



IMPROVING DUTCH POST-CONSUMER TEXTILE RECYCLING

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**A multi-criteria analysis of Scandinavian
downstream mixed textile recycling
techniques for suitable application in the
Dutch context**

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Improving Dutch post-consumer textile recycling

A multi-criteria analysis of Scandinavian downstream mixed textile recycling techniques for suitable application in the Dutch context

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Disclaimer

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1 List of abbreviations

DMTR	Downstream Mixed Textile Recycling
DTR	Downstream Textile Recycling
MCA	Multi-Criteria Analysis
PC	Post-Consumer

2 Abstract

The fast fashion industry has experienced an ever-increasing growth. Increased awareness of the negative environmental consequences has led to the belief that the current economy, and more specifically the textile industry, has to become more circular. This includes recycling of Post-Consumer (PC) textiles to avoid incineration of garments. The Netherlands has already started to manage PC textiles and tackle the issue by introducing textile collection on a municipal level. However, the textile recycling industry in The Netherlands can be improved and PC textile collection and sorting organizations such as Sympany still face major bottlenecks. Sweden, Finland, and Norway, referred to as Scandinavia, are on the frontline of textile recycling processes. Therefore, this research aims to select Downstream Mixed Textile Recycling (DMTR) processes in Scandinavia and evaluate their respective suitability in the Dutch context. The selected processes concern the recycling of PC textiles that have blended fabrics.

The Re:newcell and OnceMore techniques are two promising recycling processes respectively developed by the Swedish companies Re:newcell and Södra. Re:newcell transforms PC textiles into cellulose sludge that is then dried to create pulp called Circulose. Whereas OnceMore depolymerizes or dissolves the polyester and cotton in PC textiles to extract these from the polycotton blend and produce cellulose pulp.

To assess the potential performance of Re:newcell and OnceMore in the Dutch context, the two processes are analysed through a multi-criteria analysis using indicators categorised in four pillars: technological, environmental, social and economic. Both DMTR techniques are evaluated using qualitative and quantitative indicators to determine the efficiency of the DMTR techniques and their implementation. The indicators are direct carbon footprint of technique, specific energy consumption, emission of dangerous substances, efficiency, profitability, circularity, and operational water footprint.

Re:newcell appears to be the best option out of the DMTR processes selected in this research. It is realizable for Sympany to adapt its sorting process and deliver cellulose-rich and pure textiles as input for Re:newcell. However, the Dutch sorting processes require to be upscaled to increase efficiency. Moreover, the government's objective to improve the textile recycling industry in The Netherlands is a positive driver for the introduction of innovative DMTR processes in the next few years. It would open a market for sorting organizations such as Sympany to locally collaborate with.

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4 Introduction

The textile industry is the second most polluting industry today (Ross & Morgan, 2015), as a consequence of the fast-fashion model. Fast fashion is based on the consumption and production of large amounts of cheap clothes of low quality (Grag, 2019). These low-quality clothes are quickly replaced due to continuously changing trends and because they tear apart easily. Between 2010 and 2015, the yearly clothing sales have doubled and clothing utilisation, which is the number of times a garment is worn, has dropped from 200 to around 160 times (Ellen MacArthur Foundation, 2017). These effects of fast fashion have resulted in the increased disposal of textiles (Bhardwaj & Fairhurst, 2010).

Fashion is currently produced and consumed in a linear manner, which means that raw materials are extracted for clothing production and the products eventually end up in waste (Ellen MacArthur Foundation, 2017). This linear fast-fashion industry exerts negative pressures on the environment (Bhardwaj & Fairhurst, 2010), caused by the extraction of limited natural resources from ecosystems and by the polluting effects of waste. When consumers dispose of textiles after use, the garments pile up, which results in many of the clothing pieces being landfilled or incinerated (Niinimäki, 2020). In addition to the extraction of materials and production of waste, the current fashion industry uses large amounts of non-renewable energy (Koszewska, 2018) (Niinimäki, 2020). For example, in 2015, a total of 98 million tonnes of non-renewable resources was used to produce the clothes, which equals 2% of the global carbon budget (Ellen MacArthur Foundation, 2017).

As a response to the rising recognition that the fashion industry is unsustainable, new business models have been proposed. The circular economy is a popular approach that focuses on sustaining and regenerating raw materials and designing out waste. To reduce the pressures on raw resources, the circular economy model consists of closed loops in which raw materials and their components are kept at their highest value, so they can be used indefinitely (Koszewska, 2018).

In line with the circular economy, the recycling of clothing has become an important topic as it increases the circularity of clothes. Recycling aims at increasing the lifetimes of materials in textiles, so textile fibres stay in circulation longer. Environmentally this is more advantageous in comparison to incineration or landfilling (Schmidt et al., 2016). Within this research, we define recycling as any process that converts Post-Consumer (PC) textile waste into new materials and objects. This is different from re-use where the garment is kept at the same composition and value.

To recycle clothing, the PC clothes have to be collected at a clothing collection point, e.g. collection bins in a municipality. Our commissioner, Sympany, is actively involved in this part of the textile recycling chain. The NGO Sympany is a key player in working towards a more circular approach of textile recycling by collecting and sorting the PC textiles in the Netherlands. The organisation intends to involve all actors such as citizens, local governments, and factories in order to achieve its mission of sustainability (Sympany, 2019), which includes the reduce, reuse and recycle principles (Koszewska, 2018). Sympany collects and manually sorts PC textiles in the Dutch regions of Utrecht, Gelderland, Brabant, and Flevoland. Sympany obtains 25 million kilograms of clothes annually (Sympany, 2019). They sort these PC garments into different downstream textile streams. Currently there are five downstream textile categories, namely: white cotton, jeans, coloured cotton, mixed winter, and mixed

sweater (Sympany, 2019). The mixed winter consists of winter clothes like jackets, scarves, and caps. The mixed sweater streams include sweaters of different materials. Sympany is not able to define the exact composition because it is unknown.

During the sorting process, Sympany faces different problems. The first problem is the low quality of the collected textiles, which leads to a decreasing amount of clothes that can be reused or recycled. The second problem is the heterogeneity of the clothes, which implies a mixture of various materials within the clothing piece. It is difficult to determine the exact fabric compositions of the mixed streams. Hence, the main issue faced by sorting organizations is to sort the garments properly into different streams. However, at this moment, there are no automatic sorting technologies used by Sympany and sorting is done by hand. Lastly, the sorting and recycling of PC clothes is made more difficult because the current clothing industry and its production processes are not transparent (The Global Fashion Agenda & The Boston Consulting Group, 2018). This means that the garments' composition cannot be traced.

To overcome the current challenges in the recycling of downstream PC textiles, more effective sorting and recycling techniques are needed that could transform the current linear industry to a more circular chain. Especially for the recycling of the heterogeneous streams, which Sympany categorizes as the mixed sweater and mixed winter streams, new opportunities need to be explored. Organizations like Sympany furthermore need practical suggestions on how to improve sorting, so close collaboration between actors in the textile chain can be established.

In Scandinavia, which is defined as Norway, Sweden and Finland in this research, recycling of PC textiles is further advanced than in the Netherlands. On both the research and business scales, recycling is quickly developing as part of closed-loop systems (Norden, 2014). Many brands are taking responsibility and collaborating to explore different pathways for supply of recycled fibres (Nordic Council of Ministers, 2017). Therefore, Sympany has expressed a particular interest in understanding how the Downstream Textile Recycling (DTR) processes function in these countries.

This research is focused at the DTR processes in Norway, Sweden, and Finland. More specifically, it concentrates on Downstream Mixed Textile Recycling (DMTR) processes, because the mixed sweater and winter streams are currently the most difficult textile streams to find a recycling option for. These DMTR processes are assessed and compared in a Multi-Criteria Analysis (MCA) using four pillars: economic, technological, social, and environmental. These pillars compromise the different aspects of the DMTR processes that determine the sustainability performance of each process. Every pillar is operationalized with quantitative or qualitative indicators.

The aim of this research is to give an overview of the DMTR processes and the utilized recycling techniques in Scandinavia to improve the recycling/sorting techniques used by Dutch DMTR companies or textile sorting companies.

Resulting from this objective, the general research question is as follows:

Which selected DMTR processes in Scandinavia are suitable to be implemented in the Dutch textile recycling context to improve the Dutch DMTR processes?

Three specific research questions with sub-questions are devised, to answer the main research question.

1. What are the indicators according to the four pillars used to assess the DMTR processes situated in Scandinavia?

2. What is the performance of the selected Scandinavian DMTR processes regarding the set indicators?

2.1: What textile recycling techniques are utilised in the selected Scandinavian DMTR processes?

2.2: What are the performances of the selected recycling techniques in a MCA according to the set indicators?

3. Which recycling technique(s) used by the selected DMTR processes in the Scandinavian context are suitable to be incorporated in the Dutch context?

3.1: How do differences between the Dutch textile recycling context and the Scandinavian context affect the DMTR processes' performance?

3.2: What changes need to be applied by Dutch textile sorting companies to deliver the suitable textile input for Scandinavian DMTR techniques?

This research paper covers the specific research questions in the order given above. Each specific research question has their own chapter. Every chapter has an introduction, methods and/or data collection and an overview of the results. A conclusion is included in the chapter when relevant for answering the research question.

Chapter 5 serves as background information on the Dutch and Scandinavian context. Chapter 6 gives an overview of the indicators used. In chapter 7 an overview of the selected Scandinavian DMTR techniques will be given. Chapter 8 is about the performance of the selected DMTR techniques. In chapter 9, the differences between the Dutch and Scandinavian context will be examined firstly. Furthermore, implementation of the analysed DMTR processes in the Dutch context will be considered. In chapter 10, there will be a discussion of this research. Following, with a conclusion for our main research question in chapter 11. In the same chapter, recommendations for Sympany will be given. In the final chapter, the societal evaluation chapter, the societal context of the fast fashion industry, the values and our value-bound choices are made explicit.

5 The textile recycling context

5.1 Framing textile recycling

In this research PC waste is defined as damaged, out of fashion, or redundant clothes and fabrics, which are sorted into different streams by sorting companies. Once sorted, these streams will either become input for DTR processes or for re-use purposes as can be seen in figure 1. The re-use fraction consists of high-quality PC clothing, which are sold in second-hand stores or used for charity (Hopstaken et al., 2020). The lower quality materials will either continue in the recycling chain or the textiles will be incinerated or landfilled.

The DTR processes can be separated into upcycling and downcycling processes. On one hand, 'upcycling' means that PC fabrics are used to create materials or products of the same or higher quality as the initial piece of clothing (Shirvanimoghaddam, Motamed, Ramakrishna, & Naebe, 2020). In the upcycling processes, 'virgin' materials may be added to the PC fibres or fabrics to achieve an end result of higher quality (Sandin & Peters, 2018). On the other hand, 'downcycling' is defined as PC textiles that are converted into materials of a lower quality than the initial clothes (Shirvanimoghaddam et al., 2020).

After a garment has undergone a recycling process by a DTR company, it is referred to as recycled material in this research. The recycled material is used and becomes 'new' PC waste. The material cycle will continue until the quality of PC waste is too low to be recycled. Then the waste will be incinerated or landfilled. The textile recycling process and the textile reuse process are shown in figure 1.

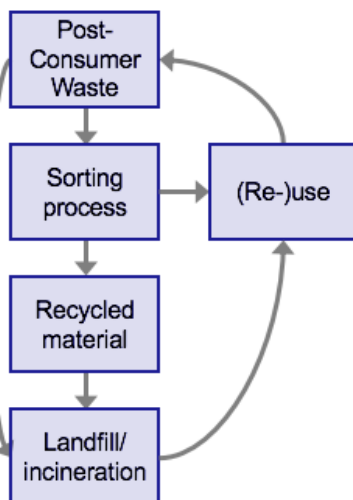


Figure 1: The general textile recycling stages (Author, 2020)

5.2 The Dutch context of textile recycling

Currently in the Netherlands, the PC textiles, such as clothing, household textiles, and curtains, can be collected from 'door to door' or in clothing collection containers (Rijksoverheid, 2020)(Den Hartog et al., 2020). A PC textile sorting company can only collect these textiles in a municipality when it has been granted a textile collection permit in exchange for a fee (Den Hartog et al., 2020). The sorting companies are required to pay additional fees per kilo of PC textiles that they collect (Van der Wal & Verrips, 2019). In figure 2 is shown what the influence of the municipality has on the PC textile recycling process.

