

Research article

# Do We Save the Environment by Buying Second-Hand Clothes? The Environmental Impacts of Second-Hand Textile Fashion and the Influence of Consumer Choices

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## Abstract

Re-use is a high R-ladder strategy in a circular economy. The environmental impacts of re-use are often underreported. This research aims to gain insights into second-hand clothing's lifecycle impact. Life cycle assessments were conducted for four frequently traded second-hand clothing items, namely t-shirts, dress, trousers and sweaters. Three types of consumers were distinguished (primary user, primary conscious user and second-hand user) and three behaviour scenarios were modelled (fashionable, average and attached consumers). We found that within the same behaviour scenario, embracing second-hand consumption instead of buying new clothes leads to up to 42% lower impacts for climate change and cumulative energy demand, 42-53% for freshwater eutrophication, and 35-53% for water scarcity footprint per use. Reuse mitigates impacts, and is particularly beneficial for high-production impact clothing items. Consuming a rarely used second-hand item can even lead to higher impacts than using a new clothing item which has longevity.

**Keywords:** Lifecycle Assessment, Clothing, Fashion, Reuse, Re-Commerce, Circular Economy, Consumer Behaviour

## 1. INTRODUCTION

The textile industry is responsible for around 10% of global GHG emissions (European Parliament, 2024a). Clothing sales are expected to triple in the coming three decades (Ellen MacArthur Foundation, 2017). Following this path, the textile industry could consume more than 26% of the total carbon budget related to the 2°C pathway (Ellen MacArthur Foundation, 2017). This pathway of more production leads to higher resource use and more waste. To stay within the planetary boundaries, the textile industry must reduce its impact. An impact reduction of 30% - 100% is required in key impact categories such as climate change, water eutrophication, and land usage, before 2050 (Sandin et al., 2015). As global climate goals increasingly get out of reach (IPCC, 2023), the urgency for the clothing industry to improve its sustainability increases.

The textile industry's material flow is almost entirely linear; almost all used materials end up as waste (Ellen MacArthur Foundation, 2017). The material flow analysis by Amicarelli & Bux (2022) estimated that in 2018 between 33-40% of the textile waste was separately collected in Europe. However, approximately 20% of these collected textiles end up as industry wipes or serve other downcycling functions (Köhler et al., 2021). Furthermore, research revealed a continuous increase in global fibre production, reaching an unprecedented 116 million tonnes in 2022. Despite years of steady growth, textile recycling saw a decline, dropping from 8.5% in 2021 to 7.9% in 2022. Moreover, most of these recycled fibres originate from plastic bottles; less than 1% of the fibres globally were from pre- and post-consumer recycled textiles (Textile Exchange, 2023). Moving to a more circular economy is critical for sustainable textile production and consumption (European Commission, 2015). In March 2024 the European Parliament introduced an

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amendment to the Waste Framework Directive, where an obligation for member states to establish separate collection systems for textiles by 2025 is included in the Extended Producer Responsibility (EPR) schemes. With this EPR, producers and retailers of textile products would be responsible for the textile waste management costs (separate collection, sorting and recycling) (European Parliament, 2024b). Several countries have plans for EPR regulation, but currently only France and The Netherlands have implemented such a scheme (Ellen MacArthur Foundation, 2024).

Studies generally agree that both the reuse and recycling of clothing lead to a reduction in environmental impact compared to incineration and landfilling (Sandin & Peters, 2018). By increasing the use efficiency, reuse and recycling decrease the demand for raw materials and reduce waste. Therefore, improving these practices is essential to the sector's pathway to sustainability. Research shows that clothing reuse is potentially more beneficial than recycling (Sandin & Peters, 2018; Schmidt et al., 2016), which is the expected result following the hierarchy of circularity strategies where reuse is considered more desirable than recycling (Potting et al., 2017). Moreover, most of the recycled textile is downcycled to industrial rags, insulation materials, etc. (Schmidt et al., 2016). Recycling technologies that can maintain the original quality of the textile are still in their infancy, with only mechanical cotton fibre recycling and 100% polyester chemical recycling being done on a small industrial scale (Harmsen et al., 2021; Schmidt et al., 2016). However, surprisingly, both scientific literature (Sandin & Peters, 2018) and industry attention often focuses on textile recycling, potentially passing over the easier loop-closing reuse strategy.

A few studies have reported the impact of the reuse of clothing, most concluding that it leads to significant environmental savings, as the additional impacts from processing and transport are significantly lower compared to the impacts of virgin material production (Babel et al., 2019; Farrant et al., 2010; Schmidt et al., 2016). However, in reviewing the research on this topic, Sandin & Peters (2018) determined that more studies should be done and more inventory data should be gathered on the collection and sorting processes. Often these processes are excluded, inducing the risk of underestimating the environmental impact of reuse. Hence, the lack of original data on these processes should be addressed.

Furthermore, consumer behaviours on the use phase of the clothing have a significant impact on the life cycle impacts of clothing. Many studies reported on the impacts of the use phase, especially on different scenarios regarding washing and drying behaviour (Beton et al., 2014; Cotton Incorporated, 2017; Sandin et al., 2019). However, the life cycle environmental impacts associated with different consumer behaviours, for example, regarding the frequency of use before disposal are rarely investigated. In addition, little is reported in the literature about the environmental impacts attributed to different consumer types (e.g. primary user or secondary user) regarding the use cycle of their clothes (new or second-hand), and how they dispose of their items (household waste or provision for reuse). All these factors could be influential for the lifetime impacts of clothing.

This research aims to fill these knowledge gaps by answering the question: How do consumer choices regarding the use of new and second-hand clothing influence the environmental impact of their clothing consumption? We analysed reuse case studies of four clothing items using environmental life cycle assessment (LCA) and gathered empirical data on the processing for reuse (collecting, sorting, and trading). The outcome of this study has two objectives. Firstly, we aim to provide evidence to consumers to act on reducing the environmental impacts of clothing consumption, informing them about the effects of second-hand (re-use) consumption. Secondly, the study can be used to inform policymakers, fashion re-commerce companies and the general public on where to focus the efforts of influencing consumer behaviour, e.g., implementing consumer nudges, or nurturing bottom-up collaborative consumption initiatives.

## 2. THEORETICAL FRAMING AND METHODS

### 2.1 Goal & scope

The goal of this LCA was to determine and compare the environmental impact of being dressed with new and second-hand items. We aim to understand the influence of primary and secondary clothing production, trading, and consumption patterns on the overall environmental impacts. The functional unit (FU) was defined as *one consumer being dressed with one item once*. This FU was defined in such a way as to allow comparison across different consumer types and different clothing items. This functional unit normalises the impacts to *one use*. The frequency of use was reflected in different behaviour scenarios. The study took a cradle-to-grave approach, including all life cycle stages from production, consumption, trading, and reuse to end-of-life. The geographical scope of the production phase was Asia (for more detailed information, see the supplementary material), and the retail-, (re)use- and end-of-life (EoL) phases were assumed to take place in the UK. This scope was defined as such because most primary clothing consumed in the UK is produced in Asia, and the case study data for second-hand clothing retailing and trading was obtained from a fashion re-commerce company operating in the UK.

We chose four clothing items: a t-shirt, a dress, a sweater, and a pair of trousers, because they are the most processed items in 2021-2022 by the second-hand trading company. A previous study also indicated that these are the most consumed clothing items in the UK (Ellebaek Laursen et al., 2006). Table 1 shows the items selected and their technical specifications. The most used material for clothing is cotton, followed by polyester (Beton et al., 2014). T-shirts and trousers are often made of knit and woven cotton respectively, and sweaters most often consist of a cotton-polyester blend (Beton et al., 2014; Nolimal, 2018). The fourth category investigated was a 100% polyester dress to represent the large number of items produced from polyester fibres.

*Table 1. Details of the Clothing Items Investigated. A Yarn Count Was Specified as Van Der Velden et al. (2014) Showed That Energy Use Differs Significantly for Producing and Using Yarn of Different Fineness. The Dtex Chosen Shows the Dress to Be Made of Much Finer Yarn, the Trousers of Much Thicker and Heavier Yarn, While the T-Shirt Is Also Made of Relatively Fine Yarn*

	T-shirt	Dress	Trousers	Sweater
<b>Material</b>	100% cotton	100% polyester	100% cotton	50% cotton, 50% polyester
<b>Weight</b>	180 gram	500 gram	450 gram	450 gram
<b>Fabric</b>	Knitted	Woven	Woven	Knitted
<b>Yarn count (fineness)<sup>1</sup></b>	150-200 dtex	115 dtex	470 dtex	250 dtex

<sup>1</sup> Dtex measures the linear density, the number of grams per 10 000 meters of yarn. The higher the dtex, the heavier and denser the yarn, and the lower the value, the finer the yarn.

Defining consumer profiles according to their likely behaviour is one of the main approaches used in LCA to assess the variability of impacts according to different consumers (Polizzi et al., 2016). So in order to; 1) distinguish primary and secondary users, and 2) distinguish different types of primary users, three main consumer types were established:

1. *Primary users* who buy a new item, use it for a while, and then throw it away.
2. *Primary conscious users* who buy a new item, use it for a while, and then make it available for reuse.
3. *Second-hand users* who buy a second-hand item, use it, and then throw it away.

The lifetime of the use of clothing (per consumer) is often not predominantly determined by its technical lifetime but by consumer choices and personal preferences (WRAP, 2017). For example, a dress can be disposed of not because it is worn out and unwearable, but because it is considered out of fashion. To explore the influence of these choices and preferences, behaviour scenarios with different numbers of uses were investigated. Within each *consumer type*, we further distinguish different *behaviour scenarios*: fashionable users, attached users and average users. The three behaviour types are summarised as follows:

For an *average user*, the average number of times a person uses a clothing item (i.e., average use) was estimated based on literature (and described in section 2.2.4.) and adjusted in each consumer behaviour scenario to reflect the corresponding use behaviour.

The *fashionable user* represents a consumer who desires a high turnover rate in their wardrobe, and the clothing items are used much less than the average user.

The *attached user*, in contrast, tends to keep wearing the same clothes for as long as possible.

Table 2 shows the summary of the different consumer types and behaviour scenarios and the assumed number of uses depending on the different consumer behaviours. In the table, the number of uses is expressed as a fraction of the number of uses for an average baseline use. E.g., the *primary fashionable user* is assumed to use an item for only 25% of the amount an *average user* would.

The difference between the *primary user* and *primary conscious user* consumer types is the disposal method; EoL or to re-sale for reuse. As the *attached user* represents a consumer who tends to use their clothes for as long as possible this behaviour scenario assumes that no additional use cycle is possible anymore. Hence for the *primary conscious user* type there is no *attached* behaviour scenario.

Table 2. Consumer Behaviour as Modelled for the Different Scenarios. The Numbers Between Brackets Function as an Example; They Indicate the Number of Times Each Consumer Would Wear a T-Shirt Before Discarding or Selling. For the Other Clothing Items, the Uses per FU for the Different Scenarios Are Shown in the  $S_i$ , Table S12

Consumer behaviour scenarios		Fraction of lifetime	Method of EoL: disposal
Consumer types	Behaviour scenarios	compared to an average use	or re-sold for reuse
<i>Primary user</i>	<i>Fashionable user</i>	0.25 (10) <sup>a</sup>	EoL <sup>b</sup>
	<i>Average user (baseline)</i>	1 (40) <sup>a</sup>	EoL <sup>b</sup>
	<i>Attached user</i>	2 (80) <sup>a</sup>	EoL <sup>b</sup>
<i>Primary conscious user</i>	<i>Fashionable conscious user</i>	0.25 (10) <sup>a</sup>	Re-sold for reuse
	<i>Average conscious user</i>	1 (40) <sup>a</sup>	Re-sold for reuse
	<i>Fashionable second-hand user</i>	0.125 (5) <sup>a</sup>	EoL <sup>b</sup>
<i>Second-hand user</i>	<i>Average second-hand user</i>	0.5 (20) <sup>a</sup>	EoL <sup>b</sup>
	<i>Attached second-hand user</i>	1 (40) <sup>a</sup>	EoL <sup>b</sup>

<sup>a</sup> Uses assumed for a t-shirt in absolute numbers for the different scenarios as the average use for this item is 40 times (section 2.2.4.). Example of how the fraction  $\times$  average use = the number of uses for the respective scenario.

<sup>b</sup> EoL for textiles was modelled as 20% incineration with energy recovery and 80% landfill (section 2.2.5.)

According to the analysis of Sandin & Peters (2019), generally, LCA researchers within the textile sector consider the impact category climate change as the most relevant category, followed by energy use, acidification, eutrophication, and water use. Based on this and the available data, the following four impact categories were chosen for this study:

- Global warming potential (GWP100) in kg CO<sub>2</sub>-eq. (IPCC, 2013)
- Cumulative Energy Demand (LHV) in MJ (PRé & Ecoinvent, Frischknecht et al., 2007)
- Water Scarcity Footprint in m<sup>3</sup> water eq. deprived (AWARE, Boulay et al., 2018)
- Freshwater eutrophication in kg P-eq. (ReCiPe 2016, Huijbregts et al., 2017)

## 2.2 Life Cycle Inventory (LCI)

### 2.2.1 System boundary and allocation approach

Figure 1 shows the system boundaries we propose for the three types of consumers. For the *primary (conscious) user* type, the lifecycle starts with fibre, fabric, and garment production, then the retail and use phase, ending with end-of-life (EoL) waste management.

For the *second-hand users*, the activities related to the trading and using of second-hand items are fully allocated to the second-hand users, since they are the only ones benefiting from it. However, the “cradle” and “grave” system boundaries are no longer clear since these are shared by both the primary and the secondary users of the items. In LCA, often a system expansion approach is taken to handle this complication. However, as this research aims to distinguish the impacts from primary and secondary users, the system expansion approaches are not applicable. Firstly, the system expansion by enlargement approach (Corona et al., 2019; Shen, Nieuwlaar, et al., 2011) cannot be applied because it would result in a system

containing multiple consumers indistinguishable from one another, and therefore, will not fit the goal of this LCA. Secondly, most studies investigating reused clothing apply the system expansion by substitution approach (Sandin & Peters, 2018). Assuming a 1:1 substitution rate, i.e., the second-handed clothes have the same quality and perceived value as the new ones and hence primary production of a new clothing item is avoided, even though this might not be the best representation of the situation (Sandin & Peters, 2018). This simplification is done as determining the substitution rate is difficult due to the lack of a measurable quality characteristic. For instance, a consumer survey showed that most UK consumers indicated that they dispose of their clothing for other reasons than it not being wearable anymore (torn, holes, etc.). Most respondents disposed of items as they did not fit, were not needed, or were not liked anymore (WRAP, 2017). So how a consumer perceives the quality of their clothing depends highly on personal preference and less on physical lifetime.

