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SCIENTIFIC REPORT

Environmental assessment of two business models

- a life cycle comparison between a sales and a rental business model in the apparel sector in Sweden

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1. Introduction

Economic activity and growth are historically coupled with environmental impact (Rockström et al., 2009). The prevailing model for generating economic value is the so-called "take-make-dispose" model, where resources are extracted, formed into products and then sold to be used and disposed, most commonly in a way that they cannot be recovered or reused (Blomsma and Brennan, 2017). On a company level, this is embodied in so-called "linear business models". The concept of "business model" has many interpretations, often diverging (De Angelis, 2018), but one common definition is provided by Osterwalder and Pigneur (2010), namely that a business model is "the rationale of how an organization creates, delivers, and captures value". In a linear business model, a company captures value (i.e. generates profit) via the continuous sale and turnover of products, which has implications in terms of resource consumption and environmental impact. Since the profit generation of a linear business model is so tied to the use of materials and energy, it is necessary to adopt alternative ways of doing business in order to reduce global environmental degradation.

The concept of generating economic value at a reduced environmental impact has been termed "decoupling", which promises to achieve a reduction of damage on the environment and on human health while avoiding economic losses (Bocken et al., 2016). Often, decoupling is discussed on a macro-level, for example to decouple a nation's gross domestic product from carbon emissions (European Commission, 2015; International Resource Panel, 2011). However, such decoupling necessarily involves the micro-level of e.g. companies who can implement economically sustainable business models that also significantly reduce environmental impact, for example by using a rental model instead of a model built on product sales. There are several proposed ways of achieving such company-level decoupling, e.g. via sustainable business models (SBM), product-service systems (PSS) and Circular Business Models (CBM) (Geissdoerfer et al., 2018; Lüdeke-Freund et al., 2018).

Sustainable business models are defined by Geissdoerfer et al. (2018) as "business models that incorporate pro-active multi-stakeholder management, the creation of monetary and non-monetary value for a broad range of stakeholders, and hold a long-term perspective". The multiple stakeholders can be other actors along the value chain, but also the environment and society which are seen as primary stakeholders (Evans et al., 2017). SBM is thus a wide concept, where all dimensions of sustainability are taken into account.

A subcategory of SBMs are product-service systems (PSS), which can be defined as "a mix of tangible products and intangible services, designed and combined so that they are jointly capable of fulfilling final customer needs" (Tukker and Tischner, 2006). The idea is that a focus on final user needs will enable more service-based systems with radically lower environmental impacts compared to product-oriented systems where incentives lie with maximising product sales. PSS can be divided into three main categories (Tukker, 2004). The first category is *product-oriented PSS*, where the PSS is mainly based on the sale of products with additional services provided (e.g. selling a vehicle with a maintenance contract). The second category is *use-oriented PSS*, where the product plays an essential role but the provider keeps the ownership of the product (e.g. leasing or sharing models). The third category is *result-oriented PSS*, where a function or result is provided, without any specification of what products are involved. The three categories can be placed on a spectrum stretching from what Tukker (2004) calls a pure product business model on one hand to a pure service on the other hand, where customer needs are completely satisfied by only tangible products or intangible services, respectively. Product-oriented PSS are close to the pure product end of the spectrum, while use-oriented PSS are in the middle and result-oriented PSS are close to the pure service end. In relation to SBMs, PSS tends to be primarily concerned with the environmental dimensions and less on the social dimensions of sustainability (Kurdve and De Goey, 2017).

Another subcategory of SBM, which partially overlaps with PSS, is circular business models (CBM). CBMs lack a universally agreed upon definition (Geissdoerfer et al., 2018), but Linder and Williander (2017) define CBMs as "a business model in which the conceptual logic for value creation is based on utilizing economic value retained in products after use in the production of new offerings". Compared to SBMs and PSS, CBMs are more explicitly aimed at closing resource loops by e.g. reusing and remanufacturing, and thus at the reduction of resource consumption and environmental impacts.

This study does not include investigations of the social dimension, and hence we do not consider the full scope of SBMs. Rather, we are interested in different ways for a company to capture value (making money) and will in this study consider PSS (which we interpret to also encompass the concept of CBM and other business models for resource efficiency).

Despite their potential, implementing PSS is not in itself a guarantee to reduce the environmental impacts of economic activity (Pieroni et al., 2019; Tukker, 2015). Simplified methods and rules-of-thumb have been developed to estimate the environmental performance of PSS and similar solutions (Bocken et al., 2016; European Commission, 2008; Kirchherr et al., 2017). However, detailed holistic assessments are necessary to reveal in what situations and contexts PSS can lead to environmental improvements, taking a systemic perspective that considers e.g. the whole life cycle of a product (Böckin et al., 2020; Kravchenko et al., 2019).

Environmental assessment methods are typically applied to single product systems (Kjaer et al., 2016), and not to the business model employed by a company to provide that product. Therefore, attempts at systemic environmental assessments of business models are scarce. In most of the cases that do exist, a translation is first made of the business model into physical consequences for specific product characteristics like product life length (Bech et al., 2019) or number of uses (Allais and Gobert, 2017) thus excluding economic aspects. A further example is the study by Diener et al. (2015), who translated a PSS business model into specific product characteristics by considering the potential design implications from shifting to a PSS model. In other cases, both environmental and economic dimensions are assessed, e.g. via combining life cycle assessment (LCA) and life cycle costing (LCC). Kaddoura et al. (2019) carry out a parallel LCA and LCC on PSS solutions, and also here there is a translation from the business model to the physical properties of the products. Likewise, Zhang et al. (2018) carry out LCA and LCC in parallel and relate their results to the life cycle of energy intensive equipment. However, their assessment is done from a societal perspective and they aggregate the costs for different actors along the value chain, which reduces the usefulness to decision-making in the individual companies. Hence, the literature is lacking truly integrated economic and environmental assessments, particularly such that are useful for companies to make environmentally and economically informed decisions (Nußholz, 2020).

Many studies claim to be assessing business models, but they mostly consider value creation and delivery activities, while largely disregarding value capture strategies. In other words, they investigate resource efficiency strategies or circular measures rather than business models per se (De Angelis, 2018). Consequently, there is a lack of studies investigating the environmental consequences of different ways of capturing value or making money.

The purpose of this study is to address these research gaps by developing a method for carrying out a detailed quantitative and systemic assessment of different business models while integrating both economic and environmental dimensions. This report has an additional purpose in reporting underlying data for, and results from, the study on a detailed level and in a transparent manner. Rather than giving a scientific description of a business model, the method is meant to be usable by companies, to guide their business decisions toward decoupling. The present study is carried out on a real case representing the situation of a Swedish apparel company. The assessment will be done comparing different ways for the company to make money or capture value (instead of comparing how customers use their products). This will let us investigate whether alternative business models like PSS can actually achieve decoupling in a real case.

Specifically, the aim of the study is to assess and compare the environmental performance of two separate models for value capture of a company in the Swedish apparel sector. The models considered are a pure product model, in the form of a sales business model and a use-oriented PSS, in the form of a rental business model (henceforth, the terms sales model and rental model will be used). Three research questions were formulated:

1. Can a rental business model reduce environmental impact compared to a sales business model while maintaining the economic performance?
2. What are the environmental and economic hotspots in the different business models?
3. How can a life cycle assessment be made on a value capture model rather than the use of a product?

This report will address these research questions by first presenting the method used in section 2 and the definition of the goal and scope of the assessment in section 3. This is followed in section 0 by a detailed presentation of how the life cycle model was built and populated with data. Impact assessment results are presented in section 5, followed by interpretation in section 6, a discussion of the results of the cases study in section 7, a methodological discussion in section 8 and finally conclusions in section 9.

2. Method

To fulfil the aim and address the research questions, we develop an LCA methodology for assessing business models from an integrated economic and environmental perspective. The key methodological issue to solve is the establishing of a basis of comparison between the business models of a company. Because business models necessarily include economic aspects, it is not enough, as is customary in mainstream LCA, to simply consider the physical properties and material flows related to a product. Instead, the basis of comparison is here taken to be based on the economic performance of the business models. Once the comparative basis is established in the form of a functional unit, the physical and monetary flows of the system then have to be connected. To do that, inspiration is taken from the field of Product Chain Organization (PCO) which employs a socio-material approach to material flows (Lindkvist and Baumann, 2017), in order to find out what parts of the product life cycle are under the responsibility of the company in question and what is not. We formulate the methodology based on a systemic and quantified case study comparing a sales business model and a rental business model of a real company. The assessment is done on a product-level, but the objects of study are the different models through which the company captures value (makes money). In the sales model, the value proposition is based on selling the ownership of the product while in the rental model it is instead based on providing access to the products.

Regarding the basis of comparison between the business models, arguably the main purpose of a company, from their own perspective and that of their owners and shareholders, is to generate profit[1]. Because the unit of analysis for the assessment is two different ways that a company can capture value from a product, we argue that the function to consider for the comparison should be the profit generated during a certain amount of time, via the transactions between the company and its customers. This should then be reflected in the functional unit, which should be expressed in economic terms rather than physical terms, as is mainstream LCA praxis. Consequently, in order to be comparable, the two product-related business models (henceforth referred to simply as business models) should generate the same amount of profit in the same amount of time. Subsequently, economic flows need to be connected to physical flows of material and energy in order to assess and compare the environmental impact of the business models.

A systemic approach is adopted, which means to identify the interconnections between the environmental and economic dimensions related to the life cycle of a product. Specifically, we consider the physical material and energy flows of the business models as well as the interaction points where the exchange of physical products occurs between the company and external actors, which is where revenues and costs are generated. The identification of both the physical flows and the interactions points (e.g. sales transactions), is crucial for being able to include all relevant monetary flows of the business model in the assessment. Particularly relevant are the interaction points between the company and its suppliers, which is when the company officially obtains the ownership of the product and becomes responsible for its handling. Other fundamental interaction points regard the transactions between the company and its customers, since the object of analysis is the way in which the company captures value.

The first step of the modelling process is to investigate the two business models by identifying and relating the monetary flows of the system to physical flows of energy and material (see section 3.6). Examples of such connections are the production costs related to producing one unit of the product,

[1] It should be noted that this is a conventional and narrow view of profit and value capture, which can additionally include added values other than monetary ones, such as increased strategic fit for the company or improved employee motivation (Geissdoerfer et al., 2018).

or the revenues from selling the product. Some monetary flows are included despite not being directly connected to physical flows, because they vary between the two business models and can potentially affect the comparison. These "indirect" monetary flows then have to be related to physical flows by connecting them to other variables.

Subsequently, after identifying all relevant relations between physical and monetary flows and, after modelling them according to the setup of the business model[2], they are used to calculate the profit level in the sales model. By postulating that the sales model and the rental model should achieve the same profit, it is then possible to derive the corresponding number of transactions and products needed to achieve that profit. This gives the basis for the quantitative comparison between the environmental implications of the two business models, which is done by applying LCA methodology (see section 2.1).

Coupling physical and monetary flows in the manner described here stands in contrast to the more common approach to simply apply LCA and LCC in parallel while using the same functional unit based on the physical properties or function of the product considered. Therefore, it is important to evaluate the method and its usefulness in addressing the research questions. Such an evaluation can investigate e.g. whether the assessment of business models was possible to carry out, the relevance of the results and their usefulness for different actors (see section 8 for a discussion on this).

2.1. Life Cycle Assessment

LCA is defined as "a technique for assessing the environmental aspects and potential impact associated with a product" (ISO 14040, 2006). It aims at collecting all the relevant inputs and outputs related to a product system in order to evaluate their environmental impacts and, then, interpreting the results referring to the objectives of the study. LCA has four main phases, namely 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and 4) interpretation.

As mentioned in section 2, the goal and scope definition in this study does not follow the conventional procedure of defining a functional unit based on physical product-properties, but instead uses economic performance as a basis for comparison and then connects monetary flows with physical flows (see above and in section 3.5). Phases 2, 3 and 4, however, are implemented according to standard LCA procedure, using OpenLCA software.

For the impact assessment, impact categories are chosen to reflect a wide range of environmental impacts, but also in part to match the interests of the company in question. Because of the company's expressed ambition to operate within the planetary boundaries, they are used as a starting point for choosing impact categories (Steffen et al., 2015). Planetary boundaries refer to Earth system thresholds that should not be surpassed in order to guarantee the flourishing and development of humanity. Nine different boundaries have been established, representing the limit of the "safe operating space" (Rockström et al., 2009). These nine boundaries are presented in Table 1, together with the analogous impact categories recommended by the International Reference Life Cycle Data System (ILCD) (Hauschild and Huijbregts, 2015) which are guidelines and common rules provided by the EU on how to perform consistent, robust and quality-assured life-cycle studies (Wolf et al., 2012).

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[2] The setup of a business model can include things like price levels, volumes and number of stores and employees. See section 3.1 for a description of the business model setup in the studied case.

Table 1: Planetary boundaries (Steffen et al., 2015) and mid-point environmental impact indicators in LCA recommended by ILCD (Hauschild and Huijbregts, 2015). Adapted from Tillman et al. (2020).

Planetary boundaries	Mid-point indicators in LCA as recommended by ILCD	Level of correspondence between impact categories
Climate change	Climate change	High level of correspondence
Stratospheric ozone depletion	Ozone layer depletion	
Biogeochemical flows (nitrogen and phosphorus cycles)	Freshwater, marine and terrestrial eutrophication	
Novel entities (chemical pollution)	Freshwater ecotoxicity	
	Human toxicity (cancer and non-cancer)	
Atmospheric aerosol loading	Photochemical ozone creation	Some correspondence
	Respiratory effects, inorganic	
Ocean acidification	Freshwater acidification	
Biospheric integrity (biodiversity loss)	Resources land use	
Land system change	Resources land use	
Freshwater use	Resources dissipated water	
-	Resources minerals and metals	No correspondence
-	Resources fossils	
-	Ionising radiation	

There is a varying degree of correlation between the planetary boundaries and the ILCD impact categories (Tillman et al., 2020). Climate change, ozone depletion, eutrophication and human- and ecotoxicity are included in similar ways in the two frameworks. However, the ILCD indicators of photochemical ozone creation potential and respiratory effects are meant to represent direct human health impacts. The corresponding planetary boundary is atmospheric aerosol loading, but this is instead mainly meant to represent effects on monsoon rains. Furthermore, acidification in ILCD represents impacts from e.g. nitrogen and sulphur oxides on land and water ecosystems, while ocean acidification in the planetary boundaries instead represents the effects of carbon dioxide being dissolved in oceans, thus lowering pH levels and affecting marine life. Moreover, the ILCD standard does not include an indicator that matches the planetary boundary of biospheric integrity, while the closest category can be said to be land use, since it is a driver of biodiversity loss. Lastly, there are some differences between land system change and freshwater use in the planetary boundaries and land use and water use in ILCD, while the planetary boundaries do not include a category for abiotic resource depletion. Despite these discrepancies, the life cycle impact assessment in this study is done based on ILCD categories, which is then classified according to the most closely corresponding planetary boundaries.

Weighting is also employed, as a way to summarise results, and to carry out sensitivity analysis in a comprehensible manner. In this study, the ReCiPe Endpoint (H,A) method (Goedkoop et al., 2013) is chosen as a weighting method, since it is one of the most widely used among LCA practitioners (Dekker et al., 2019).

A key step in comparing the two business models is the interpretation of results. Hence, a thorough sensitivity analysis is performed to study the robustness of the model. This was done by investigating the effects on the results from varying the input parameters in order to control for data uncertainties and methodological choices, especially regarding dominant life cycle stages and how the business models are set up.

2.2. Identifying monetary flows

In this study, we define monetary flows as the money flows that a company incurs in the form of costs or revenues of a business model. In order to define a functional unit for the life cycle assessment, the monetary flows are identified based on the physical flows and transactions of the business model. The profit of a business model is estimated by identifying the monetary flows in terms of costs and revenues from the company's perspective and categorizing them into a cost structure and different types of revenue streams.

2.2.1. Defining a cost structure for a product related business model

A company's cost structure defines and categorises the costs and expenses the company will incur while operating a business model. In this study, we defined a cost structure by first following the physical flows of material and energy, and subsequently identifying the related costs and then categorising them into different stages according to when the company takes over the responsibility of the products. Here, "responsibility" means that the company has physical control over the product and its handling and sustains the associated costs[3].

Such an approach allows us to effectively track both the direct and indirect costs of the business model. Direct costs are directly related to the production, distribution and transaction of products and depend on changes in the volume of production or in the necessary handling activities related to the business model. Conversely, indirect costs are not directly tied to the production, distribution and transaction of goods or products and they can be considered fixed costs[4].

Intuitively, direct costs are monetary flows that are strictly tied to the physical product flows and can thus be easily tracked and quantified. In contrast, indirect costs are fixed costs and are thus more difficult to track, unless the one carrying out the study has full access to the company's financial details. They can be identified by considering the company's activities after taking over responsibility for the product (e.g. costs necessary to store the products or to pay employees that handle the products).

2.2.2. Defining revenue streams for a product related business model

Revenue streams represent the sources of income for companies or the ways in which a company captures value. We only include revenues that are generated by a product-specific business model (i.e. not all possible revenues generated by an entire company, but only those that depend on a specific product). Revenues are identified by considering the transactions that occur between the company and its customers. Since two different business models are being compared (a sales and a rental model) revenue streams in the two models depend on different value propositions. They can be input-based revenues when costumers pay for a product in order to obtain the ownership of that good or usage-based revenues when customers pay for the use of a product or service (Lewandowski, 2016).

2.3. Applying the method on a case company

The method described above is applied on a specific case in the context of an apparel company based in Sweden. The object of the case study is a garment and two different ways of capturing value from delivering the function of the garments to the company's customers. The (anonymous) company is a Swedish company that operate stores across the country, but they are active in markets across the world. They aim to offer high quality technical products while guaranteeing low environmental impacts. They do this both via the design of the garments and by adopting new business models.

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[3] "Ownership" is a similar but separate concept, where e.g. a company can have the ownership of a product, but when they rent it to a customer it is the customer who is responsible for it

[4] Costs can also be semi-fixed, meaning that they are fixed up until a certain threshold, after which they reach another level

The company puts effort into designing for extended garment lifetimes and durability, and into material selection for comfort, function and environmental performance. For example, they try to use recycled materials as much as possible and they enable recyclability and biodegradability by keeping natural and synthetic fibres separate. In addition, the company encourage customers to return garments once they reach their end-of-life, after which the garments are sent for material recycling.

Regarding business models, while it is a common view that a company has one overarching business model, in our interpretation, a company can have several parallel business models, e.g. in relation to different products in their portfolio. The company in this case has a sales business model where they sell the ownership of the products to their customers. In parallel they also aim to adopt alternative business models, such as a rental business model which is the main subject of this study. In the rental model, customers can rent garments for one or more days at a time, which means that the company keeps the ownership of garments and is thus responsible for e.g. product maintenance. Revenues derive from rental transactions and from second-use sales (of garments that are removed from the rental service because they are no longer deemed fit due to wear and tear).

3. Goal and scope definition

The aim of the study is to compare two different ways for a company to capture value from a product, and whether a rental model can reduce environmental impacts compared to a sales model, without compromising economic performance. Environmental and economic dimensions are integrated by basing an environmental assessment on connections between monetary and physical flows. The object of the assessment is a Swedish company's business models for a particular product (see section 3.2 for details). The time of reference is a business period of one month (30 days). Due to the short time horizon, the time-value of money is not considered, and discounting of cash flows is not implemented.

Data collection was carried out following four main collection methods. See Table 2 for what processes in the life cycle that each method was applied to:

1) Scientific literature search
2) Web searches and online tools (e.g., Google Maps, Sea Rates and World Freight Rates)
3) LCA database search (Ecoinvent, 2019)
4) Personal communication with experts
   a) A researcher in the field of chemical recycling of polyester at RISE (Research Institutes of Sweden) was interviewed, first through online contact and then through a field visit to their small-scale chemical recycling plant.
   b) A specialised worker in a reparation store was interviewed to collect information on the reparation of garments and the most common reparation procedures for outdoor garments
   c) Personal communication with representatives of the case study company, who provided data both for the economic and environmental modelling. In particular, information was provided on the material and design of the jackets as well as information on their logistics, business model and supply chain.

Table 2: Overview of what data collection methods were used in different parts of the modelling

	1	2	3	4a	4b	4c
Economic data and business model setup	X					X
Inventory data on face fabric	X		X	X		X
Inventory data on other components			X			X
Inventory data on garment production	X					
Inventory data on transports		X	X			X
Inventory data on use phase	X		X		X	X
Inventory data on End-of-Life		X	X			X
Inventory data on background processes			X			

When it comes to data quality, for the product specification, the use phase and the business model setups, the goal was to represent the real situation of the company as closely as possible. Hence, specific data were gathered from the company, that were either based on empiric observations or estimations (see a summary of this in Appendix A.1). For the rest of the life cycle there was a lack of data available, why generic data and processes were used. In particular, data for garment and fibre production were gathered from Roos et al. (2019), who provide a generic life cycle inventory for (among other things) polyester textile products that matched the production system in this study. Similarly, for economic data, some were given by the company while others had to be collected from literature.

The results of the assessment were generated and presented according to ILCD impact categories, and then classified into different planetary boundaries (see section 2.1). Furthermore, weighted results (based on the endpoint method ReCiPe (H,A)) are presented to serve as a basis for the subsequent sensitivity analysis.

Below follows some details on the setup of the company's business models (section 3.1) and of the product chosen to represent the business models (section 3.2) and its life cycle (3.3). Then, a detailed description of the costs and revenues of the business models is given in section 3.4, which is followed by the definition of the functional unit in section 3.5. Finally, in section 3.6, monetary and physical flows are connected to form the basis of our LCA comparison.

3.1. The business model setup

At present, the main business model of the company is a sales model. However, the company also offers a repair service to their customers, which means that there is actually a service element included in the sales model. For simplicity, only sales happening through the company's own stores, and only on the Swedish market, are considered here, even though they also sell their products in other stores and in other countries. We assume that there are four stores spread across Sweden (all supplied by one central warehouse) and each store can sustain a certain number of products being stored and sold. The sales model means that every garment produced is distributed to one of the stores and then sold to a customer and thus the number of transactions during a certain period is equal to the number of garments that need to be produced.

The company is also considering the implementation of a rental model. In reality the sales model and the rental model are not mutually exclusive but for clarity they will be considered as two separate models in this study. In this rental model, each garment can generate a large amount of rental transactions (compared to the single sales transaction in the sales model). Garments that are deemed too worn-out from repeated rentals are removed from the rental stock and sold 2nd hand. Furthermore, the company are considering offering rental customers the option of purchasing the garments they have used, at a reduced price after the rental period, but this is not considered in our model.

In the rental model, products available for renting can be rented for differing periods of time, at different prices. The garments must regularly be laundered and repaired, which the company is responsible for. This means that not all garments can be rented all the time, which lowers what we call the "rental efficiency", dictating how large share of the garments in the rental stock can be out being rented with customers at any given time. Another factor, besides laundry and repairs, that lowers the rental efficiency is the fact that a certain over-capacity of the stock is necessary for any rental model, so that the company can have garments of various sizes available for incoming rental customers, even when taking into account fluctuations in demand. In theory, also a product sales model can count on an over-stocking of garments, but this is not considered in our model.

A garment is kept in the rental model as long as it looks new and fresh, but after some use it reaches the end of its rental lifetime, after which it is removed from the rental model and sold second hand at a reduced price. This means that the rental model has some revenues also from these second hand sales.

3.2. Jackets as representative garments

A particular model of jacket was chosen to represent the available garments in the rental and sales models (instead of considering all available types and models of garments). This choice was made to simplify modelling and data collection and was based on what the company considers a representative garment. Its design and function are thus equal in the two models. The jacket is waterproof and breathable which guarantees a high freedom of movement, suitable for e.g. skiing, kayaking or hiking. The jacket is composed of three layers: an outer layer called a face fabric (with a water repellent that is free from fluorocarbons), an interior layer called a backing fabric and an intermediate layer laminated to the face fabric, referred to as a membrane which is water-proof while also enabling humidity to escape from the body of the wearer. Of additional components, only zippers are considered in this study (at a weight assumed to be 0,03 kg), since they influence reparation activities to a higher degree than e.g. buttons and labels (see section 4.2.7). The face fabric is made of recycled polyester while the backing, membrane and zipper are made of virgin polyester. Data for the exact weight of the different components was not available, but the estimation used in this study is presented in Table 3. The total weight is known to be 0,815 kg, and the face fabric to constitute 70% of the weight of the fabric components (i.e. excluding the zipper). The membrane and backing are assumed to have equal weight, in similarity to the modelling of Holmquist (2020).

Table 3: Material composition of the jacket

Component	Weight
Face fabric	0,550 kg
Waterproof membrane	0,118 kg
Backing	0,118 kg
Zipper	0,030 kg
Total	0,815 kg

3.3. Life cycle flow chart of a jacket

The life cycle of the jacket is presented in Figure 1, which shows all processes that are included in the system boundaries. The flowchart is simplified and represents a general situation, not any of the two specific business models. The production of the three layers, all taking place in Japan, are shown separately. The face fabric is woven, while the backing layer is knitted and the membrane is made through production of a polyester film. Garment production takes place in Estonia, while the use phase and End-of-Use take place in Sweden.

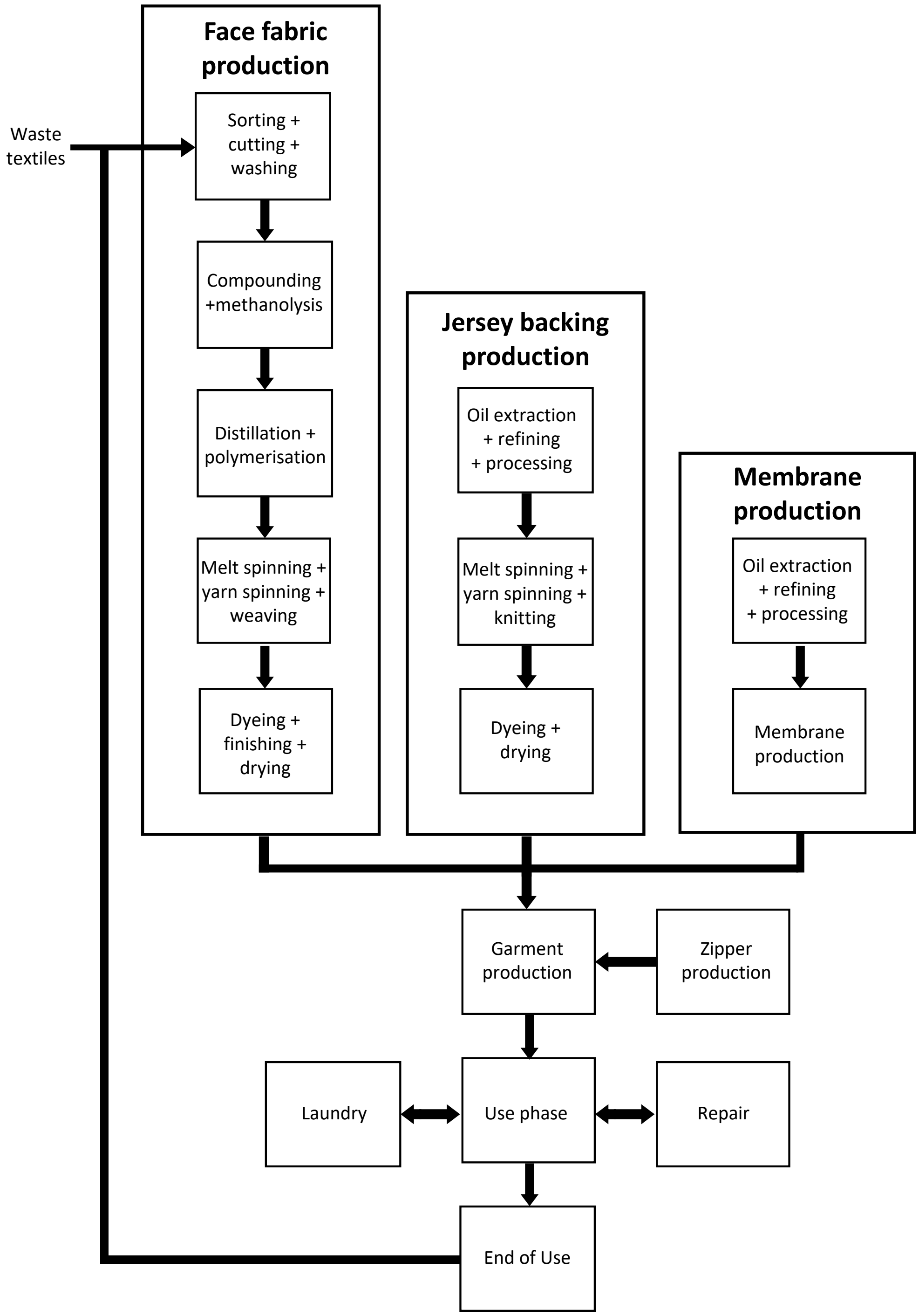

Figure 1: Flowchart showing the life cycle of a jacket, aggregated to represent both the rental and the sales model. Transports are included in the arrows and in some cases within boxes.

3.4. Cost structure and revenue streams of the jacket business models

Only costs associated with the business models are considered here. Furthermore, the study only considers the running costs of the models, thus excluding costs such as the initial investment costs or the transition costs of starting or shifting to a new business model. In addition, costs that were the same for the two business models (such as the design cost) were excluded, since they do not directly affect the comparison. The scale of the rental model is here stipulated to be large enough to achieve the same profit levels as in the sales model, which can require e.g. a different number of stores (of the same size) as in the sales model.

Based on the interaction points between the company and other value-chain actors (as described in section 2), the cost structure of the business models was established as three main stages which represent the different levels of "responsibility" of the company (adapted from International Electrotechnical Commission (2017)). The three main stages are:

- Realisation: this stage includes the activities of external suppliers for producing and manufacturing the product in question, in this study it mainly includes the production of textiles and garments. All costs related to the production are aggregated in the price that the company pays to its suppliers and, from the company's perspective, this is a direct cost.
- Utilisation: the company becomes responsible for the handling of the product (at least up to the point of handing it over to the customer). Thus, in addition to direct costs, the company also has to face recurring indirect costs for sustaining the business model. The utilisation stage involves costs of use and handling of the jackets, where handling means e.g. product maintenance, packing, unpacking, folding, storing and registering the jackets.
- Retirement: A company may or may not be responsible for End-of-Life operations, depending on its internal decisions, regulations and on agreements between the company and waste management companies. In this case study, the retirement stage becomes a responsibility of the company when it collects used garments for recycling. It includes costs for collecting old garments and for transporting them to the recycling plant. End-of-life costs for jackets that do not get collected are borne by the customers and hence not included in the costs of the company.

These three stages can be divided into more detailed costs categories which are defined and characterised as a fixed or variable cost in Table 4.

Table 4: Categorisation and specification of cost structure for the jacket business model

Business model stage	**Costs**		**Cost variable name**
	Interpretation/ subdivision	**Type**	
Realisation	Production costs	Direct and variable costs (depend on volume of production)	C_{prod}
Utilisation	Distribution costs	Direct and variable costs (depend on volume of production)	C_{distr}
	Overhead costs	Indirect and semi-fixed costs (depend on number of stores)	C_{OH}
	Employee costs	Indirect and semi-fixed costs (depend on number of stores)	C_{emp}
	Maintenance costs	Direct and variable costs (depend on number of transactions)	C_{maint}
Retirement	End-of-Life costs	Direct and variable costs (depend on volume of collected jackets)	C_{EoL}

In more detail, the realisation stage is interpreted to include all costs related to the production of jackets, which are considered as direct and variable costs since they vary with the volume of produced jackets. Here, production costs are defined as the aggregate of:

- the cost of the production of textile fibres, the fabric and the finished jackets
- the costs of transportation between the different factories and warehouses, until the finished jackets reach the warehouse of the company in Sweden (these costs can be termed "external distribution")

In other words, all of these costs are considered to be included in the production cost and are embodied in the price that the company pays to its supplier in Estonia.

The utilisation stage includes all expenses associated with operating and administering the business model and it is here divided into distribution, overhead, employee and maintenance costs. Distribution costs can theoretically be divided into internal and external distribution. However, external distribution is already included in our definition of production costs above and only internal distribution costs are included here. They occur once products are delivered to the company which is then responsible for their management. The internal distribution costs include costs for distributing jackets from the central warehouse to the company stores.

Overhead costs are the indirect and recurring costs of e.g. rent, utilities and storage. We consider them semi-fixed, as they are independent of production volume, except if sales increase to a level where e.g. a new store has to be opened.

Employee costs are the costs related to the employees that operate the stores, including social fees etc. Also this can be considered semi-fixed, as the number of employees remains the same unless there is a large increase in sales transactions or e.g. a new store opens.

Maintenance costs include the costs related to product maintenance such as reparation and laundry activities. Maintenance costs are variable and depend on the number of transactions.

The last stage of the cost structure is the retirement stage, which includes costs from the transportation of collected jackets to the chemical recycler in Japan in order to recover material for the fibre production for new face fabric. These costs are variable and depends on the volume of collected garments. Thus, in this case, the retirement costs are still covered by the company which is responsible for part of the end-of-life procedures.

In addition to costs, the business model also generates revenue. Different types of revenue streams are shown in Table 5 (Lewandowski, 2016), where all revenues are generated during the utilisation stage since that is where we find the interaction points (and thus the transactions) between the company and the costumers. The two business models considered in this study capture value following two different schemes. For the sales model, all revenues derive from selling the ownership of new jackets. Conversely, the rental model captures value mainly via usage-based revenues, where customers pay to rent a jacket for a certain number of days. Note, however, that in the rental model there are also some input-based revenues, based on the sale of second hand jackets once they are removed from the rental service (see section 4.1.4).

Table 5: Categorisation and specification of revenue streams in the jacket business model

Business model stage	**Revenues**		**Revenue variable name**
	Interpretation/subdivision	**Type**	
Utilisation	Input-based	Product sale	RE_s
		Second hand sale	$RE_{r,2nd\ hand}$
	Usage-based	Rental service	RE_r

3.5. Definition of functional unit

In order to make an environmental assessment of a business model, the function of a business model needs to be established. We argue that the function of a business model is to generate profit. Consequently, when assessing the environmental consequences of a business model, it should be done using profit as the basis for comparison or, in LCA terminology, the profit should be expressed in the functional unit. Here, the functional unit is defined as “a certain amount of profit, π, over a business period, T, from the transactions of jackets for a company in the apparel sector in Sweden".

Thus, contrary to mainstream LCA praxis, the functional unit is expressed in economic terms rather than physical terms. For the assessment it is necessary to connect the related economic flows to physical flows of material and energy in the two business models. Specifically, we want to find the number of products that need to be produced during time T (denoted q_s and q_r), as well as the number of transactions that take place in the same time (denoted t_s and t_r). The transactions occur in the retail and use phases and are illustrated for the two business models in Figure 2.

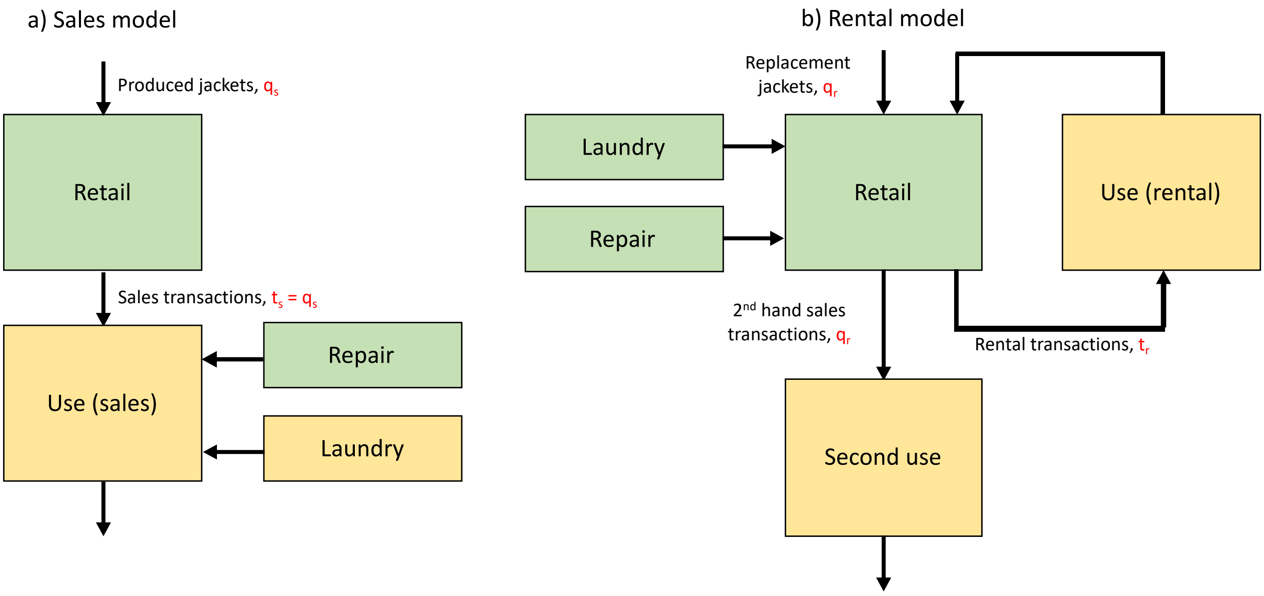

Figure 2: Partial flowcharts showing the retail and use phases in the two business models. Transactions are coloured red. The colour of the boxes represent which actor is responsible for the handling of the products in the different models (green for the company and yellow for the customers). Note that repairs in the sales model are carried out by the company.

