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The Life Cycle Sustainability Assessment framework through the lens of the systemic approach

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Summary

Abstract

Promoting more sustainable societies, companies and customer behaviors are crucial challenges for the flourishing of societies and the well-being of citizens. Investigating and assessing the sustainability is therefore fundamental in order to enable governments, companies and customers to orient their policies, decisions and habits, respectively, towards more sustainable practices. However, so far, sustainability assessment methods show many gaps due to the complexity of this concept and the multitude of factors to include in the assessment that concur to advance or hamper more sustainable transitions. One promising framework for the assessment of sustainability is the Life Cycle Sustainability Assessment. In this dissertation, the systemic approach is presented as fundamental to identify interconnections, enabling practitioners in the Life Cycle Thinking field to advance the LCSA. Thus, three different studies are presented here to show how the adoption of the systemic approach allowed to identify relevant interconnections. In the first study, monetary and physical flows were connected in an integrated way in order to assess the environmental performance of two different business models with the same economic performance. To evaluate the two business models, the Life Cycle Assessment was performed using the profit as functional unit. In the second study, the systemic approach is used to estimate, with a theoretical approach, the level of circularity of a territorial system (at meso-macro level) through the creation of a circularity index based on the structure of the Life Cycle Assessment. The third research reports a preliminary literature review of the concept of well-being in the social sciences. The study highlights how the absence of a systemic approach in the assessment of social performance within the Social Life Cycle Assessment can lead to underestimate the relationships that take place within a system, preventing the social performance of a company from being scientifically assessed in terms of improving or maintaining the level of well-being of its stakeholders. As results, the three studies reveal important interconnections to keep in mind, and possible approaches or methods to apply in sustainability research.

Keywords: Sustainability, Systemic Approach, Life Cycle Sustainability Assessment Framework, Interconnections, Well-being

1. Introduction

Sustainability is a widely known concept introduced in many political agenda and environmental programs by governments and enterprises worldwide in order to promote alternative ways of producing, consuming and living the life. The importance of sustainability lies on the need to stimulate transactions towards societies in which vital biophysical limits and thresholds set by the Earth System are not overcome and humanity can flourishing within those limits (Meadows et al., 1972; Rockstrom et al., 2009; Jorgenses et al., 2015).

On a political level, sustainability has received major attention, for example through its operationalization as Sustainable Development Goals (SDGs) established by the UN Agenda 2030, and, on a private level, by increasing the number of attempts to improve sustainable practices within companies of any size according to environmental programs (Ehrenfeld, 2012). Yet, sustainability still appears as a difficult concept to grasp and assess. According to Barbier (1987) the sustainable development is defined as an "interaction among three elements: the biological and resource system, the economic system, and the social system". On the other hand, according to the Brundtland Report (1987), development is considered sustainable if "[…] meets the needs of the present without compromising the ability of future generations to meet their own needs". Such definitions refer to two main aspects: the interconnections between three different dimensions of sustainability and the importance to satisfy needs which deals with these dimensions without compromising future generation opportunities to do the same.

One of the first representations of sustainability was based on the interconnection of the three different spheres that symbolize the above-mentioned dimensions. However, despite being accepted for a long time, such picture is criticized since it erroneously assumes the three dimensions as separated and autonomous entities (Giddings et al., 2002). According to Pulselli et al. (2015) a more correct representation of the sustainability is based on a three-storey pyramid (Fig. 1). At the foundations of the pyramid there is the environment which provides natural assets and thus crucial inputs both to society (at the second storey) and to economy (at the top level). The conceptualisation of Pulselli et al. (2015) embodies the logical, physical, relational and thermodynamic order recognized by sustainability scholars. Such representation leads to three main considerations: first, the three dimensions cannot be considered separately but they are components of a whole system (i.e. the pyramid); secondly, relations and interconnections exist between environment, society and economy affecting outcome of policies and measures promoting sustainable development; third, socio-economic systems depend on the environment, which is thereby placed at the foundations of sustainability.

