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Environmental assessment of end-of-life textiles in Denmark

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Abstract

The European Union is on its way to a circular economy through eco-design, waste prevention, reuse and recycling of products and materials. This study analyzes the environmental effects of end-of-life textile management in Denmark. First, a Mass Flow Analysis was performed for textile flows from sales to consumers to end processes, which revealed that absolute consumption has grown significantly over the last years. Data on generation and management of used textiles indicated that around 40% are discarded with residual waste, another 40% are captured by collection for reuse channels, and around 17% constitute user-to-user flows. A Life Cycle Assessment was carried out showing the potential environmental effects. This assessment included system expansion to cover the impact of the most likely final cycle of end-of-life, which differ substantially depending on the geographical location of reuse. A sensitivity analysis addressed the key factor of substitution. Overall, the results show that reuse is preferable to other end-of-life options- even with low primary production substitution rates.

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Keywords: Textiles;Circular Economy;Reuse;Mass Flow Analysis;Life Cycle Assessment;Denmark

1. Introduction

Reuse is the first step after prevention in the waste hierarchy and a crucial strategy in the so-called "circular economy". Today, a main goal of the European Union (EU) is to "close the loop" of product life cycles with the circular economy. A better way of waste collection and management could lead to high rates of reuse and recycling by putting back into the economy whole products or materials [1].

Textiles are often discarded once they are perceived as being damaged or have gone out of fashion. The discarded textiles contain reusable items which could have an extended lifetime in their repurposed form. Therefore many charitable organizations (e.g. Red Cross) and private collectors (e.g. Trasborg Denmark) gather used textiles by means of containers, and resell them as second-hand textiles in Denmark and abroad [2]. In 2010, 89,000 metric tons (t) of used textiles were sold in Danish markets [3]. This corresponded to 16 kg per capita per year [2]. This amount also corresponded to 338 kg CO_2 equivalent and 72 liter water consumption in the production stage (per person per year) [4]. The production of textiles has significant environmental costs in relation to water consumption, use of chemicals and use of land [5]. In a survey, the European Commission mentioned that clothing accounts 2% to 10% of consumers´ environmental impacts [6]. Extending the lifetime of textile can thus have substantial environmental benefits by avoiding the production of new textiles [7].

According to Tojo et al. [2] 14% of all Danish textile exports were used clothing. From 2010 and on, the export of used textiles has been fluctuating but followed a relative downward trend [8]. During the same period, the growth rate in flea markets and online sales increased by 24% [5]. Previous surveys estimated that, 46% of the used textiles are collected for reuse and recycling via Non-Governmental Organizations (NGOs) and private collectors, whereas the rest

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of them ended up in mixed waste streams for energy recovery [9].

Previous studies reported material flows for textiles for Denmark [2, 3]. However, the data used is outdated (around 2010), and does not include direct reuse channels. Better knowledge of textile flows is important in order to exploit the circulation of used textiles. Additionally, Schmidt et al. [3] carried out a Life Cycle Assessment (LCA) with data from 2010 focusing on treatment of several types of fiber. They found that reuse has substantial benefits; however, they did not include the difference in end disposal routes between reuse options.

The main objectives of this study were to:

- Update information on textile material flows within Denmark, from consumption to the various end-of-life (EoL) reuse and disposal routes;
- Assess the environmental effects of different end-of-life management options, including the integrated system found in Denmark.

2. Methodology

Mass flow analysis (MFA) was the primary method used to estimate textile flows within Denmark. MFA is a tool for decision support in waste and resource management [10]. STAN 2.5 (Substance flow analysis) software was used for the visual presentation of MFA results. Life Cycle Assessment (LCA) was used to understand the life cycle consequences and to get a quantitative evaluation of the environmental consequences of EoL of textiles. The environmental assessment was applied as a consequential LCA (cLCA). Background LCI data was based on the Ecoinvent 3.1 Life Cycle Inventory (LCI) database (unit market process) and the assessment was facilitated by the LCA software SimaPro 8.3.0.0. Impact assessment was carried out with the ILCD (International Reference Life Cycle Data System) 2011 midpoint+ method. While results in all impacts categories were checked, only climate change potential impact is reported here.

2.1. MFA: Mapping flows in Denmark

After identification of all processes and flows for the year 2016, the stock and flows were quantified. The quantification of flows started from the time the textiles were consumed by the users until their EoL. Data sources included information from the NGOs, Statistics Denmark (trade), private collectors and other existing research studies. A description of each process and flow is given in Tables 1 and 2 respectively.