A difficulty with this system is that the availability of the collection permits is limited, which can result in competition amongst the textile sorting companies. The permits are given to the company that is willing to pay the highest price and this makes it more difficult for non-profit sorting companies to cover their costs (Den Hartog et al., 2020)(Van Veldhoven-Van der Meer, 2020b). Another difficulty is that clothing containers are often underground, resulting in moist conditions that cause damage to the textiles and reduce the textile quality. Furthermore, sometimes 'regular' waste is deposited in the textile containers, polluting the textiles (Den Hartog et al., 2020) (Van Veldhoven-Van der Meer, 2020a). The presence of regular waste between textiles has a lower occurrence with household textile collections or with textile donation points in stores (Hopstaken et al., 2020). Furthermore, the extent to which the quality of textiles is lowered by regular waste depends on whether the textile containers are emptied by hand or by crane. For example, sorting by crane increases the chances of a can of soda to open and pollute the textiles (Hopstaken et al., 2020).

To improve the PC textile recycling in the Netherlands, the Dutch government is currently working with a 'circular textile 2020-2025' group consisting of organisations and companies involved in the textile (recycling) industry, including local authorities (Van Veldhoven-Van der Meer, 2020a). One of their ambitions is to adjust the current textile collection system to create a national 'uniform collection-structure' for textiles to reduce the damage to textiles in the collection containers. Additionally, the 'circular textile' group aims to give the PC textile collection permits to the most circular sorting/recycling companies, instead of given the permits to the 'highest bidder' (Den Hartog et al., 2020). The government, together with the textile stakeholders' group, has influence on all the steps in the textile recycling chain, which is also shown in figure 2.

5.2.1 Sorting, selling, and recycling

In 2015, the three largest textile collectors in the Netherlands were Leger des Heils, Curitas and Sympany (Gemeente.nu, 2015), see figure 2. The collected textiles in municipalities are sorted in the sorting centres. Dutch textile collectors either sort the PC clothing themselves, sell the clothes to other stakeholders involved in the textile recycling chain or export the clothes to foreign sorting companies (Hopstaken et al., 2020). In addition, there are also textiles imported to the Netherlands from other countries. The imported and exported streams of PC textiles to and from the Netherlands are not sorted yet, however they have been cleaned from the non-textile components, for example the regular waste. In addition, the wet and dirty textiles have been removed from the textile streams (Hopstaken et al., 2020).

In the Netherlands, 45% of all textile is collected separately from other waste (Van Veldhoven-Van der Meer, 2020b) (Hopstaken et al., 2020). These collected items are sorted into a fraction of 53% for reuse, 33% for recycling, and a waste stream of 14% (Van Veldhoven-Van der Meer, 2020b)(Hopstaken et al., 2020).

The higher quality textiles suitable for re-use are removed from the main PC stream and the remainder of the PC textiles is separated by a variety of different methods in sorting centres. The methods enclose sorting by hand or by automatic techniques, see figure 2. After sorting, a fraction of the downstream PC textiles is recycled with upcycling or downcycling methods as can be seen in figure 2. For up- and downcycling, mechanical or chemical recycling processes are used. An example of a chemical recycling process is producing cellulose from the cotton fibres in PC garments (Van Veldhoven-Van der Meer, 2020a).

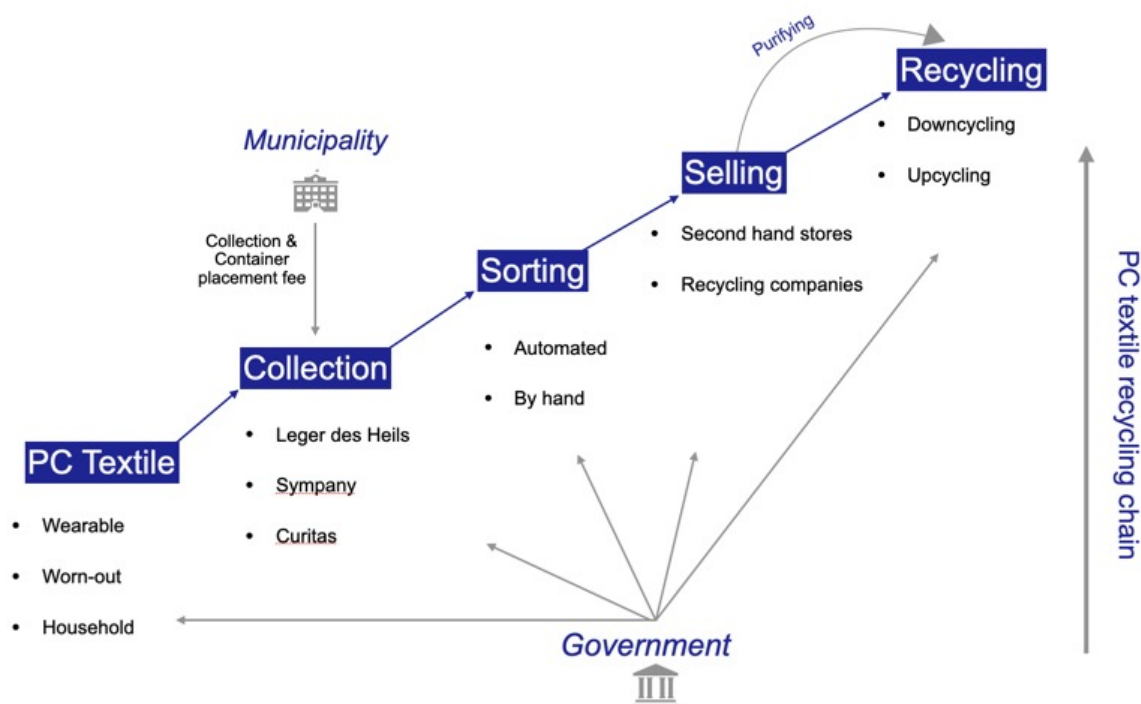


Figure 2: The Dutch PC textile recycling chain (Author, 2020)

5.3 The Scandinavian context of textile recycling

In Scandinavia, three projects are established to stimulate textile reuse and recycling. Firstly, a *Nordic Strategy for collection, sorting, reuse, and recycling of textiles*. Secondly, an *extended producer responsibility system and new business models to increase reuse and recycling in the Nordic region*. Finally, *the Nordic reuse and recycling commitment*. These projects are part of the following initiative: *The Nordic region – leading in green growth* (Norden, 2014). The Nordic initiatives involve the whole of Scandinavia including Denmark and Iceland. However, this research only incorporates the general aims of the projects and data based on the countries relevant for our research: Norway, Sweden, and Finland. One of the drivers for establishing these projects is the EU Waste Framework directive, which aims for a recycling target of 50% for municipal waste (European Commission, 2019). In this chapter, an overview will be given of the Scandinavian context in which the recycling processes are taking place.

The collection of PC textiles is dominated by a few charitable organisations in each Scandinavian country, where the PC clothes are collected in collection containers in municipalities. The regulations regarding the placing of a container differ per country, but it is mainly determined by the municipality and their corresponding criteria (Norden, 2014). After collection, there are different options for processing the collected clothes. Below, an overview is given of the textile processes per Scandinavian country following with an overall conclusion.

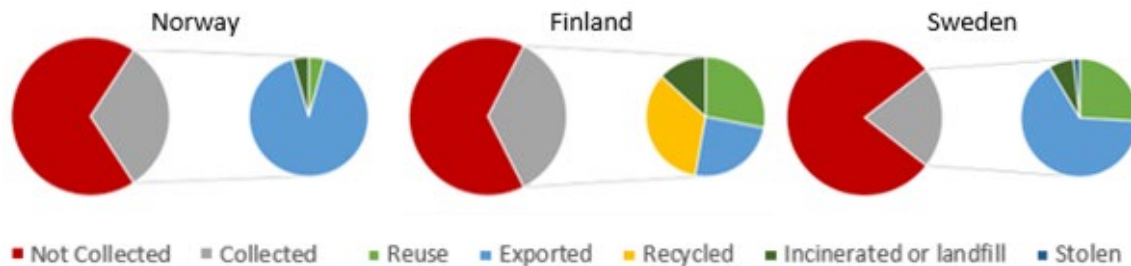


Figure 3: Overview of the collected fraction and its further purpose in the Scandinavian context (Author, 2020), based on (Norden, 2014)

5.3.1 Norwegian context

The supply of pre-consumer textiles in Norway is equal to 22 kilograms per capita per year. It is estimated that 32% of the supply is collected by collection companies. The largest fraction of the collected PC textile, 91.3%, is exported to other countries due to high labour costs in Norway. The collection companies sell the clothes mostly to eastern European countries for sorting or re-use. Also, a small fraction is sent to Africa or Asia for re-use of recycling of the materials. In Norway, 4.3% of the collected clothes is reused and the other 4.3% is incinerated (Norden, 2014). About half of the supply of clothes that is not collected ends up at the municipal waste. It can be assumed that these clothes are incinerated (Norden, 2014), (European Environment Agency, 2013c), which is a total of 39% for Norway (Norden, 2014).

5.3.2 Finnish context

The supply of pre-consumer textiles in Finland equals 13.5 kilogram per capita, of which 35% is collected annually (Norden, 2014). The collection of PC textiles in Finland is already well established. However, improvement is needed when implementing recycling processes on a more industrial scale (Heikkilä et al., 2019). Currently, 28% of the collected clothes is reused in Finland, 34% is recycled and 24.8% is exported to Eastern Europe, Russia, Africa, or Asia. Only 13.2% of the collected clothes is incinerated or landfilled in Finland (Norden, 2014). Since 2016, Finland has maintained a ban on landfilling textile waste (European Environment Agency, 2013a). Hence, the part of the PC textiles that was landfilled in the past, now has to find a new purpose. Still, a large part of the PC textiles is not collected yet, equal to 64% of the annual clothing supply. It is estimated that 86% of the not-collected textiles ends up at the municipal waste and therefore becomes incinerated.

5.3.3 Swedish context

In Sweden, the supply of pre-consumer clothes equals 15 kilograms per capita per year of which only 21% is collected annually. This is a relatively low percentage in comparison to Norway and Finland. The sorting of PC textiles in Sweden happens manually. Therefore, they work together with other European countries and stakeholders to sort the clothes more efficiently, for example, by using half

automatically sorting. An example of collaboration is that the collection companies in Sweden work together with Boergroep in the Netherlands (Norden, 2014). The re-use in Sweden is equal to 26% of the collected clothes. 66% is exported, unsorted, to other European countries for re-use and recycling. Only 7% of the collected textiles is incinerated. In Sweden, a small fraction of the clothes collected is stolen from the containers. The precise numbers are not known, but it is estimated that between 1.7% and 3.4% of the collected textiles are stolen from containers (Norden, 2014). Still, 78% of the PC textiles are not separately collected (Norden, 2014) and hence it is estimated that a majority of this fraction ends up at the municipal waste and is incinerated (Norden, 2014), (European Environment Agency, 2013b).

Figure 3 shows an overview of the fraction of the clothing supply that is collected separately. Furthermore, it shows what the purposes are of the collected fraction. From figure 3, we can conclude that a large fraction of the PC textiles in Scandinavia is currently not collected separately. However, Europe aims that the collection of waste, including textile waste, has to be 100% separately in 2025 (Van Veldhoven-Van der Meer, 2020). Furthermore, the *Nordic textile and reuse and recycling commitment* was established with the general aim to reduce the environmental impact of textile consumption and increase competitiveness in Scandinavia. As part of this commitment, they would like to increase the transparency of the collection companies to increase the public confidence in collection companies. In addition, the legitimate actors should be granted permission to collect, sort, reuse and recycle textiles. Combined, the agreement should increase the faith of the consumers and therefore an increase in the fraction of collected clothes (Norden, 2014).

From the clothes that are collected, only a small fraction is suitable for reuse (Norden, 2014). Specific sorting is difficult because it happens manually, and the costs are relatively high. Other countries, European, African, or Asian, with corresponding stakeholders, can sort for a lower cost-price. Another option is to not sort the textiles at all and just send them to the recycler which can also be abroad. Automatic sorting is needed to sort the PC textiles in Scandinavia (Norden, 2014). Finally, there are only a few organisations in Scandinavia that can recycle these textiles. There is a lack of big recycling actors capable and willing to contribute to the large export fraction (Heikkilä et al., 2019). Currently, different companies and projects are in development regarding the recycling of PC textiles. Examples are the Telaketju project in Finland or Re:newcell and Södra in Sweden. These examples will be further expanded on in chapter 7.

6 Research Indicators

In this chapter, the following specific research question is answered: *What are the indicators according to the four pillars used to assess the DMTR processes situated in Scandinavia?*

In this report, the DMTR technique is regarded as a part of the whole DMTR process, see figure 4 below. Therefore, the data of the DMTR techniques are aggregated into specific indicators for the overall sustainability performance of the DMTR processes. The DMTR techniques are assessed with four pillars and each pillar was operationalized with indicators as can be seen in figure 4. The four pillars used in this research consist of a technological pillar and three pillars that originate from the

sustainability concept, which are the environmental pillar, the economic pillar, and the social pillar (Opon & Henry, 2019). In this chapter first the method of information gathering for the development of the indicators will be explained, after which the pillars and the indicators are introduced.

