according to the fibres. The knowledge of the company is thus very important to make adjustments on the machine. We can ring spin post-consumer textile waste yarns, in the past only rotor.

(Margot) What do you see as technical and logistical challenges for Recover?

(Carlos) Our main issues are logistics. The logistics of collection are not easy, when we collect the clothes we sort and recycle them ourselves. One of our main issues is the lack of volumes of post-consumer textile waste garments. The volumes are not so big, and we sort the items by colours, so we need a lot of items to produce one kind of yarn. A big challenge with sorting is the fact that special sorting is too expensive. A second issue is the analyse of which fibre could be obtained with a specific textile waste garment. We need to make tests with the spinning mill, the challenge is that we need to make a lot of tests for each specific textile waste sort. Our third challenge is to be able to sell the fibres. It is an expensive process! The fibres gain in profitability if the companies bring their own textile waste garments (for example unsold clothes). Sometimes we accumulate different textile waste sorts to make the fibres profitable. We see that for big brands like Patagonia the high-cost price is not a problem. Our fourth challenge is the improvement of the supply chain. Very big brands have already their own supply chains, it is difficult to work together and set-up a supply together with their partners.

(Margot) What do you think will change in the future?

(Carlos) I foresee that due to the fact that Spain will enter an EPR for 2025, which will give us more post-consumer textile waste garments. We are looking at how to improve the quality of the shredded textile waste fibres. With the rotor and ring spinning we can now get up to 75% recycled post-consumer content. We are looking at how to improve the shredding process. The cutting speed could be lowered, as the amounts of tambours and lower the amount of spikes. I am also looking at changing the angle of the tambours during shredding.