2.1.1. Consumption of textiles

To calculate the total flow of the consumed textiles, the total flows of imports and exports were quantified [8]. More specifically, they were analyzed by the EU Combined Nomenclature (CN) for the commodity of textiles. This included all 61 and 62 CN-codes. Moreover, the sales data was retrieved from the market research firm Euromonitor International [11]. According to Euromonitor International, this data was collected from different sources such as national statistics, trade associations, trade press etc. These numbers were reported in units which were converted into weight by using mass/price (weight/kroner) ratio based on average Danish export and import numbers from 2011 to 2016 [3].

2.1.2. Reuse of textiles and stock

At the EoL stage, textiles are distributed towards several destinations. An amount is reused by users who give their clothes to other users (user-to-user reuse) or sell them at flea markets or on the internet. It is difficult to determine data on this flow. For this reason, user-to-user reuse was initially left uncalculated and data reconciliation with Stan 2.5 was carried out to give insight into this flow, when all other flows were determined.

Another significant amount ends up being separately collected mostly by charities. Citizens discard their textiles in containers which NGOs places at various locations all over Denmark. The NGOs sort a portion of the collected textiles to take the best quality for resale in their second-hand stores and the rest is exported. There is also a private collector who collect textiles only for export. In addition, there is a portion of the collected textiles that cannot be reused, which is sent to recycling centers for material recovery or to incineration plants. The recycling efficiency is 93%- almost all of the fiber of the used textiles is recovered [12].

According to Laursen et al. [13], the lifetime of a T-shirt is around 5 years. Using this as an indication, it can be assumed that textiles remain in households as “stock” at least 5 years. Thus, we estimated household stock to be the sum of textiles consumption between 2011 and 2015. This also meant that there should be possible to see a connection between the total end-of-life textiles in 2016 and consumption in 2011.

Table 1. Process Description

Process	Description
1.Producers	Manufacturers and resellers of new products
2.New products	Put on market textiles
3.Users	Users of textiles and stock
4.Mixed waste	Textiles in mixed municipal solid waste
5.Used items	Textiles collected separately for reuse
6.User-to-user reuse	Direct reuse people-to-people
7.Preparation for Reuse	Collected textiles in pre-sorting facilities for reuse
8.Second-hand stores	First stop in the reuse phase
9.Incineration	Final stop of discarded textiles
10.Recycling	Used textiles going for recycling

2.1.3. Mixed waste

Lastly, there is a flow of textiles that ends up with mixed waste in the incineration plant. This flow will then be used for energy recovery (final stop of discarded textiles). This flow corresponds to the amount of textiles that end up in incineration plants from households and the business sector. More specifically, reconciliation in data was carried out with a minimum proportion of textiles in mixed waste 1.5% and maximum 3% [14, 15].

Table 2. Flow Description

Flows	Description	Sources
$A_{0\text{-}1}$	Resources used in textile production	Not calculated
$A_{1\text{-}2}$	New products of textiles in market	Not calculated
I_2, E_2	Import and export of new products	Not calculated
$A_{2\text{-}3}$	Use of textiles from consumers	Based on [8, 11]
$A_{3\text{-}4} = A_{4\text{-}9}$	Textiles collected through the municipal waste collection system	Based on [14, 15]
$A_{3\text{-}5}$	Used textiles collected for reuse	Data reconciliation with Stan 2.5
$A_{5\text{-}6} = A_{6\text{-}3}$	Used textiles going for direct reuse	Data reconciliation with Stan 2.5
$A_{5\text{-}7}$	Used textiles going to pre-sorting facilities	Sum of flows ($A_{7\text{-}8}$, A7-9, $A_{7\text{-}10}$, E_7)
$A_{7\text{-}8} = A_{8\text{-}3}$	Textiles processed in second-hand stores	Based on [16]
$A_{7\text{-}9}$	Textiles waste going for energy recovery	Based on [17]
$A_{9\text{-}0}$	Residues and flue gas from incineration plant	Sum of flows ($A_{4\text{-}9}$, $A_{10\text{-}9}$, $A_{7\text{-}9}$)
E_7	Export used textiles	Based on [8]
$A_{7\text{-}10}$	Textiles send for material recovery	Based on [2]
$A_{10\text{-}9}$	Fibre waste end up to incineration plant	Based on [12]
$A_{10\text{-}0}$	Materials recovered as secondary resources	Material recovered in market

2.2. LCA: Scenario Descriptions

Five foreground scenarios were constructed in order to compare selected handling options for used textiles. This included four theoretical scenarios, elaborating on individual options, and one scenario that represents the integrated management system found in Denmark.