Several studies (Castellani et al., 2015; Farrant et al., 2010; Nørup et al., 2019; Stevenson & Gmitrowicz, 2012) tried to more accurately determine the impacts of clothing reuse by investigating this substitution factor. For example, consumers were asked about a hypothetical situation: whether they would have bought a new item if the second-hand item they purchased had not been available. The outcomes however, varied significantly, concluding substitution factors of roughly 29% (Stevenson & Gmitrowicz, 2012), 35-63% (Nørup et al., 2019), 47% (Castellani et al., 2015), and 60-85% (Farrant et al., 2010).

Hence, using system expansion by substitution can introduce high uncertainty due to arbitrary choices. In this study, we adopt a partitioning (or allocation) approach from an attributional perspective. Based on this approach, the impacts from the production phase (the “cradle”) and the ultimate EoL phase (the “grave”) are shared between both primary and secondary users (Shen, Worrell, et al., 2011). The item’s value retention was used as the parameter for an economic allocation. We interviewed a UK-based second-hand clothes trading company, and based on the sales records in 2021-2022, we estimated the value retention of four clothing items at around 30-40% after their first lives. It is also interesting to note that, the closer an item is worn to the body, the lower its value retention, e.g., a t-shirt has a lower value retention than a sweater.

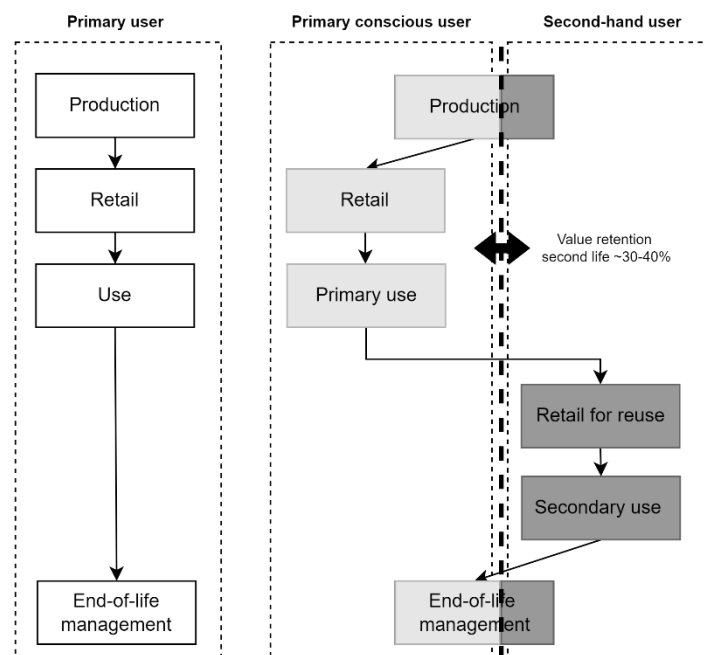


Figure 1. Simplified System Flow Diagram and Boundaries, Depicted for the Three User Behaviour Categories: Primary User, Primary Conscious User and Second-Hand User

### 2.2.2 Production

The production phase of clothing consists of multiple stages, starting with the production of the fibre, yarn, and fabric, and in the end, turning the fabric into the desired garment (confectioning) (Figure 2). The data from the database ecoinvent (version 3.7.1; Wernet et al., 2016) were taken as the starting point for many

processes. This inventory data was verified with independent literature as much as possible and adapted or complemented where needed to fit the current scope of the analysis (see SI section 1.1 for the detailed inventory). The LCA model was established in the software Simapro (version 9.1). The *MistraFutureFashion* project (Roos et al., 2015; Sandin et al., 2019), the latest Cotton Incorporated report (Cotton Incorporated, 2017), and the textiles LCA benchmarking study by Van Der Velden et al. (2014) are among the studies most used for the data comparison, verification and/or adjustments.

Due to differences in material, fabric production method, and yarn fineness, the production of the different items could use different processes/technologies. Also, different techniques can be used in multiple steps, and material losses and energy use differ substantially among them. For the four textile items, the most dominant production route was assumed. Different production techniques are assumed based on the item's material and the fabric production method (weaving/knitting). The *t-shirt* is assumed to be made of cotton staple fibre which is ring spun into yarn, then knitted into fabric, batch pre-treated and dyed, finished, then compacted, and lastly confectioned into the desired garment. The *dress* consists of polyester staple fibre which is ring spun into yarn, then woven into fabric, followed by a batch pre-treatment and dyeing process, then finished and sanforised, and finally confectioned into the dress form. The *trousers* are modelled as made from cotton staple fibres that are ring spun into yarn, then woven into fabric, continuously pre-treated and dyed, then finished, sanforised, and confectioned. Lastly, the *sweater* is assumed to consist of polyester and cotton fibres, together ring spun into yarn, then knitted into fabric, continuously pre-treated and dyed, then finished, compacted, and confectioned. The data and modelling details can be found in the supplementary materials.

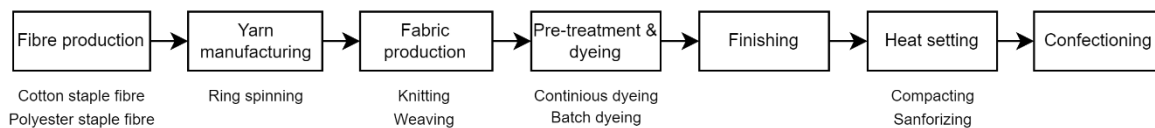


Figure 2. Production Phases Flow Diagram. Shown Under the Different Phases of Production (The Squares) Are, if Relevant, the Different Methods/Techniques That Are Taken Into Account. All Items Follow the Phases, but a Different Combination of Methods/Techniques Is Assumed for Different Items

The waste management of the process waste (loss) during production was modelled through the ecoinvent 3 process for textile and yarn waste. It assumes that most of the waste is landfilled in an unsanitary landfill. The electricity mix is not changed for the production processes already present in the ecoinvent 3 database. However, for the processes not in the ecoinvent database, the electricity mix of Sandin et al. (2019) was used. They constructed it based on the respective shares of the seven most significant contributors to Swedish clothing imports from 2013-2017, which is assumed to be similar to the UK. The inventory details are included in Section 1.1 of the SI.

### 2.2.3 Retail/distribution

The clothing was assumed to be transported from Asia to Europe over approximately 13,000 km by sea and 6,800 by air (Beton et al., 2014). The data for transport regarding distribution from the warehouses to the stores, and the stores' energy use is based on Sandin et al. (2019). They report H&M data from 2012, showing 1.9 kWh of electricity/kg garment. User transport was modelled as 15 km (to the store and back summed), 50% of this transport was done by car and 50% by bus. Only one-third of the trip was allocated to clothing items since it was assumed that the trip led to the purchase of, on average, three different products (Sandin et al., 2019).

### 2.2.4 Use

The baseline average consumer behaviour in the use phase was defined through a literature review (Beton et al., 2014; Cotton Incorporated, 2017; Daystar et al., 2019; Gwozdz et al., 2017; Presutto et al., 2007; Sandin et al., 2019). The subsequently used assumptions for the use phase of the items are summarised in Table 3. The geographical scope of the use and EOL phases is limited to the UK.

Table 3. Use Phase Characteristic Assumptions

	Dress	T-shirt	Trousers	Sweater
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Number of uses before washing	2	2	6	5
Number of uses over its lifetime	16*	40*	96*	80*
Percentage of clothing tumble dried after washing	20%	25%	25%	25%
Percentage of clothing ironed after washing	20%	15%	15%	10%

\* these use numbers are the average baseline scenario. For the other scenarios, the amount of uses is determined by multiplying these average use numbers with the factor "Fraction of lifetime compared to average use" from Table 2.

As 97% of people in the UK use a washing machine at home to do their laundry (Daystar et al., 2019), it was assumed that the washing during the use phase for every scenario is done with a household washing machine. The energy and water consumption were based on the European Commission Ecodesign preparatory study (Presutto et al., 2007). It was reasonable to assume that the average washing machine in the present can compare to the most efficient machine in 2007 (Sandin et al., 2019). With an average water temperature of 45 degrees Celsius and turning at 64% of their maximum load, a washing cycle was modelled to consume 0.19 kWh energy and 6.17 L water per kg of clothing.

The international Association for Soaps, Detergents, and Maintenance Products (A.I.S.E) conducted a study to set up a Product Environmental Footprint Category Rules (PEFCR). Together with 46 stakeholder organisations, they defined (among others) a bill of ingredients for machine laundry detergent (AISE, 2019). The recipe and the quantity indicated in the PEFCR were used to model the laundry detergent, including the chemicals, packaging, and energy used for detergent production. For wastewater management, it was assumed that the process in the UK resembles that of Switzerland. Hence, the ecoinvent 3 process for treating residential wastewater in Switzerland was used as a proxy.

Line/air drying is assumed not to have a significant environmental impact. Assuming the most efficient condenser tumble dryer in 2008, drying consumes 0.6 kWh/kg (PriceWaterhouseCoopers, 2009). The ironing of clothes was assumed to require 1.6 kWh/h of ironing (Presutto et al., 2007). For dresses and trousers around 6 min ironing is assumed on average, for t-shirts and sweaters, this is around 3 min (Presutto et al., 2007).

### **2.2.5 End-Of-Life Waste Management**

WRAP (2024) investigated the waste treatment of textiles in the UK by tracking the mass flow of items through their (multiple) lives. Based on their conclusions it was assumed that 89% of the textile waste is incinerated with energy recovery and 11% is landfilled in the UK (United Kingdom).

Incinerating polyester and cotton fabric with energy recovery can be represented by municipal incineration of PET and paperboard (Sandin et al., 2019). A substitution approach is taken to model the energy recovery of the clothes incineration. The produced heat is assumed to replace heat from natural gas for industry, and the generated electricity is assumed to replace electricity from the average UK electricity mix. A 50 km round trip with a waste collection lorry is assumed (WRAP, 2011). Based on the average calorific value of waste reported by UK's Energy from Waste statistics and the heat and electricity output of UK's incineration plants (Tolvik, 2021), an electric efficiency of 22.1% and a thermal efficiency of 4.7% for UK's waste-to-energy (WtE) plants was determined.<sup>3</sup>

### **2.2.6 Retail for Reuse**

The case study the company provided information on their second-hand clothing trading process. They offer a service where consumers can sell their used clothing online. This is a different way of trading second-hand items than a direct consumer-to-consumer exchange typical for resale consumer apps. It might add more impact due to increased logistics, but it allows for an easier exchange of items between consumers and therefore can facilitate trading in large quantities. Especially with the development of a more circular society, this type of service might increase in importance.

The sellers and buyers of the items are distributed all over the UK. Via postal service, the clothing arrives at the company's warehouse near London, where it is vetted and stored temporarily before it is resold or

<sup>3</sup> The UK focuses on electricity production in these plants, whereas most European countries use them to produce energy as a mix of power, hot water, and steam. Moreover, the overall efficiency of the WtE plants in the UK is lower compared to other European countries like the Netherlands, Germany, or Sweden (Tolvik, 2021)



donated into a new use cycle. The re-sale is also organised via postal service. The company provided information on the average postal transport distances, warehouse electricity use, transport and storage packaging, and the CO<sub>2</sub>-eq emissions induced by their data servers. This data was from spring 2022, but judged to be representative for that year. The average distance for postal service transport was determined using 100 randomly chosen orders from that timeframe.

### 3. RESULTS AND DISCUSSION

The following section starts with the results of the impact of an average primary user to explore the size and build-up of the impact of a functional unit. It is followed by an analysis of the impact of secondary use. Then the results for primary conscious users and second-hand users are compared with those of average primary users. The discussion is then extended by examining the sensitivity of the number of uses assumed for different scenarios. This section ends with a discussion of multifunctionality approaches.

#### 3.1 Average Primary User

Figure 3 shows the environmental impact per life cycle stage and clothing item, for an *average primary user* (per functional unit). Firstly, The dominance of the production phase is evident across all four impact indicators and all items, accounting for at least 72% of the total impacts. Secondly, the analysis reveals that the use phase has a comparatively minor influence in contrast to the production phase, contributing only 2-22% of the total impact. The error bars in Figure 3 show that, even when there are significant variations in the frequency of item washing, the use phase impact remains within the range of 2-35% of the total impact, with the production phase still dominant. Some studies in the LCA literature assume that items are washed and dried each time after use, leading to a relatively high impact from the use phase; responsible for around half of the impacts on water consumption and GWP (Beton et al., 2014; Cotton Incorporated, 2017). However, consumer behaviour studies in the last few years conclude that that is not the most likely scenario (Daystar et al., 2019; Gwozdz et al., 2017). When assuming several uses per wash, the life cycle impacts of the use phase are relatively small (Sandin et al., 2019). Lastly, the end of life is only a minor contributor, inducing -2 to 3% of the total impact. Partly due to the energy recovery taking place at incineration.

The differences in impacts between the clothing items are mainly caused by a combination of three factors; an item's weight, the number of uses, and the production impacts of the textile materials. For both GWP and the CED, the dress has a significantly higher impact per use (i.e., per functional unit) compared to the other items. The dress is the heaviest but the least used item of the four, and fine woven polyester has a very high production impact per kg, explaining its significantly higher impact *per use*. The differences between a t-shirt, trousers or sweater are small. Trousers and sweaters are heavier than t-shirts but are also used longer. Furthermore, the impact of textile production *per kg* remains relatively consistent across various items, except for dresses, which have nearly twice the impact compared to the other garments. For more information on the origin of the differences in production impact per kg of textile material, see Table 4.

Additionally, the production phase is also dominant for freshwater eutrophication (FE) and water scarcity. For cotton clothing, agricultural activities were seen to be the key processes responsible for these impacts due to their significant water demand (water scarcity footprint) and the use of high amounts of pesticides and fertilizers (FE) (Beton et al., 2014). Consequently, clothing items made from cotton such as t-shirts or trousers have a higher FE impact than polyester dresses. However, due to the comparatively low utilisation of the dress and its high weight, it still has the highest FE impact *per use*. The environmental impact of polyester dresses stems from two key factors: coal mining for electricity production (FE) and the wet-processing (bleaching, dyeing, etc.) of the polyester fabric (water footprint). The dress does have the lowest water scarcity footprint, a factor of 1.5-2.3 lower than the other three items that are made from cotton. The cotton garments are made of water-demanding organic material, so even though the dress is heavier and used less, its water footprint is still lower.

The findings are similar to what's published in a recent study (Sandin et al., 2019) in three folds: i) the production phase is dominant in the life cycle of a textile product, ii) the number of uses plays a key role, and iii) life cycle impacts resulted in the same number of magnitudes. For a dress Sandin et al. (2019) concluded a range of 0.05-0.7 kg CO<sub>2</sub>-eq. GWP per use, 1-11 MJ energy use per use and 0.1-0.4 m<sup>3</sup> world eq. water scarcity impact. The difference with our results comes mainly from different assumptions for the



number of uses (e.g. they assumed 26 uses for the dress, compared to 16 uses assumed in this study). The sensitivity of the number of uses will be further discussed in Section 3.4.