3.6. Connecting monetary flows with physical flows

The basis of our comparison between the sales and rental business models will be to connect monetary and physical flows in the two models via the functional unit, following a four-step procedure illustrated in Figure 3.

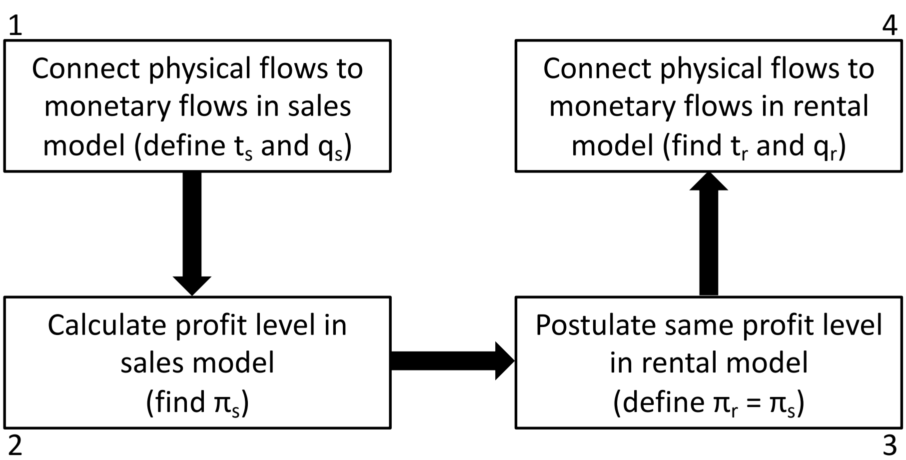

Figure 3: Procedure for finding the number of transactions (t_r) and required replacement jackets (q_r) in the rental model, based on the monetary and physical flows in the sales model.

In step 1 we connect the physical flows to the monetary flows and transactions in the sales scenario, by starting from the number of sales transactions (t_s) that occur and the related number of jackets that need to be produced (q_s), and then identifying the costs and revenues related to the business model. In step 2 we calculate the profit level of running the sales model, during an amount of time T, as π_s = revenues – costs. In step 3 we postulate that the profit level should be the same in the rental business model ($\pi_r = \pi_s$), according to the defined functional unit. Step 4 is then to connect the identified costs and revenues in the rental model to the physical flows and transactions which lets us find the number of rental transactions t_r and required number of replacement jackets q_r, thus giving us the basis for comparison between the two business models.

In more detail, in step 1 costs and revenues were connected to the physical flows and transactions in the form of the number of jackets produced (q_s) and the number of transactions (t_s) during a business period T. The sales model has revenues from product sales and costs that can be divided into production, distribution, overhead, employee, maintenance and End-of-Life costs (according to section 3.4). Each of these revenues and costs are detailed in Table 6 and connected to the number of jackets produced (q_s) and the number of transactions (t_s) (except in the case of overhead costs and employee costs, which are semi-fixed and depend on the number of stores instead).

Table 6: Revenues and costs of the sales model (according to the cost structure presented in section 3.4), connected to the number of transactions (t_s) or the number of jackets produced (q_s) (except in the case of overhead and employee costs, which are semi-fixed). Note that several help-variables are defined here, and also that the number 30 represents the days in a month, to convert between units of months and days.

Revenue or cost category	Connection to sales transactions or jackets produced	Connection in equation form
Revenues from sales transactions	= price per sales transaction * sales transactions	$RE_s = P_s*t_s$
Production costs	= production costs per jacket * number of produced jackets	$C_{prod} = k_{prod}*q_s$
Distribution costs	= distribution costs per jacket * number of produced jackets	$C_{distr} = k_{distr}*q_s$
Overhead costs	= overhead costs per store and per month * number of stores * number of months	$C_{OH} = k_{OH}*N_s*T/30$
Employee costs	= cost per employee and per month * number of stores * number of employees per store * number of months	$C_{emp} = k_{emp}*N_s*EPS*T/30$
Maintenance costs	= maintenance costs per jacket * sales transactions	$C_{maint} = k_{maint}*t_s$
End-of-Life costs	= cost of EoL per jacket * number of produced jackets * collection rate	$C_{EoL}=k_{EoL}*q_s*CR$

Now that we have a connection between the monetary and physical flows, step 2 is completed by finding the profit π_s as revenues minus costs (based on Table 6):

Equation 1:

$$\begin{aligned}\pi_s = \; & RE_s - C_{prod} - C_{distr} - C_{OH} - C_{emp} - C_{maint} - C_{EoL} = \\ = \; & P_s * t_s - k_{prod} * q_s - k_{distr} * q_s - k_{OH} * N_s * T/30 \\ & - k_{emp} * N_s * EPS * T/30 - k_{maint} * t_s - k_{EoL} * q_s * CR\end{aligned}$$

Step 3 is merely to postulate, according to our defined functional unit, that the profit in the rental model must be the same as in the sales model, i.e. $\pi_r = \pi_s$. In order to carry out step 4 and connect that profit to the rental transactions (t_r) and the number of replacement jackets in the rental model (q_r) we need to set up and solve the corresponding equation for the rental profit, during a business period of T days.

Bearing in mind that revenues in the rental model are derived from both rental transactions and second hand sales, and that the relevant costs again can be divided into production, distribution, overhead, employee, maintenance and End-of-Life costs, the equation becomes the following:

Equation 2:

$$\pi_r = RE_r + RE_{r,2nd} - C_{prod} - C_{distr} - C_{OH} - C_{emp} - C_{maint} - C_{EoL}$$

where π_r is the profit in the rental model, RE_r are revenues from rental transactions, $RE_{r,2nd}$ are revenues from 2nd hand sales, C_{prod} are production costs, C_{distr} are distribution costs, C_{OH} are overhead costs, C_{emp} are employee costs, C_{maint} are maintenance costs and C_{EoL} are End-of-Life costs.

Now, all revenues and costs in Equation 2 need to be connected to the number of transactions (t_r), after which we can solve the equation for t_r. When the number of transactions (t_r) has been found, we can derive the corresponding number of products (q_r) that need to be produced to sustain that number of transactions. Table 7 shows all elements in Equation 2, and how they depend on either the rental transactions, t_r, the number of replacement jackets, q_r or the number of stores, N_r.

Table 7: Revenues and costs of the rental model (according to the cost structure presented in section 3.4), connected to the number of transactions (t_s) or the number of jackets produced (q_s) (except in the case of overhead and employee costs, which are semi-fixed).

Revenue or cost category	Connection to rental transactions or jackets produced	Connection in equation form
Revenues from rental transactions	price per rental transaction * rental transactions	$RE_r = P_r*t_r$
Revenues from 2nd hand sales	2nd hand jacket price * number of produced jackets[5]	$RE_{r,\,2nd} = P_{2nd}*q_r$
Production costs	production costs per jacket * number of produced jackets	$C_{prod} = k_{prod}*q_r$
Distribution costs	distribution costs per jacket * number of produced jackets	$C_{distr} = k_{distr}*q_r$
Overhead costs	overhead costs per store and per month * number of stores * number of months	$C_{OH} = k_{OH}*N_r*T/30$
Employee costs	cost per employee and per month * number of stores * number of employees per store * number of months	$C_{emp} = k_{emp}*N_r*EPS*T/30$
Maintenance costs	maintenance costs per jacket * rental transactions	$C_{maint} = k_{maint}*t_r$
End-of-Life costs	cost of EoL per jacket * number of produced jackets * collection rate[6]	$C_{EoL} = k_{EoL}*q_r*CR$

While Equation 1 from step 2 could be solved by simply entering known data, in this step (4) we need to connect all terms from Table 7 to the number of rental transactions (t_r) in order to solve Equation 2. Some terms already depend on t_r, while the rest depend on either the number of products that have to be replaced during time T (q_r) or the number of stores (N_r). Consequently, our next task is to connect q_r and N_r to t_r.

Beginning with q_r, we can first express it as the product of the total stock of jackets needed to sustain the transactions in the rental model (Q_r) and the he average share of Q_r that is replaced during a period T (R_r) (see Appendix A.2 for details on how R_r can be derived depending on the ratio between the rental lifetime and the technical lifetime of the jacket):

Equation 3

$$q_r = R_r * Q_r$$

The stock Q_r can in turn be connected to the transactions t_r in the following manner. Consider an amount of product, Q_r, which during T days can generate a theoretical maximum of Q_r*T use days

[5] Because the number of produced units equals the number of units that leave the rental stock to be sold 2nd hand

[6] The share of jackets sold 2nd hand that are then returned to the store for being sent to recycling

(if every jacket is generating one use day every single day). In reality, however, a rental service cannot run on perfect efficiency, because products need to be maintained (e.g. laundry, repair) and there needs to be a certain over-capacity in the stock of products to meet demand (see section 3.1). Considering a rental efficiency E_r (meaning that a share E_r of the jackets can be out rented with customers at any particular time), the total use days generated in a month is instead Q_r*T*E_r, where Q_r is the total stock of jackets, T is the business period considered and E_r is the rental efficiency. If we let U_r be the average number of use days that every rental transaction generates, then a stock of Q_r jackets can sustain the following amount of rental transactions during period T: $t_r = Q_r*T*E_r/U_r$. This effectively gives the desired connection between the stock, Q_r, and the transactions, t_r:

Equation 4:

$$Q_r = \frac{U_r * t_r}{E_r * T}$$

Combining this with Equation 3 allows us to finally express q_r as a function of t_r:

Equation 5:

$$q_r = R_r * Q_r = \frac{R_r * U_r}{E_r * T} * t_r$$

Where q_r is the number of replacement jackets, R_r is the jacket replacement rate, Q_r is the required stock of jackets, U_r is the average number of use days generated by each rental transaction, E_r is the rental efficiency, T is the considered business period and t_r is the number of rental transactions.

Now, in order to connect the number of stores N_r to the number of rental transactions t_r we can write it as $N_r = Q_r/SS$, where SS is the store size, or the maximum capacity of rental stock that each store can sustain. Using the connection between the stock Q_r and the transactions t_r from Equation 4, we get:

Equation 6:

$$N_r = \frac{Q_r}{SS} = \frac{U_r * t_r}{E_r * T * SS}$$

All factors in the equation for the rental profit (Equation 2) can now finally be expressed in terms of t_r, the result of which is presented in Table 8, which combines Table 7 with Equation 5 and Equation 6.

Table 8: Equations representing the revenues and costs of the rental model, each expressed as a function of the number of transactions, t_r (equations derived by combining Table 7 with Equation 5 and Equation 6).

Revenue or cost category	Equations
Revenues from rental transactions	$P_r * t_r$
Revenues from 2nd hand sales	$P_{2nd*} R_r * U_r*t_r/(E_r*T)$
Production costs	$k_{prod}* R_r * U_r*t_r/(E_r*T)$
Distribution costs	$k_{distr}* R_r * U_r*t_r/(E_r*T)$
Overhead costs	$k_{OH}* U_r*t_r/(E_r*T*SS)*T/30$
Employee costs	$k_{emp}* U_r*t_r/(E_r*T*SS)*EPS*T/30$
Maintenance costs	$k_{maint} * t_r$
End-of-Life costs	$k_{EoL} * R_r * U_r*t_r/(E_r*T)* CR$

We are finally ready to solve Equation 2 to give us the number of transactions t_r required to achieve a profit of π_r:

Equation 7:

$$t_r = \frac{\pi_r}{\left(\begin{array}{c} P_r - k_{maint} + \left(P_{2nd} - k_{prod} - k_{distr} - k_{EoL} * CR\right) * \dfrac{R_r * U_r}{E_r * T} - \\ (k_{OH} + k_{emp} * EPS) * \dfrac{U_r}{30 * E_r * SS} \end{array}\right)}$$

All variables in Equation 7 are summarised in Table 9.

Equation 7 thus lets us find the number of rental transactions t_r required to reach a certain profit, depending on the monetary flows in the rental business model. The corresponding number of products that need to be replaced during period T, q_r, is then given by Equation 5, and thus we finally have the sought after connection between profit, rental transactions and physical flows of jackets. The basis for comparison between the two business models is now set, and it is time to go into detail on the data collection and modelling.

Table 9: Summary of all variables used for connecting the monetary flows, physical flows and transactions in the two business models (in alphabetical order)

General variable name	Description of variable	Variable name in sales model	Variable name in rental model
π	profit during business period T	π_s	π_r
C	total cost during period T (of production, distribution, maintenance, overhead, employee, End of Life)	C_{prod}, C_{distr}, C_{maint}, C_{OH}, C_{emp}, C_{EoL}	C_{prod}, C_{distr}, C_{maint}, C_{OH}, C_{emp}, C_{EoL}
CR	collection rate (share of jackets sold (1st or 2nd hand) that are returned for recycling)	CR	CR
E_r	rental efficiency (average share of stock, Q, that can be in use (rented) on any given day, due to maintenance and imperfect renting/over-capacity/over dimensioning)	-	E_r
EPS	number of employees per store	EPS	EPS
k	unit cost (per jacket, per month, per store, per employee)	k_{prod}, k_{distr}, k_{maint}, k_{OH}, k_{emp}, k_{EoL}	k_{prod}, k_{distr}, k_{maint}, k_{OH}, k_{emp}, k_{EoL}
N	number of stores	N_s	N_r
P	price for each transaction (P_s = price of a product sale; P_r = price of one rental transaction; P_{2nd} = 2nd hand price for products leaving rental service)	P_s	P_r and P_{2nd}
q	number of jackets produced during period T	q_s	q_r
Q	stock of product required to fulfil service (in rental scenario, Q is maintained over time T. In sales, all Q products are depleted by the end of time T)	Q_s	Q_r
R_r	average rate of replacement of product during time T of the rental service (depends on E_r and the ratio between the rental lifetime and technical lifetime)	-	R_r
SS	store size/storage capacity (how many products, Q, can be sustained by one store location)	SS	SS
t	number of transactions during business period T	t_s	t_r
T	business period under consideration	T	T
U_r	average use days per rental transaction, t	-	U_r

4. Data collection and modelling

This section presents the modelling choices and assumptions made for the modelling of monetary flows and the environmental modelling, respectively. Finally, the resulting mass balances and key flows are presented, together with the final parameter values used in defining the functional unit and connecting the monetary and physical flows.

4.1. Modelling of monetary flows

The monetary flows are modelled based on the definition of the cost structure and revenue streams of the business model for the jacket. As described in section 3.4, the main costs can be categorised as realisation costs, utilisation costs and retirement costs, while the revenues can be categorised as input-based or usage-based. Only costs sustained by the company are included and they are represented in Figure 4. As described in section 3, monetary data were mainly collected through personal communication with the company but complemented when necessary by literature searches. Here will be further detailed how we derived the costs and revenues, and data sources and modelling choices will be presented. The data themselves, however, are presented and summarised in section 4.3 (Table 11), along with the underlying business parameters.

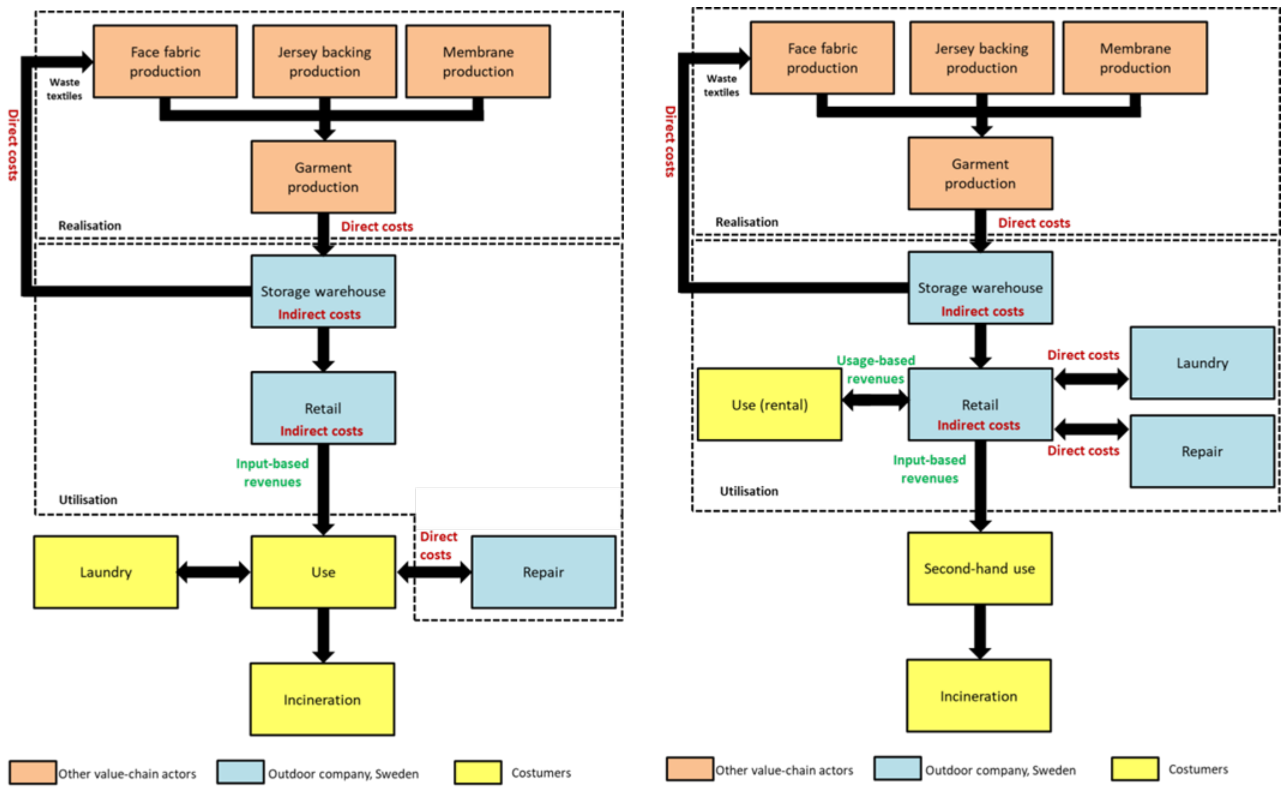

Figure 4: Life cycle flowchart showing the material flows in the two business models and the connected monetary flows that are associated with either a material flow or the activities in a process (revenues in green and costs in red).

4.1.1. Realisation costs

Realisation costs include production costs, which are all aggregated in the price that the company pays for the jacket to its suppliers. We estimate the production costs by using the jacket sales price and the company's mark-up margin. Price data were collected directly from the company, while the mark-up margin was estimated to reflect the mark-up margin of similar companies[7].

[7] The company's actual mark-up margin is confidential and was not used in this study

4.1.2. Utilisation costs

Utilisation costs are divided into distribution, overhead costs, employee costs and maintenance costs. Data were estimated by company representatives and provided through personal communication.

The internal distribution costs depend on the average distance between the central warehouse and the stores. Internal distribution costs were estimated based on Maibach et al. (2006), who provide the average cost (€/km) of a truck with a payload of 32 tonnes.

Overhead costs are semi-fixed and depend on the number of stores (for further details see section 3.4) and they were estimated through personal communication with the company.

Employee costs depend on the number of employees per store (here assumed to be one, due to lack of data) and on their salary levels. Salaries were modelled by considering an average salary of a shop assistant in Sweden (26200 SEK/month) and adding social costs, estimated at 50% of the salary costs (Business Sweden, 2020).

Maintenance costs include costs related to laundry and reparation procedures. In the sales model, customers buy the jackets and thus carry the costs for laundry, while the company still carries the cost of repairs because the repair service they offer to their customers is, for simplicity, assumed to be free of charge. In the rental model, both reparation and laundry are the responsibility of the company and the costs depends on the number of transactions, because garments are washed every time a jacket is returned after being rented, while repair interventions are necessary for 4% of all rental transactions. Data on maintenance costs, which include repairs and laundry, were collected from personal communication with company representatives who provided empiric data.

4.1.3. Retirement costs

Retirement costs include End-of-Life costs and in this study this is simply modelled as the cost of transporting collected jackets to the recycler in Japan, via truck and container ship transports. Costs from truck transportation are modelled in the same way as internal distribution costs (see section 4.1.1). Costs from ship transport were estimated by using the online freight calculator World Freight Rates (worldfreightrates.com). It is assumed that garments that are not sent to the company to be recycled are disposed as municipal waste. In this case, costumers carry the cost of the End-of-Life activities and they are not included here.

4.1.4. Input-based revenues

In the sales business model, input-based revenues depend on the number of transaction and the price of the garments. Data for the garment price were collected directly from the company.

The rental business model is mainly built on usage-based revenues (see sections 3.4 and 4.1.5) but also input-based revenues are generated when jackets are removed from the rental model and sold at a second-hand price. The reason for jackets being removed from the rental service is that their rental lifetime has expired, which is something determined by the company employees (e.g. when a jacket is deemed to no longer look new enough or for some other reason cannot fulfil the full function of a rental service). Data for the price of the second hand sales were estimated by considering similar products on the second hand market and by calculating the average range within which second hand prices fell.

4.1.5. Usage-based revenues

In the rental model, usage-based revenues are calculated by multiplying the rental price with the number of rental transactions. The price of the rental service was estimated together with the company.

4.2. Environmental modelling

The following sections describes the modelling choices and data sources for each life cycle phase. The resulting life cycle inventory with detailed data on inputs and outputs for each process in the life cycle (along with the source for each data point) is shown in Appendix B. For transparency, and as an aid for navigating the following section, see the flowchart in Figure 5 with references to the sections that presents the modelling for each respective life cycle phase.

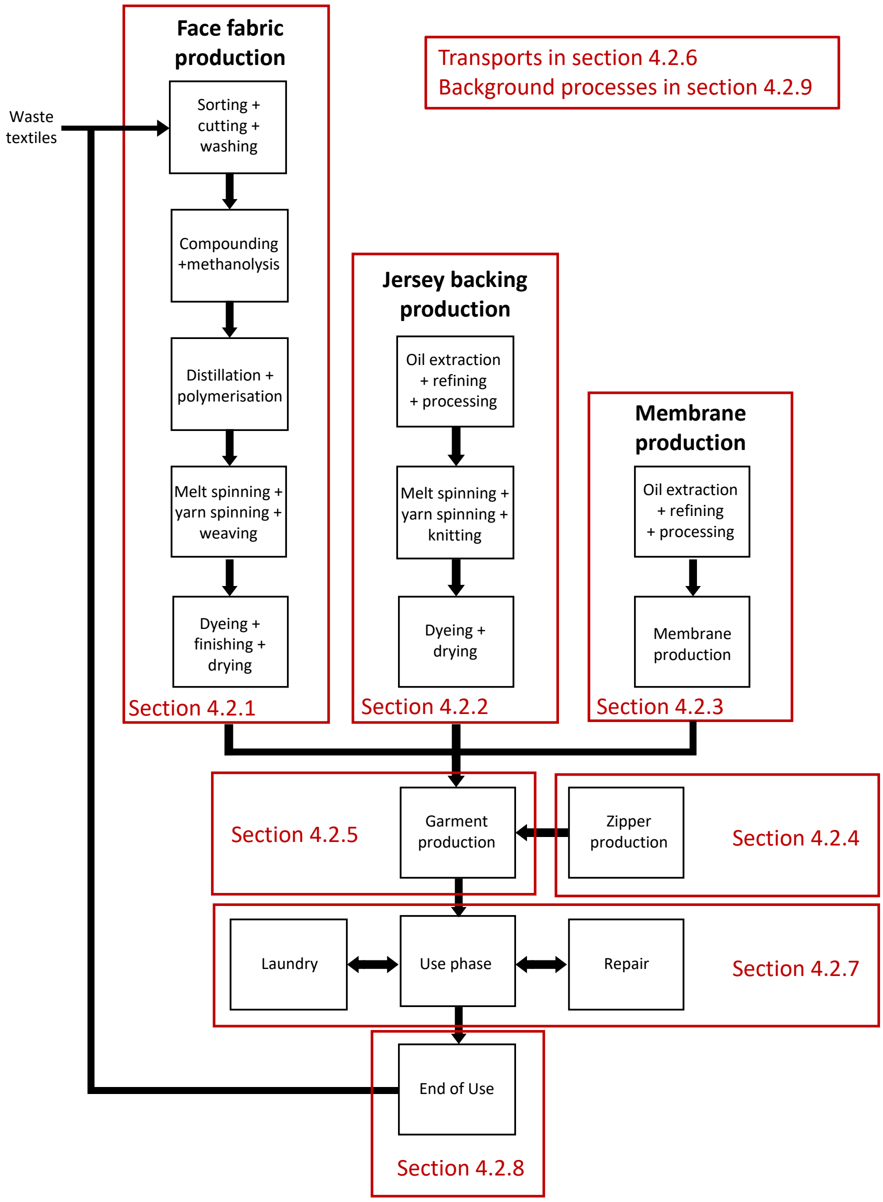

Figure 5: Life cycle flowchart with references to where in the report that the corresponding description of modelling and data sources can be found.

4.2.1. Chemical recycling of polyester

The polyester face fabric of the jacket is produced mainly by chemical recycling. This takes an input of waste polyester garments and textiles and, in several steps, breaks down the PET-polymers into Dimethyl Terephthalate (DMT) which then goes through polymerisation to produce PET granules. The yield at a lab scale is 90% (i.e. 1 kg of waste garments produce 0.9 kg of PET granules), but the yield is here estimated to be 72%, which is more realistic for an industrial scale, according to experts in the field (RISE, personal communication, February 12, 2020).

Garments and textiles for recycling are received from End-of-Life garments and from textile scraps from garment production and are then sorted, washed and shredded. Since the recycling is a two-step process, waste garments are allowed to be multi-coloured without requiring bleaching, thus requiring minimal sorting (RISE, personal communication, February 12, 2020). Consequently, sorting is not included in the environmental modelling. Washing is modelled as industrial washing according to Roos et al. (2015). A simplified modelling was done of shredding, assuming similar energy use as the cutting process in garment production (see section 4.2.5).

The two-step process for breaking down the polymers includes compounding (or glycolysis) and methanolysis. In compounding, the shredded polyester is reacted with ethylene glycol, using a sodium carbonate catalyst (NaCO3). The required heat is assumed to be provided by electricity. Following the compounding is methanolysis, which is modelled as an input of methanol and heat from steam. This produces a mixture with some DMT and ethylene glycol (EG) as well as some waste products. The waste products are separated from the DMT and EG by distillation, which is simply modelled as an input of energy from steam. Part of the waste flow is EG that is reused in the compounding process (the numbers have been matched in the model accordingly). The total energy requirements for a polyester recycling process (estimated from Patagonia Inc. (2011)) was, as an approximation, equally allocated to compounding, methanolysis and distillation (see details in Appendix A.3).

The last step of the chemical recycling process is polymerisation, which produces PET granules. It is modelled as production of amorphous PET granulate (Ecoinvent, 2019), with an additional input of a catalyst (antimony-oxide, approximated as a pure antimony input).

The subsequent step is melt spinning, where PET granules are melted and spun into polyester fibres. This is modelled according to Roos et al. (2019), except that part of the input is from the recycling process described above. However, considering the End-of-Life collection rate and the losses in the recycling process, there is also a need for a further input of virgin PET granules to balance the mass flows of the life cycle model (see section 4.2.8 for details on how benefits from recycling are allocated).

Through yarn spinning and weaving (modelled as use of electricity and lubricant) the polyester fibres are transformed into a fabric, with losses of 0.5% at each step (Roos et al., 2019). Yarn spinning is modelled as air-jet spinning (Roos et al., 2019). For the modelling of weaving, the inventory provided by Roos et al. (2019) requires a choice between weaving of fabrics of density 300 dtex or 150 dtex. We chose 150 dtex, because it more closely reflects the fabric density of the jacket in this case, in accordance with e.g. (Sandin et al., 2019). After weaving, the fabric is dyed and finished with a durable water repellent (DWR) coating. Dyeing is modelled according to Roos et al. (2019), except that the pigment is modelled as a generic organic chemical, due to lack of data. The DWR coating is known to be fluorocarbon free and will thus likely not contribute highly to toxicity impacts (Holmquist et al., 2020). Hence, the DWR was approximated as a wax emulsion coating, made with an input of generic organic chemicals (Ecoinvent, 2019). Furthermore, the recoating that is necessary over the lifetime of some jackets is left out of the model. Drying happens both after dyeing and after finishing (modelled according to Roos et al. (2019)), which finally results in the finished face fabric.

4.2.2. Production of jersey backing

The inner backing material is made of knitted jersey polyester derived from synthetic fibres based on crude oil. Extraction and refining is modelled according to generic Ecoinvent processes (Ecoinvent, 2019). The main output is purified terephthalic acid. A subsequent polymerisation process produces polymers in the form of PET granules, with the help of an antimony-based catalyst (antimony oxide), which is approximated as pure antimony (Ecoinvent, 2019).

After polymerisation there is melt spinning and yarn spinning, modelled in the same way as in section 4.2.1. The yarn is then knitted into a fabric, which is modelled as "circular knitting" (which includes a material loss of 0.5%). The knitting process and the expected material loss are modelled according to Roos et al. (2019). The backing production ends with dyeing and drying which, as in section 4.2.1, are modelled according to Roos et al. (2019).

4.2.3. Production of membrane

Similar to the jersey backing, the membrane is made of virgin polyester. Thus, refining and polymerisation is modelled as described in section 4.2.2. The membrane production is approximated as the Ecoinvent process for extrusion of plastic film (Ecoinvent, 2019).

4.2.4. Production of other components

Of the other potential components of a jacket, only zippers are considered (see section 3.2). The zipper is assumed to be made of polyester (modelled simply and generically as an amount of polyester granulate input (Ecoinvent, 2019), which is in line with estimations from the industry on the most common zipper material in jackets (Willfix.se, personal communication, May 5, 2020).

4.2.5. Garment production

First, the face fabric and membrane are laminated together. However, the lamination was not modelled, similar to the modelling done by Roos et al. (2019) who omit lamination from their inventory framework. After lamination, the textiles (including the backing) are cut, which is modelled as electricity consumption and a material loss of 15% of the input material (Roos et al., 2019). Subsequently, all layers are sewn together, where sewing is modelled as electricity consumption (Roos et al., 2019). Finally, there is finishing which is modelled in a simplified manner, assuming the addition of a virgin polyester zipper (see section 3.2), and taping, approximated by an amount of adhesive, modelled according to (Willskytt and Tillman, 2019). The scraps from garment production are assumed be transported to the manufacturer for recycling into new face fabric.

4.2.6. Transport

There is transportation throughout the production chain, and all distances are estimated using Searates (searates.com) and Google Maps (maps.google.com). Before garment production, textiles are sent from Japan to Estonia by freight cargo ship, modelled as a container ship with a maximum payload of 51 tonnes (Ecoinvent, 2019). The distance is estimated to be 21655,74 km. Once the ship arrives in Estonia, the textiles are transported by truck from the harbour to the manufacturing firm, at a distance of 3,1 km. The truck is modelled as a EURO 6 truck with a maximum payload of 32 tonnes (Ecoinvent, 2019).

Finished jackets are then transported from Estonia to the company warehouse in Sweden by truck and ferry, 497,42 km. Distribution from the warehouse to the various stores is done by truck, and the average distance is estimated to be 410 km, based on the actual locations of the stores and the central warehouse.

Regarding distribution from stores to customers, the company does not provide delivery services and instead the environmental impact depends on how costumers decide to go to the store when picking up and returning the jackets. Customers make round trips to the store via car, bike, walking or public transportation. For the modelling we used company estimates that 20% of customers go by car, 20% by bicycle, 20% walk and 40% use public transportation. The different modes of transportation were modelled in a generic manner that approximates a Swedish situation, based on Ecoinvent processes (Ecoinvent, 2019) (car travel was chosen to fulfil EURO5 standards, and public transportation was approximated by trams). The average distance between a user's residence and the store is 5 km (as estimated by the company), so in the sales model, a customer goes back and forth to the store once, meaning the total distance covered for every sales transaction is 10 km. An additional round trip of 10 km is made by the customers to return End-of-Life jackets to the stores (at an amount of jackets corresponding to the collection rate described in section 4.2.8). In the rental model, the customer has to make two round-trips, one for picking up the garment and one to return it, so the total distance per rental transaction is 20 km. Additionally, a round trip is made for the second hand jackets as well as one for the End-of-Life jackets, at 10 km each. Note that these distances are probably over-estimations (for both business models), since all the impacts from every trip are allocated to the garment, while in reality, many trips will have several purposes that should ”share the burden”.

4.2.7. Use

The use phase is modelled as two main processes: laundry and repairs. In the sales model, the users are responsible for laundry, but repairs are carried out via the company. In the rental model, the company is responsible both for laundries and repairs. Here we describe how we estimated the number of laundries and repairs required in the two scenarios, and how we modelled the laundry and repair processes themselves.

For the laundry in the sales model we follow Roos et al. (2015), who estimate that each jacket is washed on average 9 times during a 5-year life length. The number used in the present case is thus the rate of 0.15 laundries per month. In the rental model, the jackets are instead laundered after every rental transaction (case company, personal communication, December, 2020), which results in a significantly higher number of washes (see the number of rental transactions in section 4.3, Table 11).

The laundry process itself was mostly modelled according to Roos et al. (2015), who model laundry in residential washing machines using a temperature of 40° C. This was chosen despite the washing instructions of the jacket is to use cold water, in order to avoid underestimating impacts from laundry. In the sales model, laundry occurs at customer's homes, with an average load during wash of 60% (Roos et al., 2015). In the rental model, laundry happens in-house at the company. Due to lacking data, the company's machines are assumed to be similar to the residential machines and are modelled in a similar way as in the sales model[8], but with a loading of 100%, because the company reportedly makes the effort to always wash full loads. See Appendix A.4 for details on the modelling, where electricity consumption differs somewhat but water and detergent consumption are the same per kg of washed clothes because it is standard for machines to adjust the amount of water to the amount of load, and the user of the machine can adapt the amount of detergent to the amount of load (Roos et al., 2015). Additionally, the care instructions recommend hang drying and also to apply heat in order to reactivate the water-resistant surface. Thus, drying is modelled in a

[8] This likely overestimates the impacts from laundry in the rental case, because in reality a company is more likely than private citizens to be able to purchase larger, more efficient machines

simplified manner as the electricity consumption of a tumble dryer, again according to Roos et al. (2015).

Regarding repairs, we assume the same rate of repair per use day in both business models, based on company estimates (see Appendix A.5 for further details). The activities related to repairs are assumed to be mostly based on human labour and thus energy inputs are disregarded. However, material inputs are necessary to substitute faulty components. It is estimated that at least 50% of reparations are related to problems with zippers (Willfix.se, personal communication, May 5, 2020) while the rest are other types of repair interventions. Hence, repairs were simply modelled as an input of virgin polyester representing the production of zippers (according to the description in section 4.2.4).

4.2.8. End-of-Life

The End-of-Life was modelled in the same way for both business models. There is a lack of data on collection rates for the company's products because of the long lifetime of the garments, where products sold 5-10 years ago are still being used and resold on the second-hand market. The collection rate of jackets was thus arbitrarily assumed to be 50%, which is likely a high estimate even though the company encourages their customers to return their end-of-life garments. The returned jackets are transported back to the manufacturer for chemical recycling to produce new face fabric (hence all three layers are recycled into face fabric, which is possible since they are all made from polyester). The remaining 50% of jackets that are not collected are assumed to be incinerated via municipal waste management. The transport modes include both trucks and container ships that were modelled as a EURO 6 truck with a maximum payload of 32 tonnes and a container ship modelled as a freight cargo ship with a maximum payload of 51 tonnes (Ecoinvent, 2019). The estimated distance for the truck and cargo ship are estimated to be 38.8 km and 21650 km respectively (Google maps (maps.google.com); Searates (searates.com)).

The allocation of benefits from recycling was modelled via the mass balance of the system and is illustrated in Figure 6. The chemical recycling produces polyester granules which go into melt spinning for making polyester fibres for the face fabric. Some of this input to melt spinning was modelled as coming from the chemical recycling, at an amount corresponding to the 50% jackets collected (taking into account losses in the recycling process). The remaining share of input was assumed to be covered by virgin production of polyester granules (see chapter for chemical recycling).