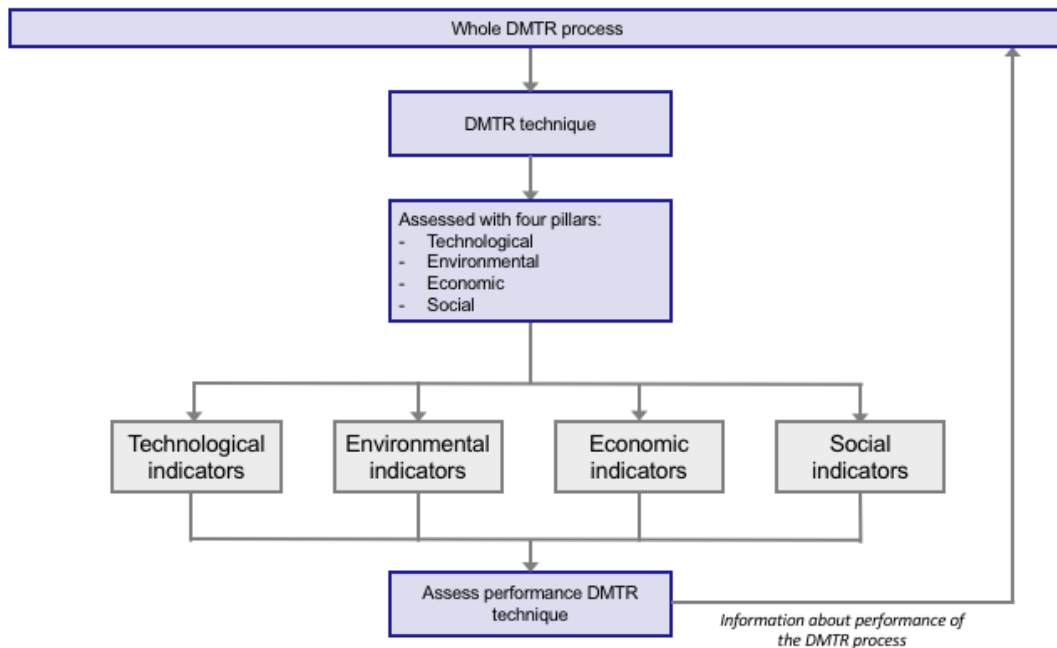


Figure 4: Assessment method of the DMTR techniques (Author, 2020)

6.1 Development of the Indicators

The pillars used in this research were first explored with scientific literature. After which the corresponding indicators of the pillars were identified and analysed. For each pillar, indicators were chosen that required quantitative or qualitative data about a DMTR technique. When choosing the indicators, it was assumed that the required data could be found online or that the data could be obtained with an interview with the DMTR company that uses the technique. In the development of the indicators for each pillar, the indicators were either used from scientific literature and governmental reports, or derived from concepts found in literature.

6.2 Technological pillar

A separate technological pillar is used in this research which focuses on the intrinsic traits of the technique that are related to the resource material use of the DMTR technique. When quantified, the technological indicators identify if a DMTR technique is viable for the production of recycled products in terms of resources. The values of the indicators in the pillar determine to what extent the evaluated DMTR technique is "sustainable" as defined by the circular economy approach. In the circular economy, recycling is most efficient, by keeping materials at their highest value (Ellen MacArthur Foundation, 2017). The two indicators chosen for the multicriteria analysis are the 'circularity', or recycling efficiency), (%) and the 'efficiency of technique' (%). Using these indicators, the DMTR techniques are compared.

6.2.1 Circularity (recycling efficiency)

The material circularity indicator proposed by the Ellen MacArthur Foundation is a practical application considering feedstock, destination after use and lifespan (Ellen MacArthur Foundation & ANSYS Granta, 2019). However, all the input data can be difficult to retrieve (Rossi et al., 2020). Therefore, it is decided to use the circularity (C) indicator, which represents the recycling efficiency. The circularity is the percentage of the PC textile input and other recycled material that is present in the final product made by the DMTR technique (Linder et al., 2017).

$$C = \frac{R+S}{M} \cdot 100\% \quad \text{Equation 1}$$

This indicator is adapted from the recycling efficiency used for the material circularity indicator. In equation 1, C is the circularity, R is the amount of feedstock from PC input textile, S is the amount of feedstock from other recycled sources and M is the mass of the recycled product, the output. The higher the circularity, the more favourable the technique.

6.2.2 Efficiency of technique

The efficiency of the technique shows to what extent all input materials are used to form the output product. These input materials are the virgin feedstock, the PC textiles, and the feedstock from other sustainable sources. The virgin feedstock is the amount of non-sustainable feedstock as input material.

$$E = \frac{V+R+S}{M} \cdot 100\% \quad \text{Equation 2}$$

Here the variables are the same as in equation 1 and V represents the virgin feedstock. Equation 2 was based on conventional concepts of efficiency and derived for this research with the variables used in equation 1. The efficiency of the technique is the opposite of how much waste is generated. A sustainable DMTR technique should aim to design out waste and pollution (Ellen MacArthur Foundation, 2017). Therefore, a higher efficiency implies a more favourable DMTR technique.

6.3 Environmental pillar

This pillar addresses the possible pollution that the subject of interest can cause (Opon & Henry, 2019). The focus of this research within the environmental pillar is on the 'resource depletion' and 'global warming' (Opon & Henry, 2019). For each of the environmental indicators the smallest value is the most favourable regarding the sustainability performance of the DMTR technique.

6.3.1 The blue component of the operational water footprint

The first environmental indicator is the operational water footprint (m³/year) per tonne of PC textiles input (m³/year/tonne). This quantitative indicator gives insight into the volume (m³) of freshwater (Gerbens-Leenes & Hoekstra, 2008) that is used by the DMTR technique to create the output products. The research focuses on the 'blue component' of this operational water footprint, which is defined as the 'amount of water withdrawn from ground- or surface water that does not return to the system from which it came' (Gerbens-Leenes & Hoekstra, 2008). Hence, the blue component within the

operational water footprint informs about the amount of water needed to recycle 1 tonne of PC textiles. The indicator displays the size of the resource depletion pressure that the DMTR technique exerts on the environment.

6.3.2 Specific energy consumption

The second environmental indicator used in this research is the specific energy consumption (Chan, Huang, Lin, & Hong, 2014) per conversion of 1 tonne of PC textiles input (GJ/tonne). This indicator provides insight into the energy needed by the DMTR techniques for the conversion of 1 tonne of PC textiles input into the produced output materials. The specific energy consumption indicates the size of the environmental pressure caused by the energy consumption of the DMTR technique. However, the specific 'environmental impacts' related to the energy usage are not represented in this energy indicator (Herva, Franco, Carrasco, & Roca, 2011).

6.3.3 Direct carbon footprint

The third environmental indicator used in this research is the direct carbon footprint of the DMTR technique per tonne PC textiles input (CO₂ equivalents/tonne). This indicator provides insight into the direct emissions of greenhouse gases, displayed in CO₂ equivalents (Herva, Franco, Carrasco, & Roca, 2011) by the DMTR techniques that occur during the conversion of 1 tonne of PC textiles input to the produced output materials. This indicator gives information about the size of the 'global warming' pressure caused by the DMTR technique.

6.4 Economic pillar

Any progress in environmental fields has to come face to face with its economic feasibility. New recycling processes are more appealing if economically sound and promising. However, if a process is not profitable it is unlikely to be adopted, despite possible environmental positives. Hence, for the economic pillar, the profitability of the DMTR techniques is analysed.

6.4.1 Profitability

The goal of this indicator is to understand how profitable a set DMTR technique could be, based on a selected case study. Albeit a simplification, this indicator provides insight on whether the process is economically promising.

This indicator will be calculated with equation 3:

$$\textit{Profitability} = \frac{\textit{Net Sales}}{\textit{PC Input Textiles}} \quad \textit{Equation 3}$$

Where 'net sales' is defined as: gross sales - sales returns - allowances - discounts. When the net sales information was not available, the 'operating profits' was used instead for the calculation of this indicator.

As the scale of the case studies of the DMTR processes assessed in this research differ, the profitability is relativized to 'profitability for each ton of input textiles'.

6.5 Social pillar

This pillar is often ignored or considered to be vague (Sharpe, 2016). However, due to the many concepts that fall under this umbrella, it is seen as a very dynamic pillar (Bostrom and Klintman, 2014).

The goal of the social angle is to ensure that the DMTR techniques do not damage human health. The techniques should not endanger workers or civilians, but rather improve their pre-existing conditions if possible (IAEA, 2005). Therefore, “Health & Safety” is the main theme of the social pillar. “Health & safety” encompasses multiple different - and often relative – variables, however this research focuses on the variables directly related with the recycling technique itself.

6.5.1 Emissions of dangerous substances or pollutants

The indicator used for the social pillar is the ‘emission of dangerous substances/pollutants’ throughout the usage of the DMTR technique. This indicator aims to examine the DMTR technique for possible health hazards in the production process of output materials. As these techniques aim to improve the current environmental impact of the textile industry it would be counterproductive if in turn they damaged human health.

The grading of this qualitative indicator will be based on whether the workers are exposed to harmful substances and the emission of substances toxic to humans. Although this approach makes the social indicators more digestible, it comes with a downside. The information obtained for this indicator is heavily dependent on the honesty and transparency of the selected companies. This is especially the case if the information comes from interviews.

6.6 Overview

Table 1 below displays an overview of all indicators used in this research and for each indicator is presented what information was needed for the calculation of the indicator. As can be seen in table 1, there are two indicators to operationalize the technological pillar, three indicators for the environmental pillar, one indicator for the economic pillar and one for the social pillar.

Table 1: Overview of the indicators used in the research (Author, 2020)

Pillar	Indicator	Information Indicator
Technological	Circularity recycling efficiency (%)	Amount of post-consumer input (tonnes) Amount final products (tonnes)
	Efficiency of technique (%)	Amount of input of products (tonnes)/ Output of products (tonnes)
Environmental	Blue component of operational water footprint (m ³ /tonne post-consumer textiles)	Amount of freshwater used b the technique (m ³) Amount of post-consumer textiles input (tonnes)
	Specific energy consumption (GJ/conversion of 1 tonne post-consumer input textiles)Direct carbon	Energy usage of technique (Gjoules) Amount of post-consumer textiles input (tonnes)
	Direct carbon footprint of technique (tonne CO ₂ equivalents/tonne post-consumer input textiles)	Amount of direct GHG emissions in CO ₂ equivalents Amount of post-consumer textiles input (tonnes)
Economic	Profitability (€/tonne post-consumer input textiles)	Operating profits regard to the technique Amount of post-consumer textiles input (tonnes)
Social	Emission of dangerous substances or pollutants	Whether the workers are exposed to harmful substances and the emission of substances toxic to humans

Finally, for all the indicators used in this research, a public/expert opinion-based weighting (Gan et al., 2017) is used, which means that mainly the opinion of experts in the field of textile recycling are used to establish the weights of importance for each indicator. This will be elaborated upon in chapter 8.

7 Selection of Scandinavian DMTR processes

In this chapter, the following specific sub-research question is answered: *What textile recycling techniques are utilised in the selected Scandinavian DMTR processes?*

In Scandinavia, there are several companies involved in the field of (downstream mixed) PC textile recycling. This chapter provides an overview of the five companies within Scandinavia that are deemed most relevant for this research. Two of these companies are based in Sweden and the other three are Finnish. The selected companies comprise of either textile recycling or sorting techniques which could be implemented within the Dutch context. The five companies will be introduced shortly, including an explanation on the criteria used to select them. Furthermore, the textile recycling techniques used by these companies will be elaborated upon.

For the selection of the companies, Scandinavia's DMTR companies were assessed according to the criteria explained in the rest of this paragraph. Considered were companies located in either Norway, Sweden or Finland. Furthermore, the textile streams that they recycle had to be PC and of mixed nature. The companies could either be on full or pilot scale as long as they require mixed PC textiles as input and are willing to collaborate with sorting or collection companies. It was also of importance that the companies could provide the information needed for the indicators. All the companies found with this selection method are described in the following paragraphs.

7.1 Re:newcell

Re:newcell is a Swedish company founded in Stockholm in 2012, based on the principle that decomposing cellulose is the key in recycling textiles. In 2017, they opened their first pulp production plant in Kristinehamn, which is able to produce 7000 tons annually. The production at this plant is a demo that can potentially be upscaled to 30.000 tons in the future (Re:newcell AB, 2019a). Re:newcell produces pulp that is called Circulose, which is made from PC cotton or high cellulosic garments (Re:newcell AB, n.d.;Re:newcell AB, 2019c). The production plant runs on 100% renewable energy, from wind and hydro energy (Re:newcell AB, 2020a;Re:newcell AB, 2020b).