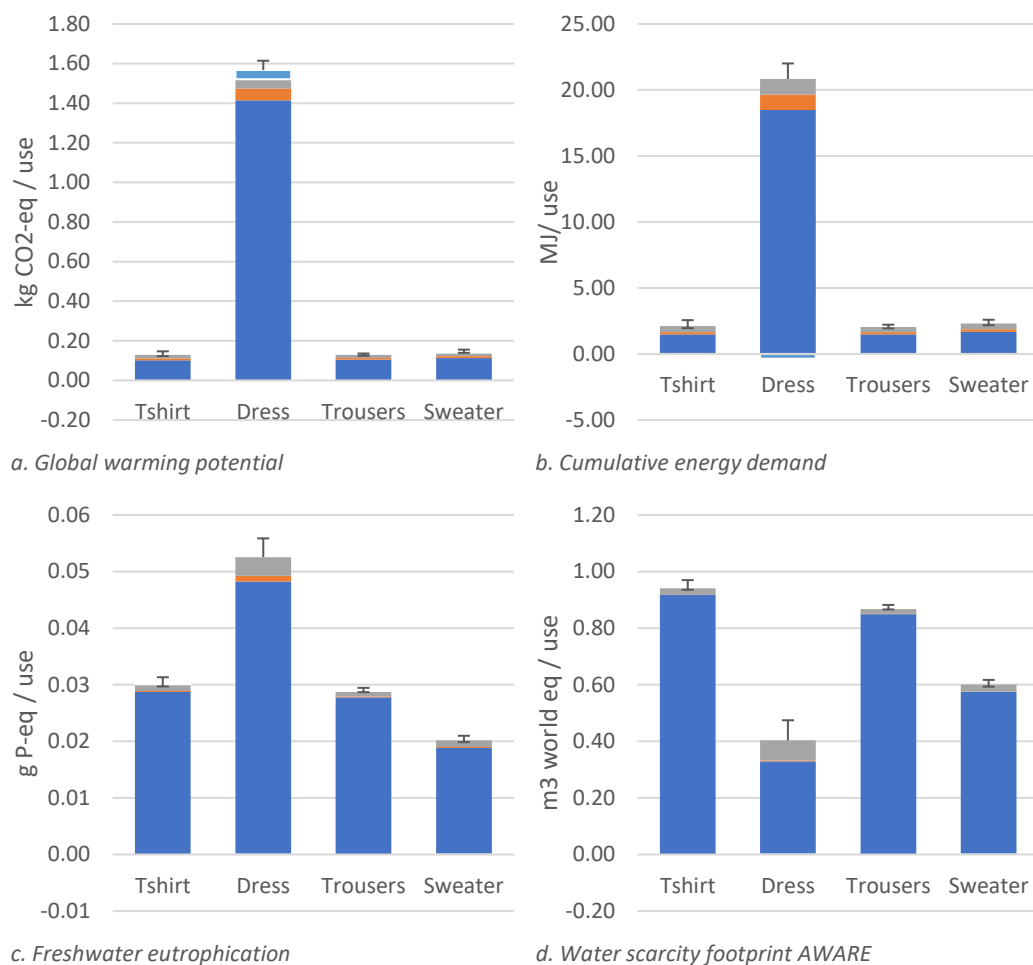


Figure 3. The Impact per Use of a Piece of Clothing by a Primary Average User for Four Impact Indicators (A-D).the Different Colours Indicate the Impact of the Respective Phases in the Life Cycle; Production, Retail, Use, Eol. The Error Bars Show How the Total Impact Changes When the Number of Uses Before Washing Changes (+/- 1 Use per Wash for the T-Shirt, -1 for the Dress, +/- 2 for the Trousers and Sweater)

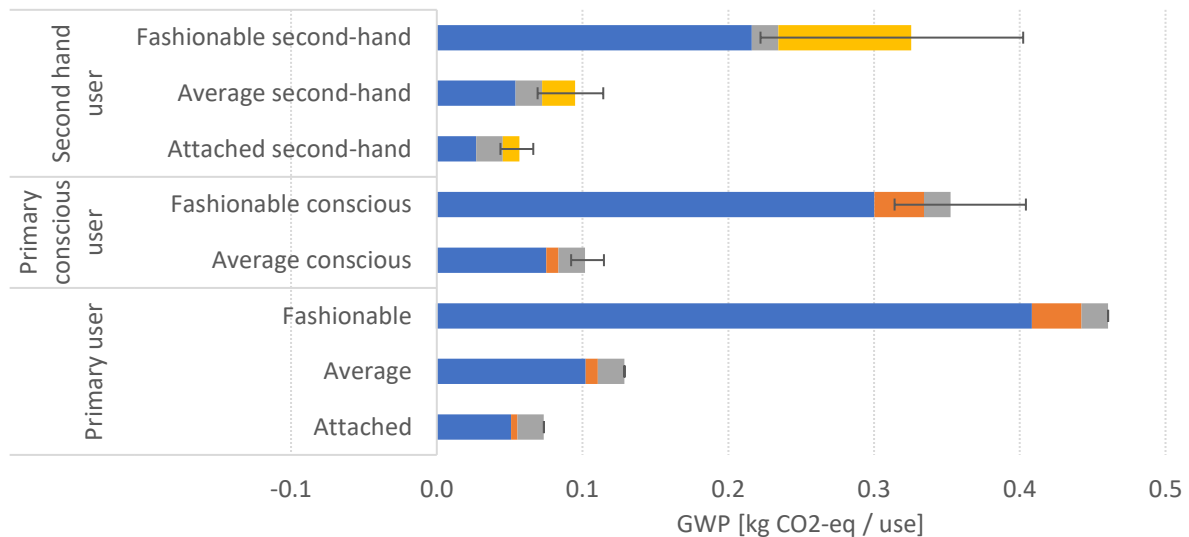
Table 4. Most Dominant Factors in the Determination of the Production Phase Impact per KG as Identified in This Study

Factor	Details
1) The fabrics' production processes	Weaving, in general, has a higher impact than knitting because of the energy (electricity) requirements; per kg textile material, the energy required for weaving is approximately 20 times more than for knitting (Van Der Velden et al., 2014).
2) the fineness of the yarn	Using a fine yarn leads to both a more energy-intensive spinning process and requires more energy for the fabric production (both for weaving and knitting); for example, a 200 dTex yarn requires roughly two times more energy to spin compared to a 400 dTex yarn (Van Der Velden et al., 2014).
3) the type of fibre material	Polyester fibres, in general, have a higher impact in terms of GWP and CED compared to cotton (Beton et al., 2014), and polyester needs a more chemical and heat-intensive dyeing process compared to cotton. But although polyester has a more straining specific production process, for cotton a lot more fibre is needed to create the same amount of material due to high losses in fibre production and yarn spinning, decreasing the difference between the impact of the materials somewhat.
4) the demands for the confectioning process	The more complicated the form of an item, the higher its losses in confectioning; hence the more output is needed from all the upstream processes, creating a higher impact.

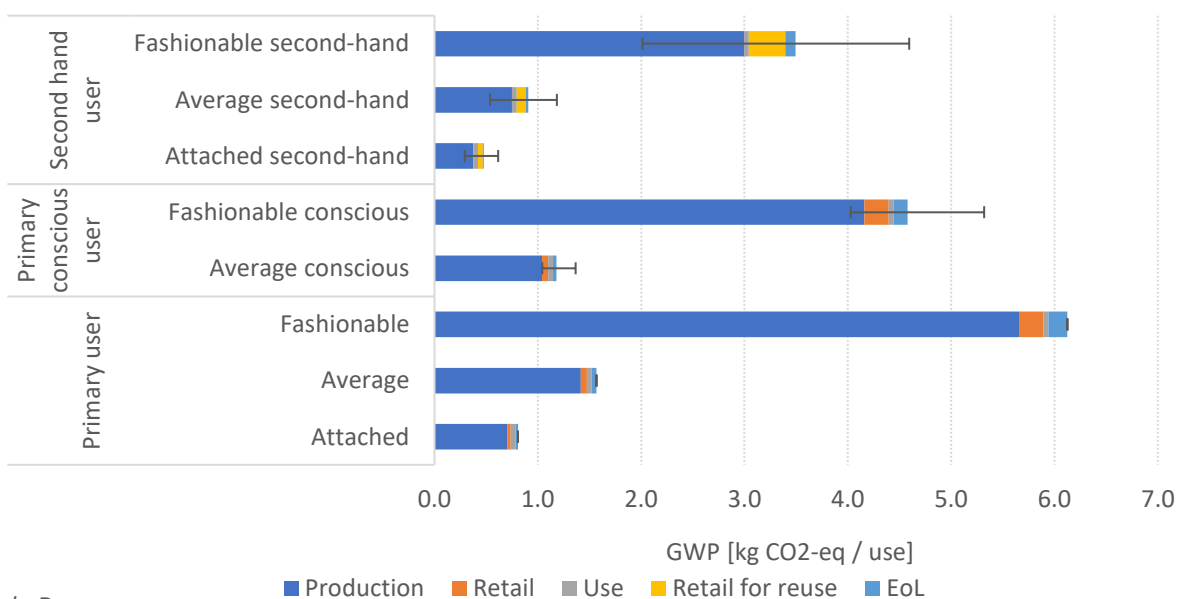
### 3.2 Reuse

The build-up of the impact of a second-hand user is still dominated by the production phase, even though it carries only part of the burden from textile production. The production phase impact is the largest contributor (40-88% of the GWP and CED per use), followed by retail for reuse (9-24% of the GWP and CED per use), as seen from the examples of a t-shirt and a dress shown in Figure 4. The total impacts of the different scenarios are shown in Table 5.

One of the goals of this research was to decrease the knowledge gap on the impact of processing clothing for a second life, by adding to the empirical data on the retail for reuse. It was found that this step induces an emission of between 0.5-0.7 kg CO<sub>2</sub>-eq per item (GWP), and demands 5.6 - 9.5 MJ of energy (CED). These added impacts are due to electricity, heating, packaging and transport in this system, hence the impacts on water scarcity and freshwater eutrophication are very small. It should be kept in mind that this is based on data from the specific system assumed here and could vary for different organisations/infrastructures. However, a report by a similar company shows comparable results; assuming a 180-gram t-shirt the retail for reuse showed to induce 0.9 kg CO<sub>2</sub>-eq. (GWP) and 8.8 MJ (CED) (Babel et al., 2019). Both systems represent clothing re-commerce in an urban environment, from mid-market brands, in the Western world.



a. T-shirt



b. Dress

■ Production ■ Retail ■ Use ■ Retail for reuse ■ EoL

Figure 4. Global Warming Potential Impact per Use of a T-Shirt (a) and a Dress (B) for the Different Consumer Types and Behaviour Scenarios. The Error Bars Show How the Impact Varies With a Varying Value Retention

Table 5. Impact per Use for the Different Consumer Behaviour Scenarios, for the Different Items and the Four Impact Categories

Impact category	Item	Consumer behaviour scenarios							
		Primary fashionable user	Primary average user	Primary attached user	Primary fashionable conscious user	Primary average conscious user	Second-hand fashionable user	Second-hand average user	Second-hand attached user
GWP (kg CO <sub>2</sub> -eq / use)	T-shirt	0.46	0.13	0.07	0.35	0.10	0.33	0.09	0.06
	Dress	6.13	1.57	0.81	4.58	1.18	3.49	0.91	0.48
	Trousers	0.47	0.13	0.07	0.37	0.10	0.26	0.08	0.05
	Sweater	0.52	0.14	0.08	0.39	0.11	0.34	0.10	0.06
CED (MJ/ use)	T-shirt	6.93	2.07	1.26	5.39	1.69	4.66	1.51	0.98
	Dress	78.35	20.47	10.83	59.16	15.67	44.33	11.97	6.57
	Trousers	6.85	1.99	1.19	5.55	1.67	3.72	1.21	0.79
	Sweater	7.73	2.26	1.34	5.91	1.80	4.95	1.56	0.99
FE (g P-eq. / use)	T-shirt	0.12	0.03	0.02	0.09	0.02	0.06	0.02	0.01
	Dress	0.20	0.05	0.03	0.15	0.04	0.11	0.03	0.02
	Trousers	0.11	0.03	0.01	0.09	0.02	0.05	0.01	0.01
	Sweater	0.08	0.02	0.01	0.06	0.01	0.04	0.01	0.01
Water footprint (m <sup>3</sup> world eq.)	T-shirt	3.70	0.94	0.48	2.73	0.70	1.99	0.52	0.27
	Dress	1.40	0.40	0.24	1.05	0.32	0.83	0.26	0.17
	Trousers	3.42	0.87	0.45	2.66	0.68	1.56	0.41	0.21
	Sweater	2.33	0.60	0.31	1.68	0.44	1.33	0.35	0.19

Figure 4 shows the impact of the different consumer scenarios for a t-shirt and a dress, Table 5 shows the results for the other items and impact categories, and Table 6 shows the change in impact when comparing consumer types for the average behaviour scenario. Firstly, when comparing consumer types, it is evident that opting for second-hand items instead of purchasing primary ones significantly reduces the environmental impacts for all four impact categories and for all four textile items studied (impact reductions between 26-53%). As little is known about the real lifetime of second-hand clothes, this study assumed that second-hand items have only half as long a lifetime (see Table 2). This conservative assumption may understate the potential impact reduction of reuse, but nonetheless; the impact per use of a second-hand user is still lower compared to that of a primary user (Table 5 and Figure 4).

The differences in the impact reductions between the items stems from the difference in production impact and value retention. The higher the contribution of the production phase the more impact reduction when this production impact can be shared over multiple lives. The size of the value retention determines how this allocation is done.