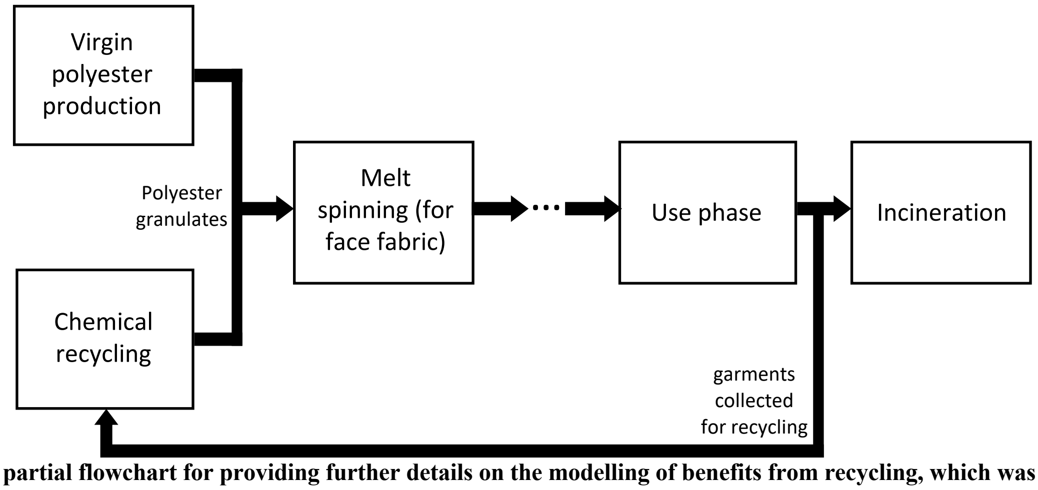

Figure 6: A partial flowchart for providing further details on the modelling of benefits from recycling, which was done by considering the inputs to melt spinning to come from the closed-loop chemical recycling on one hand and virgin polyester production on the other, depending on how many garments are collected at End-of-Life.

4.2.9. Background processes

Electricity mixes were chosen from Ecoinvent (2019) to match the location where processes take place. Textile production thus has Japanese electricity, garment production has Estonian electricity and the rest uses a Swedish electricity mix. For simplicity, low-voltage electricity mixes were used, except if the source specified differently. Other types of energy supply, such as heat, was modelled based on Ecoinvent (2019) data, as a generic global average for the textile production, but as a European average for processes taking place in Estonia and Sweden.

4.3. Final mass balance and parameter values

Based on the modelling presented in this section, the final mass balance and variable values can be presented. The mass balance for the system can be seen in Table 10, where the numbers correspond to the production of one jacket (weighing 815 g). This gives the inputs and outputs to every process in the life cycle, and the next step is to scale these inputs and outputs according to the functional unit.

Table 10: Mass balance of the life cycle of one jacket. The blue cells represent the three layers which go into lamination (face fabric, jersey backing and membrane). The zipper is added in the taping/finishing stage. The melt spinning for the face fabric takes part of its input from production of recycled PET, and the rest is supplied by virgin PET production.

Life cycle stage	Process	Input from previous process [g]	Output to next process [g]
Production of face fabric	Production of recycled PET	546	393
	Production of virgin PET	260	260
	Melt spinning	653	653
	Yarn spinning	653	650
	Weaving	650	646
	Dyeing	646	646
	Drying	646	646
	Finishing	646	646
	Drying	646	646
Production of jersey backing	Oil extraction	140	140
	Refining	140	140
	Melt spinning	140	140
	Yarn spinning	140	139
	Knitting	139	139
	Dyeing	139	139
	Drying	139	139
Production of membrane	Oil extraction	139	139
	Refining	139	139
	Membrane production	139	139
Production of other components	Zipper production	30	30
Garment production	Lamination	924	924
	Cutting	924	785
	Sewing	785	815
	Taping/finishing	815	815
Use and End-of-Life	Distribution	815	815
	Use (incl. Repair and laundry)	815	408
	End of Life	546	393

The key flows that forms the basis of comparison in this study are the number of new jackets to be produced for the business period (q_s and q_r) and the number of transactions in each scenario (t_s and t_r). The final values for these are presented in Table 11, along with the assigned values (and sources) of all other parameters relevant to the calculation of those flows, such as costs, prices and details on the rental service.

Table 11: Summary of all parameters (and their assigned values and sources) that were used in defining the functional unit and connecting monetary and physical flows. The parameters marked (*) depend on other parameters in the model.

General parameter values			
Symbol	**Name**	**Assigned value**	**Source**
T	Time	30 days	Defined
EPS	Number of employees per store	1	Assumption
k_{prod} (*)	Production costs	2500 SEK/jacket	Derived from M and P_s
k_{distr}	Distribution costs	0,14 SEK/jacket	Estimated according Maibach et al. (2006)
k_{OH}	Overhead costs	5000 SEK/store	Provided by company
k_{emp}	Employee costs	39300 SEK/ employee	Business Sweden (2019)
$k_{laundry}$	Laundry costs	70 SEK/transaction	Provided by the company
k_{repair}	Repair costs	8 SEK/transaction	Provided by the company
k_{EoL}	End-of-Life costs	18 SEK/jacket	Estimated
Parameter values for sales model			
Symbol	**Name**	**Assigned value**	**Source**
t_s	Sales transaction	200 transactions	Defined
q_s	Number of jackets produced during the period T	200 jackets	Defined
Q_s (*)	Stock of product required to fulfil service in the sales model	200 jackets	Derived (see section 3.6)
P_s	Price for buying a jacket	5000 SEK/jacket	Provided by the company
N_s (*)	Number of stores	4 stores	Provided by the company
SS_s	Storage capacity	50 jackets	Provided by the company
TL_s	Technical lifetime	1000 use days	Provided by the company
M	Mark-up margin	50 %	Estimated
Parameter values for rental model			
Symbol	**Name**	**Assigned value**	**Source**
t_r	Rental transaction	1108 transactions	Derived (see section 3.6)
q_r	Number of jackets produced during the period T	28 jackets	Derived (see section 3.6)
Q_r (*)	Stock of product required to fulfil service in the rental model	308 jackets	Derived (see section 3.6)
P_r	Price for renting a jacket	600 SEK/rent	Provided by the company
N_r (*)	Number of stores	6,15 stores	Derived (see section 3.6)
SS_r	Storage capacity	50 jackets	Provided by the company
TL_r	Technical lifetime	1000 use days	Provided by the company
P_{2nd}	Price for buying a second-hand jacket	3000 SEK/jacket	Provided by the company
RL	Rental lifetime	200 use days	Provided by the company
R_r (*)	Replacement rate	9,1 % jackets per month	Derived (see Appendix A.2)
E_r	Rental efficiency	60 %	Provided by the company
U_r	Average use days per rental transaction	5 use days	Provided by the company

5. Life cycle impact assessment

Based on the modelling in section 4, a Life Cycle Impact Assessment was performed and the impacts for the sales and rental business models were compared. Results are presented in categories according to the ILCD 2018 Midpoint impact assessment method. Furthermore, they are classified according to which planetary boundaries they correspond to (either at a high or low degree of correspondence, see section 2.1). Then, impacts weighted into a single score are presented, using the ReCiPe endpoint (H, A) method to serve as the baseline for analysing sensitivity and uncertainty in section 6. See Appendix D for detailed results on textile production processes.

The rental model resulted in reduced impacts per amount of generated profit in most, but not all, impact categories, as seen in Figure 7 presenting the impacts per functional unit from the two business models (normalised to the sales model) and in which life cycle stages impacts appear. Impacts from climate change were reduced by 43% in the rental model compared to the sales model, which also indicates a reduced pressure on the corresponding planetary boundary of climate change. The reduction was mainly due to the reduced production of jackets. Ozone layer depletion instead saw an increase of 22% in impacts in the rental model, which represents an increased impact on the planetary boundary of Stratospheric ozone depletion. This was mainly due to increased petroleum production for the customer transports, although it should be noted that the underlying Ecoinvent data for this is from the years 1999-2000 and thus potentially outdated.

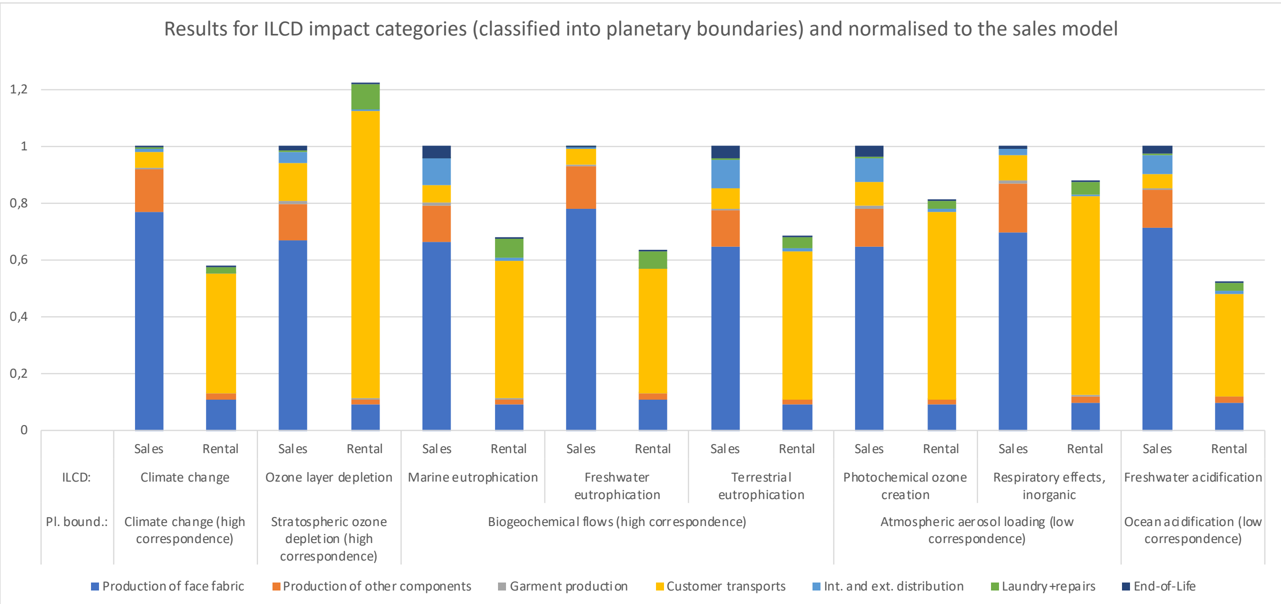

Figure 7: Impact assessment results per functional unit for eight different ILCD impact categories, normalised to the sales business model and classified into five planetary boundaries (with a note on the level of correspondence between the ILCD impact category and the planetary boundary).

The remaining impact categories show similar patterns as for climate change, in that the rental model gives lower overall impacts by reducing the production of jackets (despite increased impacts from customer transportation and laundry). Marine, freshwater and terrestrial eutrophication show reduced impacts in the rental model by 32%, 37% and 31% respectively, thus indicating a reduced pressure on the planetary boundary of biogeochemical flows. Photochemical ozone creation is reduced by 19% in the rental model, while respiratory effects are reduced by 12%. The most closely related planetary boundary to these two impact categories is atmospheric aerosol loading, although the correspondence is low. Lastly, freshwater acidification is reduced by 48%, but also in this case there is only a low correspondence to the closest planetary boundary, which is ocean acidification.

Some impact categories and planetary boundaries were not included in Figure 7 but instead summarised in Appendix C. Human toxicity (cancer and non-cancer) and freshwater ecotoxicity were excluded in the figure because the corresponding characterisation factors inadequately capture the toxic effects of textile-related chemicals, thus potentially over-emphasising toxicity impacts from background processes while underestimating the toxicity impacts from textile production (Roos et al., 2019). Regarding resource use of dissipated water, the results were highly impacted by Swedish hydropower in electricity production for public transportation and laundry. The results were dismissed since hydropower in practice does not represent water consumption or dissipated water. Similarly, impacts in the category of ionising radiation were excluded, in part because of their dependence on Swedish nuclear power for public transportation and laundry, which the authors believe has a low relevance for overall radiation levels. More importantly, however, ionising radiation does not correspond to any of the planetary boundaries and was not deemed relevant. Another excluded resource use impact was land use, where most of the impact came from road construction needed for customer transports and from forestry for biomass energy supply. However, land use was excluded because it is less relevant for polyester garments than for e.g. cotton-based garments, but also because of the low correspondence between the ILCD categories and planetary boundaries. Lastly, resource use of fossils and of minerals and metals was excluded because there is no correspondence to the planetary boundaries.

In summary, the rental model shifts impacts from production to the transportation of customers in the use phase. This shift paid off for some impact categories like climate change, while in others the impacts were greater in the rental model. Most planetary boundaries are represented in the results above, except biospheric integrity, land system change and freshwater use. Atmospheric loading and ocean acidification are represented only to a limited extent due to the low correspondence with the ILCD impact categories.

We can also consider an aggregate of all ILCD impact categories (including those with no corresponding planetary boundary, such as metal and mineral resource use), in the form of weighted impacts. Using the ReCiPe endpoint (H,A) method (see weighting factors in Appendix E), the total results turn out in favour of the rental business model, as seen in Table 12. Evidently, most of the weight is put on climate change and fossil depletion impacts, while some also comes from respiratory effects and metal and mineral depletion.

Table 12: Impacts in ReCiPe points for different categories of environmental and human health impacts.

ReCiPe subcategories [ReCiPe points]	Sales model	Rental model
ecosystem quality - agricultural land occupation	4,0	6,1
ecosystem quality - climate change, ecosystems	67,8	39,0
ecosystem quality - freshwater ecotoxicity	0,1	0,0
ecosystem quality - freshwater eutrophication	0,1	0,0
ecosystem quality - marine ecotoxicity	0,0	0,0
ecosystem quality - natural land transformation	4,4	2,9
ecosystem quality - terrestrial acidification	0,2	0,1
ecosystem quality - terrestrial ecotoxicity	0,2	0,2
ecosystem quality - urban land occupation	0,6	2,2
human health - climate change, human health	107,3	61,1
human health - human toxicity	12,7	11,0
human health - ionising radiation	0,1	0,3
human health - ozone depletion	0,0	0,0
human health - respiratory effects, inorganic	29,5	20,5
human health - photochemical oxidant formation	2,1	0,6
resources - fossil depletion	171,0	90,6
resources - metal and mineral depletion	21,1	48,0
total - total	421,0	283,2

Finally, Figure 8 shows the aggregated life cycle impacts, where overall impacts from the rental model are 33% lower than impacts from the sales model. The figure summarises the pattern seen in most results presented in the figures above, namely that the rental model results in lower impacts from production, but higher impacts from laundry in the use phase and significantly higher impacts from customer transports.

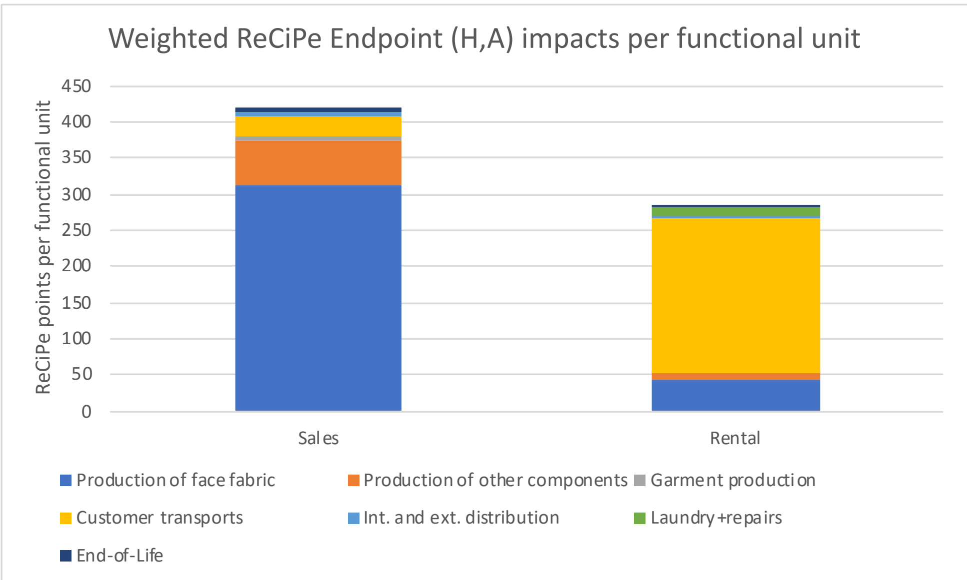

Figure 8: Weighted and aggregated life cycle ReCiPe (H,A) results per functional unit in the sales model and the rental model.

6. Interpretation

The results depend on a large number of parameters, estimations and assumptions. To investigate which of these are more or less significant, a sensitivity analysis was performed. Particular emphasis was put on investigating the effects of data that were deemed to be uncertain as well as on the parameters that affect the most dominating life cycle stages (which are textile production, customer transports and laundry). Additionally, various parameters depending on the company's business model setup were investigated, since they are subject to decisions and practices of the company and the context in which they operate. All sensitivity analyses are summarised in Table 13, where the baseline results were taken as the weighted ReCiPE (H,A) Endpoint results presented in Figure 8 in section 5. Each of the three categories of the sensitivity analysis will be described in more detail below.

Table 13: Table summarising all sensitivity analyses, divided into three categories. Every parameter change is described (including its default value, if applicable), and the resulting change in the results are shown as % changes in each business model, compared to the baseline weighted ReCiPe Endpoint (H,A) results.

Sensitivity category	Parameter that was changed (default value)	How the parameter was changed	% change sales	% change rental
Testing uncertain data	Changing mass composition of jacket	No backing (only membrane)	-8	-2
		No membrane (only backing)	+8	+2
	Changing collection rate at EoL (CR=50%)	Collection rate: CR = 0%	-4	0
		Collection rate: CR = 100%	4	0
	Changing number of employees per store (EPS=1)	0,5 employees per store	0	-2
		1,5 employees per store	0	+21
Testing dominating LC phases	Changing customer transportation habits (20% walk, 20% car, 20% bike, 40 public)	Customers only use bikes	-6	-64
		Customers only drive cars	+22	+241
	Changing fibre density of face fabric (150 dtex)	75 dtex instead of 150 dtex face fabric	+20	+4
	Changing laundry practices	Energy intensive laundry (rental)	0	+17
	Changing production location (Japan)	Production in China	+15	+3
		Production in Sweden	-33	-7
Testing business model setup	Changing rental price (P_r = 600 SEK)	Rental price -50%	0	+96
		Rental price +50%	0	-51
	Changing sales price (P_s = 5000 SEK)	Sales price -50%	0	-78
		Sales price +50%	0	+74
	Changing rental efficiency (E_r = 0,6)	Rental efficiency E_r=0,4	0	+74
		Rental efficiency E_r=0,8	0	-18
	Adding a product sales element to the rental business model	Hybrid rental model, where 5% of rental transactions end up in the jacket being sold to the customer	0	+74

6.1. Sensitivity analysis of uncertain data

Some data used as input for our model were particularly uncertain and were thus tested through a sensitivity analysis presented in Figure 9. The first point regards the mass composition of the jacket, where there were uncertainties in how much the membrane weighed relative to the other layers (conversely, the weight of the face fabric was precisely known). In the baseline model, the membrane and backing are assumed to have equal weight (see Table 3 in section 3.2), but here we tested the effects of two extreme cases. The first was to have no backing and double membrane weight and the second to have no membrane and double backing weight. The effects of these changes were minor (less than 10%) and did not alter the comparison between the business models, which indicates that this uncertainty did not affect the robustness of our model.

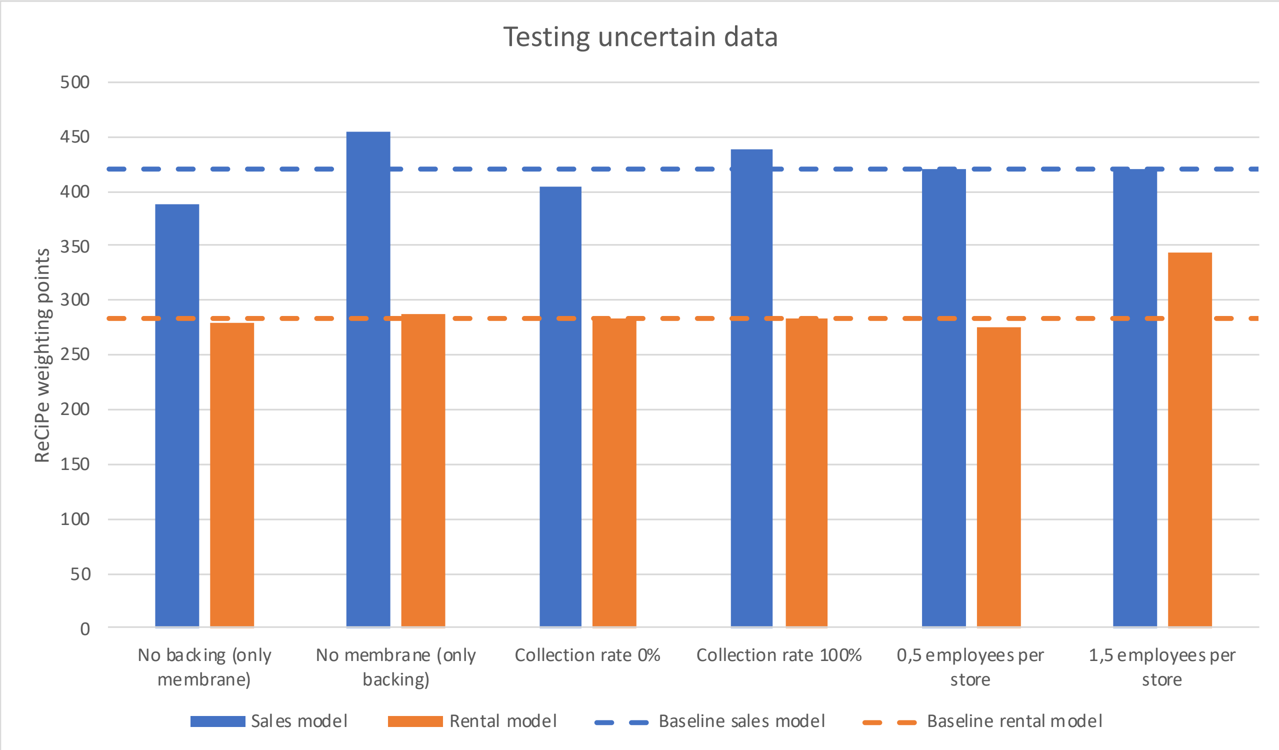

Figure 9: Sensitivity analysis of uncertain data, in ReCiPe weighting points. Dashed lines indicate the baseline results. Tested parameters include jacket mass composition, collection rate and number of employees per store.

The second uncertainty relates to the collection rate of garments at End-of-Life, which was unknown and had to be estimated by an ad-hoc guess (see section 4.2.8). The baseline collection rate was modelled as 50% of the End-of-Life jackets in both the sales and rental model, while in the sensitivity analysis, the collection rate was changed to the extreme cases of 0% and 100%, respectively. The effects of this were insignificant, only changing results less than 4% in any direction. The reason for this small effect is that most impacts from production (in either business model) come from energy consumption in later production stages such as melt spinning, yarn spinning, weaving and knitting, and this energy consumption does not depend on the origin of their material inputs. It should also be noted that the chemical recycling process for the face fabric is modelled in more detail than the corresponding fossil-based production process. Hence, the energy consumption and transportation impacts from the recycling process are likely overestimated in comparison to the energy consumption and transportation in fossil-based production. Consequently, in this study a higher collection rate gave slightly higher impacts than lower collection rates. This detail should be investigated further (with more detailed data on recycling, transportation and energy consumption) before being able to draw any conclusions regarding the benefits of collection and recycling of jackets.

The third uncertainty concerned the number of employees per store, which were assumed to be 1 in the baseline model. Since the employee costs represented a significant share of total costs in both compared business models, it was included in this sensitivity analysis by testing the effects of changing this parameter by 50%, to either 0,5 employees per store or 1,5 employees per store. The resulting change in the results for the rental model was -2% and +21%, respectively. Neither option reverses the comparison between the business models, but it can be seen that the rental model is more sensitive to this parameter, because in our model the rental service requires more stores to sustain the increased number of transactions.

In summary, these data uncertainties do not significantly affect the results of the study, except in the case of a high number of employees per store, although it still did not alter the prioritisation between the sales and rental business models.

6.2. Sensitivity analysis of dominant phases

The results presented in section 5 were largely dominated by a few specific life cycle phases, namely customer transports, textile production (mainly of the face fabric) and in some cases also laundry. The sensitivity of the results to changes in parameters that particularly affect these phases was investigated and are presented in Figure 10. First to be considered were the customer transports, since it is the single largest contributor to all impacts in the rental model. The data on customer habits is also highly uncertain, but because it is the most dominant life cycle phase the sensitivity is presented here instead of in section 6.1. Effects of customer transports were investigated by considering extreme customer habits. Instead of the mix between car driving, bicycling, walking and public transportation used in the baseline model, one scenario where all customers use bikes and one scenario where all customers drive cars were investigated. Having customers that only use bikes gave a 6% and 64% decrease of results in the sales and rental model respectively. Instead having all customers drive their car to the store gave a 22% and 241% increase in the sales and rental models, respectively, which reversed the ranking between the models. Hence, the results are highly sensitive to customer habits, especially in the rental model. It also matters whether the transport system where the business model is implemented is associated with high environmental impacts or not. For instance, in a system with a high share of public transportation run on low-carbon energy sources, the importance of customer transports for the impacts from the business model are reduced.

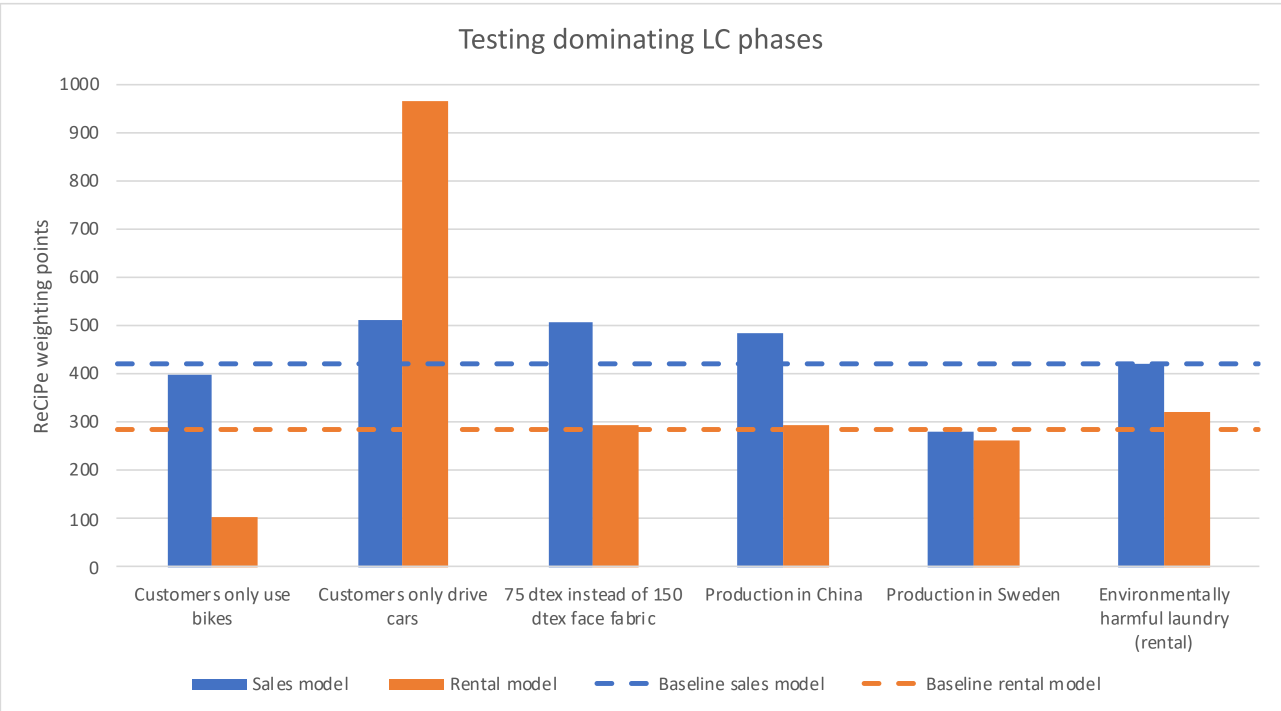

Figure 10: Sensitivity analysis of dominant life cycle phases, in ReCiPe weighting points. Dashed lines indicate the baseline results. Tested parameters include customer transportation, textile density, textile production location and laundry practices.

Also the textile production phase stood for a significant share of impacts, at least in the sales model. One of the most energy intensive processes in the textile production is the weaving of the face fabric, which is highly dependent on the density of fibres required by the finished fabric. When using the data for textile production by Roos et al. (2019), a choice could be made between a fibre density of 300 or 150 dtex. A realistic density for a jacket of the type in this study is less than 100 dtex (Sandin et al., 2019), and thus the lowest available choice of 150 dtex was chosen for the baseline model. Here, a dtex of 75 is instead investigated by extrapolating the data of Roos et al. (2019), resulting in increased impacts of 20% and 4% in the sales and rental models respectively. Thus, the results for the sales model are moderately sensitive to this parameter, but the ranking between the business models is not affected (in fact, using extrapolated data for 75 dtex favours the rental model).

Since energy consumption is the cause of a large part of the textile production impacts, it was relevant to investigate the potential environmental effects of having different electricity sources supplying the production processes. Here, this was investigated by changing the electricity mix in the chemical recycling process from a Japanese mix in the baseline model, to a high-carbon energy supply in the form of a Chinese mix on one hand, and a low-carbon energy supply in the form of a Swedish mix on the other hand. The Chinese mix resulted in a 15% and 3% increase in impacts for the sales and rental models, respectively, which did not alter the ranking between them. As a contrast, the Swedish mix gave a decreased by 33% and 7% in the sales and rental models respectively. Because textile production dominates impacts in the sales model, these are greatly reduced, to the point of removing most (but not all) of the benefits from the rental model compared to the sales model. Consequently, the results are somewhat sensitive to the background system electricity mix.

Because jackets are washed by the company after every rental transaction, laundry is a significant phase to investigate. In the baseline model, laundry takes places in Sweden (and thus with a low-carbon electricity mix), with fully loaded machines at 40 degrees. As a sensitivity analysis, an environmentally harmful laundry practice was investigated, where the number of washes was doubled (assuming that customers wash their jackets before returning them, while the company still washes them after every rental), the washing temperature was increased to 60 degrees (although the washing instruction is actually to wash the jackets cold), machines were assumed to be half-loaded and the electricity mix was defined to be an average electricity mix of the United States, to represent a high-carbon mix, as opposed to the low-carbon mix of Sweden. The results for the sales model were not affected, but the results for the rental model were 17% higher than the baseline model. Despite being an extreme and quite unrealistic scenario, it was not enough to reverse the ranking between the sales and the rental models, which indicates robustness.

6.3. Sensitivity analysis of business model set-up

The third and final category of sensitivity analyses was to explore the effects of changes in the setup of the sales and rental business models. Some key business model design options were investigated (and presented in Figure 11), including the rental price (P_r), the sales price (P_s), the rental efficiency (E_r) and finally also adding an element of product sales in the rental model (as mentioned in Section 3.1, this is the case company's actual practice, but was for clarity excluded in our model).

The rental price in the baseline model was set to 600 SEK and is here changed by 50% to 300 SEK and 900 SEK, respectively. With a lower rental price, impacts per unit of profit in the rental model are almost doubled, while a higher rental price results in a 51% reduction in impacts. Lowering the rental price means that more rental transactions are needed to reach the same profit, which increases both customer transports and the replacement of jackets. A higher rental price has the opposite effect. For completeness, changes in the sales price in the sales model were also investigated, at a 50% decrease and 50% increase, resulting in a 78% decrease and a 74% increase in impacts for the rental model, respectively. The same but reverse logic applies as for changing the rental price, namely that a higher sales price means that more rental transactions are needed to reach the same profit, and vice versa.

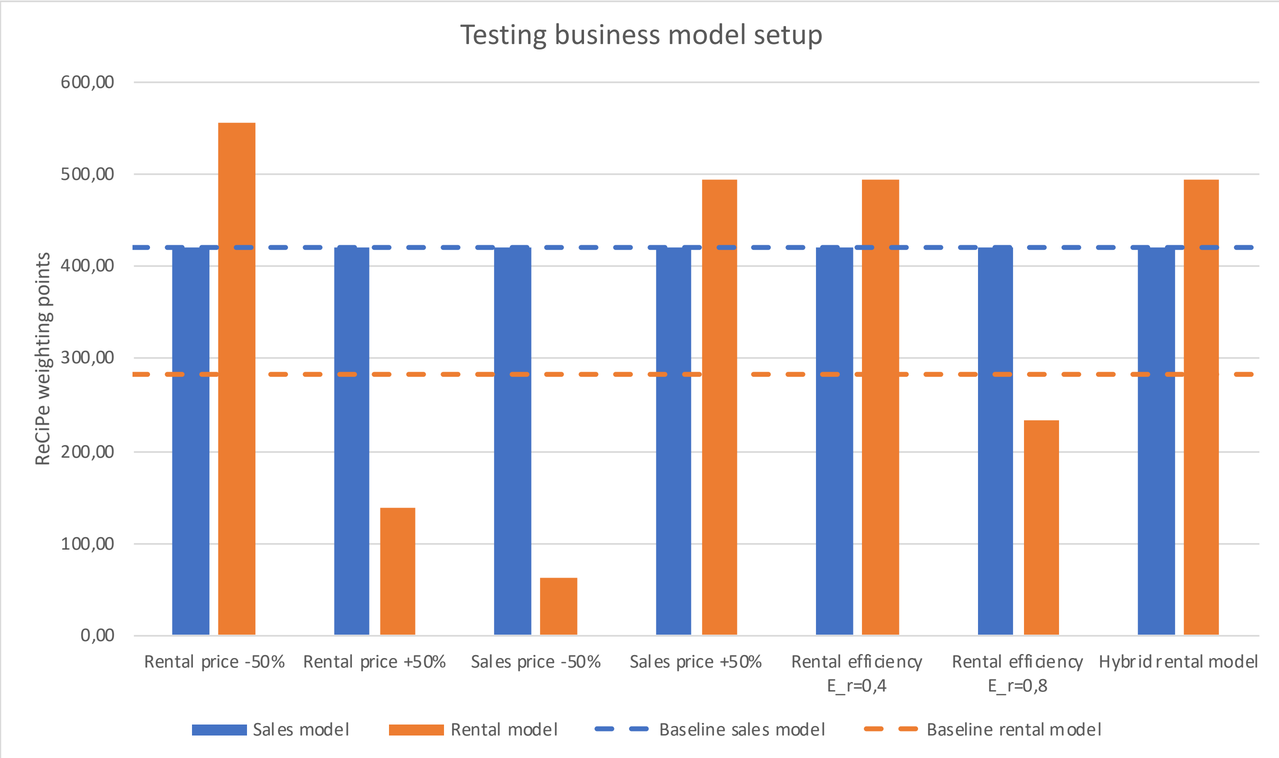

Figure 11: Sensitivity analysis of variations in business model setups, in ReCiPe weighting points. Dashed lines indicate the baseline results. Tested parameters include rental and sales prices, rental efficiency and a hybrid rental model.

The rental efficiency (E_r) of the rental model indicates that not all jackets can be rented continuously but have to be taken out of the rental loop for laundry and repairs, and additionally all rental models need an overcapacity in their stock to meet demand (see definition of rental efficiency in section 3.1). The company estimates their rental efficiency to be 60%, which was used in the baseline model. Here, the rental efficiency was changed to 40% and 80%, giving a 74% increase and 18% decrease in impacts for the rental model, respectively. Lowering the rental efficiency to 40% was enough to reverse the ranking between the sales and rental models, because the company cannot utilise their stock of jackets effectively to generate profit, thus necessitating more rental transactions (and thus replacement jackets) to compensate.

Additionally, a modification of the rental business model was investigated, which incorporates elements of product sales into the rental model (it can thus be said to be a hybrid between the sales and rental model). Specifically, in such a hybrid model the company offers rental customers the option to purchase the jacket after the rental period is over (reducing the sales price by the amount paid for the renting). This generates a one-time revenue for the hybrid model, but also necessitates the production of a new jacket. We modelled the effects of this by assuming that 5% of every rental transaction ended up in such a sale. This resulted in an impact for the hybrid model 74% higher than the baseline rental model, thus reversing the ranking and making the sales model environmentally preferable. The reason for the higher impacts in a hybrid rather than a rental model is that new jackets have to be produced to replace the sold ones, but more importantly, selling a jacket represents losing the opportunity to keep generating rental revenue from it. Thus, to reach the same profit as the sales model, more rental transactions are required overall.