The PC garments that arrive in Kristinehamn are mechanically treated to separate the buttons and zippers. The textile remainders are then shredded, decoloured, and degraded into a cellulose sludge, for which no virgin material is needed (Re:newcell AB, 2020a;Re:newcell AB, 2020b). The decolouring is done by dissolving the dyes with a reductive alkaline (Schultz, T., & Suresh, A., 2017). Afterwards, bleaching is used to remove the remainders of colour that are still present in the textiles (Schultz, T., & Suresh, A., 2017). This process produces wastewater that is contaminated with COD and BOD, which is cleaned in a wastewater treatment plant. Besides wastewater, dust production also is an important by-product (Schultz, T., & Suresh, A., 2017).

Cotton has a high cellulose content, which is needed to produce Circulose. Therefore, clothing with a high cellulose content is favoured in the recycling process. The cellulose sludge is converted into Circulose pulp by drying the sludge (Re:newcell AB, 2020a). The quality of the produced Circulose fabrics is as high as comparable products made from non-recycled virgin material (Re:newcell AB, 2020b). The produced Circulose material is sold as either pulp or fibres, from which brands can produce garments (Re:newcell AB, 2020b). Re:newcell does not collect or sort PC textiles, but they collaborate with collection and sorting companies like Sympany. From these collectors and sorters they need a PC textile stream with a cellulose (cotton or viscose) content of over 98% (Re:newcell AB, 2020b;Re:newcell AB, 2019c). Furthermore, they prefer the incoming textiles to be delivered twice per month in batches of 5 metric tons at minimum (Re:newcell AB, 2020b).

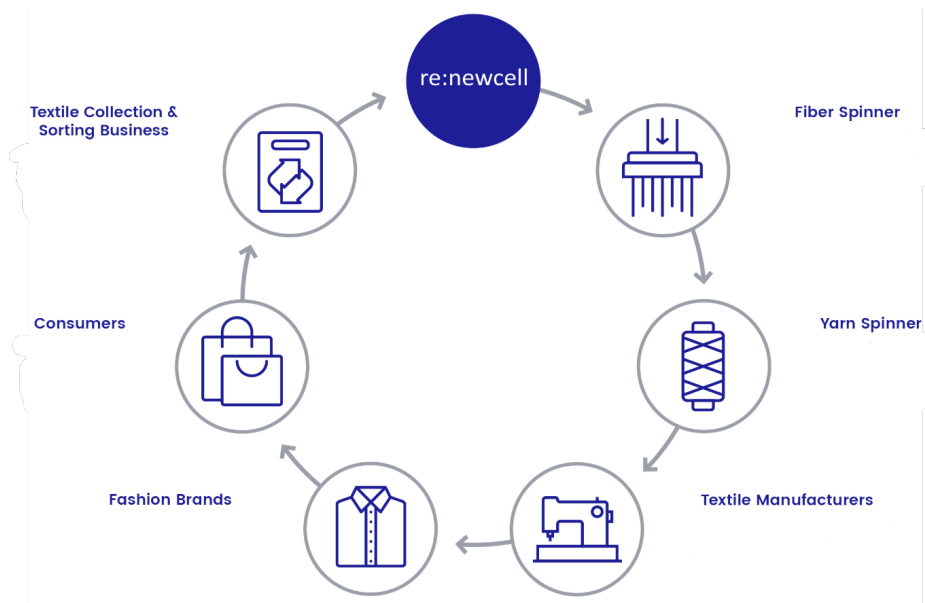


Figure 5: Re:newcell's position in the textile recycling industry (Re:newcell AB, 2019c)

As can be seen in figure 5, the pulp is pushed through a fibre spinner to form the fibres that form the base for the new textiles. The fibres are combined to produce yarn, which are converted into textiles at the textile manufacturers. The recycled fabrics are then bought by fashion brands that sew garments out of the Circulose fabric. Consumers buy the garments, discard them, and via collection and sorting companies they can end up at Re:newcell to be recycled again. Figure 5 shows Re:newcell's position in the textile recycling industry and the way this closed loop process works (Re:newcell AB, 2019c). After production of Circulose garments, it is possible to recycle them again, which closes the loop (Re:newcell AB, 2019b). So far, H&M has produced a garment in their Conscious collection made from Circulose material produced by Re:newcell (Re:newcell AB, 2020c).

7.2 Södra

Södra is a Swedish company, founded in 1938 in Skogsudden. They focus on sustainable forestry, with 52.000 forest owners as their members. Södra produces a variety of products, amongst others pulp, sawn timber, and biofuel (Södra, 2019b). The most relevant application for this research is their textile recycling project called OnceMore.

Globally, OnceMore is the first recycling technique that is able to have recycled mixed PC textile streams on a large scale (Södra, 2020). Mixed (polycotton) textile streams are used for this recycling technique. It can separate the cotton from the polyester present in these garments. In 2017, this recycling technique was tested on lab scale, generating a maximum yield of 97% (Palme et al., 2017). There are different general methods depending on whether polyester or cotton is the desired end product from a polycotton blend. In the case of OnceMore, the cotton is needed for the recycling process, causing the polyester fibres to be depolymerised or dissolved (Palme et al., 2017). The cellulose pulp produced from trees in their members' forests, is mixed with the retrieved pure cotton fibres from the polycotton separation (Södra, 2019a). This cellulose pulp is called dissolving pulp and is produced from birch trees. From these trees, the cellulose fibres are separated from the other wood elements (Södra, 2020). The raw material produced using the OnceMore technique is of high quality and is used to produce textiles (Södra, n.d.).

The recycling process takes place at their pulp mill in Mörrum, where they processed 20 tonnes of PC textiles in the autumn of 2019 (Södra, 2019c). They are still working on a decolouring technique, therefore at present they can only recycle white textiles. Furthermore, they are exploring opportunities to fulfil the aim of recovering a stream of polyester residual products. They are looking for companies that can provide Södra with sorted textile streams, either cotton, polycotton blends, viscose or lyocell. 20 tonnes were processed in 2019, generating an output of 400 (Södra, 2020a) tonnes of pulp (Södra, 2020). The target for the future is recycling 25.000 tonnes of PC textiles annually (Södra, 2019c) and to be able to recycle all PC textile streams (Södra, n.d.).

7.3 Dafecor

Dafecor is a Finnish company operating on a national industrial scale (Dafecor Oy, 2017). One of their business activities is textile recycling. It takes the surplus materials from textile production and PC textiles from the public sector, laundries and consumers. Using a mechanical recycling process, the company transforms the materials into fibres. Only a small amount of collected textiles is burnt to produce energy. The surplus material from the textile industry is manufactured into new products for various uses, such as for industrial maintenance (Dafecor Oy, n.d.). This manufacturing process does not impact the environment as it does not require any water or chemicals (Dafecor Oy, n.d.). These produced goods are mainly reused by companies in the metal and paper industries. One of Dafecor's focuses is to create partnerships and expand their network to optimize the sorting processes to facilitate recycling. For Dafecor, limited information was found online and the company did not want to give an interview, therefore the remainder of this research will not discuss Dafecor in depth.

7.4 Telaketju

Telaketju is a Finnish project that is being organized on a national scale. It aims to gather the most efficient techniques and more advanced knowledge in the field of textile recycling by involving around twenty different stakeholders. It covers the whole recycling chain: from the collection to the refining processes of end-of-pipe textiles (Heikkilä et al., 2019). TouchPoint and Fibersort are two of the stakeholders from Telaketju that will be researched in more depth, as they seem to be the most promising. They cover a variety of processes and can thus provide a broad overview of the different types of stakeholders within Telaketju.

7.5 TouchPoint

Touchpoint is a Finnish recycling company that oversees collection and sorting (TouchPoint, n.d.). Once sorted, it transforms waste PET bottles and PC textiles into workwear pieces for the employees of different companies (Touchpoint Oy, 2019). The pieces produced are composed of polyester or mixed polyester fabrics. According to A. Wulff-Kokko (personal communication, June 1, 2020), a requirement for the recycling technique is a composition of 98 to 100% of the same fabric.

Repreve is one of Touchpoints business partners and it collects the used and disposed workwear pieces. A. Wulff-Kokko (personal communication, June 1, 2020) mentions that these are then transformed into composite furniture. The composite is produced by mixing the waste textile with

adhesives. The furniture produced can be maintained in a good state for 50 years and it can be easily broken down and recycled into composite again.

A sister company RESTER was established in July 2019 (Finnish Business Information System, 2020). Touchpoint collaborates with this company (Oyj, 2020) on a project to build a textile recycling facility for 2021 in Paimio in Finland. This is the first project where Touchpoint includes PC textiles for recycling. The project requires a large investment fund of €40 million by Taaleri Kiertotalous Ky (Oyj, 2020) and involves 360 shareholders. This recycling plant will be able to process up to 6,000 tonnes of textiles per year (Oyj, 2020). For RESTER, limited information was found online because the project is in a development phase. Therefore, the remainder of this research will not discuss RESTER or Touchpoint in depth.

7.6 Fibersort

Fibersort is currently the most effective sorting technology. It uses an automated system (Circle Economy, 2008) to sort streams of textiles by scanning the piece of clothing with the NIR spectroscopy (FIBERSORT, n.d.) with a capacity of one garment per second (Valvan Baling Systems, 2015). Pressurized air is used to transfer the textile piece from the treadmill to the basket that corresponds to the category it belongs to. The PC textiles are sorted into 45 different categories (Sustainable Fashion Earth, 2020).

The Fibersort project is funded by the Interreg North West Europe. They are currently looking for partners to commercialize and test the technique (Circle Economy, 2008). However, the main challenges of this technique are the costs and feasibility on a large scale (Sustainable Fashion Earth, 2020). This technique has been launched in The Netherlands as a pilot project on 12th March 2020 (Sustainable Fashion Earth, 2020). Because Fibersort is not a 'downstream' textile recycling technique, the technique is only discussed in this chapter. Hence, the rest of this research will not elaborate on the Fibersort technique.

This research does not further include information about Dafecor and Touchpoint in our research because there is a lack of available online data for these companies. Furthermore, the companies were not willing to provide additional information through an interview. Fibersort is also not elaborated upon in the rest of the research, because it is not a 'downstream' technique. For Södra and Re:newcell a lot of information can be found online in reports, websites and scientific literature. The companies also expressed interest in an interview. Hence, for both companies the required information can be obtained for the set indicators of research question 1.

8 Analysis of the selected Scandinavian DMTR processes

In this chapter, the following specific sub-research question is answered: *What are the performances of the selected recycling techniques in a MCA according to the set indicators?*

This chapter is divided into three sub-chapters. The first sub-chapter introduces the method for gathering the data used for the calculations of the indicators for Södra and Re:newcell. Furthermore, it discusses the assumptions that were made to provide the indicators with sufficient data about the DMTR techniques. Then in the second sub-chapter, the MCA method is discussed and in the third sub-chapter the results of the MCA are presented.

8.1 Data gathering methodology

The indicator calculations used quantitative and qualitative data for each DMTR technique. This data consisted of both secondary and primary data. First, the secondary data about the DMTR technique was collected, this data was found on websites, in data sets, annual reports and scientific literature when these were available online. Secondly, the primary data was obtained by contacting the DMTR businesses via email or by performing telephone interviews.

8.1.1 Indicator data assumptions

For both Re:newcell and Södra, assumptions were made to obtain the data for the indicators.

For Re:newcell, the (Schultz & Suresh, 2017) report was assumed to represent the data specifically for the Re:newcell technique. This assumption was supported by an interview with Re:newcell, in which it was affirmed that the report included Re:newcell data. Hence, the report was used for the calculations of the indicators selected in this research.

Södra Cell is the company 'fragment' that produces pulp for the overall Södra company. The produced pulp includes pulp from hardwood, softwood, and dissolving pulp. This dissolving pulp is used in the OnceMore technique (Södra, 2020). To use the available data for the indicators, a general assumption was made for Södra.

For the indicator calculations, the volume ratio between the OnceMore technique and Södra Cell, as well as the sales ratio between Södra Cell and the total Södra company were used. These ratios were used because part of the available data was on the Södra Cell 'level' and part of the data was on the 'level' of the total Södra company. The use of the ratios was necessary to calculate the approximate data for the OnceMore technique from the Södra Cell 'level' and the total company 'level'.

The ratio between Södra and Södra Cell is 0.53, based on the ratio of the sales, as can be seen in figure 6. The total pulp production output of Södra Cell is 1,869,000 tonnes (Södra, 2020) and for OnceMore the production output is 400 tonnes (Södra, 2020a), hence the ratio between these values is 0.000214

as can be seen in the figure 6. This ratio was used to calculate the data for the OnceMore technique, and the data was then used for the indicators.