Table 6. Change in the Impact per Use (FU) When Comparing 1) an Average Second-Hand User With an Average Primary User, and 2) an Average Primary Conscious User With an Average Primary User. Negative Numbers Indicate That Compared to a Primary User Both Other Consumer Types Induce Less Impact per Use (FU)

		T-shirt	Dress	Trousers	Sweater
Second-hand user compared to primary user	GWP	- 26%	- 42%	- 41%	- 31%
	CED	- 27%	- 42%	- 39%	- 31%
	Freshwater eutrophication	- 44%	- 42%	- 53%	- 40%
	Water scarcity footprint	- 45%	- 35%	- 53%	- 42%
Primary conscious user compared to primary user	GWP	- 21%	- 25%	- 18%	- 23%
	CED	- 19%	- 23%	- 16%	- 20%
	Freshwater eutrophication	- 25%	- 24%	- 22%	- 26%
	Water scarcity footprint	- 26%	- 22%	- 22%	- 27%

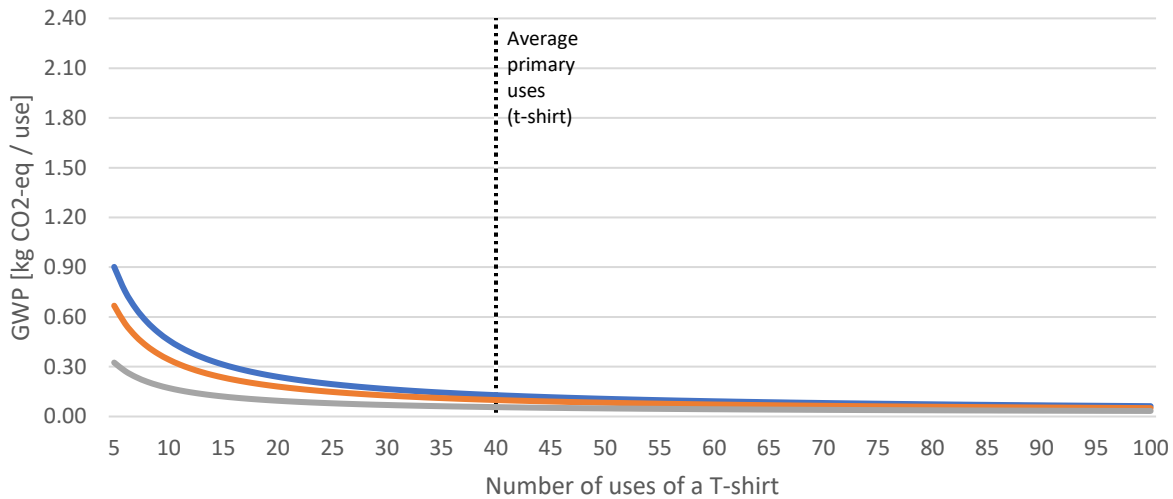
The impact from a primary conscious user is also lower than that from the primary user (Table 5). A primary conscious user, choosing to sell their item for reuse when they want to dispose of it, creates approximately 16-27% lower impacts per use compared to a primary user who throws their item away after the first use cycle (Table 6). This is dominated by the reduction of the impact from the textile production phase for the primary conscious users; part of the production impacts are shifted to the items' second life based on the allocation approach adopted.

The big differences between the fashionable, average, and attached behaviour scenarios (Figure 4) show that how often a consumer uses an item has a strong effect on the impact per use. The longer an item is used, the lower the impact per use; the high impact of the production phase can then be shared over more uses. For example, the primary fashionable user wears a t-shirt 75% less compared to the average user, creating a 3.5 times higher GWP impact. Hence, buying an item second-hand and using it as long as possible ("Attached second-hand") creates the least impact per use. This way the consumer is burdened with only part of the production impact which is then spread over many uses, increasing resource efficiency per use. With the behaviour assumptions made here the attached primary user even has lower impacts compared to the average second-hand user.

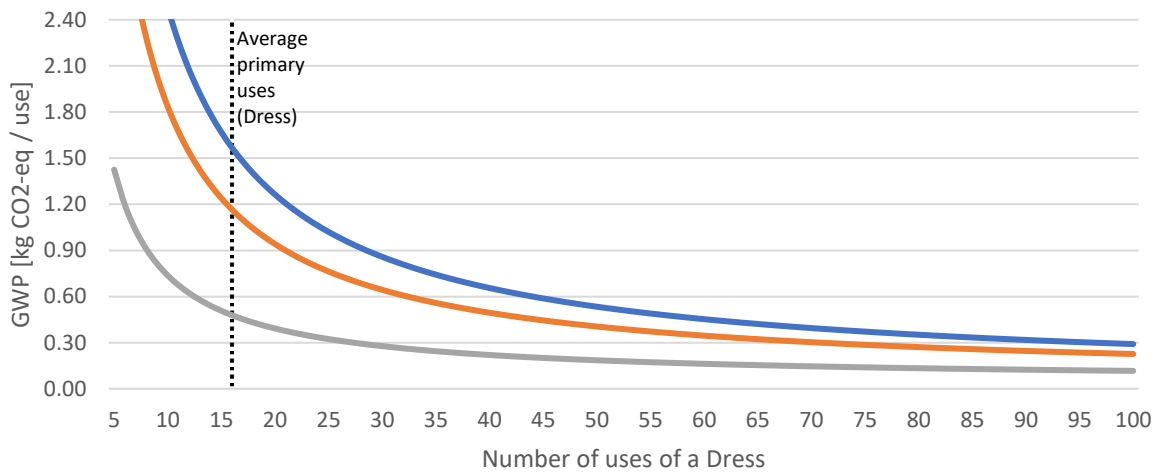
### 3.3 Sensitivity Number of Uses

Consuming second-hand does not per definition have lower impacts per use than consuming new, it depends highly on how much an item is used. For instance, the fashionable and average second-hand user scenarios create more impact per use than the primary attached user (see Figure 4). This can also be seen in Figure 5 where the impact in GWP is shown over the assumed number of uses for a t-shirt (a) and a dress (b). For the same amount of uses the additional impact of retail for reuse is less than the impact saved by the extended life of the item (the second-hand user line is always lower than the primary user line). Buying a second-hand item but only using it sparingly may have a greater impact than buying a new item and prolonging its usage. E.g. buying a second-hand dress and using it only 5 times leads to a GWP impact of 1.4 kg CO<sub>2</sub>-eq per use, but buying a new dress and using it 20 times creates 1.2 kg CO<sub>2</sub>-eq per use. Therefore, justifying the purchase of a large quantity of clothing with minimal usage through the act of buying it second-hand is not a valid excuse.

Furthermore, the impact line follows an exponential (decay) curve. Initially, there is a rapid decrease in impact as the number of uses increases, but as the usage count grows the decline in impacts becomes less pronounced. This occurs because the impact created by the use phase remains constant (one use) but the impact from the other life cycle phases is spread over a growing number of uses. The flattening of the line happens later for items with a higher production impact; showing that, for an item like a dress or trousers, it is more important to buy second-hand and to use it longer. I.e. for the impact in GWP the line flattens (a 0.005 or less GWP decrease per extra use) at around: 30 uses for a t-shirt, 70 uses for a dress, 50 uses for trousers, and 45 uses for a sweater. After this flattening, the difference per use between the consumer types becomes relatively small. This also means that, for a more special occasion or a rarely used item, the benefit of using a second-hand item is especially significant due to this exponential decrease in impact.



a. T-shirt



b. Dress

— Primary user    — Primary conscious user    — Second hand user

Figure 5. Global Warming Potential per Use of a T-Shirt (a) and a Dress (B) Shown for Different Numbers of Assumed Uses for the Three Main Consumer Behaviour Scenarios

### 3.4 Multifunctionality Approaches

This study chose to explore economic allocation based on value retention after the first life, due to the difficulties with system expansion by substitution, which relies strongly on the substitution factors that are highly uncertain for textile apparels (see Section 2.2.1). However, it is also seen that the value of clothing can reduce quickly, and not only because of physical deterioration (Entwistle, 2009). So it can also be debated whether economic value best represents the relation between the first and second life of clothing. Whether a substitution rate or value retention is used, how the shared burdens are allocated between the different consumers will be very influential for the results. The error bars in Figure 4 show how the result changes with different value retentions. The value retentions were varied based on their standard deviation of approximately 20 percentage points. The substantial size of the error bars shows the important role of the value retention in the resulting impact determination. The impact of second-hand use is much more influenced by the assumption compared to the primary users, for all behaviour scenarios. As the production impact attributed to secondary users is less than to primary users a small change in the value retention has a bigger impact on the former.

To avoid multifunctionality problems system expansion by enlargement is often used. From a policy perspective, this might be the most logical choice. It takes into account the whole system, following a product

from cradle to grave, overall its lives. It then shows whether the benefits of extending the product's lifetime exceed the impact of the extra steps that are needed to facilitate it. However, this is not possible when looking from a consumer perspective; as you merge multiple different consumers differentiating between them becomes difficult. Another way to avoid having to determine an allocation factor can be to use the cut-off approach; for a primary product assuming that its EoL is free of environmental impact, and for a secondary product assuming that its input materials come without burden. This method leads to more favourable results for the secondary consumer, as it completely attributes the production phase to the primary consumer. For example, the decrease in GWP for the average use of a t-shirt comparing it to primary use would be only 1% for the difference with a conscious consumer, but 91% for comparison with second-hand use. This might incentivise consumers more to buy second-hand, however, it does not encourage design for longevity and durability to facilitate reuse.

In aiming for a more circular society, more products will be shared over multiple consumers (reuse), and more products will use the same raw material (recycling). Hence these multifunctionality issues, in LCAs aimed at providing information at a consumer level, will become even more apparent. To better determine the impact of these products, research should continue how to best handle these issues. Especially for products where consumer behaviour is so influential for the impact more knowledge is needed on how to differentiate between multiple lives or functions.

#### 4. CONCLUSIONS AND RECOMMENDATIONS

This research aimed to gain insights into the environmental impact of clothing reuse, and how consumer behaviour influences this. We proposed to use value retention as a proxy to allocate the impacts from textile production and end-of-life waste management between the primary and secondary users. We explored the influences from three user types (primary, primary conscious and second-hand users) in combination with three behaviour scenarios (fashionable, average and attached consumers). Our key findings are summarised as the following:

- The textile production phase dominates the impact of being dressed. If we want to significantly decrease the impact of our clothing consumption, significant impacts reductions in manufacturing and processing impact are required.
- The environmental impacts of being dressed can be reduced when the item is made available for reuse at its end-of-life instead of being discarded. A decrease of 16-27% in the impacts per use is observed when comparing a primary conscious user with a primary user.
- Impact reduction through second-hand consumption is substantial. If instead of a new item (average primary user) an average second-hand item is being consumed, the impacts of being dressed can be reduced by 26-42% for climate change, 27-42% for cumulative energy demand, 42-53% for freshwater eutrophication, and 35-53% for the water scarcity footprint, per use.
- Similarly, the impact of items used by only one consumer is higher than the impact of items that are shared by primary and secondary users, within the same consumer behaviour type. This difference is higher for items with a relatively high production impact, e.g. a polyester dress; especially when the item is little used. Hence, for clothing items with high production impact, opting for second-hand consumption will result in substantial reductions in environmental impact.
- The usage frequency is an important factor in consumer choices. When an item is used more frequently throughout its lifetime, the impact per use decreases. The intense use of a new item can even lead to less impact than the use of a second-hand item which is used only a handful of times.

In aiming for a more circular society, more products will be re-used. Hence the multifunctionality issues in LCAs will remain challenging. On the assessment methodological development, there is more to develop especially when LCA is applied to assess the environmental sustainability of circularity strategies. The choices in LCA to deal with multifunctionality are goal-oriented, as shown in this study. When the goal is to inform different consumers (primary and second-hand) about the effect of their choices, the methodological challenge is about how to determine the environmental impacts arising from multiple life cycles. This study demonstrated one of the common approaches based on economic allocation between first and second lives. The sensitivity analysis showed the importance of the reliability of the value retention data. If economic

allocation is one way to deal with the challenge, more independent data on value retention should be gathered.

When the goal of the LCA is to inform policymakers for their decisions at the sectoral or country level, system expansion is still a better choice because there is no need to distinguish the impacts between different life cycles. Rather, it is more important to capture the environmental impacts on society as a whole. Another notion, it could be interesting to investigate how the impacts and consumer behaviour might change when designing clothing for longevity or recycling. These cases are out of the scope of the current study but it is highly relevant to understand the implication of any high-R strategies. Future research could explore various approaches with consequential thinking and also combine LCA with other methods such as material flow analysis. In that sense, more similar case studies should be reported to allow the future development of LCA methodology in assessing circularity strategies.

Lastly, in this study we only reported a limited amount of impact indicators. For instance, the impact of microfiber release to water and air due to wearing and washing still cannot be incorporated in the current LCA (De Falco et al., 2020), or toxicity impacts as the textile industry is an intense user of chemicals (Roos & Peters, 2015). Nevertheless, the insights gained from this study are worthy of discussion. These insights can guide well-informed decisions for companies, policymakers and even the general public in the context of circular textiles, aligning with a robust high-R strategy.



## **AUTHOR CONTRIBUTIONS**

**Astrid Klooster:** conceptualisation, methodology, data collection, conducting the research, writing

**Blanca Corona Bellostas:** conceptualization, methodology, review and editing

**Marvin Henry:** conceptualisation, methodology, review and editing

**Li Shen:** conceptualisation, methodology, supervising, reviewing, editing and writing

## **DECLARATIONS**

**Competing interests** The authors declare no competing interests.

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## SUPPLEMENTARY MATERIAL

### 1. MODELLING DETAILS

#### 1.1 Production Phase

Table S1. Material Losses in the Production Phase Summary. For the Details See Sections 1.1.1 Though 1.1.6

Parameter	Unit	T-shirt	Dress	Trousers	Sweater
Fibre production	% material loss	n.a.	n.a	n.a	n.a
Yarn spinning	% material loss	21.3%	0.5%	15%	12.1% <sup>a</sup>
Fabric weaving/knitting	% material loss	1.5%	4.8%	4.8%	1.5%
Dyeing	% material loss	9.2%	3.8%	3.8%	9.2%
Finishing	% material loss	1.0%	0.0%	0.0%	1%
Compacting/saforizing	% material loss	0.0%	0.5%	0.5%	0%
Confectioning	% material loss	15.0%	18.0%	14.0%	10%
<i>Total production</i>	<i>% material loss</i>	<i>40.7%</i>	<i>25.7%</i>	<i>33.3%</i>	<i>20.3%</i>

<sup>a</sup> 21.3% loss is assumed for the cotton fibres (0.635 kg input/kg yarn) and 0.5% for the polyester fibres (0.503 kg input/kg yarn)

The waste management of the generated waste (loss) in the production processes is assumed to be represented by the Ecoinvent process for textile and yarn waste. It assumes that most of the waste is landfilled in an unsanitary landfill.

For the production processes that were already present in Ecoinvent the electricity mix is not changed. However, for the other production processes, the electricity mix in table 2 is used. It is based on the mix used by (Sandin et al., 2019). They determined the seven biggest contributors to the Swedish clothing import (2013-2017), taking into account the country of production when the import comes from a transit country. It is assumed that the textile country import mix for Sweden is similar to that of the UK.

Table S2. Electricity Mix for the Production Phase, Based on Sandin et al (2019)

Input	Share of electricity mix
Electricity mix China	55.8%
Electricity mix Bangladesh	17.8%
Electricity mix Turkey	12.6%
Electricity mix India	6.1%
Electricity mix Pakistan	3.0%
Electricity mix Vietnam	2.6%
Electricity mix Cambodia	2.1%

#### 1.1.1 Fibre Production

Table S3. Ecoinvent 3 Processes Used for Modelling the Fibre Production Impact

Cotton fibres	Ecoinvent 3 <i>fibre, cotton {GLO}</i> market for fibre, cotton
Polyester fibres	Ecoinvent 3 <i>fibre, polyester {GLO}</i> market for fibre, polyester

The cultivation of cotton begins with field planning and ends with ginning. In this last step cotton seeds are separated from the cotton fibre. The data used is a combination (combined by Ecoinvent 3) of Cotton Incorporated (2017) data which is primary data from China, the US, India and Australia, and data from Emmenegger et al. (2018) consisting of primary data from Bangladesh and India.