6.4. Summary with reduced customer transport impacts

Because the results are dominated by and sensitive to customer transports to such a high degree, it is relevant to compare this sensitivity with the sensitivity to the other factors discussed above. Figure 12 shows all sensitivity analyses, but with the assumption that all customers use their bicycle to reach the store (i.e. no cars, no public transportation and no walking). This shows that the rental model can be significantly more environmentally beneficial than the sales model, and the only modelling factor that is sensitive enough to realistically change that is the customer habits and an unsustainable transport system, while also the hybrid business model comes close.

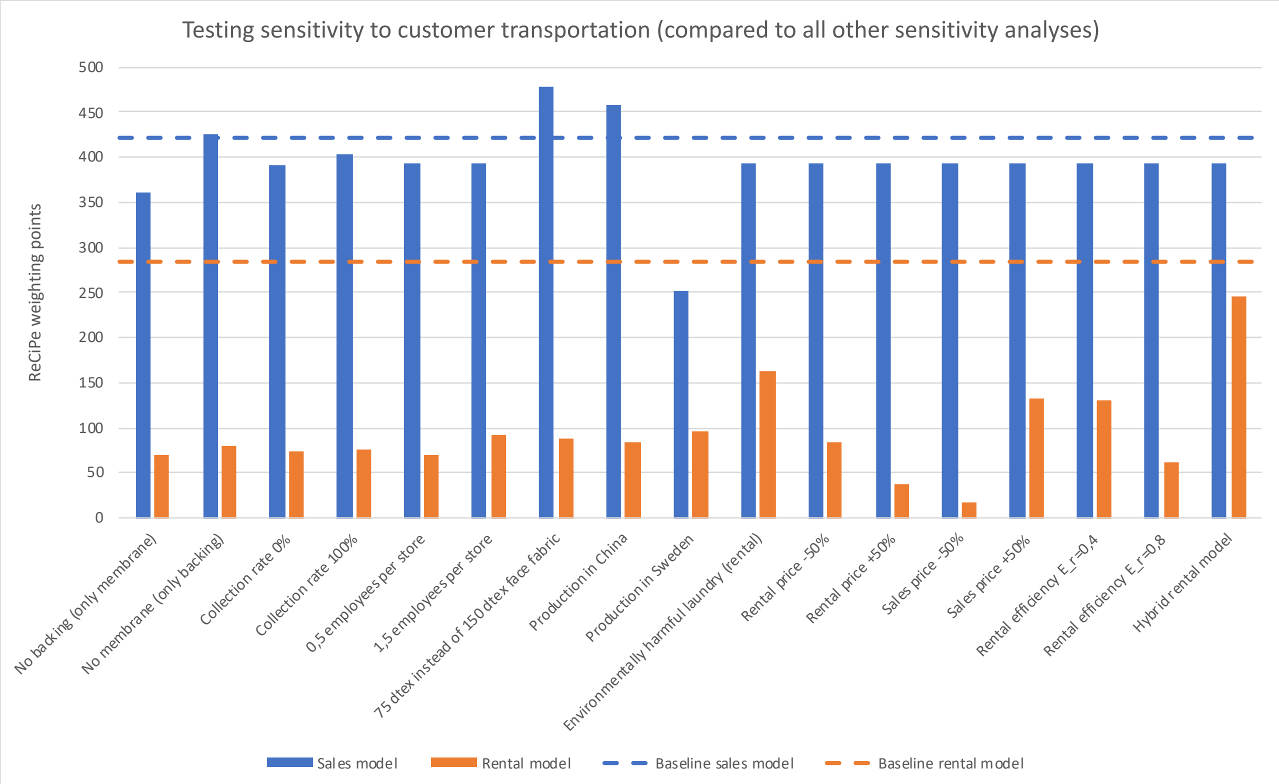

Figure 12: Summary of all sensitivity analyses, but with only bicycles for customer transportation, to get a comparison of the sensitivity to customer transportation and to other factors. Dashed lines indicate the baseline results

7. Discussion – findings from case study

The results from the life cycle impact assessment in section 5 show that the rental business model can lead to reduced overall environmental impacts compared to a sales model, while still generating the same amount of profit. The main reason for these results was that a jacket can be rented multiple times and generate more revenue in total compared to selling a jacket, thus reducing the need for producing new jackets. However, while some impact categories, like climate change, saw improvements due to the rental model, others saw deteriorations, like ozone depletion. The main reason for any deteriorations is that there is burden-shifting from production impacts that dominate the sales model to impacts from customer transportation and laundry that dominate the rental model.

Regarding the economic performance, the profit is, by model design, equal in the two business models (see section 3.5) but there is still a difference in how revenues and costs are generated, as can be seen in Figure 13. Production costs are considerably more important in the sales business model, while in the rental model employee costs are the largest cost. It is also clear that the main revenues in the rental model are from the rental transactions rather than the 2nd hand sales. This economic overview allows the investigation of the decoupling of resource consumption from the profit of the two business models. In the sales model, the profit generated by one jacket is ca 1600 SEK. By comparison, one jacket in the rental model can generate ca 11400 SEK of profit for the company. Consequently, the sales model requires 7.13 more jackets to reach the same level of profit as the rental model, which indicates decoupling (although it does not take into account the burden shifting discussed above).

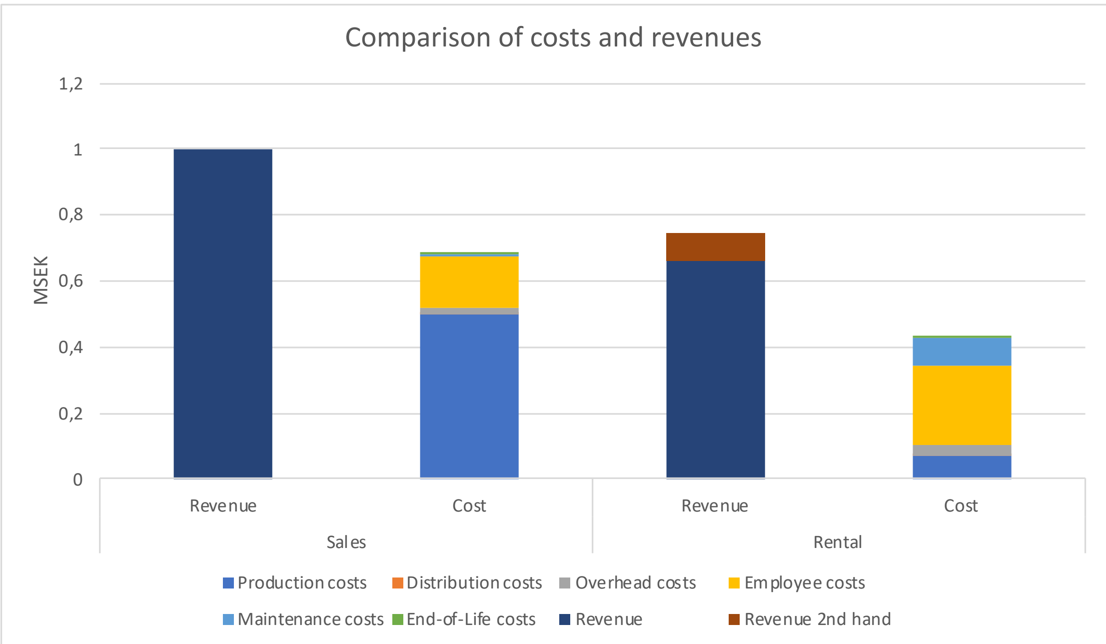

Figure 13: Economic comparison of the sales and rental models, showing revenues and costs in million SEK (MSEK). Note that this excludes some costs and does not represent all monetary flows of the company's business model.

7.1. Comparing results to other research

There is other research that partially overlaps with this study, such as integrated economic and environmental assessments of PSS or circular solutions as well as attempts at assessing different business models. An example of an integrated economic and environmental assessment is a study by Kaddoura et al. (2019) who investigate prolonged life of passive and durable products by carrying out a parallel LCA and LCC. They find that both life cycle impacts and costs can be lowered by prolonging life, which essentially shifts impacts and costs from primary production to repair processes with lower impacts, which pays off overall (although they do not consider revenues in their model, see section 8.1). This shift is similar to this study, where in the rental model, impacts are shifted from production to customer transports and laundry. However, even though this shift paid off in the baseline results, the impacts, chiefly from customer transports, are highly variable and in the worst case can give an overall environmental deterioration.

A difference between this study and many previous attempts at assessing business models is that previous assessments are limited in their modelling of the business models. They tend to connect the business model to physical flows via product design considerations, rather than integrating the economic and business model aspects to form the basis of assessment. For instance, Diener et al. (2015) investigate the material flows of a PSS model, but they establish a relationship between the business model and physical flows via the potential product design changes the new model would enable, such as more durable products. Bech et al. (2019) also evaluate the environmental performance of a PSS business model, in their case for wool garments. They assume that the business model will have consequences for how long the product will last (furthermore, they compare different materials: a wool garment in the PSS scenario and a polyester garment in the linear scenario). Hence, the basis for their comparison is the life-length of the garments, rather than the inherent characteristics of the PSS business model. Likewise, Roos et al. (2015) and Zamani et al. (2017) perform environmental assessments of clothing libraries and make a translation to the life length of the garments. A similarity to the present study, however, is that they also identify customer transports as a key factor in determining the benefits of a use-based PSS model. Similarly, Mont (2004) evaluates the economic and environmental performance of PSS business models (for drills and lawnmowers) and identifies the importance of customer travel, particularly in the case of renting.

Such assessments of business models, that base their comparisons on product characteristics rather than business model aspects, emphasise the importance of e.g. product life length for the environmental performance, which is useful for eco-design purposes. However, for a company planning its economic activities for reduced environmental impact, it is more relevant to base the assessment on the business model itself, including different ways of capturing value. A further difference between our study and comparisons based on product characteristics is, at least at first glance, they tend to reach conclusions that emphasise the importance of prolonging the life of products to reduce impacts. In our study we instead found that the greatest reduction potential lies in increased revenue from repeated transactions from a few products and in reduced customer transportation impacts. However, our model also shows that, after reducing impacts from number of jackets produced and the customer transportation, the next way to significantly reduce impacts are to increase the rental lifetime or the technical lifetime (which reduces the replacement rate of jackets but also slightly increases the number of transactions, to compensate for lost revenue from 2nd hand sales). Product design measures for prolonged life can thus indeed reduce impacts, but not as much as switching from a sales to a rental model or decreasing customer transportation impacts at a level that is obscured by other reduction measures.

7.2. Robustness and sensitivity

The results presented and discussed are meant to provide an answer to the question of whether a rental model can profitably reduce environmental impacts. The answer is yes, but this is more or less sensitive to some key factors that affect the robustness of the results. As shown in the sensitivity analysis in section 6, the results were most sensitive to the modelling of customer transports, which in its two extremes could make the rental model either vastly superior or inferior to the sales model. Arguably, however, rental models will likely be more commonly implemented in the future, where transportation systems are more like to be sustainable, e.g. with electric vehicles running on green electricity. Hence, considering this factor, future rental models are more likely to reduce environmental impacts than not. Moreover, the impacts from customer transports depend not only on the sustainability of the underlying transport system but, crucially, also on customer habits, such as what modes of transport that average customers tend to use. Additionally, it matters whether trips are made exclusively to pick up or return rental garments or if pick-ups are combined with other errands. In our model, all impacts from customer transports are allocated to the rental garments, but if in reality trips to the store were done on the way to or from another errand, then a lower share of transport impacts should be allocated to the rental garment.

This dependence of the results on customer behaviour tells us that in order to be sure of the environmental benefits of a rental model, there is a need for detailed knowledge of customer behaviour. This corroborates the findings from the literature review of Piontek and Müller (2018), that costumer habits in use-oriented business model are still unknown but it is crucial to reduce these uncertainties in order to implement environmentally sustainable business models. However, a rental model does offer the opportunity for better knowledge of customers' habits because of the many repeated interactions over time between the company and its customers.

The results were also sensitive to laundry practices and related energy consumption, where an extreme case of more frequent and less efficient laundries in the rental model, combined with higher washing temperatures and a high-carbon electricity mix, contribute to make the sales model the environmentally preferable option. Efforts to reduce laundry impacts are thus important for a rental business model and is especially important in regions with a high-carbon electricity mix.

In addition to laundry, also production processes were sensitive to changes in the underlying energy system. Having a green source of electricity in production processes such as weaving has a large potential for reducing overall impacts. Consequently, in a future with more sustainable energy generation, the benefits of a rental model might be limited compared to a sales model, unless also customer transports and laundry practices are sustainable. Companies selling textile products can thus greatly reduce their products' environmental burden by demanding that their suppliers use sustainable electricity (because the textile production dominates life cycle impacts, at least in the sales scenario).

Furthermore, the results were sensitive to variations in the business model setup, e.g. how the company sets their prices, what efficiency can be achieved and whether they incorporate elements of product sales into their rental model. Since our model is based on the connection between economic and physical flows, it is to be expected that results are sensitive to economic parameters like the sales or rental prices, which is why it is important to run the model on accurate economic data. In this study, some of the economic and business-related parameters were thus chosen in a way to contribute to the robustness of the results. An example is that we assumed that no over-stocking of jackets was necessary in the sales model (unlike in the rental model with its lower than 100% rental efficiency) even though in a real case a company is likely to over-stock in order to meet fluctuations in demand. These methodological aspects will be further discussed in section 8.

In summary, the results of this assessment are robust overall, except for some key aspects like customer transportation, laundry and some details of the business model setup. To ensure decoupling of environmental impacts from economic performance when implementing a rental model, it is important to carefully plan and design the business model setup and its related practices, e.g. regarding the rental price and rental efficiency. Furthermore, knowledge about customer behaviour is crucial, and the company should use the opportunities offered by a rental model (with close and continuous interaction with customers) to generate more knowledge about customer behaviour and to influence the customers to adopt sustainable habits and behaviours.

7.3. Limitations and future research

There were some limitations to the comparison between the rental and the sales business models in this study, regarding data gaps, economic perspectives and design considerations.

One of the most significant data gaps of the study is that of toxicity effects. Toxic chemicals are used in textile production but their effects are often poorly characterised in LCA due to a lack of inventory data and of life cycle characterisation factors, which means that many impact assessment methods (including the ILCD method used in this paper) underestimates the toxic effects of textile production on human health and on environmental systems (Roos et al., 2019). Future research on textile products can better represent toxic impacts by using the USEtox impact assessment method for toxicity, including the characterisation factors for textile-related chemicals presented by Roos et al. (2018).

Regarding the economic considerations in this study, because of the short time perspective of one business month, we considered only the company's running costs and revenues related to the sales and rental models. Compared to the economic evaluation of PSS models by Tukker (2004), our study thus excludes considerations of capital/investment needs and of long term economic risks, which might affect the possibility and willingness of the company to implement a PSS model, but also intangible value like the marketing value of having an innovative and green image or the benefits of a sustained customer relationship with returning rental customers. Additionally, acquisition costs (e.g. costs of marketing) and design costs are excluded, which could alter the profitability of the business models. Another aspect that was not included in this study regards economies of scale, which are reductions in a company's costs, or improvements in their efficiency, due to learning processes, increased experience or business growth. This was excluded partly because of the short time horizon of the present study and also because, in the case of economies of scale in production, the company only take up a fraction of the volume of products that their suppliers produce. Hence, a change in the case company's transactions is not likely to significantly change the scale of production for their suppliers.

Furthermore, we do not distinguish between the value offered to customers in the two business models, which can differ in terms of tangible values (e.g. price differences) and intangible values (e.g. ease of access, sense of control and brand value), thus affecting whether customers will accept the offering (Tukker, 2015). The main reasons for excluding these aspects were lack of data and confidentiality (but also for simplicity reasons, see further details in section 8), but in theory these factors can be incorporated into future versions of the model, as long as the data is available. We thus recommend that future research comparing business models from an integrated environmental and economic perspective incorporates the perspectives excluded here, in order to give a more complete comparison.

Lastly, the high rate of laundry in the rental model compared to the sales model might be expected to affect the technical lifetime of the jacket, which was excluded in this study. Future research should take this into account, although the durability of such jackets is likely less affected by washing than e.g. cotton T-shirts (Schellenberger, 2019). Furthermore, in this study the design of the garments is assumed to be identical in the sales and rental business models. Yet, as indicated by e.g. Diener et al. (2015), a shift to a PSS business model is likely to enable several design changes, such as a more durable product, which would let the company generate more revenue over the lifetime of each garment.

8. Discussion - methodological learnings

The assessment carried out in this study compared a company's sales and rental business models from an integrated environmental and economic perspective. For this purpose, a new variant of LCA methodology (termed Busines Model LCA) was developed. A central innovation of the developed method is how the functional unit is defined. Contrary to mainstream LCA praxis, the functional unit was not defined based on the physical features or function of a product but was instead defined based on the economic performance of a business model. This choice was made to be able to assess and compare the environmental performance of different business models from a company's perspective, specifically to investigate whether a rental model can reduce environmental impacts while still making the same amount of money as a sales model. Consequently, the presented method needed to integrate economic and environmental dimensions in the assessment while still enabling a robust environmental assessment.

In the following sections, the developed method will be compared to previous attempts at assessing business models or integrating environmental and economic dimensions found in literature (see section 8.1). In addition, in order to test and identify differences in the assessment specifically due to the adoption of an unconventional functional unit, a comparison will be made to a more conventional functional unit (see section 8.2). Lastly, the model's advantages and drawbacks will be presented, along with potential future research in section 8.3.

8.1. Comparing life cycle studies integrating environmental and economic dimensions

In literature there are several life cycle studies aimed at combining or integrating economic and environmental elements of a PSS or other solutions for resource efficiency. Here, some representative examples will be discussed, followed by a comparison with the method developed in this study.

Kaddoura et al. (2019) performed an environmental and economic assessment of five different versions of PSS, to assess how prolonging the lifetime of products may yield economically and environmentally sustainable circular strategies. For the assessment, LCA and LCC were performed in parallel and, to be able to compare economic and environmental results, both results were aggregated into the system's main life cycle phases. Similarly, Zhang et al. (2018) assess energy-consuming equipment by integrating LCA and LCC. The integration of the two methodologies is based on the division of the lifecycle into system and subsystem levels. However, while both the methods used by Zhang et al. (2018) and Kaddoura et al. (2019) enabled environmental and economic assessment of PSS, there are some key limitations regarding the level of integration of the environmental and economic dimensions. Conventional LCA and LCC are not able to identify existing interconnections and relationships between the two different dimensions. According to Weinberger et al. (2015), one fundamental aspect in integrating the different dimensions of sustainability is to implement a systemic approach, interrelating the different dimensions and considering them as indivisible parts of a whole system. Adopting a systemic approach in this case means identifying, quantifying and measuring the relations between the different environmental and economic elements that characterize the system. Elements are integrated when it is possible to measure the effect that a change in one element produces in the other. This perspective is missing in the methods that apply LCA and LCC in parallel but separately.

Additionally, LCC is frequently applied in order to reconstruct the cost structure of a business model by identifying all the costs incurred by a company. However, although revenues can in principle be included in a LCC (Kambanou and Sakao, 2020), revenues and profit are often excluded in practice. Without considering revenues and profit, the economic assessment will be incomplete and may lead to faulty conclusions regarding the economic sustainability of a business model. For example, it is possible that a transition to a PSS contributes to increased costs, but it can also increase revenues, leading to higher profitability and thus economic sustainability. Therefore, assessing the economic performance of a company only based on costs does not guarantee a robust evaluation.

The method used in this study, with a profit-based functional unit, overcomes these limitations. In particular, the profit-based functional unit was defined by adopting a systemic approach that allowed the identification of interrelations between physical and monetary flows and the quantification of the number of transactions necessary to ensure economic sustainability. Using such a functional unit proved to be a robust tool to measure the cause-effect relations between the economic and environmental elements of the business models. For example, from the sensitivity analysis in section 6.3 it emerged that an increase in the rental price reduces environmental impacts (because fewer jackets and transactions are then needed to reach the same profit). A company implementing a rental model should thus set the rental price as high as possible without exceeding customer's willingness to pay. Rental efficiency was another business-related parameter important for the environmental results, where a low efficiency represents an inefficient utilisation of the stock of rental jackets. To compensate, more jackets and rental transactions are necessary, thus reversing the ranking between the business models. Hence, a company implementing a rental business model should aim to maximise the rental efficiency in order to achieve decoupling.

In addition to identifying interconnections and relations between the different environmental and economic elements of the business model, the profit-based functional unit enabled us to consider both costs and revenues. Consequently, the limitations of LCC considering only costs and not revenues were avoided.

8.2. Comparing the use of different functional units

Mainstream praxis in life cycle-based assessments is to define a functional unit based on the functions delivered by a product, most often related to its physical properties. However, PSS combine tangible and intangible elements and tend to include different sub-functions that cannot be separated (Kjaer et al., 2016). Intangible elements regard e.g. the behaviour or the preferences of customers, while the multiple sub-functions include all the activities required to providing the final function of the PSS. An example of a sub-function in this study is the laundry process, which in the rental model occurs after every rental transaction, but in the sales model occurs considerably less often, or customer transports, which occur more often in the rental than the sales model. According to Kjaer et al. (2016), both the intangible elements and the sub-functions represent a challenge for LCA practitioners in the PSS field when the functional unit is identified. In particular, they suggest to carefully reflect on how broad or narrow the functional unit should be and how the it ensures the comparability of alternatives and sub-functions. Therefore, these aspects should be considered when selecting an alternative functional unit to compare with the profit-based functional unit.

In previous LCA studies assessing collaborative consumption in the apparel field, the functional unit applied is often "one use of a garment", meaning a use that occurs within a period of 24 hours (Roos et al., 2015; Zamani et al., 2017). The choice of this functional unit is to some extent able to consider the sub-functions mentioned above, and allows the investigation of effects of interventions on the environmental performance of the production system (Roos et al., 2015). Interventions can e.g. be different ways to design a product or changing the behaviour of customers in handling the products.

In order to investigate the effects of the choice of functional unit in the present study, the assessment of the baseline scenario is here repeated but with "one use day" as a functional unit, instead of the one based on profit. Therefore, all physical flows were related to this functional unit[9] and impacts were calculated by adopting the ReCiPe Endpoint (H,A) weighting method.

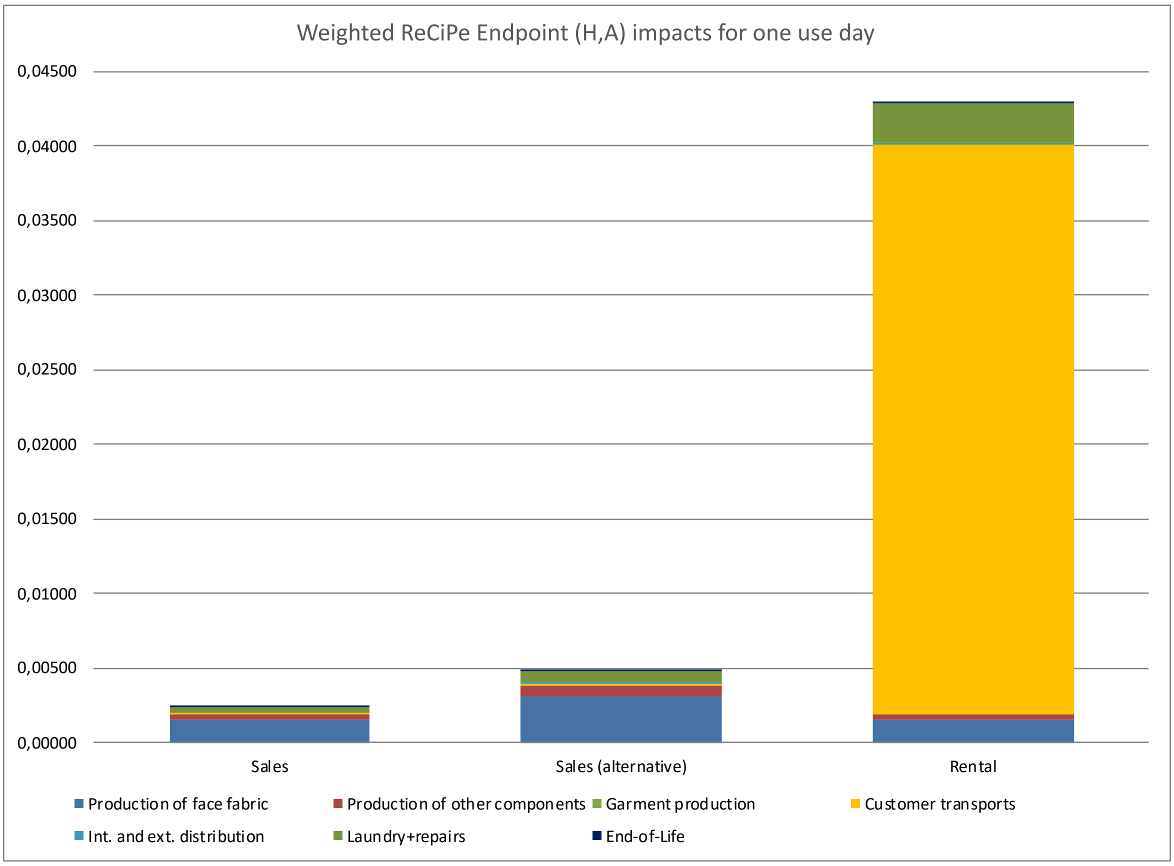

Figure 14: Weighted impacts using a functional unit of one use day, comparing the sales model, an alternative sales model (taking into account how fashion can affect the jacket's technical lifetime) and the rental business model.

Figure 14 shows that when fulfilling the function of one use day with a rental model, there is an approximately twenty-fold increase in impacts compared to the sales model because of increased customer transportation and laundry activities. Impacts from production are the same both for the rental and the sales model, since one jacket has to be produced in both cases and the jacket generates the same amount of use days over its lifetime. The assumption that a jacket can be used for the same amount of days in the rental and sales model does not consider customers values on the one hand and the effect of clothing libraries on the lifetime of garments on the other hand. Indeed, due to fashion reasons, customers that buy a jacket may replace it prematurely, which means that the jacket will generate less use days than the expected technical lifetime. Contrarily, rental models or clothing libraries intensify the use of garments, which makes them less sensitive to such fashion effects. In order to capture customer choices related to fashion, a further scenario has been considered namely "sales (alternative)" in Figure 14. This scenario represents customers discarding jackets after half the technical lifetime, which means that impacts are more or less doubled compared to the original sales model due to the need for producing an additional jacket. However, impacts in the rental model are still considerably higher.

[9] See Appendix F for further specifications.

These findings are in contrast with what was obtained by applying the profit-based functional unit, and it highlights the weakness of a "use-based f.u." for assessing business models. Such a f.u. captures changes in product design or material inputs but fails to capture the effects of changes in the business model. Consequently, a more suitable functional unit to apply when assessing business models is one based on profit, which captures e.g. the effects of changes in e.g. a company's number of transactions or production volume. These aspects tend to be difficult to include in mainstream LCA assessments since they are affected by economic factors and interactions between the company and the customers. Nevertheless, future research might compare the present functional unit with other variants commonly used in literature as well, to get a more complete and fair comparison.

These aspects that are difficult to include with a use-based functional unit, can instead be included with a profit-based functional unit, as in this study by incorporating insights from the field of Product Chain Organization (PCO) which employs a socio-material approach to material flows (Lindkvist and Baumann, 2017). In PCO, environmentally relevant organizational processes are identified by considering how material flows are affected by both actions and actors (Lindkvist and Baumann, 2017). The material flows are followed through all the relevant phases of the lifecycle and the organisational processes and action nets are identified. Socio-material interaction points can then be identified where different action nets interact.

Different business models can alter the way in which customers have access to and interact with a product, and a PCO approach enabled the identification and quantification of the number of interactions between the company and its customers. The material and money flows of the business models could then be found based on the type of these interactions. As presented in section 4.1, the interactions between the company and its customers are different for different business models and lead to different environmental-economic interdependencies. For example, in the rental model a garment can be rented several times before being sold as a second-hand garment. Therefore, the number of interactions in the rental model is higher than in the sales model. Conversely, the only way to achieve more transactions in the sales model is to increase the volume of production, thus also strongly affecting the environmental performance of the company. Hence, the profit-based functional unit allowed us to internalise qualitative and quantitative aspects related to interactions that are normally excluded from environmental assessments but that significantly affect the environmental performance of a business model. This last aspect, together with the integration of economic and environmental elements (described in section 8.1) within the functional unit indicate a pivotal translation point between the conventional functional unit and business model/PSS functional unit. Indeed, the profit-based functional unit can be considered a hybrid and inter-disciplinary tool that shifts the level of the assessment from the product to the business model level. This enables the investigation of the dynamics of a business model and their effect in terms of environmental impacts, which is in line with the purpose of this study to provide a method that is relevant and useful for a company to guide their business choices towards decoupling.

8.3. Advantages, drawbacks and future research

Here, advantages and drawbacks of the developed method will be discussed, based on the comparisons with other life cycle studies, from sections 8.1 and 8.2. The profit-based functional unit proved key to overcoming issues related to assessing business models and integrating economic and environmental dimensions in the assessment.

A company applying our method would be able to plan a more sustainable business model by making environmental considerations without compromising profit levels. The method would also let them estimate the level of decoupling of their business models, which can encourage the company in pursuing a higher eco-efficiency. Furthermore, a novelty of the method is that it reveals the interdependencies between economic and physical flows, thus enabling a company to adapt not only the product design or production system (as a more mainstream LCA would) but also to adapt its business model, e.g. by aiming for a higher rental efficiency. Therefore, the method implemented in this study could be useful for LCA practitioners and companies that want to improve the environmental performance of a business model and still maintain profitability. It is also possible to identify possible inefficiencies that derive from technical processes, e.g. regarding laundry practices and from economic decisions, e.g. regarding the business model setup. Thus, this method is not designed as a tool to increase profits, but rather to indicate how to design or plan a business model in order to make it more environmentally sustainable while keeping the same profit level.

In addition to the various advantages of the method developed in this study there are also disadvantages. The first regards the required level of accuracy for economic data. The cost structure should include all costs that the company incurs when running their business model. Over- or underestimating costs can lead to errors in the assessment and thus assumptions should be avoided while site-specific data can highly contribute to reduce uncertainties. Another potential disadvantage concerns the many different types of data necessary to perform the assessment. In more conventional LCA, only data related to physical flows of material and energy are required. To perform assessments with the method developed in this study, however, different economic data are also necessary, which demands multi-disciplinary competences of the practitioners performing the assessment. Furthermore, such economic data are often confidential (at least regarding revenues), which makes them difficult to obtain and use.

Another drawback is related to the systemic approach which is applied to identify the functional unit. The systemic approach requires a high level of awareness about the system characteristics and processes under investigation in order to ensure a robust and accurate modelling of interconnections. Therefore, contrary to what is typical of mainstream LCA praxis, the functional unit suggested in this report is the product of a more complex and time-consuming learning process that requires more scoping and preparation in order to integrate the economic aspects of the assessment.

Furthermore, our model depends on several assumptions regarding customer habits, such as transport choices, laundry practices and to what extent garments are returned for recycling. However, the sensitivity analysis revealed how customer behaviour (particularly transportation habits) can significantly affect the environmental performance of a business model. Hence, it is important to gain more knowledge and understanding of customer behaviour and how it can potentially be changed to reduce environmental impacts. Other aspects of customer behaviour that can be important but difficult to include in our method is how much they value intangible aspects like ownership (as opposed to renting) or using garments that have been used before. On the other hand, because the profit-based functional unit takes the perspective of the company, it means that the assessment will be less sensitive to some aspects of customer behaviour like changing fashion trends (as indicated by the discussion in section 8.2). It can also be mentioned that a rental model will be less sensitive to fashion trends than a sales model, since garments are used more intensely and can be replaced by updated models after a shorter time than is the case in a sales model.

Lastly, the functional unit was defined by adopting a static economic perspective which disregards the time value of money and hence discounting was not considered. This was mainly because of time constraints and to keep this first iteration of the method as simple as possible. Nevertheless, it is a disadvantage since in practice the economic considerations of companies include uncertainty and long-term risk. However, discounting can and should be used in future implementations of the method, which would enable a more dynamic assessment that considers the time-value of money. In addition, the method can also be adapted to include social dimensions in the assessment of the business model. Future research could also apply this method on other types of business models, such as online sales, to assess if alternative business models can be advantageous both from an environmental, social and economic point of view.

9. Conclusions

This study has presented a novel approach to assessing and comparing the environmental consequences of a company using a sales business model or a rental business model to capture value from jackets in Sweden. The object of analysis was a product-level business model and the assessment was done by connecting economic flows with physical flows of material and energy to define a basis of comparison built on a certain amount of profit. Results showed that the use-oriented PSS, in the form of a rental model, led to lower environmental impacts overall compared to the product sales model, while still maintaining the same economic performance. The main reason for this was that the company can get more money out of each jacket by repeatedly renting it instead of selling it only once. However, the results were sensitive to the sustainability of the transport and energy systems, as well as some customer habits and business model parameters such as rental price and rental efficiency. A key take-away was that a sustainable implementation of use-oriented PSS requires a detailed knowledge of customer habits. Another was the need for careful business planning, where one noteworthy detail was the negative effect of offering rental customers the option of purchasing their jackets after renting them. Given the significant effect on the rental model results, this practice should be avoided.

In order to perform the environmental assessment of different ways to capture value, the functional unit was based on profit, rather than on the function or physical properties of the product. This enabled the integration of economic and environmental elements in the assessment and the inclusion of interactions between the company and external actors.

One of the main contributions of this study is that it offers a method for environmental assessment of different ways for a company to make money, by integrating economic aspects into the environmental assessment. Hence, one of the key novelties of the developed method is that, by coupling the economic and physical flows of a business model, it allows a company to directly see the impact of business decisions on their environmental performance and plan their activities accordingly.

Future research can be done on how to take into account intangible value (like the value of ownership) into the assessment, as well as expanding the time perspective and include e.g. investment costs and not only running costs. Similar quantified assessments should also be done on other types of products and other types of business models.

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Appendix A Further details on calculations and modelling

Appendix A.1 Summary of the basis for data obtained from company

Most data obtained from the company regarded product specifications, economic data and rental model setup. Some of these data were the company's own estimations while other data were based on their empiric observations, see Table 14.

Table 14: For the data that was obtained directly by the case company (via personal communication), this table indicates whether the basis for those data were the company's own estimations or if the estimation was based on their empiric observations.

Data	Basis for data
Technical lifetime of the garment (number of uses and/or years)	Estimation based on empiric observation
Expected rental lifetime of the garment (before it is removed from the rental stock)	Estimation
Expected average number of reparation procedures during the rental lifetime of the garment	Estimation based on empiric observation
Expected average number of washes during the rental lifetime of the garment	Estimation based on empiric observation
Expected average amount of time needed to wash garments before they can be rented again	Estimation based on empiric observation
Expected average amount of time needed to repair a garment	Estimation based on empiric observation
Average customers' transportation habits	Estimation
Expected average reparation cost per garment	Estimation based on empiric observation
Expected average washing cost per garment	Estimation based on empiric observation

Appendix A.2 Regarding how the replacement rate, R_r, was derived:

The replacement rate in the rental model was derived by simulating the ageing of the garments as they are used in the rental service. Assuming that the stock, Q_r, contains a uniform distribution of garments with different ages, each day of use increases a garment's age by one day. Because of the rental efficiency, E_r (which is smaller than 1), on any given day only a share of the stock is out generating use days and thus ageing. There are two equivalent ways to implement this. The more intuitive way is to assume that on any given day, some percentage (E_r) of garments are being used and only those specific products should have their ages increased by one day, while the remaining garments ($1-E_r$) are unused and thus do not age. However, an alternative but equivalent interpretation was chosen, namely to every day increase the age of every garment in the stock by E_r% of a day instead of one full day. This is less intuitive, but simpler to simulate. As the days pass in the simulation, some garments will reach their maximum rental lifetime RL, at which point a newly produced garment takes their place in the stock. Counting how many garments are replaced on average over a period T in the simulation lets us calculate the replacement rate R_r as the share of jackets that needs to be replaced during time T.

Note that the replacement rate depends on the rental lifetime RL, which is dictated by the company employees who decide when garments are too worn out to be rented again at a similar rental price etc. In turn, the rental lifetime depends on the technical lifetime TL. If the technical lifetime is increased then also the rental lifetime will increase because it will take a longer time to become worn out, which will reduce the replacement rate of garments.