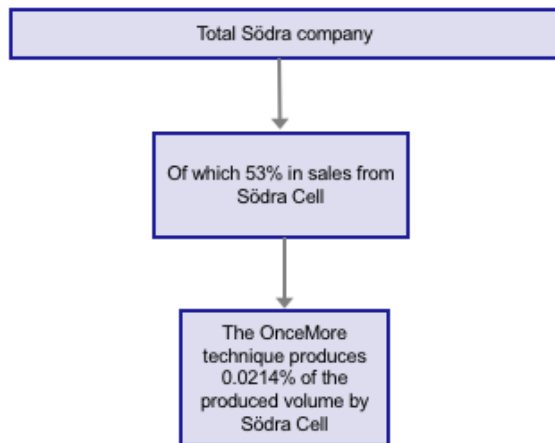


Figure 6: Different company levels within Södra and their ratio (Author, 2020), based on (Södra, 2020)

The calculations of the final indicator values for each DMTR technique are elaborated in Appendix A along with the references that have been used for these calculations. The resulting indicator values which are used for the MCA are shown in table 2 below. In addition to the indicator values, table 2 also shows the difference in PC textile input for each technique.

Table 2: Indicator data for the Södra OnceMore technique and the Re:newcell technique (Author, 2020), based on (Södra, 2020) and (Schultz & Suresh, 2017).

	DMTR techniques	
	OnceMore Södra	Re:newcell
Input for technique	20 tonnes	7000 tonnes
Indicators		
Operational water footprint, blue component	448.05 m ³ /tonne	377 m ³ /tonnes
Specific energy consumption	182.95 GJ/tonnes	21 GJ/tonne
Direct carbon footprint of technique	-52.2 tonnes CO ₂ equivalents	-2 ton CO ₂ equivalents/tonne
Emission of dangerous substances/pollutants	Yes	Yes
Profitability	26,868.95 krona/tonne	-2,552.571 krona/tonne
Efficiency of technique	-	90%
Circularity (recycling efficiency)	5%	100%

The data for the efficiency of the technique of the Södra OnceMore technique is not presented in table 2 since that data was not available.

8.2 Multi-criteria analysis

The MCA structures the data found for the indicators and compares the data of the selected DMTR techniques in a clear overview. This overview gives insight into the sustainable performances of the total DMTR processes. The MCA results were used in a transparent method to compare the DMTR techniques. In this subchapter, the method of the MCA is presented.

The MCA can include qualitative and quantitative indicators consisting of data with differing units. However, to compare the DMTR techniques with one another and give an indication about the overall performance per DMTR technique, all data needs to be standardized into the same ‘measurement unit’ (Mourits, Van Asseldonk & Velthuis, 2006). In this research, a simple and qualitative scaling method was used for the standardization of the indicator data. The performance of each indicator was assigned a -, - -, or - - - when the performance was unfavourable and a +, ++, or +++ when the performance was favourable (Department for Communities and Local Government, 2009). Table 3 shows the standardization methods for the indicators.

In table 3, ‘the emissions of dangerous substances’ is a qualitative indicator, meaning that it can be answered with a yes or no instead of + or -. Also, the profitability indicator is included as a ‘yes’ or ‘no’ qualitative indicator in the MCA, because there is no reference standard in literature for DMTR techniques’ profitability that can be compared with the profitability of Re:newcell and Södra. For the environmental indicators table 3 shows a range of percentages corresponding to the + or - symbols. These percentages display the recycling technique performance per indicator compared to the production process of virgin cotton fibres. The recycling techniques can be compared to the production of virgin cotton fibres, because the OnceMore and Re:newcell processes have cotton as the main component and cotton fibres are produced.

Table 3: Standardization method per indicator for the MCA (Author, 2020)

Pillars	Indicators	Type in MCA	Method	Conclusion
Environmental	Operational water footprint, blue component	Quantitative	0% - 50% more than the virgin cotton production	-
			50% - 100% more than the virgin cotton production	--
			> 100% more than the virgin production	---
	Direct carbon footprint of technique		0% - 50% less than the virgin cotton production	+
			50% - 100% less than the virgin cotton production	++
			> 100% less than the virgin cotton production	+++
Social	Emission of dangerous substances/pollutants	Qualitative	Emission of dangerous substances/pollutants	Yes
			No emission of dangerous substances/pollutants	No
Economic	Profitability	Qualitative	Profitable	Yes
			Not profitable	No
Technological	Efficiency of the technique	Quantitative	0% - 15%	---
			15% - 30%	--
			30% - 50%	-
			50% - 70%	+
	Circularity (recycling efficiency)		70% - 85%	++
			85% - 100%	+++

In the MCA the colours green, orange and red are used to clearly communicate the results of the qualitative and quantitative indicators. The colours are used according to table 4 below. The colour 'green' means that the indicators are displaying favourable values, 'orange' means that the values are in the range between favourable and unfavourable and 'red' means that the values are unfavourable.

Table 4: Colour coding for each standardization method for quantitative and qualitative indicators (Author, 2020)

Colour codes	Corresponding symbol		
	Quantitative indicators	Qualitative symbols	
		Profitability	Emission of dangerous substances/pollutants
Green	+++ ++	Yes	No
Orange	+ -		
Red	-- ---	No	Yes

Furthermore, each indicator in the MCA was ascribed a relative weight regarding the other indicators. This weight was in the range of 0 to 1 and it was determined by Paulien Harmsen and 4 other experts in the field of textile recycling. The average weight per indicator is shown in the table 5 below. Within the 0-1 range, the 0 means 'not important' for the performance of the DMTR techniques and the 1 means 'highly important'. The indicators have been ranked from high importance to low importance in the table 6, according to their average weights.

8.3 Results of the Multi-Criteria Analysis

To assign weights to each of the indicators, 5 experts were asked to give their professional opinion. The weights they gave and the average weight value can be seen in table 5.

Table 5: The weights assigned to the indicators by experts in the field of textile recycling (Author, 2020)

Pillar	Indicator	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Average weight
Environmental	Operational water footprint, blue component	0.8	0.4	0.7	0.3	0.6	0.56
	Specific energy consumption	0.8	0.5	0.7	1	0.6	0.72
	Direct carbon footprint of technique	0.8	0.6	0.8	1	0.6	0.76
Social	Emission of dangerous substances/pollutants	0.9	0.8	1	0.5	0.4	0.72
Economic	Profitability	0.5	1	1	0.4	0.2	0.62
Technological	Efficiency of the technique	0.7	0.6	0.8	0.5	0.8	0.68
	Circularity (recycling efficiency)	0.7	0.5	0.6	0.5	0.8	0.62

This average value for the weights shown in table 5, was used in the MCA to rank the indicators on their importance. The overview of the multi criteria analysis is shown in table 6 below and the calculations for the MCA values are described in the appendices. The calculation methods for the indicators can be found in Appendix A and the calculation methods for the standardization of the environmental indicators can be found in Appendix B.

Table 6: The multi-criteria analysis (Author, 2020)

Indicators	Type of Indicator	Weight of Indicator	DMTR Techniques	
			OnceMore	Re:newcell
Direct carbon footprint of technique	Quantitative	0.76	++	+++
Specific energy consumption	Quantitative	0.72	---	++
Emission of dangerous substances/pollutants	Qualitative	0.72	Yes	Yes
Technique efficiency	Quantitative	0.68		+++
Profitability	Qualitative	0.62	Yes	No
Circularity (recycling efficiency)	Quantitative	0.62	---	+++
Operational water footprint, blue component	Quantitative	0.56	++	++

In table 6 it can be seen that for the direct carbon footprints of the techniques, both OnceMore and Re:newcell are assigned three plusses as their carbon footprint is > 100% less than for virgin cotton production. Hence, both the OnceMore technique and the textile recycling technique from Re:newcell are performing better than the virgin cotton production with respect to the greenhouse gas emissions. This performance of the techniques is favourable since the carbon footprint was assigned the highest weight compared to the other indicators in this research.

Furthermore, table 6 shows that the specific energy consumption indicator presents large differences between OnceMore and Re:newcell. For OnceMore the energy consumption is > 100% more than for the virgin cotton production, while for Re:newcell the energy consumption is 50%-100% less than the virgin cotton production. Also, as mentioned in chapter 7.1, the Re:newcell operates only on renewable energy. Hence, for this indicator the Re:newcell technique is more favourable than the OnceMore technique as the energy performance is more sustainable.

Both the OnceMore technique and Re:newcell emit dangerous substances or pollutants, resulting in two times a 'yes' in table 6 for this qualitative indicator. As this indicator is ranked high in table 6, it is important to take this into account, although the extent of the emission was not discussed in this research.

The efficiency of the OnceMore technique is not known, hence the box in table 6 is empty for this indicator. For Re:newcell, the efficiency is > 85%, which means it received three plusses in table 6. As there is no value for OnceMore, the results cannot be compared.

The OnceMore technique is profitable as its profitability is > 0 Swedish krona. For Re:newcell their profitability is < 0 Swedish krona, which means that they are not profitable and receive a 'no' in table 6. However, as this method is qualitative it is not visible from table 6 how much profit or loss the companies make. In this case, OnceMore has a profit of 26,868 Swedish krona per tonne, which is 2,557.31 euros/tonne, and Re:newcell hitherto has had a loss of 2,552 Swedish krona per tonne, which is a loss of 242.9 euros/tonne. However, in an interview with Re:newcell, it was said that Re:newcell expects to become profitable in the coming years.

For the circularity of both techniques there is a large difference between the results for OnceMore and Re:newcell. Re:newcell is completely circular and does not add virgin input materials to the process, therefore this technique gets three plusses. While OnceMore adds lots of virgin input materials and hence the percentage of recycled textiles in the final products output is very low, which receives three minuses. Therefore, for this indicator Re:newcell is the more favourable technique for efficient PC textile recycling.

Finally, the blue component of operational water footprint has the lowest weight in this research and therefore the indicator is considered to have less influence on the overall sustainability performance of the techniques. The water footprint for both OnceMore and Re:newcell is 50-100% lower than for the virgin cotton production. Hence, both OnceMore and Re:newcell are more sustainable in this aspect than the virgin cotton production.

9 Comparison of Scandinavian and Dutch contexts

In this chapter, the following specific research is answered: *Which recycling technique(s) used by the selected DMTR processes in the Scandinavian context are suitable to be incorporated in the Dutch context?*

The selected DMTR processes are all part of the Scandinavian context; hence, this chapter examines which of these DMTR processes could be adopted in the Dutch context. To do so, the Dutch and Scandinavian contexts are compared to find relevant differences in the textile recycling chain, stakeholders, and policies. This is further examined case by case, to determine whether the specific textile recycling techniques can be implemented in the Dutch context. Finally, necessary changes for the implementation of the DMTR processes are assessed and discussed.

9.1 Differences in the textile chain

In this sub-chapter, the following specific sub-research question is answered: *How do differences between the Dutch textile recycling context and the Scandinavian context affect the DMTR processes' performance?*

The PC textile chain in both the Netherlands and Scandinavia appears to be similar. Firstly, the household waste, which includes PC textiles, is collected in the municipalities (Den Hartog et al., 2020) (Norden, 2014). Secondly, the textile waste is collected and sorted by dedicated companies (Hopstaken et al., 2020) (Norden, 2014) and these sorted textile streams are sold and exported to downstream companies, businesses, or countries.

However, by looking more in depth into the Scandinavian and the Dutch contexts, the differences become apparent after textile collection in the municipalities. Although the role of the municipalities is very similar in both contexts – the municipalities control and regulate the waste infrastructure and permit system (Den Hartog et al., 2020) (Norden, 2014) – the approach differs noticeably. This difference is highlighted by how the collected clothes are treated. In the Netherlands around 86% of

all PC textile waste is either reused or recycled, and only 14% is incinerated (Van Veldhoven-Van der Meer, 2020) (Hopstaken et al., 2020). Although countries like Sweden and Finland appear to have a lower percentage of incinerated textile waste, their annual textile collection is relatively low compared to that of the Netherlands. This means that most textile waste in Scandinavia is disposed of alongside general waste and thus incinerated (Norden, 2014) (European Environment Agency, 2013b). Accordingly, the total incinerated percentage of textiles is higher in the Scandinavian countries as more ends up in general waste, as can be seen in figure 3 of the Scandinavian Context. Overall, less clothing is available for recycling processes compared to the Dutch context.

This gap between the Scandinavian and Dutch contexts is further amplified by the difference in the importance of the collecting and sorting companies. Although sorting companies exist in both contexts, they are less relevant stakeholders in Scandinavia than they are in the Netherlands (Hopstaken et al., 2020) (Norden, 2014). This is caused by high labour costs for sorting in Scandinavia and thus the sorting of textiles is often delegated to other European companies for cheaper prices. It can therefore be concluded that compared to the Dutch context, the Scandinavian context lacks important actors in the textile chain, such as sorting companies like Sympany. These actors allow for a faster and cheaper availability of specific PC textiles that can be used as input for DMTR processes.