The functional unit was the same for all scenarios "the management of one metric ton of used textiles discarded by consumers from the point of collection until its final destination". Due to a lack of unit processes in the Ecoinvent database, wool products had to be redistributed between the two major fiber types put on the market in Denmark: cotton 56% and polyester 44%. Recycling, which is a minor management option, was not included in the LCA.

The scenarios are described below:

Scenario 0: Reference without reuse in Denmark - A part of the current system in Denmark is that households and business sectors discard textiles in municipal mixed collection system (green bins). Incineration is a source of providing electricity and district heating in the Danish society. The energy efficiency of new plants is 76% for heat production and 23 % for electricity production [3]. The marginal electricity supply was (Ecoinvent, high voltage DK, market) a combination of hard coal (70%) and wind (30%). The heat marginal was natural gas (boiler). Cotton and polyester are incinerated considering a lower heat value (LHV) of 17 GJ/ton and 21.5 GJ/ton respectively [3].

Scenario 1: Reuse in Denmark - Another part of the current system in Denmark is that households and business sectors discard the textiles in a separate collection system (donations, NGO containers, second-hand shops etc.). In sorting facilities approximately 5% of the textiles collected are determined as waste and end up in the incineration plants [17]. In the scenario we assumed that the rest is reused in the country until the final end-of-life (incineration).

Scenario 2: Full reuse in Europe - Meanwhile another part of the management system in Denmark exports the collected used textiles unsorted ("original") for sorting in facilities around Europe, set up for this purpose. It was assumed that the pre-sorting facilities in Denmark are just a stop before exporting. In this study Poland was taken (as proxy) for the first receiving country for the sorting process [3]. In the sorting facilities in Poland, 10% of the textiles are discarded and end up in landfill [3]. After reuse, it was assumed that 70% of the textiles are incinerated and 30% are directed to landfill. As waste treatment, incineration is gaining ground in Europe, but district heating is largely unavailable outside Scandinavia. Therefore, it was assumed that only electricity is produced from incineration with an efficiency of 23% [3]. The avoided marginal electricity supply in this case was a combination of coal (10%) and nuclear (85%).

Scenario 3: Full reuse in Rest of the World (RoW) - It was beyond the scope of this study to model reuse in each country to which Denmark exports textiles. Therefore, a generic RoW model was determined for this scenario. It was assumed that Denmark exports the collected used textiles "original" to Europe and then to RoW. Textiles are sorted in sorting facilities in Europe. Poland was the first receiving country for the sorting process. In the sorting facilities, 10% of the textiles are discarded and end up in landfill [3]. Europe is an intermediary for the export of used textiles in Asia and Africa. The transportation is performed by freight lorry till harbour, by ship till Asia and/or Africa and then by freight lorry to the point of user distribution. It is known that landfilling and especially open dumping are very common in this part of the world. Thus, after reuse the final end-of-life for the textiles is disposal in landfills.

Scenario 4: Integrated management of textiles in Denmark - Scenario 4 is created to give a general view of the management system of textiles in Denmark. It combines the previous four scenarios. The functional unit was distributed in the whole system according to the determined mass flows (fig. 1, 2). It has to be mentioned that the process of user-to-user transfer is not taken into account. This direct reuse never comes into end-of-life and cannot be influenced by changes in the management system. Fig. 2 illustrates the flowchart of