Appendix A.3 Regarding how energy consumption was allocated in chemical recycling

An overall energy use of 11.962 MJ was used for chemical recycling of polyester to produce 1 kg of dimethyl terephthalate (Patagonia, 2011). In our model, chemical recycling includes the processes compounding, methanolysis and distillation, which produces 0.621 kg of dimethyl terephthalate from 1 kg of polyester garments (RISE, personal communication, February 12, 2020). As an approximation, the total energy consumption was allocated equally to each process.

Appendix A.4 Regarding the modelling of laundry electricity consumption

In the sales business model, clothes are washed in machines at a 60% load (3.6kg in a machine of maximum 6 kg load), and the total electricity use for one cycle is 0.81 kWh (Roos et al., 2015). In the rental model, the clothes are washed at full load (which is 6 kg, i.e. 2.4 kg more than in the sales model) and the electricity consumption is increased at an amount estimated as the average load dependency of 0.08 kWh per additional kg found by Faberi (2007). This results in a 1.0 kWh electricity use at full load in the rental scenario. For one jacket (0.815 kg), the electricity consumption for laundry in the sales model (with 60% load) is thus 0,815kg*0,81kWh/3,6kg = 0.183 kWh and in the rental model (at full load) it is 0.815kg*1kWh/6kg = 0.136 kWh.

Appendix A.5 Regarding rate of repairs in the sales business model

In the rental business model, we use the company estimate that 4% of all rental transactions are expected to result in a repair intervention. For the sales model, we assume the same rate of repairs, but we need to translate the 4% repairs per rental transactions into repairs per use day or business period. Assuming that every rental transaction corresponds to five use days on average (see U_r in Table 11, section 4.3), every use day can be said to result in 4/(100*5)= 0.008 repairs. A jacket depletes its technical lifetime in ten years, which corresponds to 1000 use days. Hence, each period T of one month generates 8.333 use days and, consequently, the number of repairs required per month in the sales model is 8.333*0.008 = 0.0664.

Appendix B Life cycle inventory

Here, the flows relating to every process in the life cycle of the jackets are presented, as extracted from the model in OpenLCA. This includes the product that each process generates, all inputs of material and energy, as well as outputs in terms of emissions and waste. For every flow, the provider is presented, along with the source of the data and any clarifying comments.

In some cases, the amount of a flow includes references to parameters, which are either local parameters (only used in that process) and described in the same table or global parameters (used in several processes) and summarised and described here in Table A 1.

Table A 1: Global parameters used throughout the LCI processes in OpenLCA

GLOBAL PARAMETERS		
Variable name	**Value**	**Description**
CR	0.5	Collection rate
Customer_transport_bike	2 km	Distance corresponding to 20% of an average round trip to the store
Customer_transport_car	2 km	Distance corresponding to 20% of an average round trip to the store
Customer_transport_tram	4 km	Distance corresponding to 40% of an average round trip to the store
Laundries_T	0.15	Number of laundries during time T (of a customer-owned jacket)
Rental lifetime	200	Number of use days before jackets are replaced in rental stock
Repairs_T	0.06666664	Number of repairs during time T
Second_hand_lifetime	800	Number of use days that rental jackets are used after sold 2nd hand
Technical lifetime	1000	Total number use days before a jacket is completely worn out
q_s	t_s	Reference number of jackets produces in sales model during time T
t_s	200	Reference number of sales transactions during time T
q_r	28	Number of replacement jackets produced during time T
t_r	1107.8	Number of rental transactions during time T

Appendix B.1 LCI Chemical recycling of polyester

INDUSTRIAL WASHING						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Washed garments		1.0	kg			
Inputs						
Detergent		0.009	kg	Detergent production		Roos et al. (2015)
electricity, medium voltage		0.4	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - JP		Roos et al. (2015)
heat, for reuse in municipal waste incineration only		1.9	kWh	treatment of municipal solid waste, incineration | heat, for reuse in municipal waste incineration only | Cutoff, U - JP		Roos et al. (2015)
Sorted polyester garments		1.0	kg			Mass balance
tap water		12.0	kg	market for tap water | tap water | Cutoff, U - RoW		Roos et al. (2015)

SHREDDING GARMENTS						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						

Shredded garments		1.0	kg			
Inputs						
electricity, low voltage		0.001	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - JP		Roos et al. (2015)
Washed garments		1.0	kg	Industrial washing - JP		Mass balance

COMPOUNDING						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Mixture A		1.1	kg			
Inputs						
electricity, low voltage		2.06345	MJ	market for electricity, low voltage | electricity, low voltage | Cutoff, U - JP		Patagonia (2011)
ethylene glycol		0.01	kg	market for ethylene glycol | ethylene glycol | Cutoff, U - GLO	Reduced from 0.1 kg due to the reuse of EG 0.09 kg of EG from the distillation process	RISE (2020)
Shredded garments		1.0	kg	Shredding garments - JP		Mass balance
soda ash, dense		5.0E-5	kg	market for soda ash, dense | soda ash, dense | Cutoff, U - GLO		RISE (2020)

METHANOLYSIS						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Mixture B		1.2	kg			
Inputs						
heat, from steam, in chemical industry		2.063445	MJ	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RoW		Patagonia (2011)
methanol		1.5	kg	market for methanol | methanol | Cutoff, U - GLO		RISE (2020)
Mixture A		1.1	kg	Compunding - JP		RISE (2020)

DISTILLATION						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Mixture C		1.2	kg			
Inputs						
heat, from steam, in chemical industry		2.063445	MJ	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RoW		Patagonia (2011)
Mixture B		1.2	kg	Methanolysis - JP		RISE (2020)

POLYMERISATION (RECYCLED)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
PET granulates (recycled)		1.0	kg			
Inputs						
antimony		0.00025	kg	market for antimony | antimony | Cutoff, U - GLO		Ecoinvent (2019)

chemical factory, organics		4.0E-10	Item(s)	market for chemical factory, organics | chemical factory, organics | Cutoff, U - GLO	Estimation	Ecoinvent (2019)
electricity, medium voltage		0.194	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - JP	EcoSpold01Location=UCTE	Ecoinvent (2019)
heat, district or industrial, natural gas		0.665	MJ	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U - RoW	Amount industrial survey - distribution according to cumulated data	Ecoinvent (2019)
heat, district or industrial, other than natural gas		0.965	MJ	market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Cutoff, U - RoW	EcoSpold01Location=RER	Ecoinvent (2019)
Mixture C		1.4285714286	kg	Distillation - JP	Assuming 30% losses/waste, so to produce 1 kg of PET granules, we need: 1.4285714286 kg of Mixture C (from 1/0.7)	RISE (2020)
nitrogen, liquid		0.0298	kg	market for nitrogen, liquid | nitrogen, liquid | Cutoff, U - RoW	EcoSpold01Location=RER	Ecoinvent (2019)
steam, in chemical industry		0.94	kg	market for steam, in chemical industry | steam, in chemical industry | Cutoff, U - RoW	European average value, based on industrial survey	Ecoinvent (2019)
Water, cooling, unspecified natural origin		0.0064	m3		European average value, based on industrial survey	Ecoinvent (2019)
Water, unspecified natural origin		1.63E-4	m3		European average value, based on industrial survey	Ecoinvent (2019)
Outputs						
average incineration residue		4.0E-4	kg	market for average incineration residue | average incineration residue | Cutoff, U - RoW	EcoSpold01Location=CH	Ecoinvent (2019)
BOD5, Biological Oxygen Demand	Emission to water/surface water	1.6E-4	kg		European average value, based on industrial survey	Ecoinvent (2019)
COD, Chemical Oxygen Demand	Emission to water/surface water	0.00102	kg		European average value, based on industrial survey	Ecoinvent (2019)
DOC, Dissolved Organic Carbon	Emission to water/surface water	2.62E-4	kg		Estimated, based on rules in Frischknecht 2003	Ecoinvent (2019)
hazardous waste, for underground deposit		9.0E-5	kg	market for hazardous waste, for underground deposit | hazardous waste, for underground deposit | Cutoff, U - GLO	EcoSpold01Location=DE	Ecoinvent (2019)
Hydrocarbons, unspecified	Emission to water/surface water	4.99E-4	kg		European average value, based on industrial survey	Ecoinvent (2019)
municipal solid waste		8.79239085343996E-4	kg	market for municipal solid waste | municipal solid waste | Cutoff, U - RoW	EcoSpold01Location=CH	Ecoinvent (2019)
municipal solid waste		3.13254825266099E-7	kg	market for municipal solid waste | municipal solid waste | Cutoff, U - CY	EcoSpold01Location=CH	Ecoinvent (2019)
municipal solid waste		4.47659830738294E-7	kg		EcoSpold01Location=CH	Ecoinvent (2019)
NMVOC, non-methane volatile organic compounds, unspecified origin	Emission to air/high population density	9.0E-5	kg		European average value, based on industrial survey	Ecoinvent (2019)
Particulates, < 2.5 um	Emission to air/high population density	2.5E-7	kg		European average value, based on industrial survey	Ecoinvent (2019)
Particulates, > 10 um	Emission to air/high population density	3.2E-7	kg		European average value, based on industrial survey	Ecoinvent (2019)
Particulates, > 2.5 um, and < 10um	Emission to air/high population	4.3E-7	kg		European average value, based on industrial survey	Ecoinvent (2019)

	density					
Polyethylene waste		0.4285714286	kg			Ecoinvent (2019)
Suspended solids, unspecified	Emission to water/surface water	1.0E-6	kg		European average value, based on industrial survey	Ecoinvent (2019)
TOC, Total Organic Carbon	Emission to water/surface water	2.62E-4	kg		Estimated, based on rules in Frischknecht 2003	Ecoinvent (2019)
waste plastic, mixture		0.00203197996782466	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - BR	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		2.26546646106207E-5	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - PE	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		1.35769068630604E-4	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - CO	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		5.60774878444612E-5	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - IN	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		5.32508173304272E-5	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - ZA	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		1.02679937592291E-5	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - CY	EcoSpold01Location=CH	Ecoinvent (2019)
Water	Emission to air/unspecified	0.002513415	m3		Calculated value based on literature values and expert opinion. See comments in the parametres' comment field.	Ecoinvent (2019)
Water	Emission to water/unspecified	0.004049585	m3		Calculated value based on literature values and expert opinion. See comments in the parametres' comment field.	Ecoinvent (2019)

MELT SPINNING (FACE FABRIC)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Recycled polyester fibre		1.0	kg			
Inputs						
antimony		2.0E-4	kg	antimony production | antimony | Cutoff, U - RoW		Roos et al. (2019)
electricity, low voltage		1.5	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - JP		Roos et al. (2019)
heat, from steam, in chemical industry		2.2	MJ	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RoW		Roos et al. (2019)
lubricating oil		0.01	kg	market for lubricating oil | lubricating oil | Cutoff, U - RoW		Roos et al. (2019)
manganese		2.0E-4	kg	manganese production | manganese | Cutoff, U - RoW		Roos et al. (2019)
PET granulates (recycled)		share_rec	kg	Polymerisation (recycled) - JP	share_rec = 0.602068525 (see mass balance)	Mass balance
polyethylene terephthalate, granulate, amorphous		share_virg	kg	market for polyethylene terephthalate, granulate, amorphous | polyethylene terephthalate, granulate, amorphous | Cutoff, U - GLO	share_virgin = 1 – share_rec (virgin PET to compensate for losses in recycling and collection)	Mass balance
Outputs						
dimethyl terephthalate (dmt)	Emission to air/unspecified	1.0E-5	kg			Roos et al. (2019)

YARN SPINNING (FACE FABRIC)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Recycled polyester yarn		1.0	kg			
Inputs						
electricity, low voltage		4.41	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - JP		Roos et al. (2019)
lubricating oil		0.0016	kg	market for lubricating oil | lubricating oil | Cutoff, U - RoW		Roos et al. (2019)
Recycled polyester fibre		1.005025126	kg	Melt spinning (face fabric) - JP		Mass balance
Outputs						
ACRYLAMIDE	Emission to air/high population density	4.8E-9	kg			Roos et al. (2019)
Formaldehyde	Emission to air/high population density	4.8E-10	kg			Roos et al. (2019)
waste yarn and waste textile		0.005025126	kg	market for waste yarn and waste textile | waste yarn and waste textile | Cutoff, U - GLO		Roos et al. (2019)

WEAVING (150 DTEX)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Recycled polyester fabric		1.0	kg			
Inputs						
electricity, low voltage		9.87	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - JP		Roos et al. (2019)
lubricating oil		0.0305	kg	market for lubricating oil | lubricating oil | Cutoff, U - RoW		Roos et al. (2019)
Recycled polyester yarn		1.005025126	kg	Yarn spinning (face fabric) - JP		Mass balance
waste yarn and waste textile		0.005025126	kg	market for waste yarn and waste textile | waste yarn and waste textile | Cutoff, U - GLO		Roos et al. (2019)

DYEING FACE FABRIC						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Face fabric dyed		1.0	kg			
Inputs						
chemical, inorganic		0.08	kg	market for chemicals, inorganic | chemical, inorganic | Cutoff, U - GLO		Roos et al. (2019)
chemical, organic		0.2136	kg	market for chemical, organic | chemical, organic | Cutoff, U - GLO		Roos et al. (2019)
electricity, low voltage		0.7	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - JP		Roos et al. (2019)
ethoxylated alcohol (AE7)		0.215	kg	ethoxylated alcohol (AE7) production, petrochemical | ethoxylated alcohol (AE7) | Cutoff, U - RoW		Roos et al. (2019)
formic acid		0.03	kg	market for formic acid | formic acid | Cutoff, U - RoW		Roos et al. (2019)
heat, from steam, in chemical industry		8.333	kWh	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RoW		Roos et al. (2019)

hydrogen peroxide, without water, in 50% solution state		0.03	kg	market for hydrogen peroxide, without water, in 50% solution state | hydrogen peroxide, without water, in 50% solution state | Cutoff, U - RoW		Roos et al. (2019)
Recycled polyester fabric		1.0	kg	Weaving (150 dtex) - JP		Mass balance
silicone product		0.003	kg	market for silicone product | silicone product | Cutoff, U - RoW		Roos et al. (2019)
sodium hydroxide, without water, in 50% solution state		0.005	kg	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, U - GLO		Roos et al. (2019)
sodium percarbonate, powder		0.01	kg	market for sodium percarbonate, powder | sodium percarbonate, powder | Cutoff, U - RoW		Roos et al. (2019)
tap water		78.0	kg	market for tap water | tap water | Cutoff, U - RoW		Roos et al. (2019)
Outputs						
1,2-dihydro-6-hydroxy-1,4-dimethyl-2-oxo-5-[[3-[(phenylsulphonyl)oxy]phenyl]azo]nicotinonitrile	Emission to air/high population density	6.0E-7	kg			Roos et al. (2019)
1,2-dihydro-6-hydroxy-1,4-dimethyl-2-oxo-5-[[3-[(phenylsulphonyl)oxy]phenyl]azo]nicotinonitrile	Emission to water/fresh water	3.0E-6	kg			Roos et al. (2019)
2-(3-oxobenzo[b]thien-2(3H)-ylidene)benzo[b]thiophene-3(2H)-one	Emission to air/high population density	1.3E-5	kg			Roos et al. (2019)
2-(3-oxobenzo[b]thien-2(3H)-ylidene)benzo[b]thiophene-3(2H)-one	Emission to water/fresh water	6.5E-5	kg			Roos et al. (2019)
2-Ethyl-1-Hexanol	Emission to air/unspecified	3.0E-6	kg			Roos et al. (2019)
2-Ethyl-1-hexanol	Emission to water/fresh water	3.0E-4	kg			Roos et al. (2019)
2-methyl-4-isothiazolin-3-one	Emission to water/fresh water	3.0E-7	kg			Roos et al. (2019)
5-chloro-2-methyl-4-isothiazoline-3-one	Emission to water/fresh water	3.0E-7	kg			Roos et al. (2019)
Ammonium sulphate	Emission to water/fresh water	0.002	kg			Roos et al. (2019)
C9-11 Alcohol ethoxylate	Emission to water/fresh water	6.0E-4	kg			Roos et al. (2019)
Calcium carbonate	Emission to water/fresh water	0.002	kg			Roos et al. (2019)
COD, Chemical Oxygen Demand	Emission to water/fresh water	2.0E-4	kg			Roos et al. (2019)
Diethanolamine	Emission to water/fresh water	3.0E-5	kg			Roos et al. (2019)
Dimethyl siloxane, reaction product with silica	Emission to water/fresh water	1.5E-5	kg			Roos et al. (2019)
Ethoxylated alcohol (NPEO)	Emission to water/fresh water	1.5E-4	kg			Roos et al. (2019)
Ethylene oxide	Emission to air/high population density	1.5E-8	kg			Roos et al. (2019)
Ethylene oxide	Emission to water/fresh water	1.5E-6	kg			Roos et al. (2019)

Fatty methylester sulfonates	Emission to water/fresh water	9.0E-4	kg			Roos et al. (2019)
Formaldehyde	Emission to air/high population density	1.5E-8	kg			Roos et al. (2019)
Formaldehyde	Emission to water/fresh water	1.5E-7	kg			Roos et al. (2019)
Formic acid	Emission to air/high population density	3.0E-5	kg			Roos et al. (2019)
Formic acid	Emission to water/fresh water	0.003	kg			Roos et al. (2019)
Hydrogen peroxide	Emission to air/high population density	3.0E-5	kg			Roos et al. (2019)
Hydrogen peroxide	Emission to water/fresh water	3.0E-4	kg			Roos et al. (2019)
Isotridecanol ethoxylated	Emission to water/fresh water	0.002	kg			Roos et al. (2019)
Nonylphenol	Emission to water/fresh water	1.5E-7	kg			Roos et al. (2019)
Octadecanoic acid, ester with 2,2-bis(hydroxymethyl)-1,3-propanediol	Emission to water/unspecified	2.0E-4	kg			Roos et al. (2019)
Oxirane, methyl-, polymer with oxirane, decyl ether	Emission to water/fresh water	0.00425	kg			Roos et al. (2019)
Phosphonic acid, disodium salt	Emission to air/high population density	1.2E-5	kg			Roos et al. (2019)
Phosphonic acid, disodium salt	Emission to water/fresh water	0.0012	kg			Roos et al. (2019)
sludge from pulp and paper production		0.5	kg	market for sludge from pulp and paper production | sludge from pulp and paper production | Cutoff, U - RoW		Roos et al. (2019)
Sodium carbonate (Na2CO3)	Emission to water/fresh water	5.1E-4	kg			Roos et al. (2019)
Sodium hydroxide	Emission to water/fresh water	5.06E-4	kg			Roos et al. (2019)
Sodium lauryl sulphate (alcoholsulfate)	Emission to water/fresh water	3.0E-7	kg			Roos et al. (2019)
Sodium mono(2-ethylhexyl)estersulfate	Emission to water/fresh water	8.5E-4	kg			Roos et al. (2019)
Thiosulfate	Emission to water/fresh water	4.5E-7	kg			Roos et al. (2019)

DRYING FACE FABRIC A						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Face fabric dyed, dried		1.0	kg			
Inputs						
electricity, low voltage		0.8	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - JP		Roos et al. (2019)

Face fabric dyed		1.0	kg	Dyeing face fabric - JP		Mass balance
heat, from steam, in chemical industry		2.2	kWh	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RoW		Roos et al. (2019)

FINISHING (DWR)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Face fabric finished		1.0	kg			
Inputs						
DWR (wax emulsion)		0.01	kg	DWR (approx based on organic chemicals) - JP		
Face fabric dyed, dried		1.0	kg	Drying A - JP		

DWR PRODUCTION						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
DWR (wax emulsion)		1.0	kg			
Inputs						
chemical, organic		0.326	kg	market for chemical, organic | chemical, organic | Cutoff, U - GLO		
tap water		0.674	kg	market for tap water | tap water | Cutoff, U - RoW		

DRYING FACE FABRIC B						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Face fabric		1.0	kg			
Inputs						
electricity, low voltage		0.8	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - JP		Roos et al. (2019)
Face fabric finished		1.0	kg	Finishing (DWR) - JP		Mass balance
heat, from steam, in chemical industry		2.2	kWh	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RoW		Roos et al. (2019)

Appendix B.2 LCI Production of jersey backing

REFINING (BACKING)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Purified terephthalic acid (backing)		1.0	kg			
Inputs						
acetic acid, without water, in 98% solution state		0.0554999421428199	kg	market for acetic acid, without water, in 98% solution state | acetic acid, without water, in 98% solution state | Cutoff, U - GLO	Weighted average of reported input	Ecoinvent (2019)
chemical factory,		4.0E-10	Item(s)	market for chemical factory, organics | chemical factory, organics | Cutoff, U - GLO		Ecoinvent (2019)

organics						
chemical, inorganic		6.12426586651359E-4	kg	market for chemicals, inorganic | chemical, inorganic | Cutoff, U - GLO	Sum input parameter covering partly confidential information on additives, solvents, catalysts. Weighted average of reported input materials.	Ecoinvent (2019)
chemical, organic		0.00744986723522292	kg	market for chemical, organic | chemical, organic | Cutoff, U - GLO	Sum input parameter covering partly confidential information on additives, solvents, catalysts. Weighted average of reported input materials.	Ecoinvent (2019)
cobalt		2.19550075103395E-4	kg	market for cobalt | cobalt | Cutoff, U - GLO	Weighted average of reported input	Ecoinvent (2019)
compressed air, 600 kPa gauge		0.345986261722217	m3		Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.0106818798905516	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RAF	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		6.2988416321517E-4	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - NZ	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.154876083916439	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RAS	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.0646666756538316	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - US	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.00346170434504085	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - AU	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.00510509698409366	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - Canada without Quebec	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.0221657027196663	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RLA	Weighted average of reported input	Ecoinvent (2019)
heat, from steam, in chemical industry		1.85538221940177	MJ	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RoW	Weighted average of reported input	Ecoinvent (2019)
manganese		2.17465665147622E-4	kg	market for manganese | manganese | Cutoff, U - GLO	Weighted average of reported input	Ecoinvent (2019)
natural gas, high pressure		0.0144328111469741	m3	market for natural gas, high pressure | natural gas, high pressure | Cutoff, U - RoW	Weighted average of reported input	Ecoinvent (2019)
natural gas, high pressure		4.52832967790106E-4	m3	market for natural gas, high pressure | natural gas, high pressure | Cutoff, U - DZ	Weighted average of reported input	Ecoinvent (2019)
natural gas, high pressure		0.00615497651058913	m3	market for natural gas, high pressure | natural gas, high pressure | Cutoff, U - US	Weighted average of reported input	Ecoinvent (2019)
natural gas, high pressure		7.53838835152195E-4	m3	market for natural gas, high pressure | natural gas, high pressure | Cutoff, U - JP	Weighted average of reported input	Ecoinvent (2019)
nitrogen, liquid		0.0345895606327028	kg	market for nitrogen, liquid | nitrogen, liquid | Cutoff, U - RoW	Weighted average of reported input	Ecoinvent (2019)
sodium hydroxide, without water, in 50% solution state		0.0140730383951395	kg	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, U - GLO	Weighted average of reported input	Ecoinvent (2019)
Water, cooling, unspecified natural origin		0.00167303857224816	m3		Weighted average of reported input	Ecoinvent (2019)
Water, river		0.00143331398171261	m3		Weighted average of reported input	Ecoinvent (2019)
Water,		0.00279463700762329	m3		Weighted average of reported	Ecoinvent

unspecified natural origin					input	(2019)
Water, well		7.89904428759875E-5	m3		Weighted average of reported input	Ecoinvent (2019)
xylene		0.658542674032142	kg	xylene production | xylene | Cutoff, U - RoW	Weighted average of reported input	Ecoinvent (2019)
Outputs						
Arsenic, ion	Emission to water/unspecified	2.61569479847883E-10	kg		Weighted average of reported emissions	Ecoinvent (2019)
Benzene	Emission to air/unspecified	8.71440476251031E-6	kg		Weighted average of reported emissions	Ecoinvent (2019)
Cadmium, ion	Emission to water/unspecified	6.17539974979212E-11	kg		Weighted average of reported emissions	Ecoinvent (2019)
Carbon dioxide, fossil	Emission to air/unspecified	0.106455870204869	kg		Weighted average of reported emissions	Ecoinvent (2019)
Carbon monoxide, fossil	Emission to air/unspecified	9.7233004119408E-4	kg		Weighted average of reported emissions	Ecoinvent (2019)
Chromium, ion	Emission to water/unspecified	4.10394897480312E-8	kg		Weighted average of reported emissions	Ecoinvent (2019)
Cobalt	Emission to water/unspecified	1.74820350571484E-6	kg		Weighted average of reported emissions	Ecoinvent (2019)
Copper, ion	Emission to water/unspecified	4.41718084013793E-10	kg		Weighted average of reported emissions	Ecoinvent (2019)
Dinitrogen monoxide	Emission to air/unspecified	6.64665589052946E-7	kg		Weighted average of reported emissions	Ecoinvent (2019)
hazardous waste, for incineration		4.72996103061763E-5	kg	market for hazardous waste, for incineration | hazardous waste, for incineration | Cutoff, U - RoW	Weighted average of reported waste	Ecoinvent (2019)
Lead	Emission to water/unspecified	4.70038388598827E-10	kg		Weighted average of reported emissions	Ecoinvent (2019)
Mercury	Emission to water/unspecified	9.90817322912507E-10	kg		Weighted average of reported emissions	Ecoinvent (2019)
Methane, fossil	Emission to air/unspecified	2.03583389986713E-4	kg		Weighted average of reported emissions	Ecoinvent (2019)
Methanol	Emission to air/unspecified	8.88155473382894E-6	kg		Weighted average of reported emissions	Ecoinvent (2019)
Methyl acetate	Emission to air/unspecified	1.61463065129819E-5	kg		Weighted average of reported emissions	Ecoinvent (2019)
municipal solid waste		8.91522259402042E-5	kg	market for municipal solid waste | municipal solid waste | Cutoff, U - RoW	Weighted average of reported waste	Ecoinvent (2019)
municipal solid waste		4.53913742457428E-8	kg		Weighted average of reported waste	Ecoinvent (2019)
municipal solid waste		3.17631067868827E-8	kg	market for municipal solid waste | municipal solid waste | Cutoff, U - CY	Weighted average of reported waste	Ecoinvent (2019)
Nickel, ion	Emission to water/unspecified	5.67318954373915E-8	kg		Weighted average of reported emissions	Ecoinvent (2019)
Nitrogen oxides	Emission to air/unspecified	6.21985277649807E-5	kg		Weighted average of reported emissions	Ecoinvent (2019)
Nitrogen, organic bound	Emission to water/unspecified	3.5417765190208E-5	kg		Weighted average of reported emissions	Ecoinvent (2019)
NMVOC, non-methane volatile organic compounds, unspecified origin	Emission to air/unspecified	3.77924582985745E-4	kg		Weighted average of reported emissions	Ecoinvent (2019)
Phosphorus	Emission to water/unspecified	5.34348379342779E-6	kg		Weighted average of reported emissions	Ecoinvent (2019)
sewage sludge		3.73977673932847E-6	m3	market for sewage sludge | sewage sludge | Cutoff, U - RoW	Weighted average of reported waste	Ecoinvent (2019)
Sulfur dioxide	Emission to air/unspecified	3.12074197405166E-6	kg		Weighted average of reported emissions	Ecoinvent (2019)
Suspended solids, unspecified	Emission to water/unspecified	3.92535574831055E-5	kg		Weighted average of reported emissions	Ecoinvent (2019)
Toluene	Emission to air/unspecified	1.17687287338685E-5	kg		Weighted average of reported emissions	Ecoinvent (2019)
waste mineral oil		3.73702291623645E-5	kg	market for waste mineral oil | waste mineral oil | Cutoff, U - RoW	Weighted average of reported waste	Ecoinvent (2019)

wastewater, average		0.00547835323834142	m3	market for wastewater, average | wastewater, average | Cutoff, U - RoW	Weighted average of reported waste	Ecoinvent (2019)
Water	Emission to air/unspecified	5.01911571674447E-4	m3		Calculated to close water balance	Ecoinvent (2019)
Xylene	Emission to air/unspecified	3.63437525198466E-5	kg		Weighted average of reported emissions	Ecoinvent (2019)
Zinc, ion	Emission to water/unspecified	1.29893359831234E-7	kg		Weighted average of reported emissions	Ecoinvent (2019)

PET GRANULATE PRODUCTION (BACKING)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
PET granulates (backing)		1.0	kg			
Inputs						
antimony		3.33333333E-5	kg	market for antimony | antimony | Cutoff, U - GLO		Ecoinvent (2019)
chemical factory, organics		4.0E-10	Item(s)	market for chemical factory, organics | chemical factory, organics | Cutoff, U - GLO	Estimation	Ecoinvent (2019)
electricity, medium voltage		0.194	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - JP	EcoSpold01Location=UCTE	Ecoinvent (2019)
ethylene glycol		0.334	kg	market for ethylene glycol | ethylene glycol | Cutoff, U - GLO	EcoSpold01Location=RER	Ecoinvent (2019)
heat, district or industrial, natural gas		0.665	MJ	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U - RoW	Amount industrial survey - distribution according to cumulated data	Ecoinvent (2019)
heat, district or industrial, other than natural gas		0.965	MJ	market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Cutoff, U - RoW	EcoSpold01Location=RER	Ecoinvent (2019)
nitrogen, liquid		0.0298	kg	market for nitrogen, liquid | nitrogen, liquid | Cutoff, U - RoW	EcoSpold01Location=RER	Ecoinvent (2019)
Purified terephthalic acid (backing)		0.875	kg	Refining (for backing) - JP		Mass balance
steam, in chemical industry		0.94	kg	market for steam, in chemical industry | steam, in chemical industry | Cutoff, U - RoW	European average value, based on industrial survey	Ecoinvent (2019)
Water, cooling, unspecified natural origin		0.0064	m3		European average value, based on industrial survey	Ecoinvent (2019)
Water, unspecified natural origin		1.63E-4	m3		European average value, based on industrial survey	Ecoinvent (2019)
Outputs						
average incineration residue		4.0E-4	kg	market for average incineration residue | average incineration residue | Cutoff, U - RoW	EcoSpold01Location=CH	Ecoinvent (2019)
BOD5, Biological Oxygen Demand	Emission to water/surface water	1.6E-4	kg		European average value, based on industrial survey	Ecoinvent (2019)
COD, Chemical Oxygen Demand	Emission to water/surface water	0.00102	kg		European average value, based on industrial survey	Ecoinvent (2019)
DOC, Dissolved Organic Carbon	Emission to water/surface water	2.62E-4	kg		Estimated, based on rules in Frischknecht 2003	Ecoinvent (2019)
hazardous waste, for underground deposit		9.0E-5	kg	market for hazardous waste, for underground deposit | hazardous waste, for underground deposit | Cutoff, U - GLO	EcoSpold01Location=DE	Ecoinvent (2019)
Hydrocarbons, unspecified	Emission to water/surface water	4.99E-4	kg		European average value, based on industrial survey	Ecoinvent (2019)

municipal solid waste		4.47659830738294E-7	kg		EcoSpold01Location=CH	Ecoinvent (2019)
municipal solid waste		3.13254825266099E-7	kg	market for municipal solid waste | municipal solid waste | Cutoff, U - CY	EcoSpold01Location=CH	Ecoinvent (2019)
municipal solid waste		8.79239085343996E-4	kg	market for municipal solid waste | municipal solid waste | Cutoff, U - RoW	EcoSpold01Location=CH	Ecoinvent (2019)
NMVOC, non-methane volatile organic compounds, unspecified origin	Emission to air/high population density	9.0E-5	kg		European average value, based on industrial survey	Ecoinvent (2019)
Particulates, < 2.5 um	Emission to air/high population density	2.5E-7	kg		European average value, based on industrial survey	Ecoinvent (2019)
Particulates, > 10 um	Emission to air/high population density	3.2E-7	kg		European average value, based on industrial survey	Ecoinvent (2019)
Particulates, > 2.5 um, and < 10um	Emission to air/high population density	4.3E-7	kg		European average value, based on industrial survey	Ecoinvent (2019)
Suspended solids, unspecified	Emission to water/surface water	1.0E-6	kg		European average value, based on industrial survey	Ecoinvent (2019)
TOC, Total Organic Carbon	Emission to water/surface water	2.62E-4	kg		Estimated, based on rules in Frischknecht 2003	Ecoinvent (2019)
waste plastic, mixture		5.60774878444612E-5	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - IN	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		2.26546646106207E-5	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - PE	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		1.02679937592291E-5	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - CY	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		5.32508173304272E-5	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - ZA	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		1.35769068630604E-4	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - CO	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		0.00203197996782466	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - BR	EcoSpold01Location=CH	Ecoinvent (2019)
Water	Emission to air/unspecified	0.002513415	m3		Calculated value based on literature values and expert opinion. See comments in the parametres' comment field.	Ecoinvent (2019)
Water	Emission to water/unspecified	0.004049585	m3		Calculated value based on literature values and expert opinion. See comments in the parametres' comment field.	Ecoinvent (2019)

MELT SPINNING (BACKING)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Virgin polyester fibre		1.0	kg			
Inputs						
antimony		2.0E-4	kg	antimony production | antimony | Cutoff, U - RoW		Roos et al. (2019)
electricity, low voltage		1.5	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - JP		Roos et al. (2019)
heat, from steam, in chemical industry		2.2	MJ	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RoW		Roos et al. (2019)

lubricating oil		0.01	kg	market for lubricating oil | lubricating oil | Cutoff, U - RoW		Roos et al. (2019)
manganese		2.0E-4	kg	manganese production | manganese | Cutoff, U - RoW		Roos et al. (2019)
PET granulates (backing)		1.0	kg	PET granulate production (for backing) - JP		Mass balance
Outputs						
dimethyl terephthalate (dmt)	Emission to air/unspecified	1.0E-5	kg			Roos et al. (2019)

YARN SPINNING (BACKING)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Virgin polyester yarn		1.0	kg			
Inputs						
electricity, low voltage		4.41	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - JP		Roos et al. (2019)
lubricating oil		0.0016	kg	market for lubricating oil | lubricating oil | Cutoff, U - RoW		Roos et al. (2019)
Virgin polyester fibre		1.005025126	kg	Melt spinning (backing) - JP		Mass balance
Outputs						
ACRYLAMIDE	Emission to air/high population density	4.8E-9	kg			Roos et al. (2019)
Formaldehyde	Emission to air/high population density	4.8E-10	kg			Roos et al. (2019)
waste yarn and waste textile		0.005025126	kg	market for waste yarn and waste textile | waste yarn and waste textile | Cutoff, U - GLO		Roos et al. (2019)

KNITTING						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Jersey backing		1.0	kg			
Inputs						
electricity, low voltage		1.22	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - JP		Roos et al. (2019)
lubricating oil		0.08	kg	market for lubricating oil | lubricating oil | Cutoff, U - RoW		Roos et al. (2019)
Virgin polyester yarn		1.005025126	kg	Yarn spinning (backing) - JP		Mass balance
Outputs						
ACRYLAMIDE	Emission to air/high population density	2.4E-7	kg			Roos et al. (2019)
Formaldehyde	Emission to air/high population density	2.4E-8	kg			Roos et al. (2019)
waste yarn and waste textile		0.005025126	kg	market for waste yarn and waste textile | waste yarn and waste textile | Cutoff, U - GLO		Roos et al. (2019)