9.2 Differences in policies

Both the Netherlands and Scandinavia, except for Norway, are subject to EU waste Framework directives (Directive 2008/98/EC). This framework is focused on waste prevention and waste hierarchy in general. Regardless, it is a driving force for improvement in the PC textile sector in EU countries (European Commission, 2019).

However, the way this framework and the increasing importance of textile waste are shaping policies is different in the Scandinavian and Dutch contexts. In Scandinavia, projects and policies are starting to take shape with the goal of stimulating reuse and recycling (Norden, 2014). These goals mainly target the municipality level and downstream stakeholders. In Sweden, following the EU waste Framework Directive there is a strong focus on waste prevention, through awareness campaigns, the adoption of extended producer responsibility and municipality-based textile related initiatives (Naturvårdsverket 2013)(Mistra Future Fashion, 2019). Other initiatives, such as the Green Public Procurement in Sweden aim to add additional environmental requirements on recycling.

On the other hand, the Netherlands appears to be focused more on improving the PC textile recycling chain itself. Dutch goals from the government include a national collection structure for textile waste and a meritocratic permit system (Den Hartog et al., 2020). These goals are to be achieved working alongside stakeholders in the textile recycling field.

Therefore, Dutch policies aim to improve the entire chain's efficacy and sustainability, whilst Scandinavian policies aim to reduce the need of the chain itself, by preventing textile waste. Viewing this from the perspective of DMTR processes makes the future of the Dutch context seem more appealing.

9.3 Implementation of the analysed DMTR processes in the Dutch context

In this subchapter, the following specific sub-research question is answered: *What changes need to be applied by Dutch textile sorting companies to deliver the suitable textile input for Scandinavian DMTR techniques?*

Different DMTR techniques may require to be adapted before they can be implemented in the Netherlands. However, the reasoning behind this necessary adaptation is case specific, which can be seen as limitations of the processes and will be explored case by case.

9.3.1 Södra

The strength of Södra's OnceMore process lies in the use of dissolving pulp produced from Birch trees (Södra, 2020). However, this pulp is produced by Södra itself, as it is an established stakeholder in sustainable forestry in Sweden (Södra, 2019b).

Because of this dependency on large quantities of dissolving pulp, the OnceMore process is less likely to be implemented in the Dutch context, since the Netherlands does not possess the space for large industrial forests. Södra's unique position allows the process to be more economically feasible and more sustainable – due to lower transportation etc.

Therefore, the Södra technique can be implemented in the Dutch context. However, as tree pulp has to be bought and transported, the OnceMore technique will be more expensive and polluting in the Dutch context than it is for Södra. These higher costs and pollution would make the technique less competitive in the Netherlands.

9.3.2 Re:newcell

To achieve similar environmental results for the Re:newcell technique in the Dutch context, the Re:newcell process needs to run on renewable energy (Re:newcell AB, 2020a; Re:newcell AB, 2020b). Furthermore, due to high COD and BOD concentration, the Re:newcell process requires its wastewater to be treated at a wastewater treatment plant (Schultz, T. et al, 2017).

Both criteria are feasible in the Netherlands. Therefore, a similar process can be implemented effectively in the Dutch context.

9.3.3 Dafecor and Touchpoint

For both Dafecor and Touchpoint not enough specific information about the processes is available. Thus, it cannot be confidently determined whether a similar process can be implemented effectively in the Dutch context.

9.4 Textile input for Scandinavian DMTR techniques

Table 7 shows an overview of the investigated DMTR techniques in which the input material needed for each case can be compared. The undesirable components that need to be removed from the PC textiles to provide the input for the DMTR techniques and scale of textile input is also provided for both DMTR processes.

Table 7: Overview of the investigated and various attributes (Author, 2020)

Recycling process	Input material	Undesirable components	Scale of input
Södra	Polycotton blends, Cotton, Viscose, Lyocell. 97% cotton required	Physical contaminants such as buttons or zippers	Large scale
Re:newcell	Textiles containing cellulose (98%), such as cotton or viscose	Physical contaminants such as buttons or zippers	5 metric tons, twice per month

Table 7 shows trends in the desired inputs. Both analysed DMTR processes prefer textiles that have already been freed of physical contaminants. In addition, the textile input materials range from polycotton blends to lyocell, however, cellulose-rich textiles appear to be favoured. Furthermore, “pure” textiles and blends are preferred by both Södra and Re:newcell. In table 7 it can also be seen that large input scales seem to be preferred over small scales.

The information presented in table 7 can be used to give sorting companies recommendations to increase their likelihood to cooperate with such DMTR processes.

9.4.1 Suggestions to improve the Dutch textile sorting based on findings

From this research, some suggestions were made regarding changes that Dutch sorting companies can apply to improve and optimize their processes. Sorting companies that are intending to cooperate with DMTR processes similar to Re:newcell, can provide a textile output that incorporates the following guidelines:

- Specific sorting of cellulose-rich textiles and “pure” textiles.
- Removal of physical contaminants (e.g. buttons or zippers) from all textile streams directed to DMTR processes
- Increase in scale of the sorted textile output

Overall, this research composes guidelines on the cellulose-rich and pure textiles input that is needed in the recycling process of the Re:newcell technique. The guidelines can be used as a building block for sorting organizations for them to focus on a certain type of output to produce or deliver at the end of the sorting process.

For the first two guidelines, a combination of manual and automatic sorting could be developed and adopted to improve the sorting process. Dutch sorting companies could progressively switch to an automatized system to be more efficient. Processes like Fibersort, as discussed in chapter 7.6, appear enticing to increase the sorting efficiency. However, this topic should be discussed in-depth in a separate research. The current mechanical sorting used by Dutch companies remains interesting for

the removal of physical contaminants (e.g. buttons and zippers) and can help sort clothes based on their quality.

There are no clear suggestions for the last guideline, as it is dependent on factors external to the sorting companies themselves. However, an increase in efficiency of the textile sorting process could lead to an increase in scale. Scaling up the sorting process would allow organizations to deliver larger amounts of sorted fabrics to recycling companies.

10 Discussion

In this chapter first the results found in the research are discussed. Then the limitations of the methodology are introduced and afterwards it is explained why the research is still valid and relevant despite the assumptions made.

The Swedish DMTR techniques of Re:newcell and OnceMore are relatively new and advanced. Re:newcell operates on a larger scale with 7000 tonnes of textile input compared to 20 tonnes for OnceMore. The Re:newcell technique requires around 9 times less energy compared to OnceMore and the low CO₂ equivalent footprint of Re:newcell can be explained by the production plant relying only on renewable sources of energy. Nevertheless, the overall score of direct carbon footprint, the most important indicator in this research, is excellent for both DMTR techniques when they are compared to average scores in the production of pure cotton fibres.

The closing of production and consumption loops to reach circularity for a DMTR technique is a complex task to achieve while remaining profitable. On the one hand, Re:newcell achieves 100% circularity, but has a negative profitability. Nevertheless, Re:newcell is confident that the technique will become profitable in the coming years as they stated in the interview. On the other hand, OnceMore reaches only 5% circularity, but is cost-effective. For the OnceMore technique, several virgin materials are added in the production, which suggests that the principle of circularity is violated. Indeed, OnceMore requires a large input of Birch wood fibers which is not naturally present in the Netherlands and importing these fibres would increase the production costs of the cellulose pulp and because of transport emissions the sustainability performance of the technique would decrease. Currently, both DMTR techniques cause environmental damages, because they release harmful compounds into the environment during their production processes.

The results mentioned above were obtained by making assumptions for the selection of the indicators, the assessment of the DMTR techniques in the MCA, and the collection of data from companies. The limitations of these assumptions will be discussed one by one.

When selecting the pillars and corresponding indicators, choices were made. The selection of criteria was not a limitation in itself, instead it set a frame for the research. The aim of this research was to provide an integrated and reliable framework by doing thorough literature research on the indicators and consulting ir. P.F.H. Harmsen for advice. However, the framework that the research presented did not involve the Dutch government or Sympany in the selection of the indicators. These important stakeholders in the Dutch textile recycling industry were not involved due to constraints in time and

in resources. It may therefore be contested whether the indicators chosen in this research align well enough with the values and interests of these stakeholders. Nevertheless, the indicators chosen in this research were relevant and provided information about important aspects of the DMTR techniques of Södra and Re:newcell. The indicators were relevant, because ir. P.F.H. Harmsen, who has a broad expertise in the textile recycling field in the Netherlands, reviewed the chosen indicators and provided suggestions on how to improve them.

When the selected indicators were used in the MCA, an expert opinion-based weighting was included by scientists from Wageningen University & Research. On the one hand, the use of opinion-based weights of the indicators could have created a skewed representation of the DMTR techniques (Gan et al., 2017). This is because the opinion of these researchers can differ from opinions held by the commissioner, the Dutch government or other recycling companies in the recycling field. On the other hand, this opinion-based weighing resulted in a transparent and clear weighing method within the research. Also, the weights that the experts assigned individually to each indicator differed a lot based on the background of the expert. This suggests that the average of assigned weights did not present a skewed representation of importance for the indicators. Hence, it was assumed that the assigned weights also partly represented the importance of indicators for the textile recycling stakeholders.

Collecting the data for the research was largely dependent on the transparency of Scandinavian DMTR companies. Especially, the information about the costs of a process was regarded as private information of a company. Therefore, actors involved in the recycling process were hesitant to share this information, which resulted in the exclusion of Dafecor in the research.

On the one hand, time restrictions limited the gathering of all available information and data about the DMTR techniques. For example, interviews could not be scheduled in the time provided for the research. On the other hand, the required data for Södra and Re:newcell was available online and therefore, the indicators could be calculated, using assumptions for this available data.

These necessary assumptions to calculate the indicator values limited the research, because the conclusions that were drawn from the MCA did not fully represent reality. In the report (Schultz & Suresh, 2017) regarding Re:newcell it was stated that the data represented the Re:newcell technique, as well as the transportation of the textile clippings used by the Re:newcell technique. However, based on recommendations from Re:newcell, the report was used to derive the data for the indicators. Therefore, the data in this research still represented the approximate performance of the technique and the comparison between Södra and Re:newcell was still valid.

For Södra, there was no online data available about the OnceMore technique that could be used for the indicators and hence it was decided to work with ratios to calculate the required data. The used method resulted in approximate data for the indicators for the OnceMore technique and therefore these values did not fully represent the true data of the OnceMore technique. However, the indicators in the MCA were still usable for the comparison between Södra and Re:newcell, because the values give insight into the performance of the OnceMore technique.

Another challenge and limitation to the data collection was language. While the interviewees were fluent in English, many reports, mostly financial or governmental reports, were only available in the local language. To collect as much suitable information as possible, Google Translate™ was used to translate texts from Finnish and Swedish to English. This might have affected the interpretation of the collected data and therefore the validity of the results obtained. However, because most of the indicators have specific units and Google Translate™ is relatively accurate, this method is largely reliable to determine whether the data is suitable.

11 Conclusion

Currently in the Netherlands, collectors and sorting companies face major problems due to a lack of automatic sorting technologies, blends of mixed fabrics within clothing, the low quality of clothes or mixed waste in collecting containers. To improve the current textile recycling processes in the Netherlands, examples of DMTR processes from Scandinavia were researched. This research focused on the following research question: *Which selected DMTR processes in Scandinavia are suitable to be implemented in the Dutch textile recycling context to improve the Dutch DMTR processes?*

In this research both the OnceMore and Re:newcell techniques were assessed with indicators in a MCA. The implementation of these DMTR processes in The Netherlands appears to be realizable since the market of textile recycling has a high potential in the Dutch context. Pre-existing collection and sorting companies in The Netherlands are willing to collaborate in the implementation of new DMTR processes.

According to the results of this research, Re:newcell appears to be the most suitable Scandinavian DMTR technique to be implemented in the Dutch textile recycling industry. This is due to its high recycling efficiency and low pressures on the environment. Furthermore, the technique does not require additional resources as input for production, in contrast to the Birch wood pulp that is needed for OnceMore. The Netherlands aims to improve the entire textile recycling chain's efficacy and sustainability, whilst Scandinavian policies aim to reduce the need of the chain itself by preventing waste. Therefore, one can foresee a favourable landscape in The Netherlands for implementing DMTR processes such as Re:newcell, because the Dutch government is working towards a more circular textile economy.