For polyester fibres, melt spinning of PET granules is used to produce polyester filaments (European Commission, 2022). Then for apparel these filaments are cut into pieces producing staple fibres. The fibres can also be used as filaments, but because of performance differences spun yarns are usually preferred for apparel (Wilson, 2011)(European Commission, 2022). In the melt spinning process, PET granules are melted and extruded through small holes (spinnerets) forming long threads, that after cooling harden into a fibre. Data from Ecoinvent 3 for average global polyester fibre production is used. For this production process more data sources were found which support the Ecoinvent data used; the Ecoinvent data on energy use

corresponds largely with the findings of other studies (Sandin et al., 2019; Shen et al., 2012; Van Der Velden et al., 2014).

### 1.1.2 Yarn Production (Ring Spinning)

Fibre is used to produce yarn by a process called spinning. There are different yarn spinning techniques, but because of its high quality yarn, the wide range of raw materials and various types of yarn outputs, ring spinning has been the dominant method since its development in the nineteenth century, followed by open-end rotor spinning (Yin et al., 2021). In 2019 the number of ring spindles and open-end rotors were estimated at 223 and 7.4 million respectively. Thus Yin et al. (2021) estimate that ring spinning will stay the dominant spinning method in the coming years (based on ITMF data from the same year). Hence it is assumed here that ring spinning is used to produce the different types of yarns. Depending on their end use (knitted fabric or woven fabric), the yarns have to have different characteristics. Weaving yarns have to be durable, strong and not stretch much, where yarns for knitting are designed to be soft and stretchy. The energy use for the production of the yarn is highly dependent on the yarn count (dtex), the finer the yarn, the higher the energy use (Van Der Velden et al., 2014).

For cotton yarn production for knitting (t-shirt) data used is from the Ecoinvent 3 process *Yarn production, cotton, ring spinning, for knitting GLO*, which is based on data from Cotton Incorporated (2017). It is comparable to the results study from Sandin et al. (2019) who assumed 4 kWh/kg output for a 169 dtex cotton yarn for knitting, based on the studies by Hansen et al. (2007) van der Velden et al. (2014) and Kaplan & Koç, (2007). Based on the Cotton Inc. data a mass loss of 21.3% is assumed, this corresponds with the assumption by Sandin et al. (2019) based on data from Hansen et al. (2007).

For cotton yarn production for weaving (trousers) data from Cotton Incorporated (2017) is used as implemented in Ecoinvent 3. From the mills participating in their study the majority used ring spinning, compared to air jet or rotor spinning. The report states that per kg of spanned yarn for weaving 2.34 kWh electricity and 3.83 MJ heat are needed, and a 15% mass loss occurs. This corresponds mostly with the assumption 2 kWh of electricity/kg spanned yarn and an 11% mass loss of Sandin et al. (2019), for a 470 cotton/elastane woven fabric. It was chosen to use the first as it was based on primary data, while the second was partly based on data from the 1980s, and heat use was not reported.

After production of the polyester staple fibres these are also spun into yarn, just like cotton. However, for cotton most of the material losses in ring spinning are due to the opening, carding and combing of the fibres, for synthetic or viscose fibres no combing is needed and the losses in carding and opening are significantly lower (Sandin et al., 2019). A material loss of 0.5% is assumed based on data from Sandin et al., (2019) which was retrieved from a synthetic staple yarn production facility in South Korea. The EPIDTEX (Hansen et al., 2007) study reported a material loss in ring spinning of synthetic fibres of 9%, but as this was based on data from 1980 the assumption of Sandin et al. (2019) is assumed to be more up to date. For ring spinning of a fine (around 120 dtex) carded yarn for weaving (dress) 6.72 kWh/kg is needed (Kaplan & Koç, 2007).

For a blended cotton/polyester yarn for knitting (sweater) little information was found. As most spinning plants produce yarns from different kinds of fibres (Kaplan & Koç, 2007), it is assumed that spinning this kind of blended yarn can be compared with that of 100% cotton knitting yarn. The mass loss for respectively the cotton and the polyester fibres was again assumed 21.3% and 0.5%, with an electricity consumption of 3.5 kWh/kg. This is a bit lower than for the cotton knitting yarn for a t-shirt as it has a higher dtex.

For the cotton and cotton/polyester yarn spinning, no lubricant was assumed to be needed as cotton contains natural materials that provide lubrication in spinning (Ecoinvent 3). A small amount however was assumed to be needed for the spinning of polyester (0.0016 kg/kg yarn, (Sandin et al., 2019)). The transportation needed as modelled in Ecoinvent for the ring spinning of knitted cotton is assumed to be the same for all the yarns.

Table S4. Modelling Details for Yarn Production

Cotton yarn for knitting (t-shirt)	Ecoinvent 3: <i>yarn, cotton {GLO}</i> yarn production, cotton, ring spinning, for knitting, with transport data from <i>yarn, cotton {GLO}</i> market for yarn, cotton
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Cotton yarn for weaving (trousers)	Ecoinvent 3: <i>yarn, cotton {GLO}</i>   <i>yarn production, cotton, ring spinning, for weaving with transport data from yarn, cotton {GLO}</i>   <i>market for yarn, cotton</i>
Polyester yarn for weaving (dress)	Ecoinvent 3: <ul style="list-style-type: none"> <li>- 0.0016 kg/kg output lubricant: 20% polyacrylamide, 10% acrylic acid and 70% ultrapure water (GLO, market datasets Ecoinvent 3)</li> <li>- 6.72 kWh/kg output electricity (mix as defined in table 2)</li> <li>- transport data from <i>yarn, cotton {GLO}</i>   <i>market for yarn, cotton</i></li> </ul>
Cotton/polyester yarn for knitting (sweater)	Ecoinvent 3: <i>yarn, cotton {GLO}</i>   <i>yarn production, cotton, ring spinning, for knitting</i> , altered to an electricity use of 3.5 kWh/kg, with transport data from <i>yarn, cotton {GLO}</i>   <i>market for yarn, cotton</i>

### 1.1.3 Fabric Production (Weaving/Knitting)

As already briefly touched upon before, yarn can be made into fabric by knitting or weaving. In weaving two yarns are interlaced to produce a fabric, while with knitting the fabric is made by forming a series of intermeshing loops with a single yarn (Harmsen et al., 2021). Weaving mostly produces fabric with little stretch, while knitted fabrics are often stretchy.

The t-shirt and sweater are assumed to be made of knitted fabric. The Ecoinvent database has been used and adjusted. It is based on data from Cotton Incorporated (2017); they report a heat and electricity use of respectively 1.36 MJ and 0.265 kWh, per kg fabric. This largely corresponds with the data used for knitting a 169 dtex tshirt by Sandin & Peters (2018) were they concluded that data from Cotton Inc (2016), ITMF (2010) and Idemat (2012) suggest electricity usage of the same order of magnitude (0.21 kWh/kg). A mass loss of 1.5% is assumed, corresponding with the results of all the studies named in this paragraph. Van der Velden et al. (2014) gives an estimation on how the energy use differs with the fineness of the yarn (dtex), estimating for 169 dtex (t-shirt) around 0.26 kWh/kg and for 250 dtex (sweater) around 0.17 kWh/kg. Consequently, for knitting of the t-shirt the Ecoinvent process was used as it was based on Cotton Incorporated (2017). For knitting the sweater its electricity use was lowered to 0.17 kWh/kg and the heat use was assumed to decrease with the same factor too.

Weaving is needed for the trousers and dress. Before the yarn can be woven into fabric it first has to be warped/beamed, where multiple yarns are combined together to create the desired thread count. Secondly the warp is sized/slashed, adding chemicals (mainly starch for cotton) to increase the strength of the yarns for protection during the weaving process, this process also includes a drying step (Cody, 2012). Sandin et al., (2019) report that acrylic acid best represents a sizing agent used for polyester (0.05 kg/kg fabric), as it one of the main sizing agents next to starch (SJFZXM, n.d.). This study assumed starch and acrylic acid for cotton and polyester respectively, however sizes are often blends (European Commission, 2022). At this point the yarn can be woven into fabric. For the trousers data from the Ecoinvent 3 process for woven cotton is used. This data comes from the Cotton Incorporated (2017) report mentioned earlier. Cotton Incorporated (2017) shows per kg of woven cotton fabric 3.1 kWh of electricity and 2.3 MJ of heat, and a material loss of 4.8%. It is validated by Van der Velden et al. (2014), as they report for 400dtex around 3 kWh/kg fabric. They base these estimates on data from ITMF (2010), primary data and Koç & Çinçik (2010).

The weaving of polymers will most probably not differ much from the weaving of cotton (Van Der Velden et al., 2014). So for the weaving of the polyester fabric (dress) the data from van der Velden et al., (2014) for weaving 120 dtex was used, showing around 12 kWh/kg fabric.

Table S5. Modelling Details for Fabric Production

Cotton knitted fabric (t-shirt)	Ecoinvent 3: <i>textile, knit cotton {RoW}</i>   <i>textile production, cotton, circular knitting with transport data from Textile, knit cotton {GLO}</i>   <i>market for</i>
Cotton woven fabric (trousers)	Ecoinvent 3 <i>textile, woven cotton {RoW}</i>   <i>textile production, cotton, weaving with transport data from Textile, woven cotton {GLO}</i>   <i>market for</i>
Polyester woven fabric (dress)	Ecoinvent 3: 0.05 kg/kg output <i>acrylic acid {RoW}</i>   <i>market for acrylic acid</i> and 12 kWh electricity (mix as defined in table 2), transport data from <i>Textile, woven cotton {GLO}</i>   <i>market for</i>
PES/cotton knitted fabric (sweater)	Ecoinvent 3: <i>textile, knit cotton {RoW}</i>   <i>textile production, cotton, circular knitting</i> , altered to have an electricity use of 0.17 kWh/kg output, with transport data from <i>Textile, knit cotton {GLO}</i>   <i>market for</i>

### 1.1.4 Wet Processing (Pre-treatment and Dyeing)

To make the fabric ready for use the wet processing step is needed. It includes pre-treatment, dyeing and finishing.

Before dyeing is possible the fabric first has to be pre-treated, removing impurities/cleaning and being bleached. Woven cotton pre-treatment consists of the steps desizing, scouring and bleaching. Desizing removes any size or starchy material that was added for weaving. Scouring removes oils, fats and waxes in order to improve absorbency for dyeing, using alkali (like sodium hydroxide). Lastly, bleaching is done with oxidizing agents, improving the fabric's whiteness (Harane & Adivarekar, 2017) For knitted fabric desizing is not necessary as no sizing agent was added.

For the pre-treatment of knitted cotton (t-shirt) Cotton Incorporated (2017) data was used. As it represents data for pre-treatment of knitted cotton fabric specifically, based on data from 6 different plants from different parts of the world. Their research shows a 1.5% mass loss in this process. This is in line with the 1% loss Hansen et al. (2007) reported.

After pre-treatment the fabric is ready for dyeing. For cotton this is mostly done with reactive dyes with the batch dyeing method (Tobler-Rohr, 2011). Cotton Inc based their dyeing and pre-treatment data of knit cotton on the use of a Jet dyeing machine (Cotton Incorporated, 2017). It shows a total mass loss of 9.2%. Their steam, electricity and water use was compared with data from the BAT reference document for the textiles industry (European Commission, 2022). The energy use data from Cotton Inc was around 30% higher than those reported in the BAT document. The Ecoinvent process based on this pre-treatment and dyeing data from Cotton Inc is used, as it included also the water and chemical use.

Where batch dyeing is often used for knitted fabric, continuous dyeing is most common for woven cotton fabrics (Sandin et al., 2019). To represent this dyeing method and its required pre-treatment the Ecoinvent process for the continuous dyeing of woven cotton is used. This data is also based on the report of Cotton Incorporated (2017), which shows a material loss of 3.8%. As the paragraph indicates, for the woven cotton trousers it is assumed that fabric/piece dyeing takes place apropos to yarn dyeing, as it is the most cost effective method. Yarn dyeing would be necessary for woven colour patterns and hence for jeans (as they are generally woven from white and indigo coloured yarn) (Tobler-Rohr, 2011).

Polyester fabrics (dress) are almost exclusively dyed with batch dyeing methods (European Commission, 2022). Where cotton is mostly dyed with reactive dyes polyester is dyed with disperse dyestuff (Tobler-Rohr, 2011). Data to represent the pre-treatment and dyeing process for woven polyester fabric is taken from Sandin et al. (2019). Dyeing polyester with disperse dyes is here assumed to be done with a Jet dyeing machine, dyeing the fabric orange/red with the main dye component being aniline. They used a combination of primary data and literature. The same mass loss was assumed as for batch dyeing cotton fabric (3.8%) in the same type of machine. Emissions for this process could not be attained hence the (over)estimation was made that all chemical inputs were also outputs as water emissions. Added to this were the COD and BOD emissions from the sizing agent used (a polyacrylate), acquired from the textiles BAT report from the European Commission (2022).

For the pre-treatment and dyeing of polyester/cotton mixes, disperse dyes are used for the polyester portion and the cotton component is dyed with reactive, vat and indirect dyes. These dyes stain the other component only slightly and can easily be removed (European Commission, 2022). The process for the cotton/polyester sweater is modelled by combining (50/50) the cotton knit dyeing and pre-treatment (as explained above) and polyester knit dyeing and pre-treatment. For this last process data is used as presented in Roos et al. (2019) which is part of the MistraFutureFashion project and a preparatory study for Sandin et al. (2019). The same mass loss was assumed as for continuously dyeing woven cotton fabric (9.2%).

Table S6. Modelling Details for Pre-treatment and Dyeing

Dyed cotton knitted fabric (t-shirt)	Ecoinvent 3: <i>batch dyeing, fibre, cotton {RoW}</i>   <i>batch dyeing, fibre, cotton</i>
Dyed cotton woven fabric (trousers)	Ecoinvent 3: <i>continuous dyeing, fibre, cotton {GLO}</i>   <i>market for continuous dyeing, fibre, cotton</i>

Dyed polyester woven fabric (dress)	(Sandin et al., 2019): <i>Table B-35: Dyeing polyester weave for jacket, 70 dtex</i> , with the electricity mix as defined in table 2
Dyed PES/cotton knitted fabric (sweater)	50% the processes for dyeing cotton knitted fabric, and 50% (Sandin et al., 2019): <i>Table B-33 Dyeing polyester tricot for dress, 114 dtex</i> , with the electricity mix as defined in this study

### 1.1.5 Wet Processing (Finishing & Heat-Setting)

The last part in this wet-processing stage is finishing. Here the dyed fabric is treated with softeners and certain chemicals (like small amounts of water repellents and antimicrobials) to make it ready for use. The Ecoinvent processes for finishing respectively knit and woven cotton are used, also for the polyester and polyester/cotton fabric, as specific data on the finishing of those materials was not available. These Ecoinvent processes are based on data from Cotton Incorporated (2017). That study reports a 1% mass loss, corresponding with the findings of Hansen et al., (2007).