DYEING (BACKING)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Jersey backing dyed		1.0	kg			
Inputs						
chemical, inorganic		0.08	kg	market for chemicals, inorganic | chemical, inorganic | Cutoff, U - GLO		Roos et al. (2019)
chemical, organic		0.2136	kg	market for chemical, organic | chemical, organic | Cutoff, U - GLO		Roos et al. (2019)

electricity, low voltage		0.7	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - JP		Roos et al. (2019)
ethoxylated alcohol (AE7)		0.215	kg	ethoxylated alcohol (AE7) production, petrochemical | ethoxylated alcohol (AE7) | Cutoff, U - RoW		Roos et al. (2019)
formic acid		0.03	kg	market for formic acid | formic acid | Cutoff, U - RoW		Roos et al. (2019)
heat, from steam, in chemical industry		8.333	kWh	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RoW		Roos et al. (2019)
hydrogen peroxide, without water, in 50% solution state		0.03	kg	market for hydrogen peroxide, without water, in 50% solution state | hydrogen peroxide, without water, in 50% solution state | Cutoff, U - RoW		Roos et al. (2019)
Jersey backing		1.0	kg	Knitting - JP		Mass balance
silicone product		0.003	kg	market for silicone product | silicone product | Cutoff, U - RoW		Roos et al. (2019)
sodium hydroxide, without water, in 50% solution state		0.005	kg	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, U - GLO		Roos et al. (2019)
sodium percarbonate, powder		0.01	kg	market for sodium percarbonate, powder | sodium percarbonate, powder | Cutoff, U - RoW		Roos et al. (2019)
tap water		78.0	kg	market for tap water | tap water | Cutoff, U - RoW		Roos et al. (2019)
Outputs						
1,2-dihydro-6-hydroxy-1,4-dimethyl-2-oxo-5-[[3-[(phenylsulphonyl)oxy]phenyl]azo]nicotinonitrile	Emission to air/high population density	6.0E-7	kg			Roos et al. (2019)
1,2-dihydro-6-hydroxy-1,4-dimethyl-2-oxo-5-[[3-[(phenylsulphonyl)oxy]phenyl]azo]nicotinonitrile	Emission to water/fresh water	3.0E-6	kg			Roos et al. (2019)
2-(3-oxobenzo[b]thien-2(3H)-ylidene)benzo[b]thiophene-3(2H)-one	Emission to air/high population density	1.3E-5	kg			Roos et al. (2019)
2-(3-oxobenzo[b]thien-2(3H)-ylidene)benzo[b]thiophene-3(2H)-one	Emission to water/fresh water	6.5E-5	kg			Roos et al. (2019)
2-Ethyl-1-Hexanol	Emission to air/unspecified	3.0E-6	kg			Roos et al. (2019)
2-Ethyl-1-hexanol	Emission to water/fresh water	3.0E-4	kg			Roos et al. (2019)
2-methyl-4-isothiazolin-3-one	Emission to water/fresh water	3.0E-7	kg			Roos et al. (2019)
5-chloro-2-methyl-4-isothiazoline-3-one	Emission to water/fresh water	3.0E-7	kg			Roos et al. (2019)
Ammonium sulphate	Emission to water/fresh water	0.002	kg			Roos et al. (2019)
C9-11 Alcohol ethoxylate	Emission to water/fresh water	6.0E-4	kg			Roos et al. (2019)
Calcium carbonate	Emission to water/fresh water	0.002	kg			Roos et al. (2019)
COD, Chemical Oxygen Demand	Emission to water/fresh water	2.0E-4	kg			Roos et al. (2019)
Diethanolamine	Emission to water/fresh water	3.0E-5	kg			Roos et al. (2019)
Dimethyl siloxane, reaction product with silica	Emission to water/fresh water	1.5E-5	kg			Roos et al. (2019)
Ethoxylated alcohol (NPEO)	Emission to water/fresh water	1.5E-4	kg			Roos et al. (2019)
Ethylene oxide	Emission to air/high population density	1.5E-8	kg			Roos et al. (2019)
Ethylene oxide	Emission to water/fresh water	1.5E-6	kg			Roos et al. (2019)
Fatty methylester sulfonates	Emission to water/fresh water	9.0E-4	kg			Roos et al. (2019)
Formaldehyde	Emission to air/high population	1.5E-8	kg			Roos et al. (2019)

	density					
Formaldehyde	Emission to water/fresh water	1.5E-7	kg			Roos et al. (2019)
Formic acid	Emission to air/high population density	3.0E-5	kg			Roos et al. (2019)
Formic acid	Emission to water/fresh water	0.003	kg			Roos et al. (2019)
Hydrogen peroxide	Emission to air/high population density	3.0E-5	kg			Roos et al. (2019)
Hydrogen peroxide	Emission to water/fresh water	3.0E-4	kg			Roos et al. (2019)
Isotridecanol ethoxylated	Emission to water/fresh water	0.002	kg			Roos et al. (2019)
Nonylphenol	Emission to water/fresh water	1.5E-7	kg			Roos et al. (2019)
Octadecanoic acid, ester with 2,2-bis(hydroxymethyl)-1,3-propanediol	Emission to water/unspecified	2.0E-4	kg			Roos et al. (2019)
Oxirane, methyl-, polymer with oxirane, decyl ether	Emission to water/fresh water	0.00425	kg			Roos et al. (2019)
Phosphonic acid, disodium salt	Emission to air/high population density	1.2E-5	kg			Roos et al. (2019)
Phosphonic acid, disodium salt	Emission to water/fresh water	0.0012	kg			Roos et al. (2019)
sludge from pulp and paper production		0.5	kg	market for sludge from pulp and paper production | sludge from pulp and paper production | Cutoff, U - RoW		Roos et al. (2019)
Sodium carbonate (Na2CO3)	Emission to water/fresh water	5.1E-4	kg			Roos et al. (2019)
Sodium hydroxide	Emission to water/fresh water	5.06E-4	kg			Roos et al. (2019)
Sodium lauryl sulphate (alcoholsulfate)	Emission to water/fresh water	3.0E-7	kg			Roos et al. (2019)
Sodium mono(2-ethylhexyl)estersulfate	Emission to water/fresh water	8.5E-4	kg			Roos et al. (2019)
Thiosulfate	Emission to water/fresh water	4.5E-7	kg			Roos et al. (2019)

DRYING (BACKING)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Jersey backing dried		1.0	kg			
Inputs						
electricity, low voltage		0.8	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - JP		Roos et al. (2019)
heat, from steam, in chemical industry		2.2	kWh	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RoW		Roos et al. (2019)
Jersey backing dyed		1.0	kg	Dyeing backing - JP		Mass balance

Appendix B.3 LCI Production of membrane

REFINING (MEMBRANE)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Purified terephthalic acid (membrane)		1.0	kg			

Input						
acetic acid, without water, in 98% solution state		0.0554999421428199	kg	market for acetic acid, without water, in 98% solution state | acetic acid, without water, in 98% solution state | Cutoff, U - GLO	Weighted average of reported input	Ecoinvent (2019)
chemical factory, organics		4.0E-10	Item(s)	market for chemical factory, organics | chemical factory, organics | Cutoff, U - GLO	Calculated based on literature data published by the industry. For this activity, no information was readily available concerning infrastructure and land-use. Therefore, the infrastructure is estimated based on data from two chemical factories, the BASF site of Ludwigshafen and the chemical factory in Gendorf (which are both located in Germany), which produce a wide range of chemical substances. Based on this data, the following assumptions are made: the built area amounts to about 4.2 ha, the plant has an average output of 50'000 t/a and a lifespan of fifty years. The estimated infrastructure amount is therefore 4.00 E-10 units per kg of produced chemical. References: Althaus H.-J., Chudacoff M., Hischier R., Jungbluth N., Osses M. and Primas A. (2007) Life Cycle Inventories of Chemicals. ecoinvent report No. 8, v2.0. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH. Gendorf (2000) Umwelterklärung 2000, Werk Gendorf. Werk Gendorf, Burgkirchen.	Ecoinvent (2019)
chemical, inorganic		6.12426586651359E-4	kg	market for chemicals, inorganic | chemical, inorganic | Cutoff, U - GLO	Sum input parameter covering partly confidential information on additives, solvents, catalysts. Weighted average of reported input materials.	Ecoinvent (2019)
chemical, organic		0.00744986723522292	kg	market for chemical, organic | chemical, organic | Cutoff, U - GLO	Sum input parameter covering partly confidential information on additives, solvents, catalysts. Weighted average of reported input materials.	Ecoinvent (2019)
cobalt		2.19550075103395E-4	kg	market for cobalt | cobalt | Cutoff, U - GLO	Weighted average of reported input	Ecoinvent (2019)
compressed air, 600 kPa gauge		0.345986261722217	m3		Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.0221657027196663	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RLA	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.00346170434504085	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - AU	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.0646666756538316	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - US	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.154876083916439	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RAS	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.0106818798905516	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RAF	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.00510509698409366	kWh	market group for electricity, medium voltage | electricity,	Weighted average of reported input	Ecoinvent (2019)

				medium voltage | Cutoff, U - Canada without Quebec		
electricity, medium voltage		6.298841632151 7E-4	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - NZ	Weighted average of reported input	Ecoinv ent (2019)
heat, from steam, in chemical industry		1.855382219401 77	MJ	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RoW	Weighted average of reported input	Ecoinv ent (2019)
manganese		2.174656651476 22E-4	kg	market for manganese | manganese | Cutoff, U - GLO	Weighted average of reported input	Ecoinv ent (2019)
natural gas, high pressure		0.006154976510 58913	m3	market for natural gas, high pressure | natural gas, high pressure | Cutoff, U - US	Weighted average of reported input	Ecoinv ent (2019)
natural gas, high pressure		4.528329677901 06E-4	m3	market for natural gas, high pressure | natural gas, high pressure | Cutoff, U - DZ	Weighted average of reported input	Ecoinv ent (2019)
natural gas, high pressure		7.538388351521 95E-4	m3	market for natural gas, high pressure | natural gas, high pressure | Cutoff, U - JP	Weighted average of reported input	Ecoinv ent (2019)
natural gas, high pressure		0.014432811146 9741	m3	market for natural gas, high pressure | natural gas, high pressure | Cutoff, U - RoW	Weighted average of reported input	Ecoinv ent (2019)
nitrogen, liquid		0.034589560632 7028	kg	market for nitrogen, liquid | nitrogen, liquid | Cutoff, U - RoW	Weighted average of reported input	Ecoinv ent (2019)
sodium hydroxide, without water, in 50% solution state		0.014073038395 1395	kg	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, U - GLO	Weighted average of reported input	Ecoinv ent (2019)
Water, cooling, unspecified natural origin		0.001673038572 24816	m3		Weighted average of reported input	Ecoinv ent (2019)
Water, river		0.001433313981 71261	m3		Weighted average of reported input	Ecoinv ent (2019)
Water, unspecified natural origin		0.002794637007 62329	m3		Weighted average of reported input	Ecoinv ent (2019)
Water, well		7.899044287598 75E-5	m3		Weighted average of reported input	Ecoinv ent (2019)
xylene		0.658542674032 142	kg	xylene production | xylene | Cutoff, U - RoW	Weighted average of reported input	Ecoinv ent (2019)
Outputs						
Arsenic, ion	Emission to water/unspec ified	2.615694798478 83E-10	kg		Weighted average of reported emissions	Ecoinv ent (2019)

Benzene	Emission to air/unspecified	8.71440476251031E-6	kg		Weighted average of reported emissions	Ecoinvent (2019)
Cadmium, ion	Emission to water/unspecified	6.17539974979212E-11	kg		Weighted average of reported emissions	Ecoinvent (2019)
Carbon dioxide, fossil	Emission to air/unspecified	0.106455870204869	kg		Weighted average of reported emissions	Ecoinvent (2019)
Carbon monoxide, fossil	Emission to air/unspecified	9.7233004119408E-4	kg		Weighted average of reported emissions	Ecoinvent (2019)
Chromium, ion	Emission to water/unspecified	4.10394897480312E-8	kg		Weighted average of reported emissions	Ecoinvent (2019)
Cobalt	Emission to water/unspecified	1.74820350571484E-6	kg		Weighted average of reported emissions	Ecoinvent (2019)
Copper, ion	Emission to water/unspecified	4.41718084013793E-10	kg		Weighted average of reported emissions	Ecoinvent (2019)
Dinitrogen monoxide	Emission to air/unspecified	6.64665589052946E-7	kg		Weighted average of reported emissions	Ecoinvent (2019)
hazardous waste, for incineration		4.72996103061763E-5	kg	market for hazardous waste, for incineration | hazardous waste, for incineration | Cutoff, U - RoW	Weighted average of reported waste	Ecoinvent (2019)
Lead	Emission to water/unspecified	4.70038388598827E-10	kg		Weighted average of reported emissions	Ecoinvent (2019)
Mercury	Emission to water/unspecified	9.90817322912507E-10	kg		Weighted average of reported emissions	Ecoinvent (2019)
Methane, fossil	Emission to air/unspecified	2.03583389986713E-4	kg		Weighted average of reported emissions	Ecoinvent (2019)
Methanol	Emission to air/unspecified	8.88155473382894E-6	kg		Weighted average of reported emissions	Ecoinvent (2019)
Methyl acetate	Emission to air/unspecified	1.61463065129819E-5	kg		Weighted average of reported emissions	Ecoinvent (2019)
municipal solid waste		4.53913742457428E-8	kg		Weighted average of reported waste	Ecoinvent (2019)
municipal solid waste		3.17631067868827E-8	kg	market for municipal solid waste | municipal solid waste | Cutoff, U - CY	Weighted average of reported waste	Ecoinvent (2019)
municipal solid waste		8.91522259402042E-5	kg	market for municipal solid waste | municipal solid waste | Cutoff, U - RoW	Weighted average of reported waste	Ecoinvent (2019)
Nickel, ion	Emission to water/unspecified	5.67318954373915E-8	kg		Weighted average of reported emissions	Ecoinvent (2019)
Nitrogen oxides	Emission to air/unspecified	6.21985277649807E-5	kg		Weighted average of reported emissions	Ecoinvent (2019)
Nitrogen, organic bound	Emission to water/unspecified	3.5417765190208E-5	kg		Weighted average of reported emissions	Ecoinvent (2019)
NMVOC, non-methane volatile organic compounds, unspecified origin	Emission to air/unspecified	3.77924582985745E-4	kg		Weighted average of reported emissions	Ecoinvent (2019)

Phosphorus	Emission to water/unspecified	5.343483793427 79E-6	kg		Weighted average of reported emissions	Ecoinvent (2019)
sewage sludge		3.739776739328 47E-6	m3	market for sewage sludge | sewage sludge | Cutoff, U - RoW	Weighted average of reported waste	Ecoinvent (2019)
Sulfur dioxide	Emission to air/unspecified	3.120741974051 66E-6	kg		Weighted average of reported emissions	Ecoinvent (2019)
Suspended solids, unspecified	Emission to water/unspecified	3.925355748310 55E-5	kg		Weighted average of reported emissions	Ecoinvent (2019)
Toluene	Emission to air/unspecified	1.176872873386 85E-5	kg		Weighted average of reported emissions	Ecoinvent (2019)
waste mineral oil		3.737022916236 45E-5	kg	market for waste mineral oil | waste mineral oil | Cutoff, U - RoW	Weighted average of reported waste	Ecoinvent (2019)
wastewater, average		0.005478353238 34142	m3	market for wastewater, average | wastewater, average | Cutoff, U - RoW	Weighted average of reported waste	Ecoinvent (2019)
Water	Emission to air/unspecified	5.019115716744 47E-4	m3		Calculated to close water balance	Ecoinvent (2019)
Xylene	Emission to air/unspecified	3.634375251984 66E-5	kg		Weighted average of reported emissions	Ecoinvent (2019)
Zinc, ion	Emission to water/unspecified	1.298933598312 34E-7	kg		Weighted average of reported emissions	Ecoinvent (2019)

PET GRANULATE PRODUCTION (MEMBRANE)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
PET granulates (membrane)		1.0	kg			
Input						
antimony		3.3333333E-5	kg	market for antimony | antimony | Cutoff, U - GLO		Ecoinvent (2019)
chemical factory, organics		4.0E-10	Item(s)	market for chemical factory, organics | chemical factory, organics | Cutoff, U - GLO	Estimation	Ecoinvent (2019)
electricity, medium voltage		0.194	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - JP	EcoSpold01Location=UCTE	Ecoinvent (2019)
ethylene glycol		0.334	kg	market for ethylene glycol | ethylene glycol | Cutoff, U - GLO	EcoSpold01Location=RER	Ecoinvent (2019)
heat, district or industrial, natural gas		0.665	MJ	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U - RoW	Amount industrial survey - distribution according to cumulated data	Ecoinvent (2019)
heat, district or industrial, other than natural gas		0.965	MJ	market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Cutoff, U - RoW	EcoSpold01Location=RER	Ecoinvent (2019)
nitrogen, liquid		0.0298	kg	market for nitrogen, liquid | nitrogen, liquid | Cutoff, U - RoW	EcoSpold01Location=RER	Ecoinvent (2019)
Purified terephthalic acid (membrane)		0.875	kg	Refining (for membrane) - JP		Mass balance
steam, in chemical industry		0.94	kg	market for steam, in chemical industry | steam, in chemical industry | Cutoff, U - RoW	European average value, based on industrial survey	Ecoinvent (2019)

Water, cooling, unspecified natural origin		0.0064	m3		European average value, based on industrial survey	Ecoinvent (2019)
Water, unspecified natural origin		1.63E-4	m3		European average value, based on industrial survey	Ecoinvent (2019)
Outputs						
average incineration residue		4.0E-4	kg	market for average incineration residue | average incineration residue | Cutoff, U - RoW	EcoSpold01Location=CH	Ecoinvent (2019)
BOD5, Biological Oxygen Demand	Emission to water/surface water	1.6E-4	kg		European average value, based on industrial survey	Ecoinvent (2019)
COD, Chemical Oxygen Demand	Emission to water/surface water	0.00102	kg		European average value, based on industrial survey	Ecoinvent (2019)
DOC, Dissolved Organic Carbon	Emission to water/surface water	2.62E-4	kg		Estimated, based on rules in Frischknecht 2003	Ecoinvent (2019)
hazardous waste, for underground deposit		9.0E-5	kg	market for hazardous waste, for underground deposit | hazardous waste, for underground deposit | Cutoff, U - GLO	EcoSpold01Location=DE	Ecoinvent (2019)
Hydrocarbons, unspecified	Emission to water/surface water	4.99E-4	kg		European average value, based on industrial survey	Ecoinvent (2019)
municipal solid waste		8.79239085343996E-4	kg	market for municipal solid waste | municipal solid waste | Cutoff, U - RoW	EcoSpold01Location=CH	Ecoinvent (2019)
municipal solid waste		3.13254825266099E-7	kg	market for municipal solid waste | municipal solid waste | Cutoff, U - CY	EcoSpold01Location=CH	Ecoinvent (2019)
municipal solid waste		4.47659830738294E-7	kg		EcoSpold01Location=CH	Ecoinvent (2019)
NMVOC, non-methane volatile organic compounds, unspecified origin	Emission to air/high population density	9.0E-5	kg		European average value, based on industrial survey	Ecoinvent (2019)
Particulates, < 2.5 um	Emission to air/high population density	2.5E-7	kg		European average value, based on industrial survey	Ecoinvent (2019)
Particulates, > 10 um	Emission to air/high population density	3.2E-7	kg		European average value, based on industrial survey	Ecoinvent (2019)
Particulates, > 2.5 um, and < 10um	Emission to air/high population density	4.3E-7	kg		European average value, based on industrial survey	Ecoinvent (2019)
Suspended solids, unspecified	Emission to water/surface water	1.0E-6	kg		European average value, based on industrial survey	Ecoinvent (2019)
TOC, Total Organic Carbon	Emission to water/surface water	2.62E-4	kg		Estimated, based on rules in Frischknecht 2003	Ecoinvent (2019)
waste plastic, mixture		1.02679937592291E-5	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - CY	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		2.26546646106207E-5	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - PE	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		0.00203197996782466	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - BR	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		5.32508173304272E-5	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - ZA	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		5.60774878444612E-5	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - IN	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		1.35769068630604E-4	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U -	EcoSpold01Location=CH	Ecoinvent

				CO		(2019)
Water	Emission to air/unspecified	0.002513415	m3		Calculated value based on literature values and expert opinion. See comments in the parametres' comment field.	Ecoinvent (2019)
Water	Emission to water/unspecified	0.004049585	m3		Calculated value based on literature values and expert opinion. See comments in the parametres' comment field.	Ecoinvent (2019)

MEMBRANE PRODUCTION						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Membrane		1.0	kg			
Input						
core board		0.00732	kg	market for core board | core board | Cutoff, U - GLO	EcoSpold01Location=RER	Ecoinvent (2019)
electricity, medium voltage		0.00873409086089859	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - AU	EcoSpold01Location=UCTE	Ecoinvent (2019)
electricity, medium voltage		0.00158923610020123	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - NZ	EcoSpold01Location=UCTE	Ecoinvent (2019)
electricity, medium voltage		0.0559254177285751	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RLA	EcoSpold01Location=UCTE	Ecoinvent (2019)
electricity, medium voltage		0.163157960512124	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - US	EcoSpold01Location=UCTE	Ecoinvent (2019)
electricity, medium voltage		0.0269510334303787	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RAF	EcoSpold01Location=UCTE	Ecoinvent (2019)
electricity, medium voltage		0.390761790805207	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RAS	EcoSpold01Location=UCTE	Ecoinvent (2019)
electricity, medium voltage		0.0128804705626145	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - Canada without Quebec	EcoSpold01Location=UCTE	Ecoinvent (2019)
EUR-flat pallet		0.00144	Item(s)	market for EUR-flat pallet | EUR-flat pallet | Cutoff, U - GLO	Typical values, based on a European and a Swiss study	Ecoinvent (2019)
heat, district or industrial, natural gas		0.601	MJ	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U - RoW	Typical values, based on a European and a Swiss study	Ecoinvent (2019)
heat, district or industrial, other than natural gas		0.2091	MJ	market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Cutoff, U - RoW	Typical values, based on a European and a Swiss study	Ecoinvent (2019)
lubricating oil		1.05E-4	kg	market for lubricating oil | lubricating oil | Cutoff, U - RoW	EcoSpold01Location=RER	Ecoinvent (2019)
packaging box factory		1.4E-9	Item(s)	market for packaging box factory | packaging box factory | Cutoff, U - GLO	Estimation	Ecoinvent (2019)
particle board, for outdoor use		2.15E-5	m3	market for particle board, for outdoor use | particle board, for outdoor use | Cutoff, U - GLO	Typical values, based on a European and a Swiss study	Ecoinvent (2019)
PET granulates (membrane)		0.99687	kg	PET granulate production (for membrane) - JP		Mass balance
polyethylene, low density, granulate		0.00215	kg	market for polyethylene, low density, granulate | polyethylene, low density, granulate | Cutoff, U - GLO	Typical values, based on a European and a Swiss study	Ecoinvent (2019)
polypropylene, granulate		6.83E-4	kg	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO	EcoSpold01Location=RER	Ecoinvent (2019)
polyvinylchloride, suspension polymerised		4.88E-5	kg	market for polyvinylchloride, suspension polymerised | polyvinylchloride, suspension	Typical values, based on a European and a Swiss study	Ecoinvent (2019)

				polymerised | Cutoff, U - GLO		
solid bleached board		9.76E-4	kg	market for solid bleached board | solid bleached board | Cutoff, U - GLO	EcoSpold01Location=RER	Ecoinvent (2019)
steam, in chemical industry		0.058	kg		EcoSpold01Location=RER	Ecoinvent (2019)
Water, cooling, unspecified natural origin		0.0437	m3		Typical values, based on a European and a Swiss study	Ecoinvent (2019)
Outputs						Ecoinvent (2019)
waste plastic, mixture		0.0211994446859629	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - BR	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		2.36353860223359E-4	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - PE	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		5.55560475178915E-4	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - ZA	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		1.0712495653568E-4	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - CY	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		5.85050847208448E-4	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - IN	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		0.00141646517489072	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - CO	EcoSpold01Location=CH	Ecoinvent (2019)
Water	Emission to air/unspecified	0.01693375	m3		Calculated value based on literature values and expert opinion. See comments in the parametres' comment field.	Ecoinvent (2019)
Water	Emission to water/unspecified	0.02676625	m3		Calculated value based on literature values and expert opinion. See comments in the parametres' comment field.	Ecoinvent (2019)

Appendix B.4 LCI Production of other components

ZIPEER PRODUCTION						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Polyester zipper(1)		1.0	Item(s)			
Inputs						
polyethylene terephthalate, granulate, amorphous		0.1141	kg	market for polyethylene terephthalate, granulate, amorphous | polyethylene terephthalate, granulate, amorphous | Cutoff, U - GLO		Ecoinvent (2019)

Appendix B.5 LCI Garment production

LAMINATION						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Laminate		1.0	kg			
Inputs						
Face fabric		0.7	kg	Drying Face fabric B - JP		Mass balance
Jersey backing dried		0.15	kg	Drying backing - JP		Mass balance
Membrane		0.15	kg	Membrane production (extrusion, plastic film | extrusion, plastic film | Cutoff, U) - JP		Mass balance

CUTTING						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Cut laminate		1.0	kg			
Inputs						
electricity, low voltage		0.001	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - ET		Roos et al. (2019)
Laminate		1.176470588	kg	Lamination - EE		Mass balance
transport, freight, lorry 16-32 metric ton, EURO6		0.176470588	t*km	market for transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RER	Transport of scrap from Estonia to Japan for recycling Weight to be transported: 0.176470588 (corresponding to scraps from cutting) Distance: 6.2 km	Roos et al. (2019)
transport, freight, sea, container ship		0.176470588	t*km	market for transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, U - GLO	Transport of scrap from Estonia to Japan for recycling Weight to be transported: 0.176470588 (corresponding to scraps from cutting) Distance: 21655.74 km	Roos et al. (2019)

SEWING AND FINISHING						
Product						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Jacket		1.0	Item(s)			
Inputs						
Adhesive		0.014507	kg	Adhesive - EE	Adhesive for taping	Willskytt et al. (2019)
Cut laminate		0.785	kg	Cutting - EE		Mass balance
electricity, low voltage		0.176855	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - ET	Electricity for sewing	Roos et al. (2019)
Polyester zipper(1)		1.0	Item(s)	Zipper production		Mass balance

ADHESIVE						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Adhesive		1.56	kg			
Inputs						
benzene		0.165	kg	benzene production | benzene | Cutoff, U - RER		Willskytt et al. (2019)
chemical, organic		0.155	kg	market for chemical, organic | chemical, organic | Cutoff, U - GLO		Willskytt et al. (2019)
corrugated board box		0.003	kg	market for corrugated board box | corrugated board box | Cutoff, U - RER		Willskytt et al. (2019)
electricity, medium voltage		3.22	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - EE		Willskytt et al. (2019)
light fuel oil		0.386	kg	market for light fuel oil | light fuel oil | Cutoff, U - Europe without Switzerland		Willskytt et al. (2019)
methylene diphenyl diisocyanate		0.002	kg	market for methylene diphenyl diisocyanate | methylene diphenyl diisocyanate | Cutoff, U - RER		Willskytt et al. (2019)
naphtha		0.457	kg	market for naphtha | naphtha | Cutoff, U - RER		Willskytt et al. (2019)
paraffin		0.221	kg	paraffin production | paraffin | Cutoff, U - RER		Willskytt et al. (2019)
Outputs						
biowaste		0.0029	kg	market for biowaste | biowaste | Cutoff, U - RoW		Willskytt et al. (2019)
Carbon, organic bound	Emission to air/high population density	3.0E-4	kg			Willskytt et al. (2019)

COD, Chemical Oxygen Demand	Emission to water/unspecified	0.032	kg			Willskytt et al. (2019)
inert waste, for final disposal		0.0014	kg	market for inert waste, for final disposal | inert waste, for final disposal | Cutoff, U - RoW		Willskytt et al. (2019)
municipal solid waste		0.0142	kg	market for municipal solid waste | municipal solid waste | Cutoff, U - EE		Willskytt et al. (2019)
Nitrogen	Emission to air/high population density	8.0E-4	kg			Willskytt et al. (2019)
Sulfur dioxide, EE	Emission to air/high population density	6.0E-4	kg			Willskytt et al. (2019)

Appendix B.6 LCI Internal and external distribution

EXTERNAL TRANSPORTATION						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Transportation of one jacket		1.0	Item(s)			
Inputs						
transport, freight, lorry 16-32 metric ton, EURO6		0.031622	t*km	market for transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RER	Weight to be transported: 0.815 kg (see mass balance) Distance: 38.8 km	Searates and Google Maps
transport, freight, lorry 16-32 metric ton, EURO6		0.00499813	t*km	market for transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RER	Weight to be transported: 0.80615 kg (see mass balance) Distance: 6.2 km	Searates and Google Maps
transport, freight, sea, container ship		17.4577748	t*km	market for transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, U - GLO	Weight to be transported: 0.80615 kg (see mass balance) Distance: 21655.74 km	Searates and Google Maps
transport, freight, sea, ferry		0.4053973	t*km	market for transport, freight, sea, ferry | transport, freight, sea, ferry | Cutoff, U - GLO	Weight to be transported: 0.815 kg (see mass balance) Distance: 497.42 km	Searates and Google Maps

INTERNAL TRANSPORTATION						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Internal transportation of one jacket		1.0	Item(s)			
Inputs						
transport, freight, lorry 16-32 metric ton, EURO6		0.334313	t*km		Weight to be transported: 0.815 kg (see mass balance) Distance: 410 km	Searates and Google Maps

Appendix B.7 LCI Use phase

USE PHASE (SALES)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Profit		319391.3	SEK 2000			

Inputs						
EoL transportation of one jacket		q_s*CR	Item(s)	EoL transportation of one jacket	CR (collection rate) = 0,5	
Internal transportation of one jacket		q_s	Item(s)	Internal distribution		
Sales transaction		t_s	Item(s)	Sales transaction - SE		
Jacket		q_s	Item(s)	Sewing and finishing - EE		
transport, passenger car, EURO 5		Customer_transport_car *t_s *CR	km	market for transport, passenger car, EURO 5 | transport, passenger car, EURO 5 | Cutoff, U - RER	Customer transportation for purchasing the jackets and then returning the EoL jackets to the stores, corresponding to 50% collection rate. Car: Customer_transport_car (2km back and forth)* 200 jackets * 0.5 (0.5 because the customer does one roundtrip for EoL collection, but only for half the jackets)	
transport, passenger, bicycle		Customer_transport_bike *t_s *CR	p*km	market for transport, passenger, bicycle | transport, passenger, bicycle | Cutoff, U - GLO	Customer transportation for purchasing the jackets and then returning the EoL jackets to the stores, corresponding to 50% collection rate. Bike: Customer_transport_bike (2km back and forth)* 200 jackets * 0.5 (0.5 because the customer does one roundtrip for EoL collection, but only for half the jackets)	
transport, tram		Customer_transports_tram *t_s *CR	p*km	transport, tram, Sweden | transport, tram | Cutoff, U - SE	Customer transportation for purchasing the jackets and then returning the EoL jackets to the stores, corresponding to 50% collection rate. Tram: Customer_transport_tram (4km back and forth)* 200 jackets * 0.5 (0.5 because the customer does one roundtrip for EoL collection, but only for half the jackets)	
Transportation of one jacket		q_s	Item(s)	External distribution	EoL transport	
Outputs						
waste yarn and waste textile		q_s*0.815*CR	kg	market for waste yarn and waste textile | waste yarn and waste textile | Cutoff, U - GLO	The weight of 50% of the 200 jackets are treated as textile waste	

USE PHASE (RENTAL)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Profit		319391.3	SEK 2000			
Inputs						
Clean jacket		q_r *Laundries_T	Item(s)	Residential laundry and drying (half-loaded) - SE	Laundry of 2nd hand jackets (during time T)	
EoL transportation of one jacket		q_r *CR	Item(s)	EoL transportation of one jacket		
Internal transportation of one jacket		q_r	Item(s)	Internal distribution		
Rental transactions		t_r	Item(s)	Rental transaction - SE		
Repaired jacket		repairs_T *q_r	Item(s)	Repair - SE	Repair of 2nd hand jackets	

Jacket		q_r	Item(s)	Sewing and finishing - EE	Production of q jackets	
transport, passenger car, EURO 5		Customer_transport_car *q_r *1.5	km	market for transport, passenger car, EURO 5 | transport, passenger car, EURO 5 | Cutoff, U - RER	Customer transportation for purchasing the 2nd hand jacket and then returning the EoL jackets to the stores, corresponding to 50% collection rate. Car: Customer_transport_car (2km back and forth)* q_r * 1.5 (1.5 because the customer does one roundtrip for buying the 2nd hand jacket, and then one more round trip for EoL collection, but only for half the jackets, hence 1+0.5)	
transport, passenger, bicycle		Customer_transport_bike *q_r *1.5	p*km	market for transport, passenger, bicycle | transport, passenger, bicycle | Cutoff, U - GLO	Customer transportation for purchasing the 2nd hand jacket and then returning the EoL jackets to the stores, corresponding to 50% collection rate. Bike: Customer_transport_bike (2km back and forth)* q_r * 1.5 (1.5 because the customer does one roundtrip for buying the 2nd hand jacket, and then one more round trip for EoL collection, but only for half the jackets, hence 1+0.5)	
transport, tram		Customer_transports_tram *q_r *1.5	p*km	transport, tram, Sweden | transport, tram | Cutoff, U - SE	Customer transportation for purchasing the 2nd hand jacket and then returning the EoL jackets to the stores, corresponding to 50% collection rate. Tram: Customer_transport_tram (4km back and forth)* q_r * 1.5 (1.5 because the customer does one roundtrip for buying the 2nd hand jacket, and then one more round trip for EoL collection, but only for half the jackets, hence 1+0.5)	
Transportation of one jacket		q_r	Item(s)	External distribution		
Outputs						
waste yarn and waste textile		q_r *0.815*CR	kg	market for waste yarn and waste textile | waste yarn and waste textile | Cutoff, U - GLO	The weight of 50% of the 200 jackets are treated as textile waste	

SALES TRANSACTION						
Product						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Sales transaction		1.0	Item(s)			
Inputs						
Clean jacket		laundries_T	Item(s)	Residential laundry and drying (half-loaded) - SE		
Repaired jacket		repairs_T	Item(s)	Repair - SE		
transport, passenger car, EURO 5		customer_transport_car	km	market for transport, passenger car, EURO 5 | transport, passenger car, EURO 5 | Cutoff, U - RER		
transport, passenger, bicycle		customer_transport_bike	p*km	market for transport, passenger, bicycle | transport, passenger, bicycle | Cutoff, U - GLO		
transport, tram		customer_transports_tram	p*km	transport, tram, Sweden | transport, tram | Cutoff, U - SE		

RENTAL TRANSACTION						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Rental transactions		1.0	Item(s)			
Inputs						

Clean rental jacket		1.0	Item(s)	Residential laundry and drying (fully loaded) - SE	Jackets are cleaned after every rental transaction	
Repaired jacket		0.04	Item(s)	Repair - SE	Jackets are repaired after 4% of rental transactions	
transport, passenger car, EURO 5		customer_transport_car *2	km	market for transport, passenger car, EURO 5 | transport, passenger car, EURO 5 | Cutoff, U - RER	Double customer transports because the customer has to both pick up and return the jacket	
transport, passenger, bicycle		customer_transport_bike *2	p*km	market for transport, passenger, bicycle | transport, passenger, bicycle | Cutoff, U - GLO	Double customer transports because the customer has to both pick up and return the jacket	
transport, tram		customer_transports_tram *2	p*km	transport, tram, Sweden | transport, tram | Cutoff, U - SE	Double customer transports because the customer has to both pick up and return the jacket	

Appendix B.8 LCI Laundry and repair

REPAIR						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Repaired jacket		1.0	Item(s)			
Inputs						
Polyester zipper(1)		0.75	Item(s)	Zipper production		Repair lady

RESIDENTIAL LAUNDRY (HALF LOADED)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Clean jacket		1.0	Item(s)			
Inputs						
Detergent		0.010595	kg	Detergent production	Detergent use, from weight of one jacket * detergent requirement per kg washed laundry (from Roos et al., 2015)	Roos et al. (2015)
electricity, low voltage		0.183375	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - SE	Washing	Roos et al. (2015)
electricity, low voltage		0.54605	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - SE	Drying	Roos et al. (2015)
tap water		5.053	kg	market for tap water | tap water | Cutoff, U - Europe without Switzerland	6.2 kg tap water per kg washed garments	Roos et al. (2015)
Outputs						
wastewater, average		0.005053	m3	market for wastewater, average | wastewater, average | Cutoff, U - Europe without Switzerland		Roos et al. (2015)

RESIDENTIAL LAUNDRY (FULLY LOADED)						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Clean rental jacket		1.0	Item(s)			
Inputs						
Detergent		0.010595	kg	Detergent production	Detergent use, from weight of one jacket * detergent requirement per kg washed laundry	Roos et al. (2015)

					(from Roos et al., 2015)	
electricity, low voltage		0.13611	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - SE	Energy use for washing, from weight of one jacket * energy requirement per kg washed laundry (from Roos et al., 2015)	Roos et al. (2015) and Faberi (2007)
electricity, low voltage		0.54605	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - SE	Energy use for drying, from weight of one jacket * energy requirement per kg dried laundry (from Roos et al., 2015)	Roos et al. (2015)
tap water		5.053	kg	market for tap water | tap water | Cutoff, U - Europe without Switzerland	6.2 kg tap water per kg washed garments	Roos et al. (2015)
Outputs						
wastewater, average		0.005053	m3	market for wastewater, average | wastewater, average | Cutoff, U - Europe without Switzerland		Roos et al. (2015)