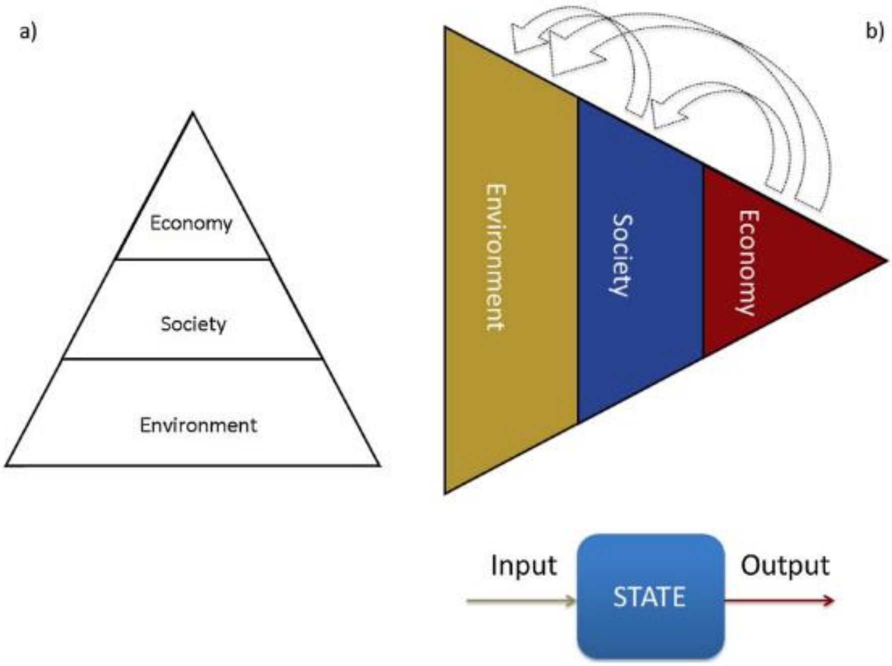

Figure 1 Sustainability representation (figure extracted from Pulselli et al.,2015)

This change of representation has important consequences, in fact it introduces important elements to consider during the assessment of sustainability such as the need to adopt a holistic and multidisciplinary approach in order to consider all the three dimensions without considering them as interchangeable and the importance of using both intensive and extensive indicators to shift the level of the analysis from site-specific or local to global scales (Bastianoni et al., 2019). In addition to these elements, it becomes relevant to require the application of a systemic approach aiming at identifying and measuring interconnections between the sub-components of a system.

The application of a systemic approach, appears fundamental to investigate the complexity of a system and " identify the points at which a system is capable of accepting positive change and the points where it is vulnerable " (Holling, 2001). Williams et al. (2017) described how the systemic approach enables to pursue sustainability deepening core concepts such as interconnections and feedback loops. Interconnections deal with the study of the relations and connections between organizations and environmental, social and economic systems. Interconnected components determine the functioning of the whole system (Williams et al., 2017) and therefore the investigation of the interconnections across scales in environmental, social and economic systems is propaedeutic for maintaining the survival of a system during time.

When interconnections exist, feedback loops occur. Feedback loops refer to the effect that one variable causes on another and these need to be measured to assess the positive or negative magnitude of their impacts on the system (Williams et al., 2017; Walker and Salt, 2006). Thus, being able to understand the complexity of a system by considering interconnections and feedbacks loops allows to manage the system correcting dangerous or harmful mechanisms or strengthening policies and measures that prove to lead to sustainability.

One promising methodological framework to assess sustainability is represented by the Life Cycle Sustainability Assessment (LCSA) which can be applied according to two different perspectives.
According the first perspective, LCSA is a recently developed life-cycle based method performed by applying simultaneously Life Cycle Assessment, Life Cycle Costing and Social Life Cycle Assessment based on the following equation LCSA= LCA + LCC + SLCA (Kloepffer, 2008). These three methodologies aim at assessing respectively environmental, economic and social impacts related to a production system. Though LCSA appears as a promising tool to assess sustainability so far it has its limitation. Firstly, the SLCA, which is the newest among the three methodologies that compose LCSA, still needs to be better developed and it is subjected to many controversies within the scientific community (Wulf et al., 2019). Secondly, a standardized procedure to perform LCSA does not exist. Only, LCA has been formalized and standardized according to recognized common rules established by International Organization for Standardization (ISO). Thirdly, LCSA still appears weak in identifying interconnections and feedback loops. Many applications of LCSA consist of parallel and independent performing the three methodologies followed by aggregating results at the end of the assessment through weighting and multi-criteria methods such as the application of the Multi Criteria Decision Analysis (Costa et al., 2019). Although such applications are useful to assess and monitor the sustainability referred to each of the three dimensions, they little integrate the three dimensions during the assessment and the relations between sub-systems remain unknown (Sala et al., 2013).