In the Cotton Inc. study they separate finishing and compacting/sanforizing. This last step are heat setting finishing processes for respectively knitted and woven fabric to reduce shrinkages, increase the density of the fabric, and facilitate dye fixation. For none of the data found on the finishing processes (Sandin et al., 2019; van der Velden et al., 2014; Cotton incorporated, 2017) it was completely clear which processes were exactly included or excluded. To prevent double counting/using the data in an incorrect manner, and as the Cotton Inc data also included information on water and chemical use it was chosen to use their finishing and consecutive sanforizing/compacting processes. The Ecoinvent processes for compacting and sanforizing are used as they are based on the data from Cotton Incorporated (2017).

Table S7. Modelling Details for Finishing

Finished cotton knitted fabric (t-shirt)	Ecoinvent 3: <i>finishing, textile, knit cotton {GLO}</i> market for finishing, textile, knit cotton
Finished cotton woven fabric (trousers)	Ecoinvent 3: <i>finishing, textile, woven cotton {GLO}</i> market for finishing, textile, woven cotton
Finished polyester woven fabric (dress)	Ecoinvent 3: <i>finishing, textile, woven cotton {GLO}</i> market for finishing, textile, woven cotton
Finished PES/cotton knitted fabric (trouser)	Ecoinvent 3: <i>finishing, textile, knit cotton {GLO}</i> market for finishing, textile, knit cotton

Table S8. Modelling Details for Heat-Setting

Compacted cotton knitted fabric (t-shirt)	(Cotton Incorporated, 2017): <i>Table 7-3: Textile production, cut-and-sew, use phase and EoL input-output values, compaction</i> , with electricity mix as defined in this study.
Sanforized cotton woven fabric (trousers)	Ecoinvent 3: <i>sanforizing, textile {GLO}</i> sanforizing, textile
Sanforized polyester woven fabric (dress)	Ecoinvent 3: <i>sanforizing, textile {GLO}</i> sanforizing, textile
Compacted PES/cotton knitted fabric (sweater)	(Cotton Incorporated, 2017): <i>Table 7-3: Textile production, cut-and-sew, use phase and EoL input-output values, compaction</i> , with electricity mix as defined in this study.

### 1.1.6 Confectioning

Now the fabric is ready for use, the last production step is cutting and sewing it into the required form. According to both Roos et al. (2015) and Sule (2012), for a cotton T-shirt 15% of the fabric is lost in the confectioning process. For the material losses of the other items data from (Beton et al., 2014) is used: dress 18%, a jersey 10%, a pair of trousers 14% material loss. For the energy and water use data information from Sandin et al. (2019) is used. They determined that for a cotton t-shirt 2.64 kWh electricity, 0.065 MJ heat and 0.182 kg water is needed per kg garment for cutting and sewing. Modelling details can be found in Appendix 8.3.1.7.

This data is supported by the results of Sule (2012), and Çay (2018). Sule (2012) did an LCA specifically on the making-up phase, consisting of cutting, sewing and packaging of cotton t-shirts. They reported energy consumption values, being 1.2 and 2 kWh per kg clothing for cutting and sewing respectively. As the main

energy use in these processes is electricity for the machines, the energy use is assumed to all be electricity. Çay (2018) also looked into this, gathering primary data from plants in Turkey on the production of one piece of knitted garment from dyed-finished fabric. They reported energy use between 0.78-1.44 MJ/piece depending on whether the product is embroidered/screen printed or not, and noted this was mainly electricity use. If assuming a piece of knitted garment refers mainly to t-shirts (around 180gr), then this data is in line with the research shows above. On the other hand, Cotton Incorporated (2017) also reported data on this phase, and their results are quite different. Reporting 0.1 kWh of electricity use/kg of cotton t-shirt. This data was based on information from the company Juki who sells machines for cutting and sewing, however, details on their calculations could not be obtained.

Table S9. Modelling Details for Confectioning

Cotton knitted t-shirt	(Sandin et al., 2019): Table B-40: T-shirt confectioning
Cotton woven trousers	(Sandin et al., 2019): Table B-41: Jeans confectioning
Polyester woven dress	(Sandin et al., 2019): Table B-42: Dress confectioning
PES/cotton knitted sweater	(Sandin et al., 2019): Table B-44: Hospital uniform confectioning

## 1.2 Transport and Retail Phase

The transport from production to retail is based on the average transport data from the IMPRO report, this report is used a lot as source for textile transport data. It reports 92% transport by sea and 8% by air for transport from Asia to Europe over approximately 13 000 km by sea and 6800 km by air (Beton et al., 2014). The data for retail transport and the energy use of the stores is based on Sandin et al. (2019). They report H&M data from 2012, showing 1.9 kWh of electricity/kg garment. This includes a small credit for energy recovery from waste incineration (~3%) from the waste management of the packaging material and textile waste (1% material loss).

It was assumed that user transport was 15 km (to the store and back summed), 50% of this transport was done by car and 50% by bus. 1/3 was attributed to the garment, as it was assumed that a shopping trip would resume in more than just one garment. These assumption are based on Sandin et al. (2019) who refer to a study that was done in preparation of their study by Granello et al in 2015 on consumer behaviour in the apparel sector.

Table S10. Modelling Details for Transport and Retail

Transport production – retail	11.96 tkm/kg	Ecoinvent 3: transport, freight, sea, container ship {GLO}  market for transport, freight, sea, container ship
	0.54 tkm/kg	Ecoinvent 3: transport, freight, aircraft, long haul {GLO}  transport, freight, aircraft, dedicated freight, long haul
	2.85 tkm/kg	Ecoinvent 3: Transport, freight, lorry 16-32 metric ton, euro6 {RER}  market for transport, freight, lorry 16-32 metric ton, EURO6
	0.32 tkm/kg	Ecoinvent 3: Transport, freight, lorry 3.5-7.5 metric ton, euro6 {RER}  market for transport, freight, lorry 3.5-7.5 metric ton, EURO6
Retail	1.9 kWh/kg	Electricity mix as defined in table 2
	2.83 km/kg	Ecoinvent 3: Transport, passenger car {RER}  market for
	2.83 personkm/kg	Ecoinvent 3: Transport, regular bus {GLO}  market for

## 1.3 Use Phase

### 1.3.1 Consumer Behaviour

In the recent years quite a lot of studies have been done on (or including) clothing consumption behaviour (Beton et al., 2014; Cotton Incorporated, 2017; Daystar et al., 2019; Gwozdz et al., 2017; Presutto et al., 2007; Sandin et al., 2019). Table S11 shows the data found in the different studies and the subsequent assumptions made for average consumption in this study. Almost no specific data was found for sweaters, so it was assumed that their use is comparable to those of trousers, both being items that are worn multiple times before washing and are made from relatively sturdy material.

The table shows that it was assumed that T-shirts are washed twice before washing, a dress a bit more and that trousers and sweaters are worn relatively long before washing. T-shirts are assumed to be washed the most over their lifetime, closely followed by trousers and sweaters, with dresses being washed

significantly less as they are worn relatively little over their lifetime compared to the other items. The third paragraph in Table S12 shows the lifetime (in number of times worn), it shows that trousers and sweaters are worn many times while t-shirts have a much shorter lifetime.

Furthermore the table shows that approximately 20-25% of drying is done at home with a tumble dryer, the rest is air-dried. Lastly ironing is investigated and assumed to take place in 10-20% of the cases, the assumption is made with a high uncertainty due to the difference in data reported in literature.

Table S11. Consumer Behaviour Data. Summary of Literature, Including the Assumptions Made for This Study (In Italics)

	Source	Dress	T-shirt	Trousers	Sweater	Note
Uses/wash	GWOZDZ 2017	2	2	8		Germany, Poland, Sweden, US
	DAYSTAR 2019		1.9	5.1		UK
	<i>THIS STUDY</i>	2	2	6	5	
Number of washes over (1 <sup>st</sup> ) lifetime	GWOZDZ 2017		22	6		Germany, Poland, Sweden, US
	DAYSTAR 2017		17	22		UK
	COTTON INC 2017		18.2	23.5		global
	<i>THIS STUDY</i>	8	20	16	16	
Number of times worn over (1 <sup>st</sup> ) lifetime	GWOZDZ 2017		36	48		Germany, Poland, Sweden, US
	DAYSTAR 2017		33	112.2		UK
	BETON 2014	15	50	92	50	
	<i>THIS STUDY</i>	16	40	96	80	
% washes dried	GWOZDZ 2017			20%		Germany and Sweden
	DAYSTAR 2017			20%		UK
	SANDIN 2019	19%	34%	29%		Europe
	COTTON INC 2017			20%		UK
	PRESUTTO 2007			25%		Europe
	<i>THIS STUDY</i>	20%	25%	25%	25%	
% washes ironed	DAYSTAR 2017		63%	68%		UK
	SANDIN 2019	18%	15%			Europe
	<i>THIS STUDY</i>	20%	15%	15%	10%	

Table S12. Number of Assumed Uses for the Different Consumer Types and Behaviour Scenarios

	T-shirt	Dress	Trousers	Sweater
Primary average user	40	16	96	80
Primary fashionable user	10	4	24	20
Primary attached user	80	32	192	160
Primary average conscious user	40	16	96	80
Primary fashionable conscious user	10	4	24	20
2nd hand average user	20	8	48	40
2nd fashionable user	5	2	12	10
2nd hand attached use	40	16	96	80

### 1.3.2 Washing

As 97% of people in the UK use a washing machine at home to do their laundry (Daystar et al., 2019), it was assumed that all the washing in the use phase is done with a residential washing machine. The energy and water consumption were based on the European Commission Ecodesign preparatory study (Presutto et al., 2007). It is reasonable to assume that the average washing machine can compare to the most efficient machine in 2007 (Sandin et al., 2019). The European Commission study reported the minimum energy consumption to be 0.88 kWh/cycle and the minimum water consumption to be 37.5 L/cycle for a full average load capacity of 5.36 kg at 60 degrees. However, they conclude that in reality washing machines often turn at only 64% of their full load, and that the washing temperature is averagely 45 degrees Celsius. Taking this into account leads to an energy consumption of 0.19 kWh/kg. It is assumed that most washing machines adjust the amount of water use to the amount of load, resulting in a water consumption of 6.17 L/kg. This source was also used in the IMPRO study and the Mistra Future Fashion (MFF) project (Beton et al., 2014)(Sandin et al., 2019). What is striking however is that the IMPRO study reports very different energy and water usages. They might have mistaken the specific energy consumption for the total energy consumption. The MFFs values differ slightly, presumably as they have taken the average energy and water use, whereas here the minimum values were taken to account for technology developments in the past 10-15 years.

The international Association for Soaps, Detergents and Maintenance Products (A.I.S.E) conducted a study to set up a Product Environmental Footprint Category Rules (PEFCR). Together with 46 stakeholder organisations they defined (among others) a bill of ingredients for machine laundry detergent (AISE, 2019). The recipe indicated by them is used, including the chemicals, packaging and energy use for production. A use of 16.7 g/kg clothing of this detergent is generally used (AISE, 2019).

For the waste water management it is assumed that the process in the UK resembles that of Switzerland. Hence the Ecoinvent 3 process for treating residential waste water in Switzerland are used to represent this.

Presutto et al., (2007) reports that washing machines have a lifetime of approximately 15 years, with around 220 cycles per year (3.4 kg/cycle). So 1/11220 part of a washing machine is attributed to every kg clothing washed.

Table S13. Modelling Details for Washing 1 KG of Clothing Once

1/11220 of a washing machine	Ecoinvent 3: <i>washing machine {GLO}</i>   market for washing machine
16.7 g detergent	(Sandin et al., 2019): <i>Table B-58: Detergent, liquid</i>
6.17 L water	Ecoinvent 3: <i>Tap water {ZA}</i>   market for tap water
0.19 kWh electricity	Ecoinvent 3: <i>Electricity, low voltage {GB}</i>   market for
1.63 g plastic EoL (packaging)	Ecoinvent 3: <i>Waste plastic, mixture {GB}</i>   market for waste plastic, mixture
6.17 L water EoL	Ecoinvent 3: <i>wastewater, from residence {CH}</i>   market for wastewater, from residence

### 1.3.3 Drying and ironing

When a dryer is used to dry the clothes after washing it is from now on referred to as drying. Line/air drying is assumed to not have a significant environmental impact. Assuming the most efficient condenser tumble dryer in 2008, an average energy use of 0.6 kWh/kg clothes for drying is used, based on the European Commission Ecodesign preparatory study for clothes dryers (PriceWaterhouseCoopers, 2009).

PriceWaterhouseCoopers, (2009) also report that dryers have a lifetime of approximately 13 years, with around 175 cycles per year. So 1/7735 part of a dryer is attributed to every kg clothing dried.

The ironing of clothes was assumed to require 1.6 kWh/h of ironing (Presutto et al., 2007). For dresses and trousers around 6 min ironing is needed, for t-shirt and sweaters this is around 3 min (Presutto et al., 2007).

Table S14. Modelling Details for Drying 1 KG of Clothing Once

1/7735 of a dryer	Ecoinvent 3: <i>dryer {GLO}</i>   market for dryer
0.6 kWh electricity	Ecoinvent 3: <i>Electricity, low voltage {GB}</i>   market for

Table S15. Modelling Details for Ironing 1 KG of Clothing Once

Dress	0.12 kWh electricity	Ecoinvent 3: <i>Electricity, low voltage {GB}</i>   market for
T-shirt	0.167 kWh electricity	Ecoinvent 3: <i>Electricity, low voltage {GB}</i>   market for
Trousers	0.133 kWh electricity	Ecoinvent 3: <i>Electricity, low voltage {GB}</i>   market for
Sweater	0.068 kWh electricity	Ecoinvent 3: <i>Electricity, low voltage {GB}</i>   market for

## 1.4 End-Of-Life Waste Management

For the end-of-life (EoL) waste management it is assumed that 89% is incinerated with energy recovery and 11% is landfilled. This is based on the most recent and relevant study done by WRAP (2024), tracking the mass flow of items through their (multiple) lives. They concluded that 84% was incinerated, 11% was landfilled and 5% was unknown. As the bulk was incinerated this study assumed most of the unknown wastestream ended up being incinerated too.