11.1 Recommendations

This research can be used as a guideline for Sympany to achieve their goal to become more circular by improving their sorting process. In this way, Sympany could focus its sorting process on the cellulose-rich input material needed by Re:newcell to cooperate with companies using this or similar DMTR techniques. Moreover, Sympany could opt for a combination of an automatized and a mechanical sorting system. The first one enables them to become more efficient and be able to treat all the clothes they receive. The second one can be used to remove physical contaminants and select textiles based on their quality.

12 Societal evaluation

This chapter is aimed at evaluating our own research in the context of the textile recycling industry. First a summary of the research is given. The second part describes the social context of the societal problem of fast fashion. The third part reflects the position of the researcher, including the research methodology and the values and interest in the research. The last part gives a final evaluation.

12.1 Summary

Post-Consumer (PC) textile collection and sorting organizations, such as our commissioner Sympany, face major bottlenecks. Mainly the heterogeneity of materials in textiles makes it hard to sort them. These textiles are called mixed textiles.

Sweden, Finland, and Norway, referred to as Scandinavia, are on the frontline of textile recycling processes. Therefore, this research aims to select DMTR processes in Scandinavia and evaluate their respective suitability in the Dutch context, so that Dutch DMTR processes can be improved. Our main research question is the following:

Which selected Downstream Mixed Textile Recycling (DMTR) processes in Scandinavia are suitable to be implemented in the Dutch textile recycling context to improve the Dutch DMTR processes?

To assess the performance of the DMTR processes, the two processes have been analysed through a Multi-Criteria Analysis (MCA) using qualitative and quantitative indicators categorised in four pillars: technological, environmental, social and economic. The indicators are direct carbon footprint of technique, specific energy consumption, emission of dangerous substances, efficiency, profitability, circularity, and operational water footprint. Weights are assigned to each indicator by five experts in the field of textile recycling. To examine which of these DMTR processes could be adopted in the Dutch context, the Dutch and Scandinavian contexts were compared to find relevant differences in the textile recycling chain, stakeholders, and policies.

Two Re:newcell and OnceMore techniques are two promising recycling processes found in the Scandinavian context. Re:newcell transforms PC textiles into cellulose sludge that is then dried to create pulp called Circulose. OnceMore depolymerizes or dissolves the polyester and cotton in PC textiles to extract these from the polycotton blend and produce cellulose pulp.

In conclusion, Re:newcell is found to be best suited to be implemented in the Dutch context, because it performs better in the MCA and the technical requirements are available in the Netherlands. It is realizable for Sympany to adapt its sorting process and deliver cellulose-rich and pure textiles as input for Re:newcell. However, the Dutch sorting processes require upscaling to meet the DMTR company's demand. Moreover, the government's objective to improve the textile recycling industry in The Netherlands is a positive driver for the introduction of innovative DMTR processes in the next few years. It would open a market for sorting organizations such as Sympany to locally collaborate with.

12.2 Reflection about the social context

The relevant societal problem is the fast-fashion industry. In the fast fashion industry, lower quality clothes are produced at a high rate and consumers buy large amounts of clothing following the latest trends. These garments are also discarded relatively quickly. Fast fashion is driven by consumer behaviour only to a small extent. More importantly, it is driven by economic and political powers involved textile production and sales. Hence, according to sociological theories the problem exists mostly in the structure of society (Foster, 2005).

Society and its institutions are programmed to maximise profits and to continuously expand production. In 1980, Allan Schnaiberg based the theory of the political economy on Marxist views. Here it is explained that due to the existence of a role distinction between employers and employees, workers are underpaid and consequently profits are generated when goods are sold. These profits are then used as investment in technology and capital, so that production further intensifies. This is a never-ending cycle, called the treadmill of production (Schnaiberg, 1993). In the case of the fast fashion industry the competition between sellers is high and fashion stakeholders are always looking for new buyers. It has caused the industry to be subdivided globally; different actors in the chain operate in different parts of the world (Robbins, Hintz, & Moore, 2014). The industry furthermore uses pull marketing strategies to influence demand for products, by reaching consumers directly (Niinimäki, 2020).

The fast fashion industry has many environmental and social consequences. Firstly, 79 trillion litres of water are consumed per year for the production of clothes (Niinimäki et al., 2020). Secondly, the industry contributes to 8-10% of the global carbon budget (Niinimäki et al., 2020). Thirdly, 35% of the annual oceanic primary microplastic pollution is caused by the textile industry (Niinimäki et al., 2020). Finally, it is estimated that the annual textile waste is over 92 million tonnes a year of which 25 million kilograms a year is collected by our commissioner Sympany (Niinimäki et al., 2020) (Sympany, 2019).

The social consequences arise because the clothing industry has moved a large part of its production to developing countries. Due to globalisation it is possible to lower production and labour costs, evade environmental regulations and find new customers for the large production of textiles. A social consequence is that the workers in developing countries work under poor labour regulation and experience little protection of human rights (Ross & Morgan, n.d.). Furthermore, there is evidence of child labour in several countries related to the fashion industry (ILAB, 2018). Also, in the production process, the clothes are dyed with potentially harmful chemicals which end up in the wastewater. This wastewater is discharged in surface water and has direct effects on surface water ecosystems and human health (Khan & Malik, 2013).

The fast fashion industry is diverse in its chain and effects. This makes it hard to address the problem of textile waste. The current linear chain requires a transition of all stakeholders towards business models based on sustaining and regenerating raw materials, instead of profits and continuously investing in increased production. To make the textile industry more sustainable, a long-term shift towards a circular textile economy is needed (Ellen MacArthur Foundation, n.d.), including the reduce, reuse, and recycle principles (Koszewska, 2018). All stakeholders in the production, consumption and recycling of the clothes need to closely cooperate. People need to buy less and change the way they

look at the clothing value. The idea of ownership needs to change through renting and swapping. Among other things, there should be improved awareness about efficient recycling, increased infrastructure, increased textile collection points and more local production. These practices should then align with the vision of a circular textile economy: higher quality garments with a higher durability, recyclable materials, use of renewable resources and energy, avoiding pollution, and fair prices that include externalities (Ellen MacArthur Foundation, n.d.).

End of the pipe solutions for the fast fashion industry allow the recycling of textile resources, however the recycling options have a small effect on the fundamental fast fashion problem behind the textile waste. End-of-pipe solutions suggest the last stage of a process before the stream is disposed of or released to the environment (Hellweg, Doka, Finnveden, & Hungerbühler, 2005). During our research, we decided to explore end-of-pipe techniques for the fast fashion problem namely, the management of the downstream textile waste. We think that small but effective steps can eventually change the whole chain. This school of thought, the ecological modernisation theory, is especially popular in Western Europe. Our context might have played a role in the solution of recycling practices as profitable businesses (Bell, 2015) (Mol & Jänicke, 2010).

12.3 Reflection on the position of the researcher

Today, research cannot be considered truly objective or value-free. In his article, Van Koppen describes that in the research cycle, societal values and norms can influence research at different phases of the research cycle (Van Koppen, n.d.). Figure 7 shows the research phases, the actors and the relevant values that have played a role in determining the course of our research through value-judgement. It is essential for researchers to be aware of these value-bound choices. The remainder of the chapter will aim at discussing these values and how they have affected our research in the different phases.

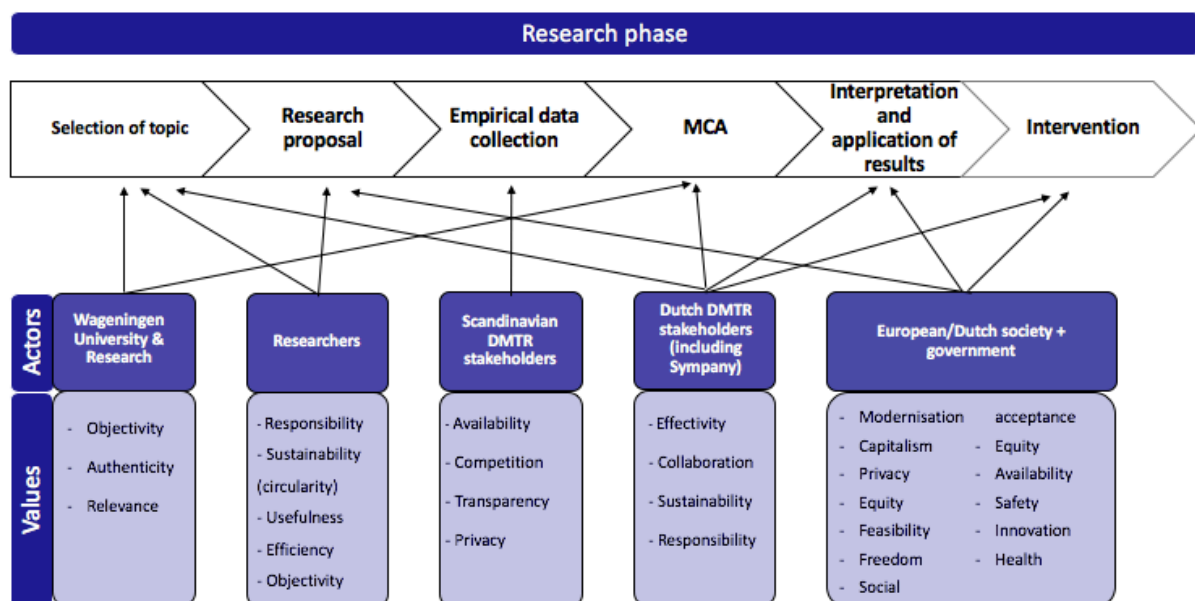


Figure 7: The research phases of our research with the influence of stakeholders and the values that have determined steps in the research cycle (Author, 2020)

12.3.1 Topic selection

Sympany, our commissioner, requested recommendations to improve the circularity of their recycling process. Our supervisor provided us with starting literature on the environmental effects of the textile industry and the circular economy approach. Values connected to this approach, such as sustainability, as well as the relevance of the topic according to Wageningen University suggested the direction of the research: to execute an analysis of alternative recycling and upgraded options of postconsumer textile streams. This was adapted to our own values as researchers shown in figure 7. We had strong intentions to help the NGO Sympany and feel useful in the change we were offering. Sympany expressed particular interest in recycling methods in Scandinavia, because these were assumed to be more advanced than in the Netherlands. We therefore decided to pursue this interest in our research. Our objective became directed at improving the Dutch DMTR processes. To Sympany this means improving their sorting.

12.3.2 Research proposal

The research proposal included the problem definition, objective, research questions and methodology. Our perspective and the commissioner's perspective upon the problem was very similar. We both value environmental protection and civil responsibility over, for example, the prevailing capitalistic values of making profits and increasing production in Dutch and European society. As Sympany wants to become more sustainable through collaboration and innovation (Sympany, 2020), our objective was to provide them with practical information on the Scandinavian DMTR processes and what they can do to improve the recycling and sorting in the Netherlands. However, we also think that a balanced recommendation should involve analysis from different angles. Therefore, we decided to use interdisciplinary indicators in a MCA. The MCA aimed at uncovering the advantages and disadvantages of a DMTR process, as well as score its overall performance based on sustainability indicators. We determined indicators related to environmental, social, economic, and technical aspects of the DMTR processes to include values from Dutch society and government, Sympany and other recycling companies. It can be concluded that this research resembles a policy-oriented research in which room is left for consideration of different values (Van Koppen, n.d.).

However, values can be conflicting. The indicators are largely in line with the predominant belief in the Netherlands and Europe that techniques should be profitable, because the economy is focused on this (European Union, 2020). Even though Sympany works as a non-profit organisation and has expressed little interest in the economic performance of the DMTR process, profitability as an indicator was included.

12.3.3 Execution of research

Even though the execution of our research was largely literature research, we experienced consequences during the data collection due to conflicting interests. We wanted to obtain as much data as possible about the indicators for the selected DMTR processes to use in the MCA and give an objective evaluation. However, the Scandinavian DMTR stakeholders were not able to share the data that we needed for the indicators, because of other priorities, time constraints, and privacy reasons. The latter were mainly related to finances and intellectual property. The effect was that we had to

make certain assumptions about the data that did not fully represent the true data of the DMTR techniques. The data gave adequate insight into the performances of the techniques, but the validity and objectivity could be questioned.

12.3.4 Multi-criteria analysis

Estimating the relative importance of weights of indicators and judging the contribution of each option to each performance criterion involve value-judgement. We have determined whether the score of an indicator in the MCA is favourable or not based on literature and logical thinking. This logical thinking is subjective and aims at what we want to achieve. It is a profitable, efficient, safe, and circular DMTR technique. Furthermore, experts in the field of textile recycling from Wageningen University & Research have assigned opinion-based weighting to the MCA. The subjectivity that pervades this should be acknowledged. While the experts focus attention on scientific performance, a core value of Sympany is also collaboration with other stakeholders, responsibility, and equity. This is not included in the MCA. An advantage of the MCA is however that the weights can be adjusted to the liking of the interpreter. This leaves the MCA open to some extent of objectivity, depending on the interpreter.