Nevertheless, according to the second perspective, LCSA can also be intended as a framework. Onat et al. (2017) claim that LCSA "is an interdisciplinary framework for integration of models rather than a method itself, and therefore there are many opportunities for integration of tools and methods to improve the applicability of LCSA". This perspective stems from the thought of Guinée et al., (2011) according to which LCSA should be intended as a tool to implement LCA by broadening the scope and the object of the analysis and deepening the relations. Broadening the scope of the analysis means covering the three dimensions of sustainability in compliance with the people, planet and prosperity approach. Broadening the object of the analysis refers to shift the assessment from the product-level to the sector or even economy-wide levels. Deepening the analysis regards the inclusion of the physical, social, economic and behavioural relations in addition to the technological ones. Contrary to LCA, LCSA should be intended as a framework to implement a transdisciplinary and integrated application of models and methods in order to address fundamental life-cycle sustainability questions (Guinée et al., 2011).

According to Onat et al. (2017) about challenges in LCSA, the systems thinking perspectives is necessary and it can be considered a "catalyzer of harmonizing tools, methods, and disciplines" (Onat et al., 2017, p.9). Indeed, the systemic approach may lead to acquire more knowledge on the behaviours of elements that compose a system, their interconnections, possible future impact aiming at redesigning systems (Onat et al., 2017). In addition, Onat et al. (2017) strongly emphasise the bound between the systemic approach and LCSA. Indeed, they state that "Like LCA, LCSA is a system-based tool and deals with systems of systems with much broader and deeper considerations (revealing macro-level impacts, consideration of social, and economic impacts, and taking into account underlying mechanisms). These aspects require LCSA practitioners and researchers to adopt systems thinking, which is defined as the ability to see the parts of bigger mechanisms, recognizing patterns and interrelationships, and restructuring these interrelationships in more effective and efficient ways" (Onat et al., 2017, p. 706).

In this thesis, LCSA will be investigated by referring to definition suggested by Onat et al (2017). Therefore, LCSA is considered as a framework to develop new models and tools to assess sustainability coping with the main three challenges highlighted by Guinéè et al. (2011).
The main research question of this thesis is: to what extent the application of a systemic approach may contribute in assessing sustainability in the Life Cycle Sustainability Assessment field?
The added value of this dissertation stems from using three different studies from different disciplinary fields to show how the application of the systemic approach can lead to identify existent interconnections within or between the three dimensions of sustainability contributing to provide possible new methodological approaches, methods or tools to apply in the LCSA. In fact, the methods presented are not considered per sè, but within a wider context in which the case studies are placed.

2. Thesis design

In this thesis three main studies addressing the research question are presented. First, in Chapter 3, a research performed during the visiting PhD period abroad at the Chalmers University of Technology in Gothenburg under the supervision of Prof. Henrikke Baumann, Prof. Anne-Marie Tillman and Prof. Thomas Zobel will be presented in order to show how the application of a systemic approach under a life cycle perspective can lead to integrate environmental and economic dimensions and identify interconnections in the context of a business model. The study was performed together with PhD student Daniel Böckin. The outcome of this study was the writing of a technical report (Böckin, Goffetti et al., 2020) co-written as co-first author with Böckin. From the technical report was extracted many of the content then used in this thesis, included tables and images.

Secondly, a study that aims at assessing the level of the circularity of a territorial system will be presented to show how it is possible to shift the level of the analysis from the product-related to the macro-system level allowing to assess the level of circularity based on virtuous site-specific practices and the level of interaction between different sub-systems. This research was performed under the supervision of Prof. Federico M. Pulselli and Prof. Simone Bastianoni and in collaboration with Dr. Nicoletta Patrizi and Dr. Elena Neri.

Thirdly, studies carried out in the SLCA field will be presented to highlight criticisms and weaknesses of the current Guidelines provided by UNEP/SETAC and to introduce an alternative systemic framework to advance the investigation of relations between organizations and ecological, social and economic systems. This research was carried out under the supervision of Prof. Henrikke Baumann and Associate professor Rickard Ardvisson. The main results of this research were two extended abstract presented during the SLCA 2020 Conference (Goffetti et al., 2020; Goffetti & Baumann, 2020) .

Lastly, in a last chapter the findings from the different research studies will be summarised and discussed to show howthe systemic approach highlighting strengths and limits or further researches.

In the following chapters the three studies are presented and major information and details about the background for the researches, ad-hoc methods, results and discussion are provided.

3. The environmental assessment of two business models

3.1. The scientific background

So far, in the business field, there was the belief that economic growth and environmental degradation are coupled (Rockström, Steffen, and Noone, 2009). As consequence, for many years, companies always produced according a "take-make-dispose" model that has lead them to exploit and transform natural resources through production processes, and sold the final products without applying reusing or recovering practices (Blomsma and Brennan, 2017). However, in the last decades, companies are trying to advance alternative ways of production and doing business encouraging a transaction from linear to more sustainable business models (Bocken et al., 2016).