Incinerating polyester and cotton fabric with energy recovery can be respectively represented by the processes of municipal incineration of PET, and paperboard (Sandin et al., 2019). As the polyester fabric is made from PET granules, and cotton and paperboard have a similar chemical structure, containing both cellulose as the major component. A substitution approach is taken, the produced heat is assumed to replace heat from natural gas for industry, and the generated electricity is assumed to replace electricity from the average UK electricity mix. A 50 km round trip with a waste collection lorry is assumed (WRAP, 2011).

With Energy from Waste statistics from the UK 2020, which indicate the average calorific value of the incinerated waste and its heat and electricity output (Tolvik, 2021), an electric efficiency of 22.1% and thermal efficiency of 4.7% for UK WfE plants was calculated (table 17).

Table S16. Waste to Energy (Wte) Literature Information and Data Used for This Study. Italics Indicate the Parameter Was Calculated Based on the Other Information in This Table, of Which the Sources Are Stated in the Last Column)

Material	Parameter	Unit	Value	Source
General waste incineration (WtE) UK 2020	Electricity generated	MWh/t	0.56	According to statistics of UK energy from waste 2020 (Tolvik, 2021)
	Heat generated	MWh/t	0.12	
	Average calorific value	MJ/kg	9.11	
	<i>Electric efficiency</i>	%	22.1%	
	<i>Thermal efficiency</i>	%	4.7%	
Polyester WtE	HHV	MJ/kg	23.1	The HHV of PET from Doka (2003)
	<i>Electricity generation</i>	<i>kWh/kg</i>	1.42	
	<i>Heat generation</i>	<i>MJ/kg</i>	1.10	
Cotton WtE	HHV	MJ/kg	17.9	The HHV of cardboard from Doka (2003)
	<i>Electricity generation</i>	<i>kWh/kg</i>	1.10	



Heat generation	MJ/kg	0.85
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Table S17. Modelling Details for the End-Of-Life Waste Management

1 kg cotton	0.05 tkm	Ecoinvent 3: <i>Municipal waste collection service by 21 metric ton lorry {CH}  processing</i>
	0.89 kg to incineration	Ecoinvent 3: <i>Waste paperboard {CH}  treatment of, municipal incineration, altered to displace 0.85 MJ of heat and 1.10 kWh of electricity (Ecoinvent 3.0: Heat, district or industrial, natural gas {Europe without Switzerland}  market for, and Electricity, high voltage {GB}  market for)</i>
	0.11 kg to landfill	Ecoinvent 3: <i>Waste paperboard {CH}  treatment of, sanitary landfill</i>
1 kg polyester	0.05 tkm	Ecoinvent 3: <i>Municipal waste collection service by 21 metric ton lorry {CH}  processing</i>
	0.89 kg to incineration	Ecoinvent 3: <i>waste polyethylene terephthalate {CH}  treatment of waste polyethylene terephthalate, municipal incineration, altered to displace 1.10 MJ of heat and 1.42 kWh of electricity (Ecoinvent 3.0: Heat, district or industrial, natural gas {Europe without Switzerland}  market for, and Electricity, high voltage {GB}  market for)</i>
	0.11 kg to landfill	Ecoinvent 3: <i>waste polyethylene terephthalate {CH}  treatment of waste polyethylene terephthalate, sanitary landfill</i>
1 kg PES/cotton	0.5 kg cotton EoL waste management as described above 0.5 kg polyester EoL waste management as described above	

## 1.5 Retail for Reuse

Table S18. Modelling Details for Processing for Second Life Processes by the Second-Hand Trading Company, per Item. Based on the Information in Table 21

2.05 Wh electricity warehouse	Ecoinvent 3: <i>Electricity, low voltage {GB}  market for</i>
11.51 g storage LDPE bag	Packaging film, low density polyethylene {GLO}  market for
63 g outbound 80% recycled HDPE bag	80% Ecoinvent 3: <i>Polyethylene, high density, granulate, recycled {Europe without Switzerland}  market for polyethylene, high density, granulate, recycled, 20% Ecoinvent 3: Polyethylene, high density, granulate {GLO}  market for. Extruded with a 5% material loss (Ecoinvent 3: Extrusion, plastic film {GLO}  market for).</i>
5 g paper invoice	Ecoinvent 3: <i>Printed paper {GLO}  market for</i>
Postal transport 1 trip 0.28 tkm <sup>1</sup>	50% by van (Ecoinvent 3: <i>Transport, freight, light commercial vehicle {RER}  market group for transport, freight, light commercial vehicle</i> ) 50% by truck (Ecoinvent 3: <i>Transport, freight, lorry 16-32 metric ton, euro6 {RER}  market for transport, freight, lorry 16-32 metric ton, EURO6</i> )
<sup>1</sup> Later the extra transport it is taken into account for the amount of items returned/items sold or donated	

### 1.5.1 Warehouse Processes

The information on the warehouse processes data was gathered from contact with the warehouse operator. When items enter the warehouse they are generally packaged in bags that have been used before, like shopping/supermarket bags or bags people have received previous orders in. As these bags would most likely otherwise have been thrown away no burden was assumed. When unpacked it is assessed whether the item is of adequate quality. If the item is accepted then it is packaged in a clear LDPE bag. It is stored temporarily. When the item is sold it is packaged in a grey recycled PE bag, an A4 paper invoice is added and then it is sent. The warehouse operator indicated that all T-shirts, jeans, dresses and sweaters are packaged in medium-sized bags.

For the electricity and heat use of the warehouse, primary data was used. The warehouse operator reported that their warehouse only uses electricity (the office heating is done with heat pumps). Three things have been taken into account in estimating what part of the electricity use of the warehouse should be attributed to the second-hand trading company. Firstly the warehouse operator indicated that the second-hand trading company uses only a very small part of their warehouse space, approximately 0.67 %. However, for sending and receiving the packages the second-hand trading company does use respectively 3 out of the 8 outbound

and 1 out of the 8 inbound benches. Lastly, a large part of the electricity use of the warehouse is for charging the forklift trucks that are not used for the second-hand trading company, only for other parties using the warehouse. Taking this into consideration the choice was made to attribute 1% of the electricity use of the warehouse to the second-hand trading company. The warehouse operator provided the electricity bill for February 2022. It was assumed that this was representative for the average monthly electricity bill, corroborated by them.

*Table S19. The Second-Hand Trading Company Warehouse Information, the Resulting Inputs for the Storing and Sending of 1 Item*

Parameter	Unit	
Electricity use warehouse for the second-hand trading company	2.1	Wh/item
Storage LDPE bag	11.5	g/item
Transport HDPE bag	62.9	g/item
Paper A4 invoice	5	g/item

*Table S20. Background Information on the Second-Hand Trading Company Processes. Some Confidential Information Has Been Left Out*

Parameter	Unit		Source
UK electricity price 2021	pounds/kWh	18.9	(Yurday, 2022)
Warehouse share THE SECOND-HAND TRADING COMPANY	%	1%	Assumption based on Cloudfulfillment
Storage LDPE bag (medium)	cm <sup>2</sup>	1670	Cloudfulfillment
	mu (thickness)	37.5	
Transport HDPE bag (medium)	cm <sup>2</sup>	5400	Cloudfulfillment
	mu (thickness)	60	
Density LDPE bag	g/cm <sup>3</sup>	0.92	(United States Plastic Corp., 2008)
Density HDPE bag	g/cm <sup>3</sup>	0.95	(United States Plastic Corp., 2008)

### 1.5.2 Postal Transport

The items are transported by UK mailing services from the first consumer to the second-hand trading company and then from the second-hand trading company to the second consumer. Hermes (the outbound mailing service) uses solely EURO 6 compliant trucks (Hermesworld, 2018). It is assumed that this is the case for both inbound and outbound packages. The average direct distances for the outbound packages were calculated using 100 random orders. It was assumed that the average inbound and outbound distances were roughly the same. So for items that are directly re-sold through the second-hand trading company the average transport distance to the consumer (Table S21) is doubled to account for both the transport from the first consumer to the second-hand trading company as the from the second-hand trading company to the second consumer. However, it has been taken into account that not all items pass quality control. This extra postal transport is added.

Transport between distribution centres is often done with large trucks, after which the packages are delivered in vans. To take this into account it was assumed that 50% of the distance is covered by the large trucks, and 50% by the vans. Table 22 shows the resulting transport distance assumed in tkm per kg clothing.

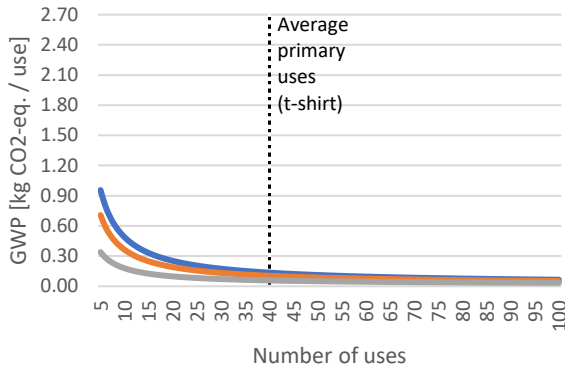
*Table S21. Postal Transport Information Second-Hand Trading Company*

Parameter	Unit	
Average road distance (one trip)	km	281
Large truck transport	%	50%
Van transport	%	50%

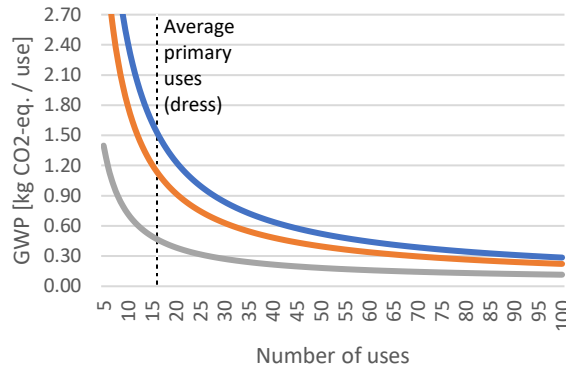
### 1.5.3 Data Servers Second-Hand Trading Company

For the data infrastructure of the second-hand trading company a web service provider is used. They provided information on the estimated CO<sub>2</sub> emissions associated with the service they provide the second-hand trading company (0.11 kg CO<sub>2</sub>/item). It was not possible to obtain information on energy or electricity use, so these processes have only been taken into account for the GWP. Furthermore, the emissions reported are those since the second-hand trading company was founded, but the item flow did not start immediately. It is not completely clear if most of the emissions reported are due the building of the data infrastructure, or from the day to day use now. If the former is the case then the emissions as calculated per item now might be an overestimation.

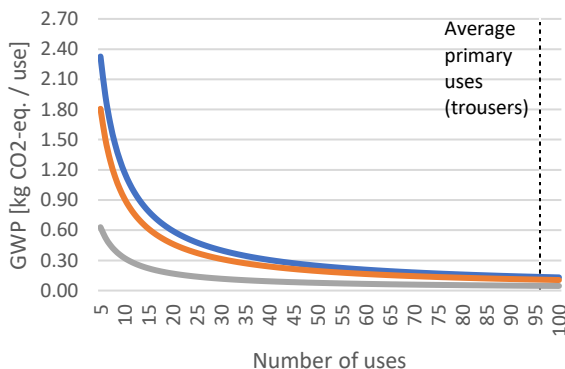
## 2. FULL LCA RESULTS



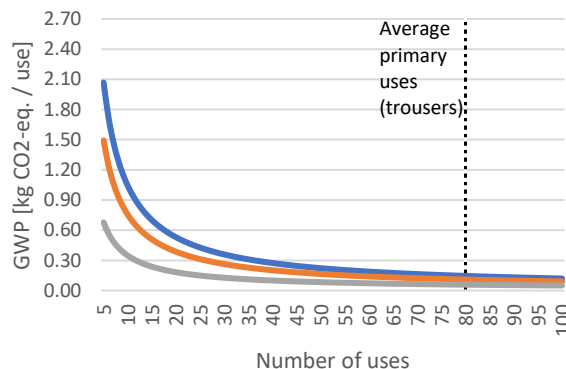
a. T-shirt - Global warming potential



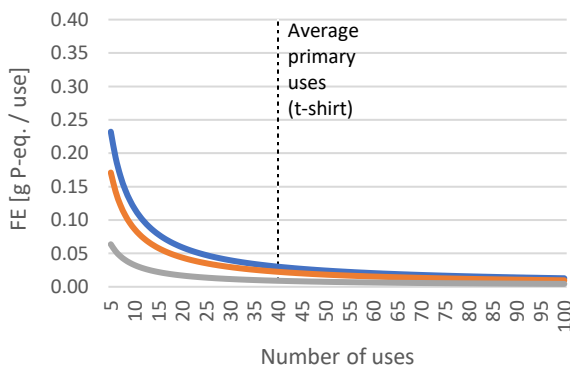
b. Dress - Global warming potential



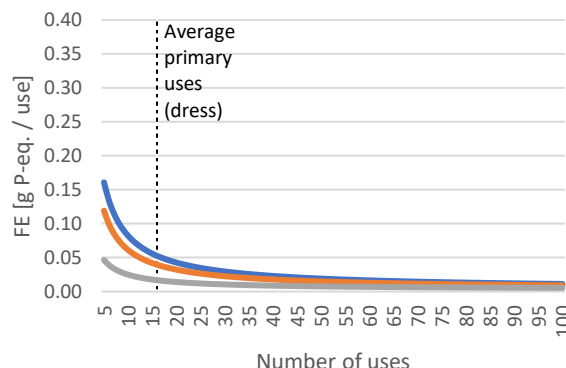
c. Trousers - Global warming potential



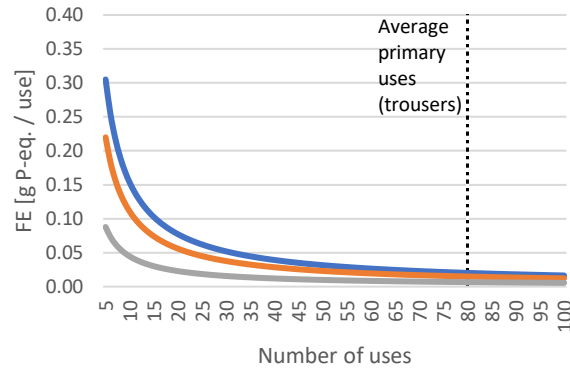
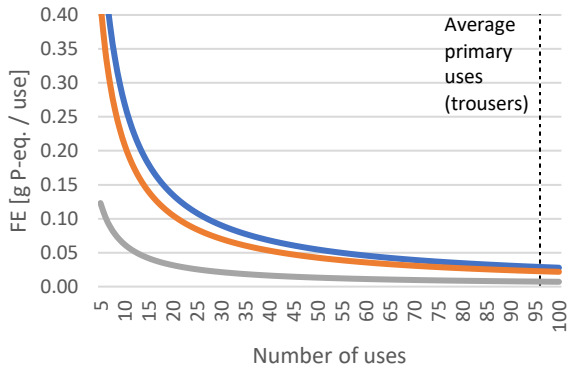
d. Sweater - Global warming potential