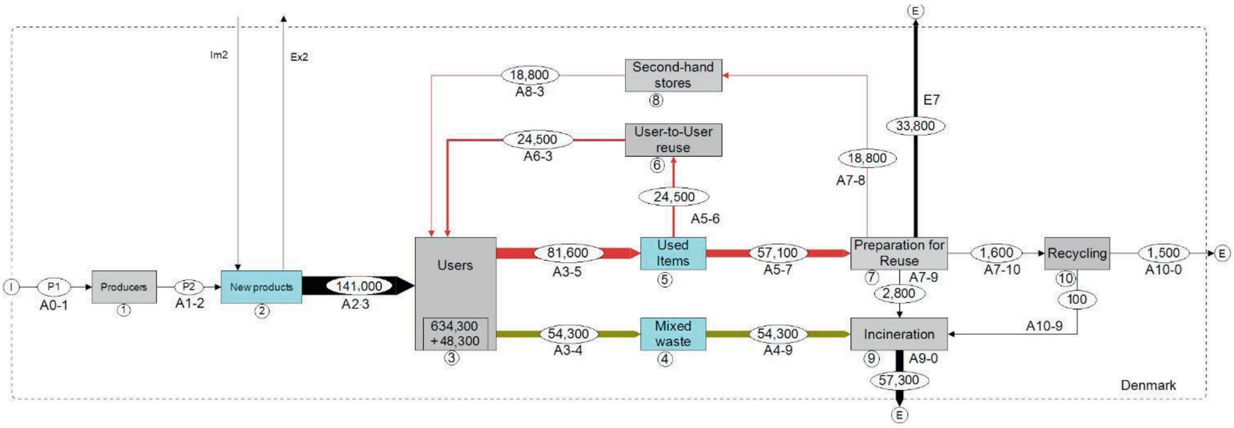

Fig. 1 Mass Flow Analysis of used textiles along their life stages within Denmark, in tones (2016)

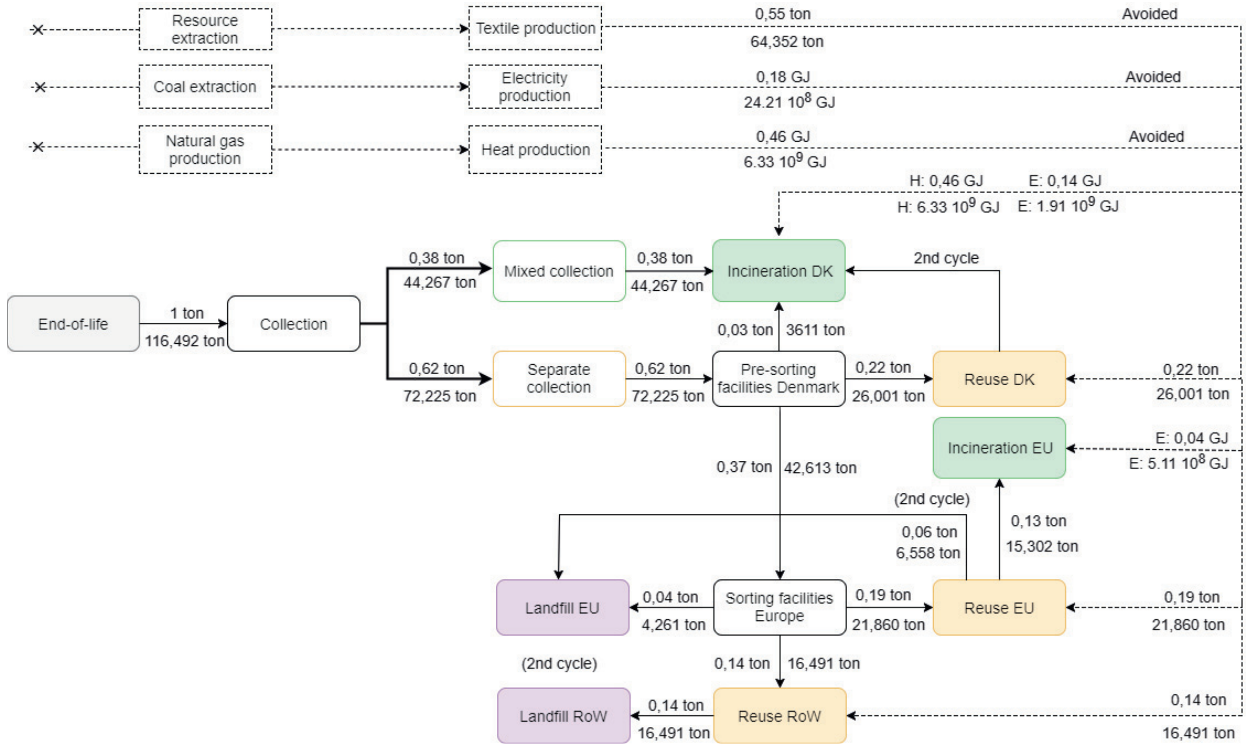

Fig. 2 Flowchart of Scenario 4, per 1 tonne and per total tonne of the system (116,492 t), dotted lines represent avoided flows, all mass flows are for the year 2016.

scenario 4 showing the distribution of 1 t of textiles and the distribution of 116,000 t of textiles for 2016.