Business models are defined as "the rationale of how an organization creates, delivers, and captures value" (Osterwalder &Pigneur, 2010). According to a narrow perspective, it may be possible to claim that the expression "capturing value" refers to the generation of profit (Böckin et al., 2020). Generally, in linear business models companies aim at obtaining profits by the selling of products (Bocken et al., 2016). In contrast, in the literature, different and alternative examples of doing business and capturing value exist such as the one represented by the product-service system (PSS).

PSS are defined by Tukker and Tischner (2006) as "a mix of tangible products and intangible services, designed and combined so that they are jointly capable of fulfilling final customer needs". As is visible from the definition, the attention of PSS is on the satisfaction of customers' needs rather than on products. Consequently, it is thought that the development of service-based in substitution to product-based systems may lead to decrease environmental impacts. According to Tukker (2004) three main categories of PSS can be identified. The first category is represented by the *product-oriented PSS* and it refers to highly materialized and tangible service systems where products are sold and possibly additional service (e.g. maintenance or reparations) are implemented by the company. The second category is *use-oriented PSS* and represents a situation in which companies maintain the ownership of products but customers have access according to different types of models, such as sharing, renting or leasing. The third category is *result-oriented PSS* and it is based on intangible services which do not require any product to fulfil customers' needs.

Despite the attention towards alternative ways of doing business, at this date there are not many studies in the literature that proves the capacity of PSS to reduce the environmental impacts (Pieroni et al., 2019; Tukker, 2015). Indeed so far, many of the assessments performed mostly focus on product system level (Kjaer et al., 2016) rather than on a business model level, which would mean having to consider in the assessment both socio and economic mechanisms in addition to the technical ones. In addition, when attempts to assess the business model are done, they do not usually consider the economic aspects in an integrated way (Böckin et al., 2020). In other words, assessment studies and proper assessment methods that investigate the decoupling of economy activities from the environmental degradation on a company level are still missing.

Therefore, this study had multiple goals. Firstly, the study aims at performing a quantitative, systemic and comparative assessment of a product-oriented and a use-oriented business model in order to understand if and to what extent alternative business model can lead to better environmental performance and if it is possible to achieve decoupling on a private level by their implementation. Secondly, the study aims at developing a new method for enabling an interconnected analysis.

The assessment was done on a real case company in the apparel sector.

3.2. Material and Method

3.2.1. The case study

The company under investigation operates in Sweden in the apparel field. The company provides high quality technical products to perform outdoor activities while promoting at the same time sustainable environmental practices (e.g. avoiding dangerous materials for the environment; promoting reusing and recycling of materials in their production). At this date, the company is running a sales business model (product-oriented PSS). However, in order to reduce its environmental performance, the company is considering the possibility to implement in the future a rental business model (use-oriented PSS).

The sales business model (hereafter simply named “sales model”) allows customers to pay a price to obtain the ownership of garments. In order to promote the prolonging lifetime of the garments, the company also offers free reparations in case of garments damaged sometimes.

Conversely, the rental business model (hereafter called “rental model”) enables customers to use garments by paying a price based on the duration of the rental use (rental use days). In the rental model the company maintains the ownership of garments and it is responsible for its handling in terms of laundry, reparations, packaging etc[1]. Particularly relevant are the laundry and reparation operations. Indeed, garments need to be laundered after every transaction, while reparation procedures occur every time a garment is damaged. Garments are rented until they are worn out (which means they look new and fresh), and once this happens, they are removed from the rental service and sold as second-hands garment at lower price compared to the price established in the sales model.

In both the sales and the rental model, the company encourages customers to return garments to the company once they reach the End-of-Life in order to send them back to the suppliers and recycling the textile material.

A representative garment for the company used for both the sales and rental models is a waterproof and breathable jacket usually used by customers who perform skiing, kayaking or hiking activities.

The jacket is composed of three layers:

- an outer layer called a face fabric which is which is water repellent and fluorocarbon free;
- an interior layer called a backing fabric;
- an intermediate layer laminated to the face fabric, referred to as a membrane, which is water-proof and allows humidity to leave the body.

The jacket is also provided with a zipper.

Further details related to the layers and the jacket are provided in Table 1.

Table 1 Specifications about the material, the weight, and the technical properties of the jacket.