12.3.5 Interpretation, application of results, intervention

Interpreting data directly induces that the conclusion is subjective to the objective of the research. Whether these results will be applied in policy by Sympany depends on many factors, like priorities, opportunities, and availability.

12.4 Final evaluation

Only two DMTR cases were discussed due to limitations of time, resources, and accessible data. However, we think that understanding the performance of the techniques might help the commissioner to search and prepare for implementation of similar recycling techniques in the Netherlands. This could be done in collaboration with another company. During our research we have become more aware of the complexity, the current inefficiency and relevance of the topic. However, we still believe our recommendations on adjustments in the sorting process can alleviate problems of adequate sorting faced by Sympany.

Words: [2193]

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15 Appendices

Appendix A: Calculations for the indicators used in the multi-criteria analysis

Calculations Södra

For Södra the following calculations were used to obtain the data for the indicators for the MCA. For each indicator we explain how the values were calculated with the available data, data that was found through literature research or with an interview. Figure A-1 shows the relationship between the data of the total Södra company, the Södra Cell part and the OnceMore technique. Figure A-1 therefore displays the three different 'levels' within Södra. These levels were the basis for the assumptions used by the calculations for Södra, the assumptions are elaborated in chapter 8.1.1.

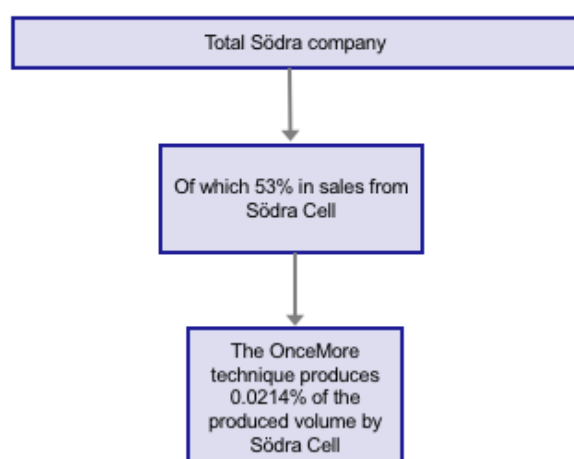


Figure A-1: Different levels within Södra and their ratio (Author, 2020), based on (Södra, 2020)

Environmental indicator, Operational water footprint; the blue component:

For the whole company, Södra uses 79 million m³ of freshwater. The only ratio between the whole company and Södra Cell provided, is the sales ratio, which is 53% (Södra, 2020). Therefore, the freshwater usage for Södra cell = 79,000,000 * 0.53 = 41.87 million m³. The ratio between Södra Cell and the OnceMore technique is the ratio between pulp production. The total pulp production of Södra Cell is 1,869,000 tonnes (Södra, 2020), for OnceMore this is only 400 tonnes (Södra, 2020a). Ratio = 400 / 1869000 = 0.00021401 = 0.0214%. Assuming that the ratio of the pulp production is the same as the ratio for the freshwater usage, the freshwater usage for OnceMore = 0.00021401 * 41,870,000 = **8,961 m³**. See also table A-1 further in the text.

Operational water footprint (m³/tonne PC input textiles)

Operational water footprint = 8,961 m³ / 20 tonnes = 448.05 m³/tonne

Environmental indicator, Specific energy consumption:

For the whole company, the energy usage can be calculated by adding the energy usage for fuel for production, electricity, district heating, and solid biofuels, which gives the following sum: $4,100,000,000,000 + 397,000,000,000 + 405,000,000,000 + 4,060,000,000,000 = 8,962,000,000,000 = 8.962 \text{ TWh}$. $8.962 \text{ TWh} = 32,263,200,000,000 \text{ Joule} = 32,263,200 \text{ Gigajoules}$ (Södra, 2020). For Södra cell this means an energy usage of $32,263,200 * 0.53 = 17,099,496 \text{ Gigajoule}$. For the OnceMore technique, this method gives an energy usage of $17,099,496 * 0.00021401 = \mathbf{3,659 \text{ Gigajoule}}$. See also table A-1 further in the text.

Specific energy consumption (GJ/conversion of 1 tonne PC input textiles)
 Specific energy consumption = $3,659 \text{ GJ} / 20 \text{ tonnes} = 182.95 \text{ GJ/ tonne}$

Environmental indicator, Direct carbon footprint of technique:

For the whole company, Södra emitted 0.6 million tonnes of CO₂ equivalents in 2018. In the meantime, the forests of their members stored 2.1 million tonnes of CO₂ and they had a substitution effect of 7.7 million tonnes of CO₂. Their net saving of CO₂ equivalents = $2.1+7.7-0.6 = 9.2$ million tonnes of CO₂ (Södra, 2020). For Södra cell this is $9,200,000 * 0.53 = 4,876,000$ tonnes of CO₂ equivalents. For OnceMore this is $4,876,000 * 0.00021401 = \mathbf{1,044 \text{ tonnes of CO}_2 \text{ equivalents}}$. See also table A-1 further in the text.

Direct carbon footprint of technique (CO₂ equivalents/tonne PC input textiles)
 Direct carbon footprint of technique = $1,044 \text{ tonnes of CO}_2 \text{ equivalents} / 20 \text{ tonnes} = - 52.2 \text{ tonnes CO}_2 \text{ equivalents/ tonne}$

Social indicator, Emission of dangerous substances/pollutants:

In the report of (Södra, 2020) it was stated that the Mörrum mill, where the OnceMore technique is situated, violated the regulations for dust, sulphur and chlorate in wastewater emissions in 2019.

Economic indicator, profitability:

The operating profits of Södra Cell are 2,511 million Swedish krona (Södra, 2020). For OnceMore this is $2,511,000,000 * 0.00021401 = 0.53737911 \text{ million} = 537,379.11 \text{ krona}$. See also table A-1 below.

Net sales/ tonne PC input textiles (euros/ tonne) (profitability)
 profitability = $537,379.11 \text{ krona} / 20 \text{ tonnes} = \mathbf{26,868.95 \text{ krona /tonne}}$

Table A-1: Calculation method used in this research for environmental, economic and technological indicators to obtain data for the OnceMore technique (Author, 2020).

	Level company	Fresh water (M³)	Energy usage (GJ)	CO ₂ equivalents	Operating profits (krona)	Efficiency (tonnes)
*0.53	Södra	79,000,000	32,263,200	9,200,000		8,881,119
	Södra cell	41,870,000	17,099,496	4,876,000	2,511,000,000	4,706,993
*0.00021401	OnceMore	8,961	3,659	1,044	537,379	1,007

Technological indicator, efficiency of technique:

There is no information about the efficiency of the technique for the OnceMore technique.

Technological indicator, circularity:

In 2019 Södra used 20 tonnes of PC textile input (Södra, 2020) to produce 400 tonnes of pulp as output (Södra, 2020a). The circularity = $20 / 400 = 0.05 = 5\%$.

Amount of PC textiles input (tonnes): 20 tonnes

Calculations Re:newcell

For Re:newcell the following calculations were used to obtain the data for the indicators for the MCA. For each indicator we explain how the values were calculated with the available data, based on our assumptions in chapter 8.1.1. The data was found through literature research or with an interview.

Environmental indicator, Operational water footprint; the blue component:

$377 * 1,000 \text{ m}^3$ per 1,000 tons of man-made cellulose fibre (Schultz & Suresh, 2017) and because Re:newcell produces 7,000 tons of dissolving pulp (Schultz & Suresh, 2017), we multiply the freshwater data with 7. $377 * 1,000 * 7 = 2,639,000 \text{ m}^3$

Operational water footprint (m^3/tonne PC input textiles)

Operational water footprint: $2,639,000 \text{ m}^3 / 7,000 \text{ tons} = 377 \text{ m}^3/\text{tonne}$

Environmental indicator, Specific energy consumption:

$21 * 1,000 \text{ GJ}$ per 1,000 tons of man-made cellulose fibre (Schultz & Suresh, 2017) and because Re:newcell produces 7,000 tons of dissolving pulp (Schultz & Suresh, 2017), we multiply the energy usage data with 7.

$21 * 1,000 * 7 = 147,000 \text{ GJ}$

Specific energy consumption (GJ/conversion of 1 tonne PC input textiles)

Specific energy consumption = $147,000 \text{ GJ} / 7,000 \text{ tons} = 21 \text{ GJ/ tonne}$

Environmental indicator, Direct carbon footprint of technique:

$-2 * 1,000 \text{ ton CO}_2$ equivalents per 1,000 tons of man-made cellulose fibre (Schultz & Suresh, 2017) and because Re:newcell produces 7,000 tons of dissolving pulp (Schultz & Suresh, 2017), we multiply the GHG emissions data with 7.

$-2 * 1,000 * 7 = -14,000 \text{ ton CO}_2$ equivalents

Direct carbon footprint of technique (CO_2 equivalents/tonne PC input textiles)

Direct carbon footprint of technique = $-14,000 \text{ ton CO}_2 \text{ equivalents} / 7,000 \text{ tons} = -2 \text{ ton CO}_2 \text{ equivalents/ tonne}$

Social indicator, Emission of dangerous substances/pollutants:

In the report of (Schultz & Suresh, 2017) it was stated that Re:newcell emitted PM 2.5 particles and 'hazardous ambient air contaminants', which are dangerous pollutants.

Economic indicator, profitability:

$-17,868 * 1,000$ Swedish krona = $-17,868,000$ krona (Re:NewCell AB., n.d).

Net sales/ tonne PC input textiles (euros/ tonne) (profitability)

Profitability = $-17,868,000 \text{ krona.} / 7000 \text{ tonnes} = -2,552.571 \text{ krona /tonne}$

Technological indicator, efficiency of technique:

Data obtained from an interview with Re:newcell: **90%**

Technological indicator, circularity:

Data obtained from an interview with Re:newcell: **100%**, so no virgin materials are needed in the process.

The amount of PC textiles input is: 7 kilo tonnes (7,000 tons) (Schultz & Suresh, 2017)

Appendix B: Calculations for the standardization of environmental indicators in multi-criteria analysis

In the MCA, the environmental indicators are shown as percentages of the virgin cotton production, the calculations are shown below.

For the blue component of the operational water footprint indicator, the value for the production of virgin cotton fibres is 5,730 m³ water / ton textile virgin cotton fibres (Bartl, 2009). The blue component is 33% of the total water footprint for cotton (Water footprint network, 2017), so the blue component is 5,730*0.33 = 1,890.9 m³ water / ton. The percentages of Södra and Re:newcell for the blue component of the operational water footprint compared to the virgin cotton fibre production are:

$((1,890.9 - 448.05)/1,890.9)*100\% = 76.3\%$ decline for the blue water footprint of the Södra OnceMore technique compared to virgin cotton textile production.

$((1,890.9 - 377)/1,890.9)*100\% = 80.1\%$ decline for Re:newcell compared to the blue water footprint for virgin cotton textile production.

For the specific energy consumption indicator, the value for the production of virgin cotton fibres is 15 Energy Consumption kWh/kg textile virgin cotton fibres (Rana et al., 2015). This is recalculated into GJ/ton: 15 kWh/kg = 15,000 kWh/ton = 54,000,000 Joule/ton = 54 GigaJoule/ton. The percentages of Södra and Re:newcell for the specific energy consumption compared to the virgin cotton fibre production are:

$((182.95 - 54)/54)*100 = 238.8\%$ increase for Södra compared to the energy consumption for virgin cotton production.

$((54-21)/54)*100 = 61.1\%$ decline for Re:newcell compared to the energy consumption for virgin cotton production.

For the carbon footprint indicator, the value for the production of virgin cotton fibres is 2.0 ton CO₂ equivalents/ tonne textile virgin cotton fibres (Bartl, 2009). The percentages of Södra and Re:newcell for the carbon footprint compared to the virgin cotton fibre production are:

$((2--52.2)/2)*100 = 2710\%$ decline for Södra compared to the energy consumption for virgin cotton production.

$((2--2)/2) *100 = 200\%$ decline for Re:newcell compared to the energy consumption for virgin cotton production.

The percentages of Södra and Re:newcell compared to the virgin cotton production are shown in table B-1 below.

Table B-1: Percentages of Södra and Re:newcell compared to the virgin cotton production (Author, 2020).

Indicator	Value virgin production	Value Södra	Value Re:newcell	Percentage Södra	Percentage Re:newcell
Blue component operational water footprint (M ³ /ton)	1,890.9	448.05	377	76.3% less than virgin	80.1% less than virgin
				++	++
Specific energy consumption (GigaJoule/ton)	54	182.95	21	238.8% more than virgin	61.1% less than virgin
				---	++
Carbon footprint (ton CO ₂ eq/ton)	2	-52.2	-2	2710% less than virgin	200% less than virgin
				+++	+++