2.2.1. Sensitivity Analysis

In this study, the substitution factor expresses the amount of new textiles which are replaced by reuse. A substitution factor of 1 is used as baseline. A high substitution factor is most likely to be found where the buyer purchases used textiles because of lifestyle attitude or environmental decisions. On the other hand, a low substitution factor is likely to be found where the purchase is rare. Because of these cases, the substitution factor varies from person to person. In Europe the relation between second-hand textiles and new purchases differ from country to country. A higher substitution factor can be assumed in scenario 3 (reuse in RoW) based on socioeconomic reasons. To represent different attitudes but also that the second life of a textile product might be shorter than the first because of degradation, a sensitivity analysis was carried out to examine the differences in results. In the sensitivity analysis the substitution factors are different for each scenario (Table 3).

Table 3. Substitution factor

Foreground scenarios	Baseline substitution factors	Sensitivity substitution factors
Scenario 0	n.a	n.a
Scenario 1	1	0.3
Scenario 2	1	0.6
Scenario 3	1	0.8

3. Results and Discussion

3.1. MFA

The mass balance of the flows is illustrated in fig.1. The amounts in fig.1 indicate how the worn textiles are distributed within Denmark in 2016. The amount of used textiles that end up in incineration plants for energy recovery is roughly the same as the amount of textiles separated for reuse. An amount of 40.5% of used textiles are collected for reuse and recycling via NGOs and private collectors, while 38.5% ended in mixed waste for incineration. After data reconciliation it was estimated that 17% of used textiles are reused through user-to-user channels. It was estimated also that from 2011 to 2016 there is a net stock increase representing approximately 4% of the used textiles (48,000 t), while the total stock could be around 650,000 t or 114 kg per capita. However, according to Watson et al. [9], 46% of used textiles were collected by NGOs and private collectors for reuse and recycling, whereas the rest of them end up in mixed waste streams for energy recovery. The difference was expected because of the increased consumption of textiles and due to the fact that in the current study direct reuse was taken in to consideration as well. So, the total reuse is 57, 5% of the consumed textiles.

It is worth noting that the amount of textiles recycled in Denmark is very small. According to Schmidt et al. [3] very few textiles go for recycling mainly due to technical challenges. Also, there are few places that sell used textiles in industries for production of rags or wipers [2].

Compared to the total Danish consumption from 2010, in 2016 the total consumption was 20 kg per capita of textiles [8]. Also, in 2016 9.4 % of all textile exports were used textiles.

3.2. LCA

The results are presented per functional unit and for the full system, which includes system expansion to include avoided energy and primary production of textiles. Negative values indicate positive effects from the reuse of textiles, whereas positive values indicate an impact. This study focused on environmental consequences in climate change. However, the characterization phase of impact assessment showed that there are also significant benefits in categories related to water and chemicals (Human toxicity, freshwater ecotoxicity, water resource depletion).

Fig. 3 (a), shows the potential environmental benefit that is achieved by replacing virgin textiles (factor 1). It has been indicated that reuse has positive effects in all scenarios. Even in scenario 0 (incineration), it seems that the energy production from the incineration of the fibers has benefits. Avoiding the use of coal and natural gas for the energy production shows savings of CO_2, even if in small quantities. It is also noticeable that the reuse in Europe and in RoW has almost the same amount of avoiding CO_2 emissions. The main reason for this small difference is because incineration does not have large benefits in central Europe and they still have landfill. Finally, scenario 4 shows the amount of emission savings (negative contribution) for the management system of textiles in Denmark (8640 kg CO_2 eq. per tonne). In all scenarios, reuse is associated with significant environmental benefits compared to incineration. Impacts, consist mainly of direct process emissions from incineration, emissions due to transport to Europe and to RoW and energy consumption in sorting facilities. Fig. 3 shows the total amount of savings in kilogram CO_2 equivalent (eq.). In Scenario 4, which represents the overall management system in Denmark, the total amount of savings is $1.01x10^9$ kg CO_2 eq, if calculated for 116,000 t of used textiles managed in the system.

Fig. 3 (b) shows that there is a meaningful relationship between environmental benefits and the substitution factor. In scenario 1 the environmental benefits from CO_2 savings have a significant decrease. However, even with such a low substitution factor, the reuse scenario in Denmark is better than the scenario 0 (incineration). The difference in the amount of CO_2 savings remains significant. The difference between scenario 2 and 3 seems to get bigger with the difference in the factor. The lower factor did not make the results worse since the benefits from the avoiding processes compared to collection and transport are remarkable. Moreover, for 116,000 t of used textiles, the total amount of savings is $5.32x10^8$ kg CO_2 eq. or around half the baseline.