e. T-shirt - Freshwater eutrophication

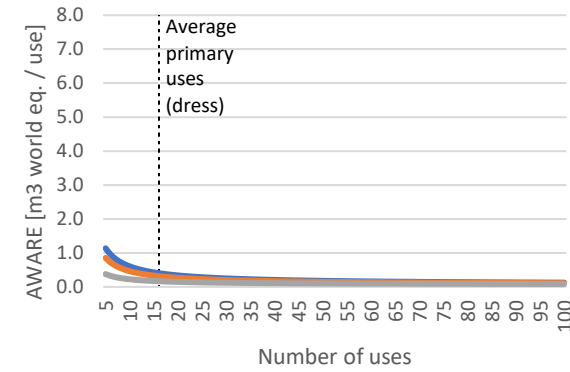
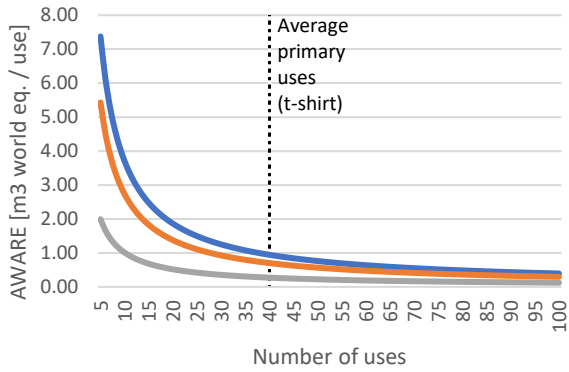


f. Dress - Freshwater Eutrophication



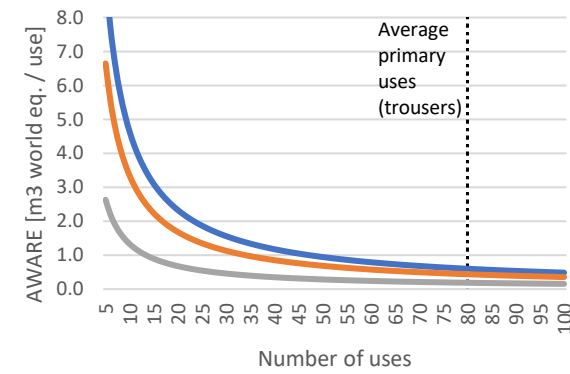
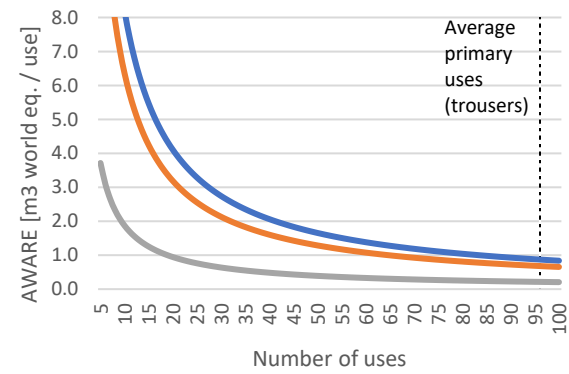
g. Trousers - Freshwater eutrophication

h. Sweater - Freshwater eutrophication



i. T-shirt - Water scarcity footprint

j. Dress - Water scarcity footprint



k. Trousers - Water scarcity footprint

l. Sweater - Water scarcity footprint

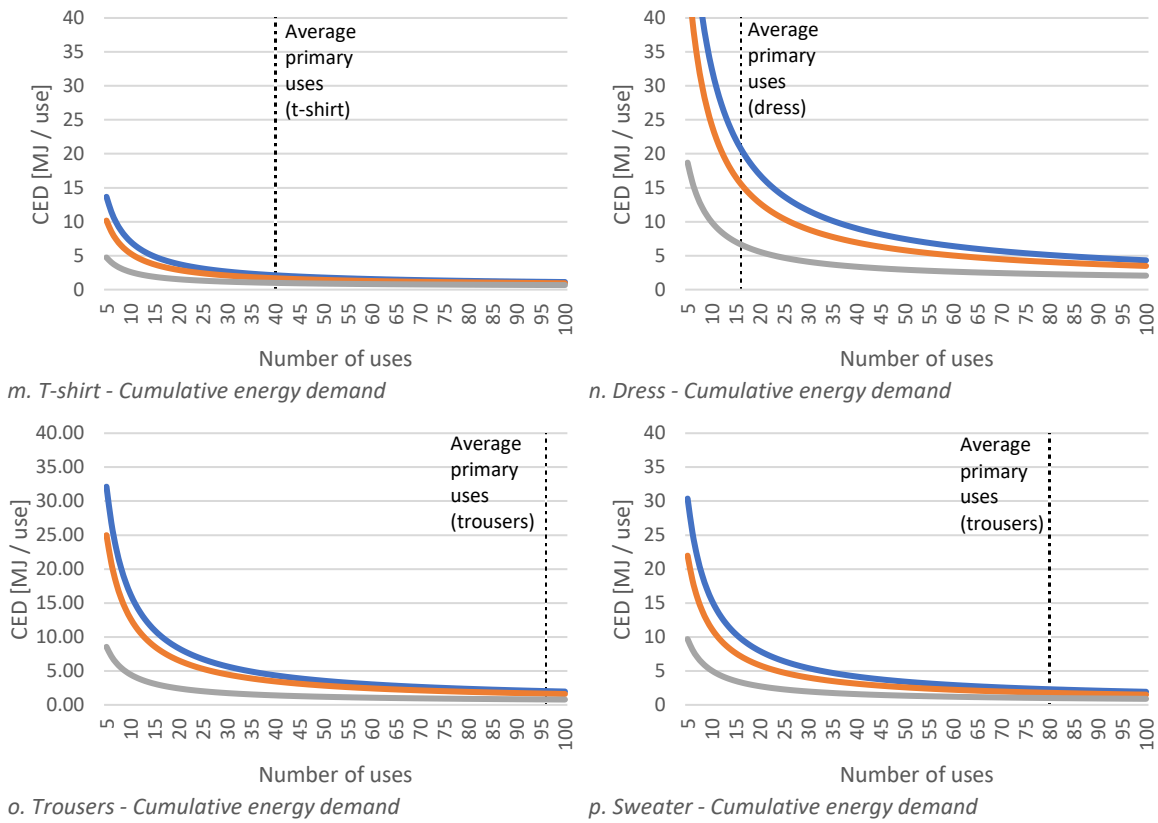


Figure S1. Impact per Use Shown Over Different Number of Assumed Uses for the Three Main Consumer Behaviour Scenarios. For All Four Impact Categories for All Four Items (A-P)

Table S22. Impact Results for the Different Items, Impact Categories and Consumer Type and Behaviour Scenarios, per Use (FU)

Item	Tshirt								
Impact category	GWP								
Unit	kg CO2-eq								
	Primary user			Primary conscious user			Second hand user		
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.051	0.102	0.408	0.075	0.300	0.027	0.054	0.216	
Retail	0.004	0.009	0.034	0.009	0.034	0.000	0.000	0.000	
Use	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.011	0.023	0.091	
EoL	0.000	0.000	-0.001	0.000	0.000	0.000	0.000	0.000	
Total	0.073	0.129	0.460	0.1017	0.352	0.057	0.095	0.325	
Item	Tshirt								
Impact category	FE								
Unit	g P-eq								
	Primary user			Primary conscious user			Second hand user		
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.014	0.029	0.115	0.021	0.084	0.008	0.015	0.061	
Retail	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.000	
Use	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	
EoL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Total	0.016	0.030	0.117	0.0225	0.086	0.009	0.017	0.064	
Item	Tshirt								
Impact category	AWARE								
Unit	m3 world eq.								
	Primary user			Primary conscious user			Second hand user		
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.459	0.918	3.672	0.675	2.700	0.243	0.486	1.944	
Retail	0.000	0.001	0.002	0.001	0.002	0.000	0.000	0.000	
Use	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.003	0.006	0.024	
EoL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Total	0.485	0.944	3.700	0.7012	2.728	0.272	0.518	1.993	
Item	Tshirt								
Impact category	CED								
Unit	MJ								
	Primary user			Primary conscious user			Second hand user		
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.744	1.488	5.954	1.094	4.378	0.394	0.788	3.152	
Retail	0.084	0.168	0.672	0.168	0.672	0.000	0.000	0.000	
Use	0.456	0.456	0.456	0.456	0.456	0.456	0.456	0.456	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.141	0.283	1.131	
EoL	-0.019	-0.039	-0.154	-0.028	-0.114	-0.010	-0.020	-0.082	
Total	1.265	2.074	6.927	1.6897	5.392	0.981	1.506	4.657	

Item	Dress								
Impact category	GWP								
Unit	kg CO2-eq								
	Primary user			Primary conscious user			Second hand user		
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.707	1.414	5.656	1.040	4.159	0.374	0.749	2.994	
Retail	0.030	0.059	0.237	0.059	0.237	0.000	0.000	0.000	
Use	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.044	0.088	0.354	
EoL	0.023	0.046	0.184	0.034	0.135	0.012	0.024	0.098	
Total	0.807	1.567	6.125	1.1805	4.579	0.478	0.909	3.493	
Item	Dress								
Impact category	FE								
Unit	g P-eq								
	Primary user			Primary conscious user			Second hand user		
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.024	0.048	0.193	0.035	0.142	0.013	0.026	0.102	
Retail	0.001	0.001	0.004	0.001	0.004	0.000	0.000	0.000	
Use	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.006	
EoL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Total	0.028	0.052	0.200	0.0397	0.149	0.017	0.030	0.111	
Item	Dress								
Impact category	AWARE								
Unit	m3 world eq.								
	Primary user			Primary conscious user			Second hand user		
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.164	0.329	1.314	0.242	0.966	0.087	0.174	0.696	
Retail	0.002	0.004	0.016	0.004	0.016	0.000	0.000	0.000	
Use	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.008	0.017	0.068	
EoL	0.000	0.000	-0.001	0.000	-0.001	0.000	0.000	0.000	
Total	0.237	0.403	1.400	0.3164	1.053	0.166	0.262	0.834	
Item	Dress								
Impact category	CED								
Unit	MJ								
	Primary user			Primary conscious user			Second hand user		
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	9.242	18.483	73.932	13.590	54.362	4.893	9.785	39.141	
Retail	0.584	1.167	4.668	1.167	4.668	0.000	0.000	0.000	
Use	1.181	1.181	1.181	1.181	1.181	1.181	1.181	1.181	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.595	1.191	4.763	
EoL	-0.179	-0.358	-1.434	-0.264	-1.054	-0.095	-0.190	-0.759	
Total	10.826	20.472	78.347	15.6745	59.156	6.574	11.967	44.325	

Item	Trousers								
Impact category	GWP								
Unit	kg CO2-eq								
	Primary user			Primary conscious user			Second hand user		
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.052	0.105	0.418	0.081	0.324	0.024	0.047	0.188	
Retail	0.004	0.009	0.036	0.009	0.036	0.000	0.000	0.000	
Use	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.007	0.014	0.056	
EoL	0.000	0.000	-0.001	0.000	0.000	0.000	0.000	0.000	
Total	0.072	0.128	0.468	0.1049	0.375	0.045	0.076	0.259	
Item	Trousers								
Impact category	FE								
Unit	g P-eq								
	Primary user			Primary conscious user			Second hand user		
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.014	0.028	0.111	0.022	0.086	0.006	0.012	0.050	
Retail	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.000	
Use	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	
EoL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Total	0.015	0.029	0.113	0.0227	0.088	0.007	0.014	0.052	
Item	Trousers								
Impact category	AWARE								
Unit	m3 world eq.								
	Primary user			Primary conscious user			Second hand user		
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.425	0.849	3.398	0.658	2.634	0.191	0.382	1.528	
Retail	0.000	0.001	0.002	0.001	0.002	0.000	0.000	0.000	
Use	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.011	
EoL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Total	0.446	0.871	3.422	0.6805	2.658	0.214	0.406	1.560	
Item	Trousers								
Impact category	CED								
Unit	MJ								
	Primary user			Primary conscious user			Second hand user		
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.742	1.484	5.937	1.151	4.602	0.334	0.667	2.669	
Retail	0.088	0.175	0.700	0.175	0.700	0.000	0.000	0.000	
Use	0.376	0.376	0.376	0.376	0.376	0.376	0.376	0.376	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.093	0.186	0.743	
EoL	-0.020	-0.040	-0.161	-0.031	-0.125	-0.009	-0.018	-0.072	
Total	1.185	1.995	6.852	1.6702	5.554	0.793	1.211	3.716	



Item	Sweater								
Impact category	GWP								
Unit	kg CO2-eq								
	Primary user			Primary conscious user		Second hand user			
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.056	0.112	0.450	0.081	0.323	0.032	0.063	0.252	
Retail	0.005	0.010	0.042	0.010	0.042	0.000	0.000	0.000	
Use	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.008	0.017	0.066	
EoL	0.002	0.004	0.016	0.003	0.011	0.001	0.002	0.009	
Total	0.081	0.144	0.525	0.1115	0.394	0.058	0.099	0.345	
Item	Sweater								
Impact category	FE								
Unit	g P-eq								
	Primary user			Primary conscious user		Second hand user			
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.009	0.019	0.075	0.014	0.054	0.005	0.011	0.042	
Retail	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.000	
Use	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	
EoL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Total	0.011	0.020	0.077	0.0149	0.056	0.007	0.012	0.044	
Item	Sweater								
Impact category	AWARE								
Unit	m3 world eq.								
	Primary user			Primary conscious user		Second hand user			
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.287	0.575	2.298	0.413	1.653	0.161	0.322	1.290	
Retail	0.000	0.001	0.003	0.001	0.003	0.000	0.000	0.000	
Use	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.002	0.003	0.013	
EoL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Total	0.313	0.600	2.326	0.4391	1.681	0.188	0.351	1.328	
Item	Sweater								
Impact category	CED								
Unit	MJ								
	Primary user			Primary conscious user		Second hand user			
	Attached	Average	Fashionable	Average	Fashionable	Attached	Average	Fashionable	
Production	0.837	1.675	6.698	1.205	4.819	0.470	0.940	3.759	
Retail	0.103	0.206	0.823	0.206	0.823	0.000	0.000	0.000	
Use	0.430	0.430	0.430	0.430	0.430	0.430	0.430	0.430	
Retail for reuse	0.000	0.000	0.000	0.000	0.000	0.110	0.220	0.881	
EoL	-0.028	-0.055	-0.221	-0.040	-0.159	-0.016	-0.031	-0.124	
Total	1.342	2.255	7.730	1.8007	5.913	0.994	1.559	4.946	