DETERGENT PRODUCTION						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
Detergent		1.0	kg			
Inputs						
citric acid		52.0	g	market for citric acid | citric acid | Cutoff, U - GLO		Roos et al. (2015)
corrugated board box		101.82	g	market for corrugated board box | corrugated board box | Cutoff, U - RER		Roos et al. (2015)
electricity, high voltage		23.53	MJ	market for electricity, high voltage | electricity, high voltage | Cutoff, U - SE		Roos et al. (2015)
ethoxylated alcohol (AE11)		20.0	g	market for ethoxylated alcohol (AE11) | ethoxylated alcohol (AE11) | Cutoff, U - GLO		Roos et al. (2015)
ethoxylated alcohol (AE3)		78.0	g	market for ethoxylated alcohol (AE3) | ethoxylated alcohol (AE3) | Cutoff, U - RER		Roos et al. (2015)
ethoxylated alcohol (AE7)		40.0	g	market for ethoxylated alcohol (AE7) | ethoxylated alcohol (AE7) | Cutoff, U - RER		Roos et al. (2015)
fluorescent whitening agent, DAS1, triazinylaminostilben type		2.0	g	market for fluorescent whitening agent, DAS1, triazinylaminostilben type | fluorescent whitening agent, DAS1, triazinylaminostilben type | Cutoff, U - GLO		Roos et al. (2015)
kraft paper, unbleached		20.42	g	market for kraft paper, unbleached | kraft paper, unbleached | Cutoff, U - GLO		Roos et al. (2015)
polyethylene, high density, granulate		7.62	g	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO		Roos et al. (2015)
sodium perborate, monohydrate, powder		87.0	g	market for sodium perborate, monohydrate, powder | sodium perborate, monohydrate, powder | Cutoff, U - GLO		Roos et al. (2015)
sodium perborate, tetrahydrate, powder		115.0	g	market for sodium perborate, tetrahydrate, powder | sodium perborate, tetrahydrate, powder | Cutoff, U - RER		Roos et al. (2015)
sodium percarbonate, powder		170.0	g	market for sodium percarbonate, powder | sodium percarbonate, powder | Cutoff, U - RER		Roos et al. (2015)
sodium silicate, spray powder, 80%		30.0	g	market for sodium silicate, spray powder, 80% | sodium silicate, spray powder, 80% | Cutoff, U - RER		Roos et al. (2015)
sodium sulfate, anhydrite		4.0	g	market for sodium sulfate, anhydrite | sodium sulfate, anhydrite | Cutoff, U - RER		Roos et al. (2015)
water, deionised		142.0	g	market for water, deionised | water, deionised | Cutoff, U - Europe without Switzerland		Roos et al. (2015)
zeolite, powder		201.0	g	market for zeolite, powder | zeolite, powder | Cutoff, U - GLO		Roos et al. (2015)

Outputs						
BOD5, Biological Oxygen Demand	Emission to water/fossil-	4.6E-5	kg			Roos et al. (2015)
Carbon dioxide	Emission to air/unspecified	0.12515	kg			Roos et al. (2015)
Carbon monoxide	Emission to air/unspecified	0.01026	kg			Roos et al. (2015)
Carbon monoxide	Emission to air/unspecified	5.6E-5	kg			Roos et al. (2015)
COD, Chemical Oxygen Demand	Emission to water/fossil-	9.5E-6	kg			Roos et al. (2015)
electricity, high voltage		0.54	MJ	market for electricity, high voltage | electricity, high voltage | Cutoff, U - SE		Roos et al. (2015)
heat, for reuse in municipal waste incineration only		0.41	MJ	market for heat, for reuse in municipal waste incineration only | heat, for reuse in municipal waste incineration only | Cutoff, U - SE		Roos et al. (2015)
Nitrogen oxides	Emission to air/unspecified	0.00301	kg			Roos et al. (2015)
Particulates, > 2.5 um, and < 10um	Emission to air/unspecified	0.00166	kg			Roos et al. (2015)
Sulfur oxides	Emission to air/high population density	6.6E-4	kg			Roos et al. (2015)
waste packaging paper		122.5	g	market for waste packaging paper | waste packaging paper | Cutoff, U - SE		Roos et al. (2015)

Appendix B.9 LCI End-of-life

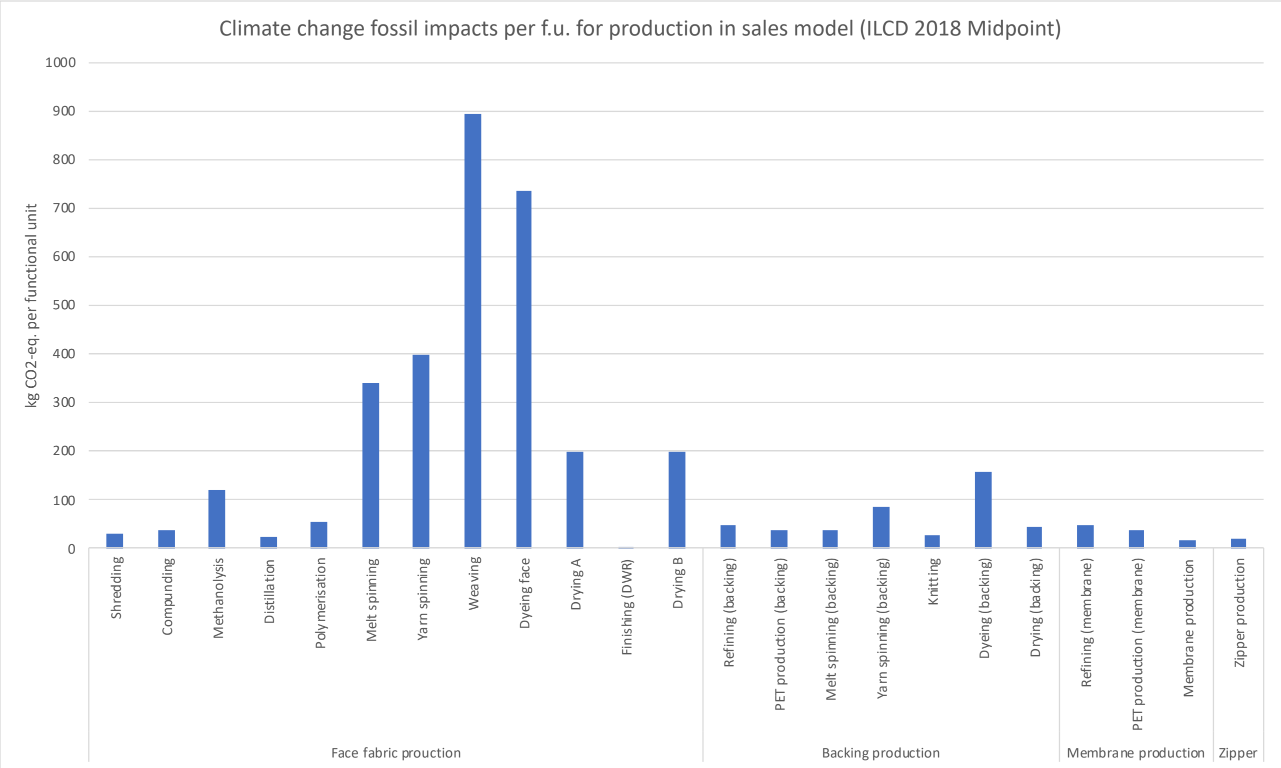
EOL TRANSPORTATION OF ONE JACKET						
Flow	Emission category	Amount	Unit	Provider	Description	Source
Product						
EoL transportation of one jacket		1.0	Item(s)			
Inputs						
transport, freight, lorry 16-32 metric ton, EURO6		0.031622	t*km	market for transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RER	Weight to be transported: 0.815 kg (see mass balance) Distance: 38.8 km	Searates and Google Maps
transport, freight, sea, container ship		17.64521455	t*km	market for transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, U - GLO	Weight to be transported: 0.815 kg (see mass balance) Distance: 21655.74 km	Searates and Google Maps

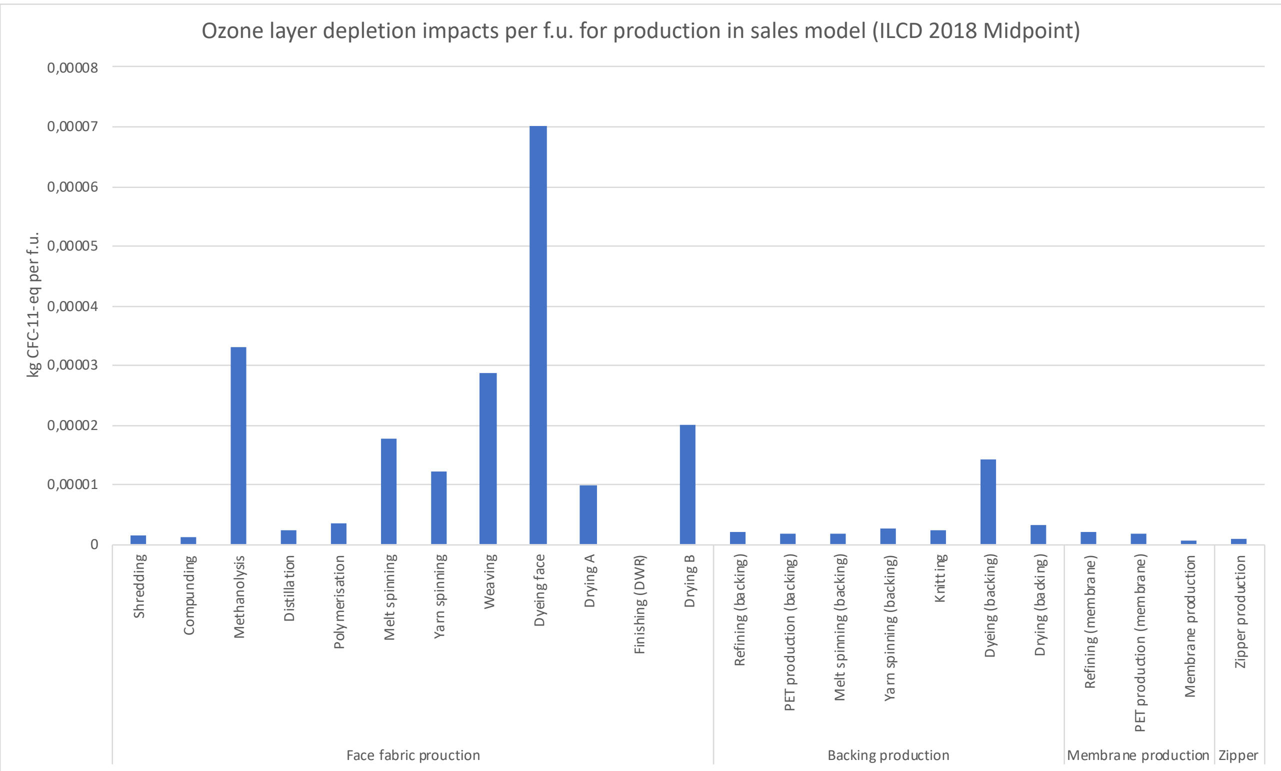
Appendix C Results for remaining impact categories

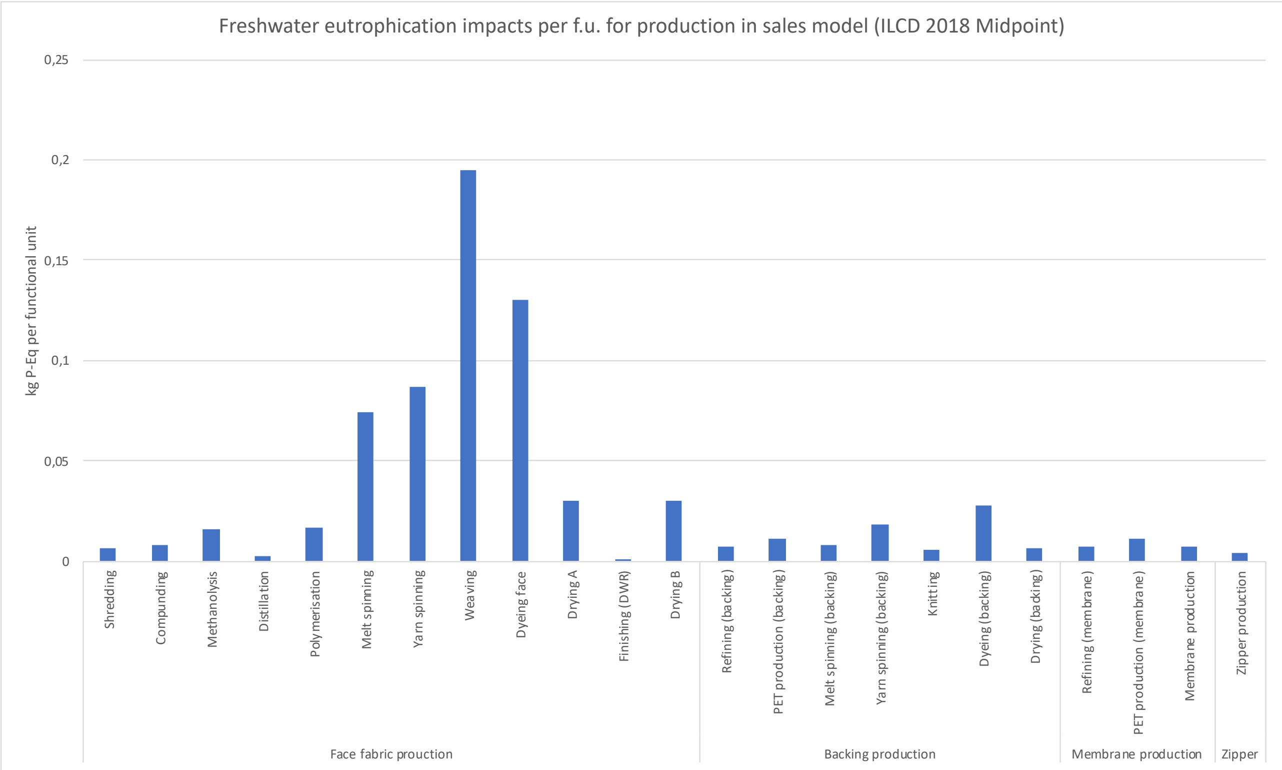
The impact categories of human toxicity (cancer and non-cancer), freshwater ecotoxicity, resource use of dissipated water, land use, fossils and minerals and metals, as well as ionising radiation, were excluded from the presentation of the results for various reasons, although all types of impacts are included in the weighted results (see section 5). The results are instead summarised here, but it should be noted that the author's judge these results to be less relevant than the ones presented in section 5. Human toxicity (cancer effects) are increased in the rental business model by ca 47% compared to the sales model, while non-cancer effects are instead reduced by 13%. Impacts on freshwater ecotoxicity are increased by ca 90% in the rental compared to the sales model. Resource use of dissipated water is increased by ca 10% in the rental model, while land resource use is increased by ca 120%, mineral and metal resource use is increased by ca 200% and fossil resource use is decreased by ca 35%. Lastly, impacts from ionising radiation are increased by 290% in the rental model.

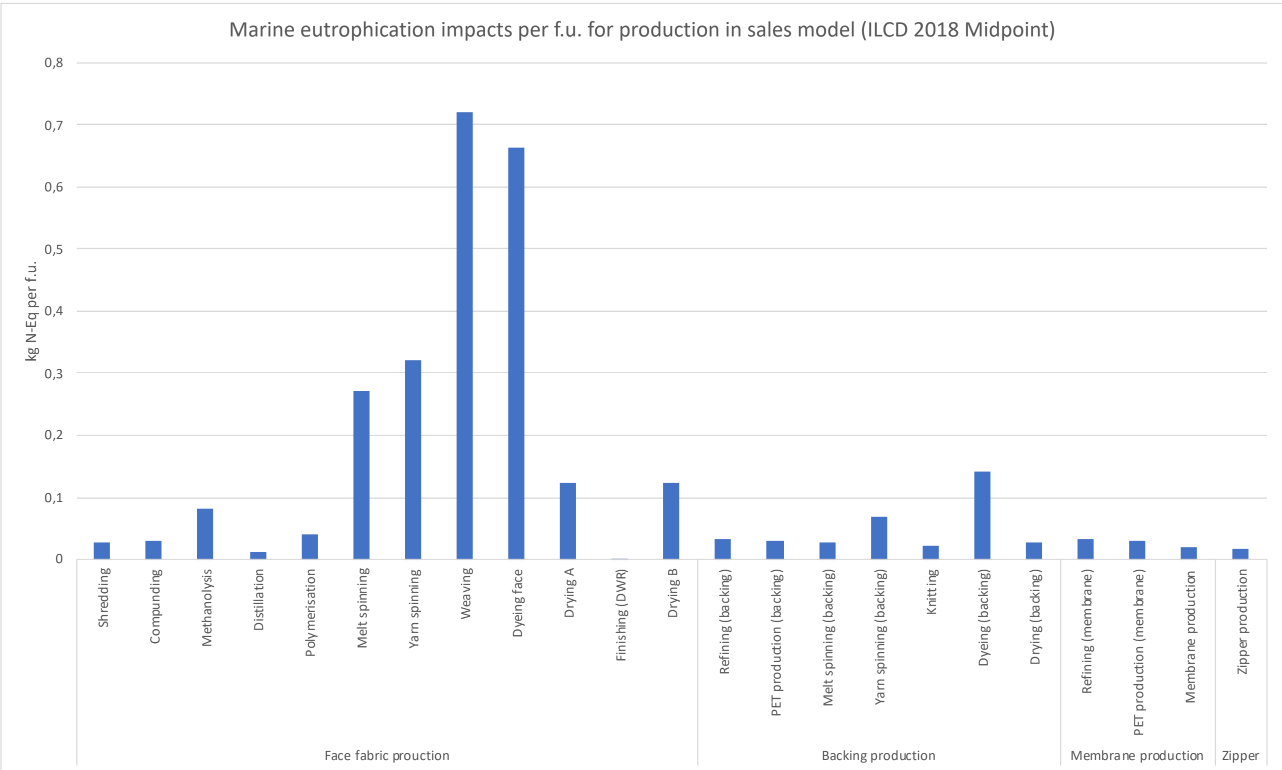
Appendix D Detailed results for textile production processes

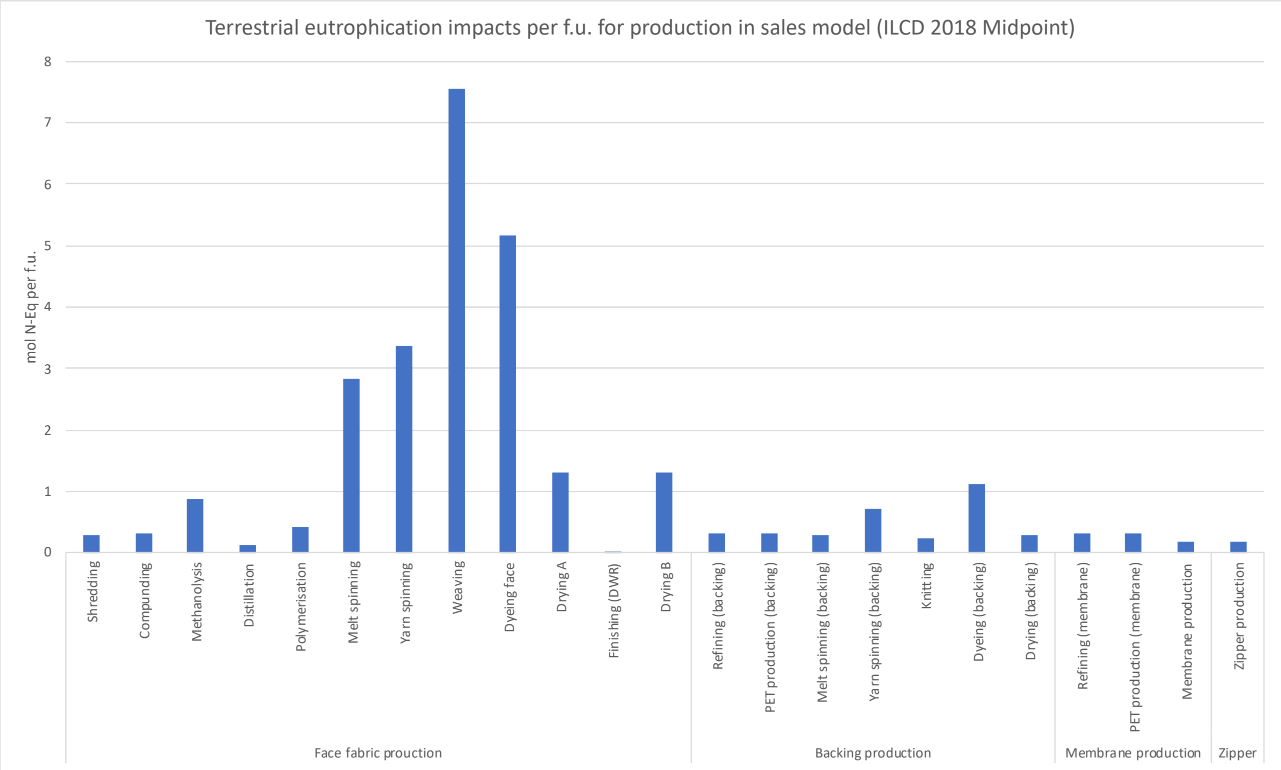
To provide further details on the results, here the impacts from textile production on each of the ILCD impact categories are presented (only for the sales model, since the rental model follows the same pattern, but at a lower level):



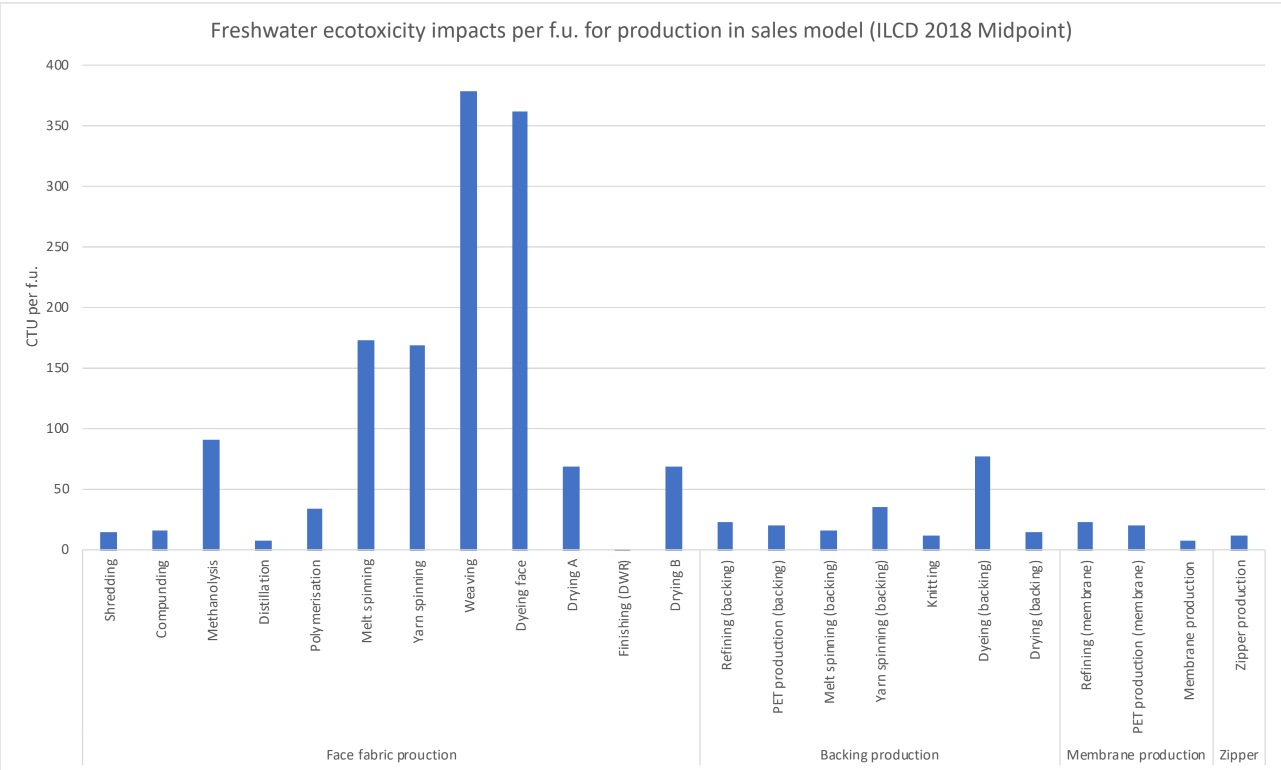



Freshwater eutrophication impacts per f.u. for production in sales model (ILCD 2018 Midpoint)
kg P-Eq per functional unit
0,25
0,2
0,15
0,1
0,05
0
Shredding
Compunding
Methanolysis
Distillation
Polymerisation
Melt spinning
Yarn spinning
Weaving
Dyeing face
Drying A
Finishing (DWR)
Drying B
Refining (backing)
PET production (backing)
Melt spinning (backing)
Yarn spinning (backing)
Knitting
Dyeing (backing)
Drying (backing)
Refining (membrane)
PET production (membrane)
Membrane production
Zipper production
Face fabric prouction
Backing production
Membrane production
Zipper

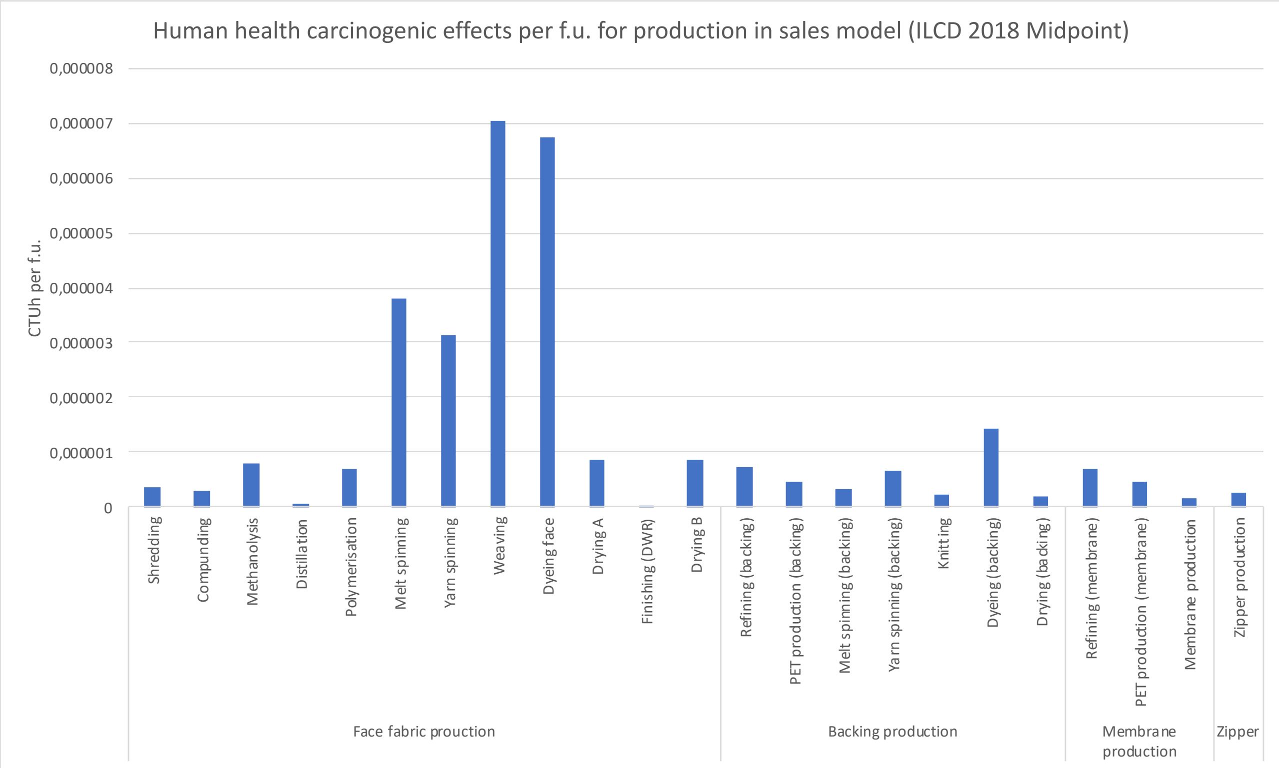

Marine eutrophication impacts per f.u. for production in sales model (ILCD 2018 Midpoint)
kg N-Eq per f.u.
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
Shredding
Compunding
Methanolysis
Distillation
Polymerisation
Melt spinning
Yarn spinning
Weaving
Dyeing face
Drying A
Finishing (DWR)
Drying B
Refining (backing)
PET production (backing)
Melt spinning (backing)
Yarn spinning (backing)
Knitting
Dyeing (backing)
Drying (backing)
Refining (membrane)
PET production (membrane)
Membrane production
Zipper production
Face fabric prouction
Backing production
Membrane production
Zipper

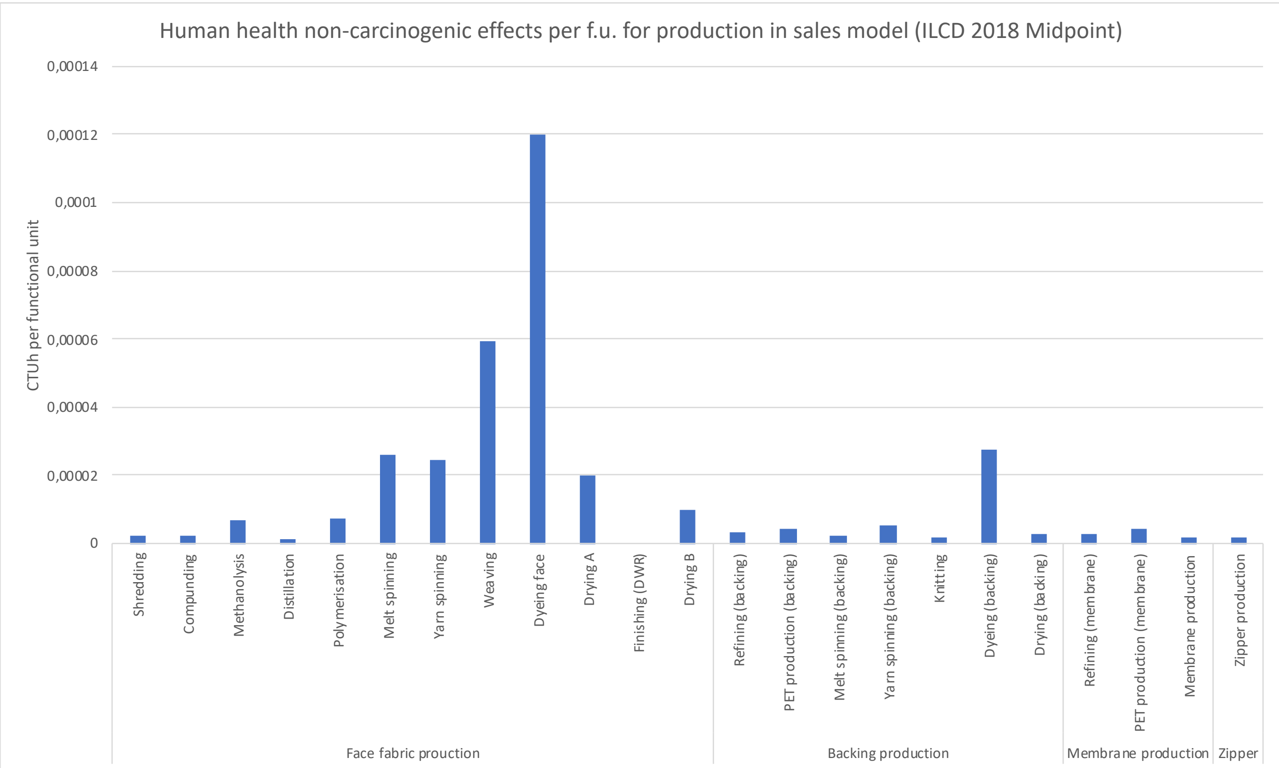


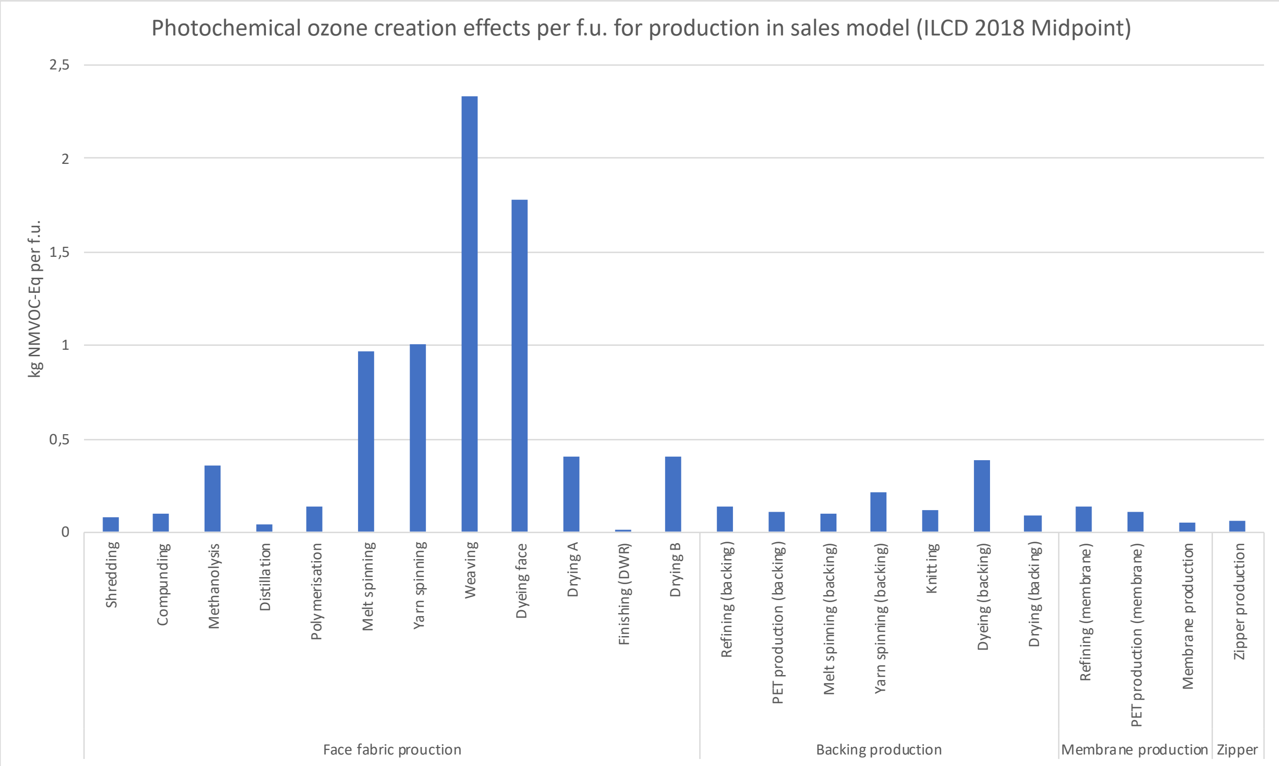
Terrestrial eutrophication impacts per f.u. for production in sales model (ILCD 2018 Midpoint)
mol N-Eq per f.u.
8
7
6
5
4
3
2
1
0
Shredding
Compunding
Methanolysis
Distillation
Polymerisation
Melt spinning
Yarn spinning
Weaving
Dyeing face
Drying A
Finishing (DWR)
Drying B
Refining (backing)
PET production (backing)
Melt spinning (backing)
Yarn spinning (backing)
Knitting
Dyeing (backing)
Drying (backing)
Refining (membrane)
PET production (membrane)
Membrane production
Zipper production
Face fabric prouction
Backing production
Membrane production
Zipper