According to Woolridge et al. [18], the quantity of virgin material that was avoided, offset the environmental burden during the processing. Furthermore, Farrant et al. [7] mentioned that their LCA results showed that the collection, processing and transport of second-hand textiles has insignificant impacts on the environment compared to the savings that are achieved by replacing virgin clothing. Thus, our results are in line with the results from previous studies. Furthermore, Schmidt et al. [3] carried out a sensitivity analysis using 0.66 and 0.33 as a substitution factor in reuse scenarios. Their result agreed with the results of the current study, giving a comprehensive view of the reuse benefits.

The large climate savings presented above, can (alone) be misleading, as they reflect only the EoL part of the full Lifecyle of textiles consumed in Denmark. Including upstream production and use phases would probably result in net climate burdens, overall. Nevertheless, our results show that part of the impact of textile consumption can be mitigated at EoL, and that reuse is the best option in this case.

4. Limitations

This study aimed to undertake a comprehensive quantification in the flows referred to Danish management system.

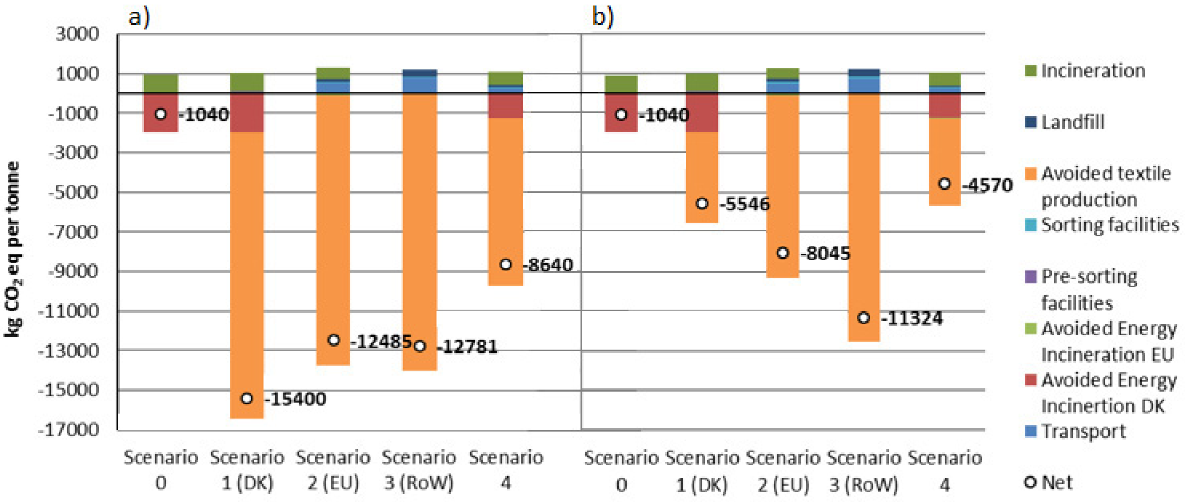

Fig. 3 Effects in climate change in kg CO_2 eq. per ton of textile for all scenarios (a) Main results; (b) Sensitivity Analysis results with modified substitution factors according to Table 3

The environmental effects related to climate change were the main outputs of this study.

4.1. Uncertainties related to MFA

The most important uncertainty was the conversion from units to weight using the ratio weight/kroner. Euromonitor International [11] provided data in units which was the main reason for the conversion. The weight was based on Danish export and import numbers, taking the average weight of both. This can be a source of error and uncertainty. In another study, the ratio based only in export data [3]. Furthermore, there is in general limited data available on textile flows throughout their life cycle. For the quantities in reuse and export flows, it is obvious that such important flows should be better monitored by authorities.

4.2. Uncertainties related to LCA

The main limitation for the LCA results was the substitution factor. For this reason, a sensitivity analysis was carried out to illustrate realistic results of the benefits.

Furthermore, the choice of the fiber types was based on scarce data in the Ecoinvent database. The absence of data in the software database did not allow to include other types of fiber, such as wool. In other studies, reuse of wool had significant environmental benefits.

5. Conclusions

The study provides increased understanding of the used textile flows in Denmark. We specifically estimate that quite substantial amounts of textile products (17%) gain a second life through direct user-to-user channels. The manufacture and use of textile products causes high environmental impact. Reuse, even with a low substitution of primary products showed high benefits (especially climate savings).

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