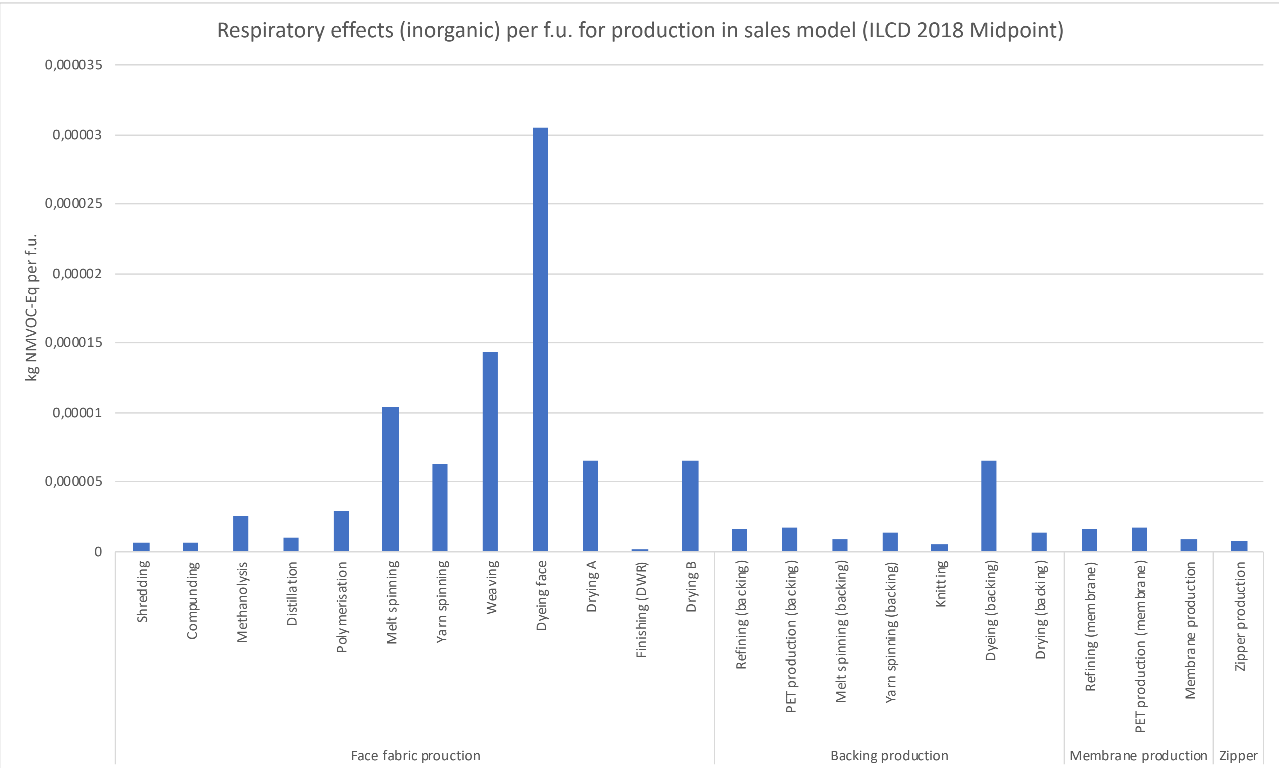


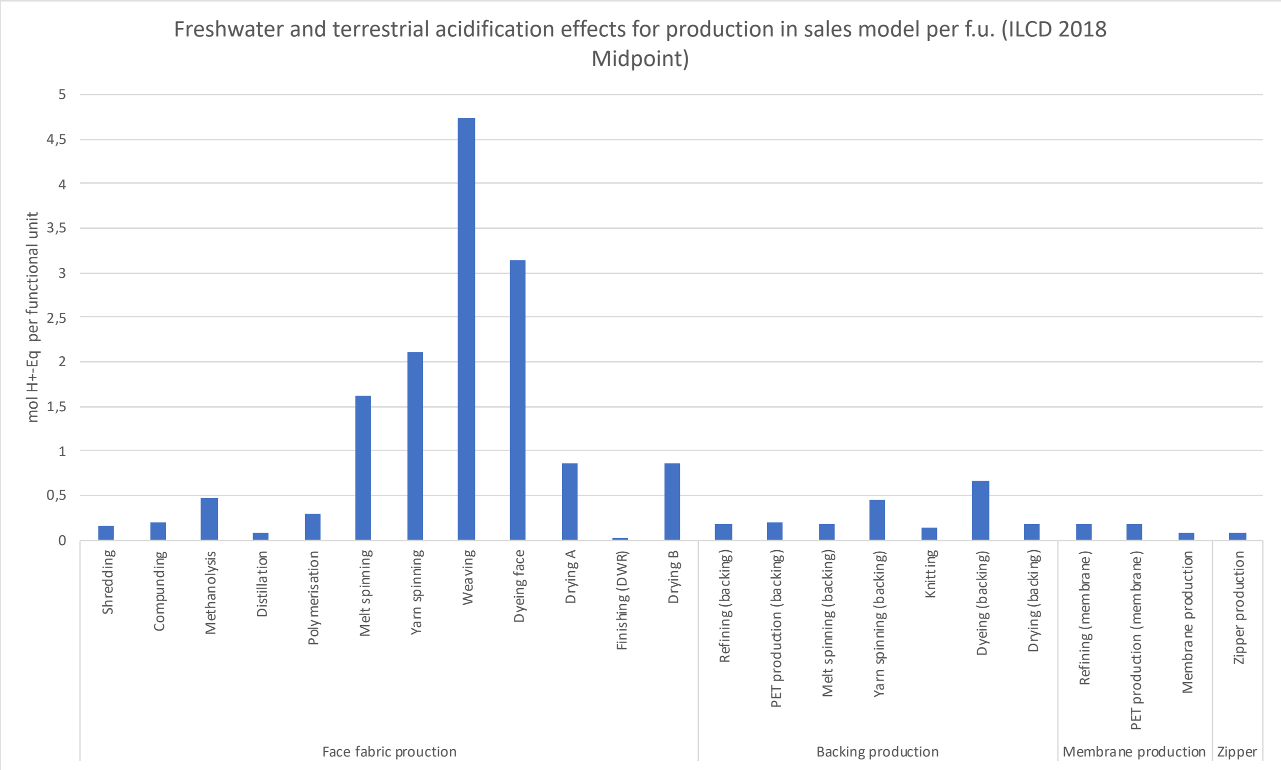
Freshwater ecotoxicity impacts per f.u. for production in sales model (ILCD 2018 Midpoint)
CTU per f.u.
400
350
300
250
200
150
100
50
0
Shredding
Compunding
Methanolysis
Distillation
Polymerisation
Melt spinning
Yarn spinning
Weaving
Dyeing face
Drying A
Finishing (DWR)
Drying B
Refining (backing)
PET production (backing)
Melt spinning (backing)
Yarn spinning (backing)
Knitting
Dyeing (backing)
Drying (backing)
Refining (membrane)
PET production (membrane)
Membrane production
Zipper production
Face fabric prouction
Backing production
Membrane production
Zipper

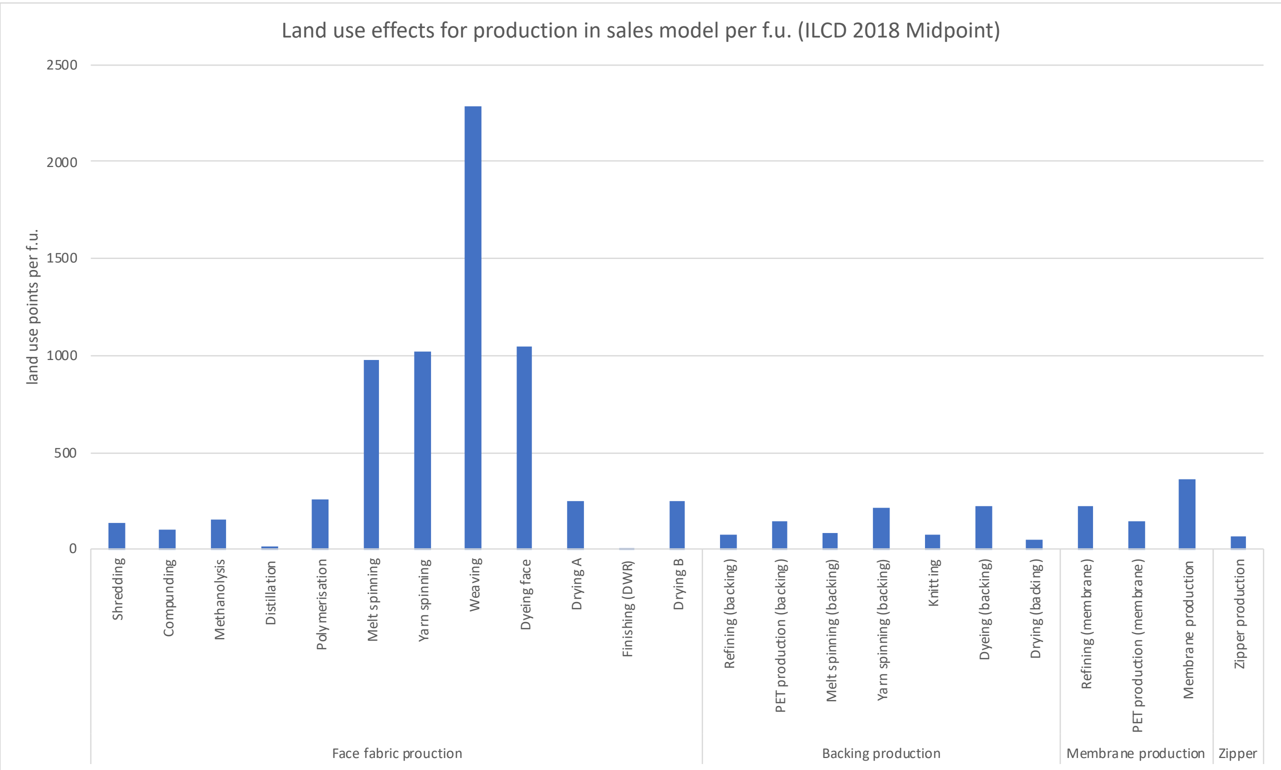

Human health carcinogenic effects per f.u. for production in sales model (ILCD 2018 Midpoint)
CTUh per f.u.
0,000008
0,000007
0,000006
0,000005
0,000004
0,000003
0,000002
0,000001
0
Shredding
Compunding
Methanolysis
Distillation
Polymerisation
Melt spinning
Yarn spinning
Weaving
Dyeing face
Drying A
Finishing (DWR)
Drying B
Refining (backing)
PET production (backing)
Melt spiming (backing)
Yarn spinning (backing)
Knitting
Dyeing (backing)
Drying (backing)
Refining (membrane)
PET production (membrane)
Membrane production
Zipper production
Face fabric prouction
Backing production
Membrane production
Zipper

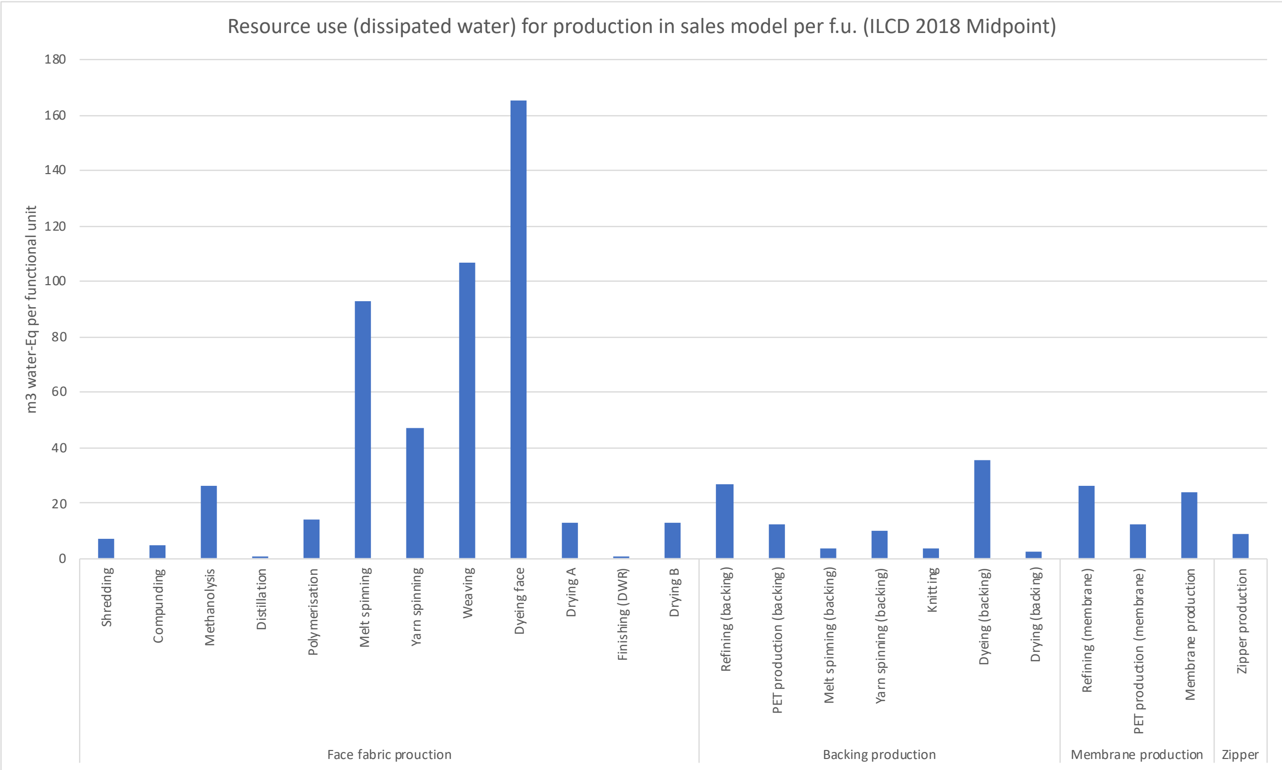

Human health non-carcinogenic effects per f.u. for production in sales model (ILCD 2018 Midpoint)
CTUh per functional unit
0,00014
0,00012
0,0001
0,00008
0,00006
0,00004
0,00002
0
Shredding
Compunding
Methanolysis
Distillation
Polymerisation
Melt spinning
Yarn spinning
Weaving
Dyeing face
Drying A
Finishing (DWR)
Drying B
Refining (backing)
PET production (backing)
Melt spinning (backing)
Yarn spinning (backing)
Knitting
Dyeing (backing)
Drying (backing)
Refining (membrane)
PET production (membrane)
Membrane production
Zipper production
Face fabric prouction
Backing production
Membrane production
Zipper

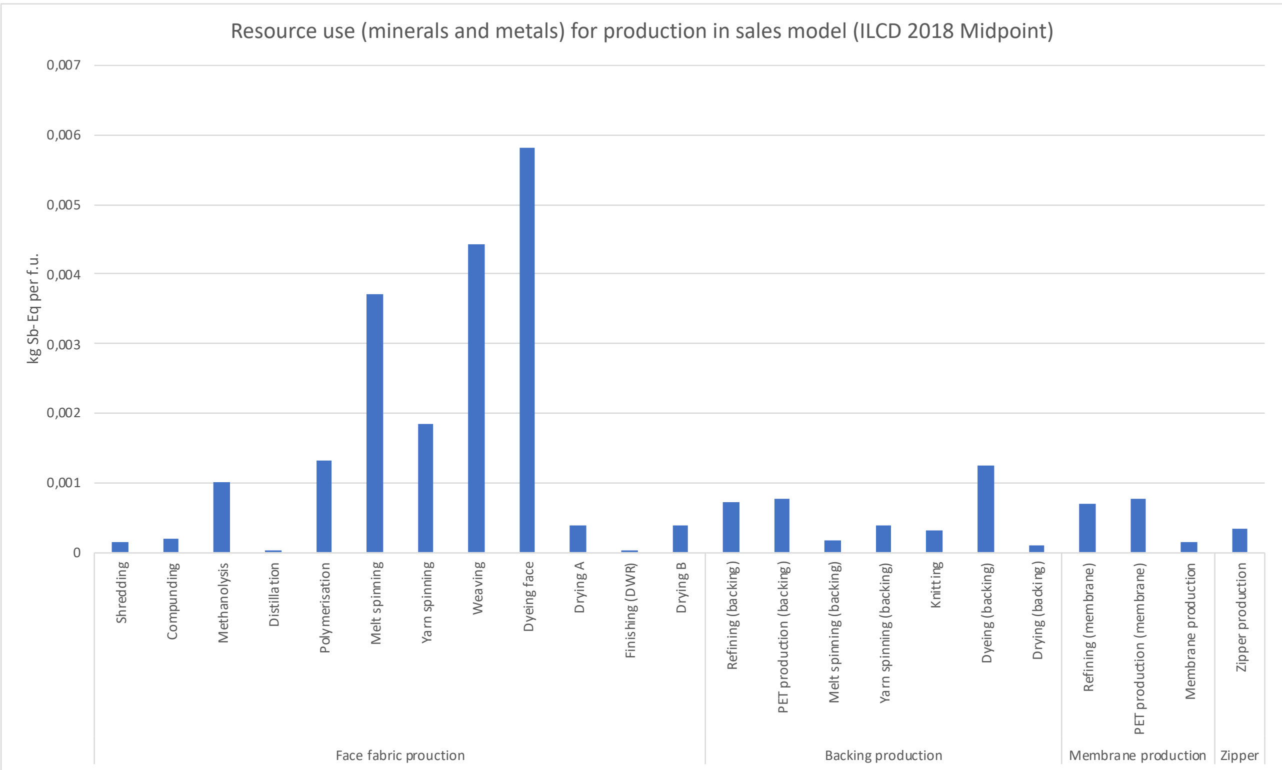

Photochemical ozone creation effects per f.u. for production in sales model (ILCD 2018 Midpoint)
kg NMVOC-Eq per f.u.
2,5
2
1,5
1
0,5
0
Shredding
Compunding
Methanolysis
Distillation
Polymerisation
Melt spinning
Yarn spinning
Weaving
Dyeing face
Drying A
Finishing (DWR)
Drying B
Refining (backing)
PET production (backing)
Melt spinning (backing)
Yarn spinning (backing)
Knitting
Dyeing (backing)
Drying (backing)
Refining (membrane)
PET production (membrane)
Membrane production
Zipper production
Face fabric prouction
Backing production
Membrane production
Zipper

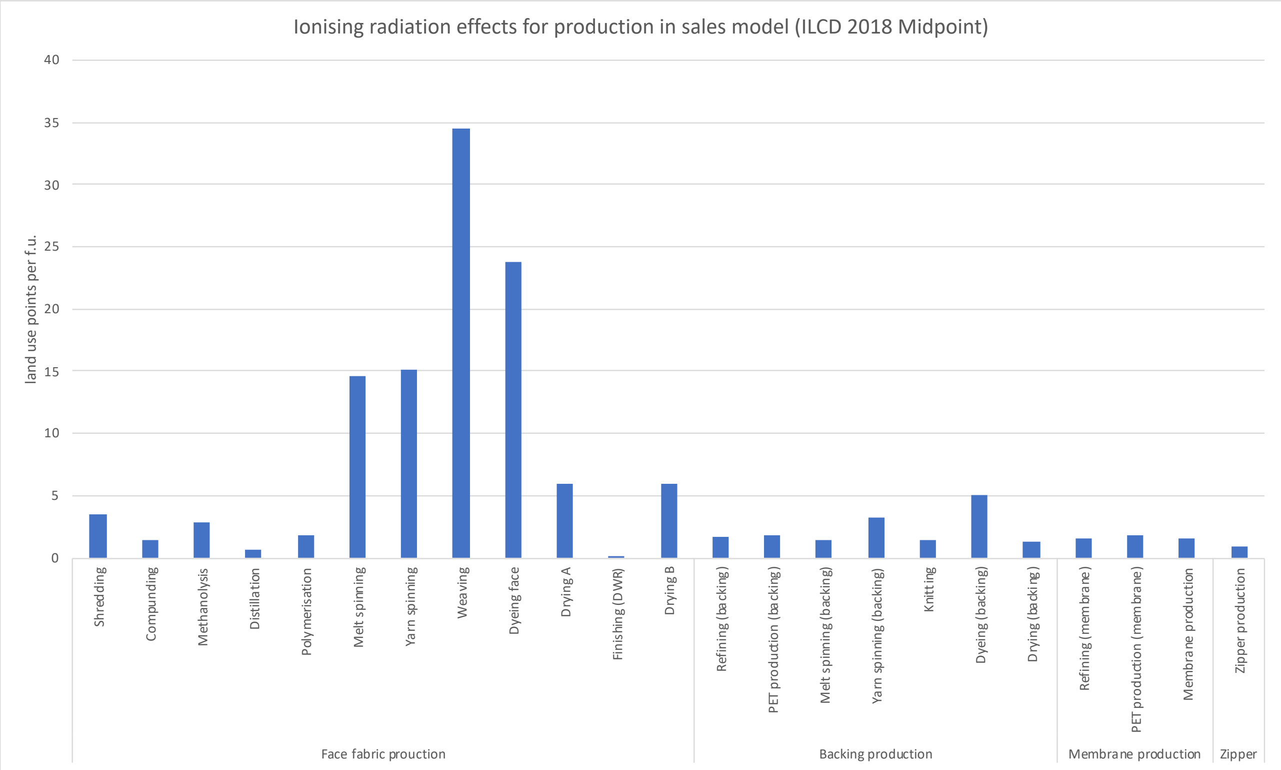

Respiratory effects (inorganic) per f.u. for production in sales model (ILCD 2018 Midpoint)
kg NMVOC-Eq per f.u.
0,000035
0,00003
0,000025
0,00002
0,000015
0,00001
0,000005
0
Shredding
Compunding
Methanolysis
Distillation
Polymerisation
Melt spinning
Yarn spinning
Weaving
Dyeing face
Drying A
Finishing (DWR)
Drying B
Refining (backing)
PET production (backing)
Melt spinning (backing)
Yarn spinning (backing)
Knitting
Dyeing (backing)
Drying (backing)
Refining (membrane)
PET production (membrane)
Membrane production
Zipper production
Face fabric prouction
Backing production
Membrane production
Zipper

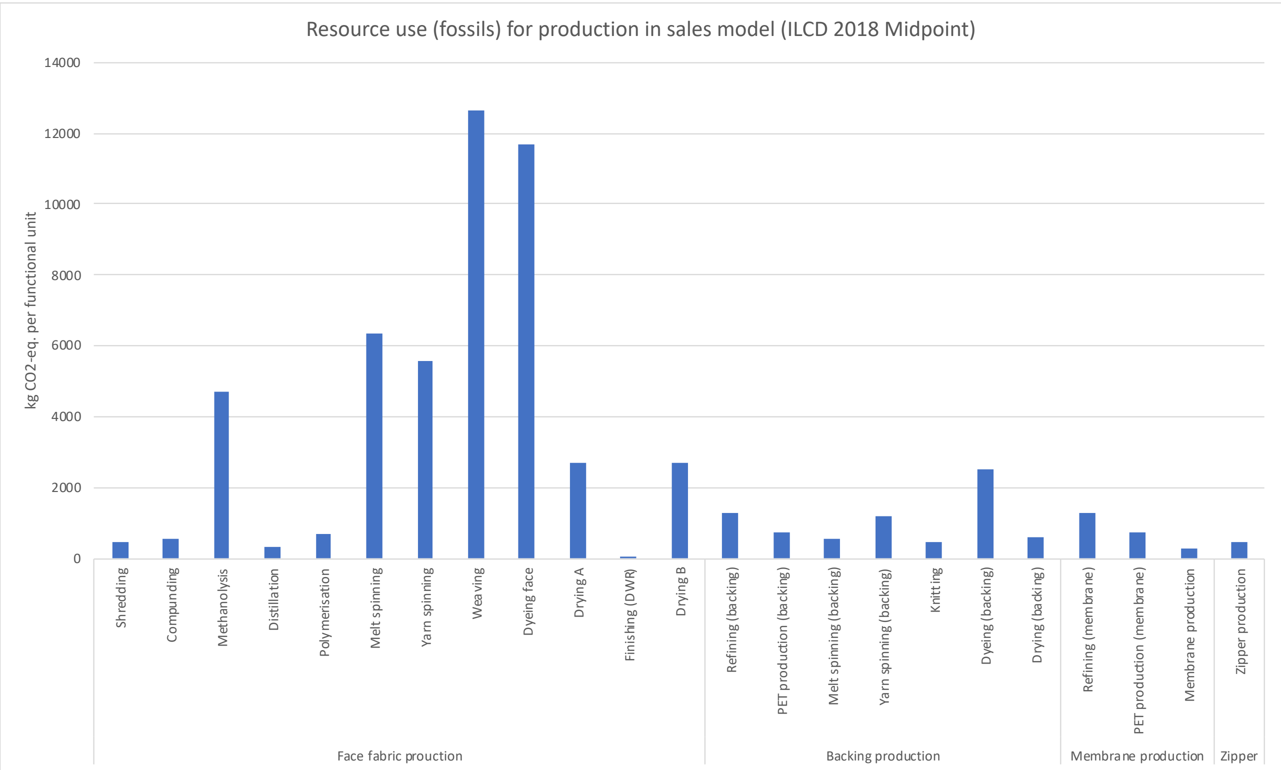

Freshwater and terrestrial acidification effects for production in sales model per f.u. (ILCD 2018 Midpoint)
mol H+-Eq per functional unit
5
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
Shredding
Compunding
Methanolysis
Distillation
Polymerisation
Melt spinning
Yarn spinning
Weaving
Dyeing face
Drying A
Finishing (DWR)
Drying B
Refining (backing)
PET production (backing)
Melt spinning (backing)
Yarn spinning (backing)
Knitting
Dyeing (backing)
Drying (backing)
Refining (membrane)
PET production (membrane)
Membrane production
Zipper production
Face fabric prouction
Backing production
Membrane production
Zipper


Land use effects for production in sales model per f.u. (ILCD 2018 Midpoint)
land use points per f.u.
2500
2000
1500
1000
500
0
Shredding
Compunding
Methanolysis
Distillation
Polymerisation
Melt spinning
Yarn spinning
Weaving
Dyeing face
Drying A
Finishing (DWR)
Drying B
Refining (backing)
PET production (backing)
Melt spinning (backing)
Yarn spinning (backing)
Knitting
Dyeing (backing)
Drying (backing)
Refining (membrane)
PET production (membrane)
Membrane production
Zipper production
Face fabric prouction
Backing production
Membrane production
Zipper


Resource use (dissipated water) for production in sales model per f.u. (ILCD 2018 Midpoint)
m3 water-Eq per functional unit
180
160
140
120
100
80
60
40
20
0
Shredding
Compunding
Methanolysis
Distillation
Polymerisation
Melt spinning
Yarn spinning
Weaving
Dyeing face
Drying A
Finishing (DWR)
Drying B
Refining (backing)
PET production (backing)
Melt spinning (backing)
Yarn spinning (backing)
Knitting
Dyeing (backing)
Drying (backing)
Refining (membrane)
PET production (membrane)
Membrane production
Zipper production
Face fabric prouction
Backing production
Membrane production
Zipper


Resource use (minerals and metals) for production in sales model (ILCD 2018 Midpoint)
kg Sb-Eq per f.u.
0,007
0,006
0,005
0,004
0,003
0,002
0,001
0
Shredding
Compunding
Methanolysis
Distillation
Polymerisation
Melt spinning
Yarn spinning
Weaving
Dyeing face
Drying A
Finishing (DWR)
Drying B
Refining (backing)
PET production (backing)
Melt spinning (backing)
Yarn spinning (backing)
Knitting
Dyeing (backing)
Drying (backing)
Refining (membrane)
PET production (membrane)
Membrane production
Zipper production
Face fabric prouction
Backing production
Membrane production
Zipper


Ionising radiation effects for production in sales model (ILCD 2018 Midpoint)
land use points per f.u.
40
35
30
25
20
15
10
5
0
Shredding
Compunding
Methanolysis
Distillation
Polymerisation
Melt spinning
Yarn spinning
Weaving
Dyeing face
Drying A
Finishing (DWR)
Drying B
Refining (backing)
PET production (backing)
Melt spinning (backing)
Yarn spinning (backing)
Knitting
Dyeing (backing)
Drying (backing)
Refining (membrane)
PET production (membrane)
Membrane production
Zipper production
Face fabric prouction
Backing production
Membrane production
Zipper


Resource use (fossils) for production in sales model (ILCD 2018 Midpoint)
kg CO2-eq. per functional unit
14000
12000
10000
8000
6000
4000
2000
0
Shredding
Compunding
Methanolysis
Distillation
Polymerisation
Melt spinning
Yarn spinning
Weaving
Dyeing face
Drying A
Finishing (DWR)
Drying B
Refining (backing)
PET production (backing)
Melt spinning (backing)
Yarn spinning (backing)
Knitting
Dyeing (backing)
Drying (backing)
Refining (membrane)
PET production (membrane)
Membrane production
Zipper production
Face fabric prouction
Backing production
Membrane production
Zipper

Appendix E ReCiPe midpoint to endpoint conversion factors

The table below shows the midpoint to endpoint conversion factors for the ReCiPe weighting method (Huijbregts et al., 2016). It indicates what impact categories are emphasised more or less by the different versions of the weighing method: the individualistic perspective, the hierarchic perspective and the egalitarian perspective. Throughout this study, the hierarchic perspective has been used for weighting.

Midpoint to endpoint conversion factor	unit	Individualistic	Hierarchic	Egalitarian
Human health				
Global Warming - Human health	DALY/kg CO2 eq.	8,12E-08	9,28E-07	1,25E-05
Stratospheric ozone depletion - Human health	DALY/kg CFC11 eq.	2,37E-04	5,31E-04	1,34E-03
Ionzing Radiation - Human health	DALY/kBq Co-60 emitted to air eq.	6,80E-09	8,50E-09	1,40E-08
Fine particulate matter formation - Human health	DALY/kg PM2.5 eq.	6,29E-04	6,29E-04	6,29E-04
Photochemical ozone formation - Human health	DALY/kg NOx eq.	9,10E-07	9,10E-07	9,10E-07
Toxicity - Human health (cancer)	DALY/kg 1,4-DCB emitted to urban air eq.	3,32E-06	3,32E-06	3,32E-06
Toxicity - Human health (non-cancer)	DALY/kg 1,4-DCB emitted to urban air eq.	2,28E-07	2,28E-07	2,28E-07
Water consumption - human health	Daly/m3 consumed	3,10E-06	2,22E-06	2,22E-06
Terrestrial ecosystems				
Global Warming - Terrestrial ecosystems	Species.year/kg CO2 eq.	5,32E-10	2,80E-09	2,50E-08
Photochemical ozone formation - Terrestrial ecosystems	Species.year/kg NOx eq.	1,29E-07	1,29E-07	1,29E-07
Acidification - Terrestrial ecosystems	Species.year/kg SO2 eq.	2,12E-07	2,12E-07	2,12E-07
Toxicity - Terrestrial ecosystems	species*yr/kg 1,4-DBC emitted to industrial soil eq.	1,14E-11	1,14E-11	1,14E-11
Water consumption - terrestrial ecosystems	species.yr/m3 consumed	0,00E+00	1,35E-08	1,35E-08
Land use - occupation and transformation	Species/(m2·annual crop eq)	8,88E-09	8,88E-09	8,88E-09
Freshwater ecosystems				
Global Warming - Freshwater ecosystems	Species.year/kg CO2 eq.	1,45E-14	7,65E-14	6,82E-13
Eutrophication - Freshwater ecosystems	Species.year/kg P to freshwater eq.	6,71E-07	6,71E-07	6,71E-07
Toxicity - Freshwater ecosystems	species·yr/kg 1,4-DBC emitted to freshwater eq.	6,95E-10	6,95E-10	6,95E-10
Water consumption -aquatic ecosystems	species.yr/m3 consumed	6,04E-13	6,04E-13	6,04E-13
Marine ecosystems				
Toxicity - Marine ecosystems	species·yr/kg 1,4-DBC emitted to sea water eq.	1,05E-10	1,05E-10	1,05E-10
Eutrophication - Marine ecosystems	Species.year/kg N to marine water eq.	1,70E-09	1,70E-09	1,70E-09
Resources				
Mineral resource scarcity	USD2013/kg Cu	1,59E-01	2,31E-01	2,31E-01
Fossil resource scarcity		**Endpoint characterisation factors**		
Crude oil	USD2013/kg	0,46	0,46	0,46
Hard coal	USD2013/kg	0,03	0,03	0,03
Natural gas	USD2013/Nm3	0,30	0,30	0,30
Brown coal	USD2013/kg	-	-	0,03
Peat	USD2013/kg	-	-	0,03

Appendix F Modelling of conventional functional unit

The life cycle assessment based on a functional unit of "one use day" (instead of profit) required us to relate the flows of the main processes to the new functional unit. In the sales model, impacts were calculated for the full technical lifetime of a jacket (1000 use days), and then divided to represent one use day. Conversely, the rental business model required us to disaggregate the lifetime of the jackets spent in rental (200 use days) and in second-hand use (800 use days), which together make up the technical lifetime. Therefore, impacts were calculated by taking into account the different uses of a jacket during these two different periods. Impacts from customer transport and laundry activities were calculated for the rental and the second-hand lifetime, respectively. Impacts related to production, distribution (internal and external), repair and end-of-life activities were converted to one use day in the same way as for the sales model. The following tables show this modelling as implemented in OpenLCA (Table E.1 and Table E.2).

Table E 1: The modelling of flows for a functional unit of "one use day" in the sales business model

"One use" sales model					
Phases	**Flow**	**Amount**	**Unit**	**Provider**	**Description**
Production	Jacket	1.0/Technical_lifetime	Item(s)	Sewing and finishing - EE	
Distribution	Internal transportation of one jacket	1.0/Technical_lifetime	Item(s)	Internal distribution	
	Transportation of one jacket	1.0/Technical_lifetime	Item(s)	External distribution	
Customer transport	transport, passenger car, EURO 5	Customer_transport_car/ Technical_lifetime	km	market for transport, passenger car, EURO 5 | transport, passenger car, EURO 5 | Cutoff, U - RER	
	transport, passenger car, EURO 5	(customer_transport_car *CR)/Technical_lifetime	km	market for transport, passenger car, EURO 5 | transport, passenger car, EURO 5 | Cutoff, U - RER	Customer return a jacket
	transport, passenger, bicycle	Customer_transport_bike /Technical_lifetime	p*km	market for transport, passenger, bicycle | transport, passenger, bicycle | Cutoff, U - GLO	
	transport, passenger, bicycle	(customer_transport_bik e *CR)/ Technical_lifetime	p*km	market for transport, passenger, bicycle | transport, passenger, bicycle | Cutoff, U - GLO	Customer return a jacket
	transport, tram	Customer_transports_tra m/Technical_lifetime	p*km	transport, tram, Sweden | transport, tram | Cutoff, U – SE	
	transport, tram	(customer_transports_tra m *CR)/Technical_ lifetime	p*km	transport, tram, Sweden | transport, tram | Cutoff, U - SE	Customer return a jacket
Laundry & Repair	Clean jacket	18/Technical_ lifetime	Item(s)	Residential laundry and drying (half-loaded) - SE	
	Repaired jacket	8/Technical_ lifetime	Item(s)	Repair - SE	
EoL	EoL transportation of one jacket	(1.0*CR)/ Technical_lifetime	Item(s)	EoL transportation of one jacket	
	Flow	**Amount**	**Unit**		
Reference flow	Sales_One Use	1.0	day		

Table E 2: The modelling of flows for a functional unit of "one use day" in the rental business model

"One use" rental model					
Phases	**Flow**	**Amount**	**Unit**	**Provider**	**Description**
Production	Jacket	1.0/Technical_lifetime	Item(s)	Sewing and finishing - EE	
Distribution	Internal transportation of one jacket	1.0/Technical_lifetime	Item(s)	Internal distribution	
	Transportation of one jacket	1.0/Technical_lifetime	Item(s)	External distribution	
Customer transport	transport, passenger car, EURO 5	customer_transport_car/Second_hand_Lifetime	km	market for transport, passenger car, EURO 5 | transport, passenger car, EURO 5 | Cutoff, U - RER	Second_hand transport
	transport, passenger car, EURO 5	(customer_transport_car*CR)/Technical_lifetime	km	market for transport, passenger car, EURO 5 | transport, passenger car, EURO 5 | Cutoff, U - RER	Customer return garment
	transport, passenger car, EURO 5	((200/5)*customer_transport_car*2)/ Rental_Lifetime	km	market for transport, passenger car, EURO 5 | transport, passenger car, EURO 5 | Cutoff, U - RER	Rental transport
	transport, passenger, bicycle	(customer_transport_bike*CR)/ Technical_lifetime	p*km	market for transport, passenger, bicycle | transport, passenger, bicycle | Cutoff, U - GLO	Customer returns garment
	transport, passenger, bicycle	((200/5)*customer_transport_bike*2)/Rental_Lifetime	p*km	market for transport, passenger, bicycle | transport, passenger, bicycle | Cutoff, U - GLO	Rental transport
	transport, passenger, bicycle	customer_transport_bike/ Second_hand_Lifetime	p*km	market for transport, passenger, bicycle | transport, passenger, bicycle | Cutoff, U - GLO	Second hand transport
	transport, tram	(customer_transports_tram*CR)/ Technical_lifetime	p*km	transport, tram, Sweden | transport, tram | Cutoff, U - SE	Customers returns garment
	transport, tram	customer_transports_tram/ Second_hand_Lifetime	p*km	transport, tram, Sweden | transport, tram | Cutoff, U - SE	Second hand transport
	transport, tram	((200/5)*customer_transports_tram*2)/Rental_Lifetime	p*km	transport, tram, Sweden | transport, tram | Cutoff, U - SE	Rental transport
Laundry & Repair	Clean jacket	(800*18/1000)/Second_hand_Lifetime	Item(s)	Residential laundry and drying (half-loaded) - SE	
	Clean rental jacket	(200/5)/Rental_Lifetime	Item(s)	Residential laundry and drying (fully loaded) - SE	
	Repaired jacket	8/Technical_ lifetime	Item(s)	Repair - SE	
EoL	EoL transportation of one jacket	(1.0*CR)/Technical_lifetime	Item(s)	EoL transportation of one jacket	
	Flow	**Amount**	**Unit**		
Reference flow	Rental_One Use	1.0	day		

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