Jacket characteristics		
Layers	**Materials description**	**Weight (kg)**
Face Fabric	Recycled polyester	0,550
Membrane	Virgin polyester	0,118
Backing	Virgin polyester	0,118
Zipper	Virgin polyester	0,30
Total	**-**	**0,815**
Technical lifetime		**1000 days**

[1] In this study, “responsibility” meant that a company obtained the physical control over the products and their handling

In this study, the assessment was performed by considering the rental and the sales business models for the representative jacket. The two business models were investigated separately even if in the reality they can fit together.

3.2.2. Life Cycle Methodology

In this study, the LCA methodology is applied in order to perform the assessment. LCA can be defined as "a technique for assessing the environmental aspects and potential impact associated with a product" (ISO 14040, 2006). LCA is standardized according to ISO 14040 and 14044 standards and it is structured on four main phases: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and, 4) interpretation.

During the first phase, the purpose of the assessment is declared and details about the production system under investigation and the intended audience are provided. The functional unit, the system boundaries and impact categories to be assessed are established. In addition, clarifications about the data quality are provided by specifying what type of data will be collected (e.g. primary, secondary data). During the second phase, data related to physical (material and energy) inputs and related outputs and wastes are collected considering the processes of the production system. In the third phase, data collected during the creation of the inventory are translated into potential contributions to environmental impacts. Lastly, in the fourth phase, results are interpreted and presented allowing to identify hotspots and possible solutions to improve the technical and environmental performance of the production system. Performing a sensitivity analysis is a useful tool at this stage in order to verify the robustness of the results.

LCA is applied according the ISO 14040 and 14044 standards but a central novelty in the research presented here regards the methodological development during the goal and scope definition phase.

3.2.3. Defining the functional unit by applying a systemic approach

In this study, a non-conventional procedure was applied to define the functional unit. In mainstream LCA praxis, the functional unit is usually selected considering the physical properties or the function of a product, however, since the object of the analysis are two different business models that a company can implement, we argued that the function should be the profit. Adopting the profit as functional unit requires an understanding of the socio-technical and economic system in order to deal with organizational and monetary aspects related to the product

and integrate them in the assessment. Therefore, to connect monetary and physical flows was necessary to investigate the product-related system in a wider way than in conventional LCA.
Here, adopting a systemic approach meant to identify interconnections between physical and monetary flows in order to understand how they concurred to determine the profit. The term "monetary flows" referred both to revenues and costs that a company incurs. Their identification was necessary to calculate the profit which is expressed by the difference between revenues and costs.

More in detail, starting from a more traditional flowchart representing the process for the representative jacket, physical flows were followed to understand when physical products were exchanged between the company and the value-chain actors in order to identify where revenues and costs were generated. The moment in which products are exchanged was defined as interaction point. The identification of the interaction points[2] (Lindkvist and Baumann, 2017) between the company and external actors such as suppliers and customers was propaedeutic for three main reasons: 1) to understand when the company becomes "responsible" for the management/handling of the products, 2) to include all relevant monetary flows of the business model according to a company perspective and, 3) to identify, model and quantify the existent relations between physical and monetary flows. In particular, the quantification of the interactions points between the company and the customers in terms of volume of products exchanged was fundamental to determine the revenues and the costs that the company incurs with its suppliers to produce new products and handling them in order to sustain in time the business model.

Therefore, by following the physical flows and by identifying the interaction points was possible to track the monetary flows that compose the cost structure and the revenue streams according to the company perspective.

The cost structure defines and categorizes the expenses that the company needs to sustain while operating a business model. In this study, a simplified cost structure based on direct and indirect cost was used. Direct costs are strictly tied and depend on the volume of production or number of transactions. Conversely, indirect costs are intended to be as fixed or semi-fixed[3]. Then, costs were associated to the different stage of the jacket life cycle in order to understand which phase mostly

[2] Examples of interaction points are represented by the sales or the rental transactions where interactions between the company and the customers occur and products are exchanged.
[3] Fixed or semi-fixed costs are given and mostly depend on variables such as the number of stores, the number of employees etc.

impact on an economic point of view. Intuitively, since direct costs are strictly tied to the physical product flows, they are more easily tracked and quantified compared with the indirect costs. It is important to specify that only the running costs of the models were considered while other types of costs such as the investment or the marketing costs were excluded because we assumed that they were equal both for the sales and rental model.

In addition, revenues were categorized according to Lewandowski (2016), namely by subdividing revenues as ‘input-based revenues’ when the company receives money by selling the ownership of a good and, ‘usage-based revenues’ when the company receives money by giving the right to customer to access the use of the product.

3.3. Model development

The starting point of the development of our method was the creation of the flowchart that represents the representative jacket life cycle (Fig. 2).

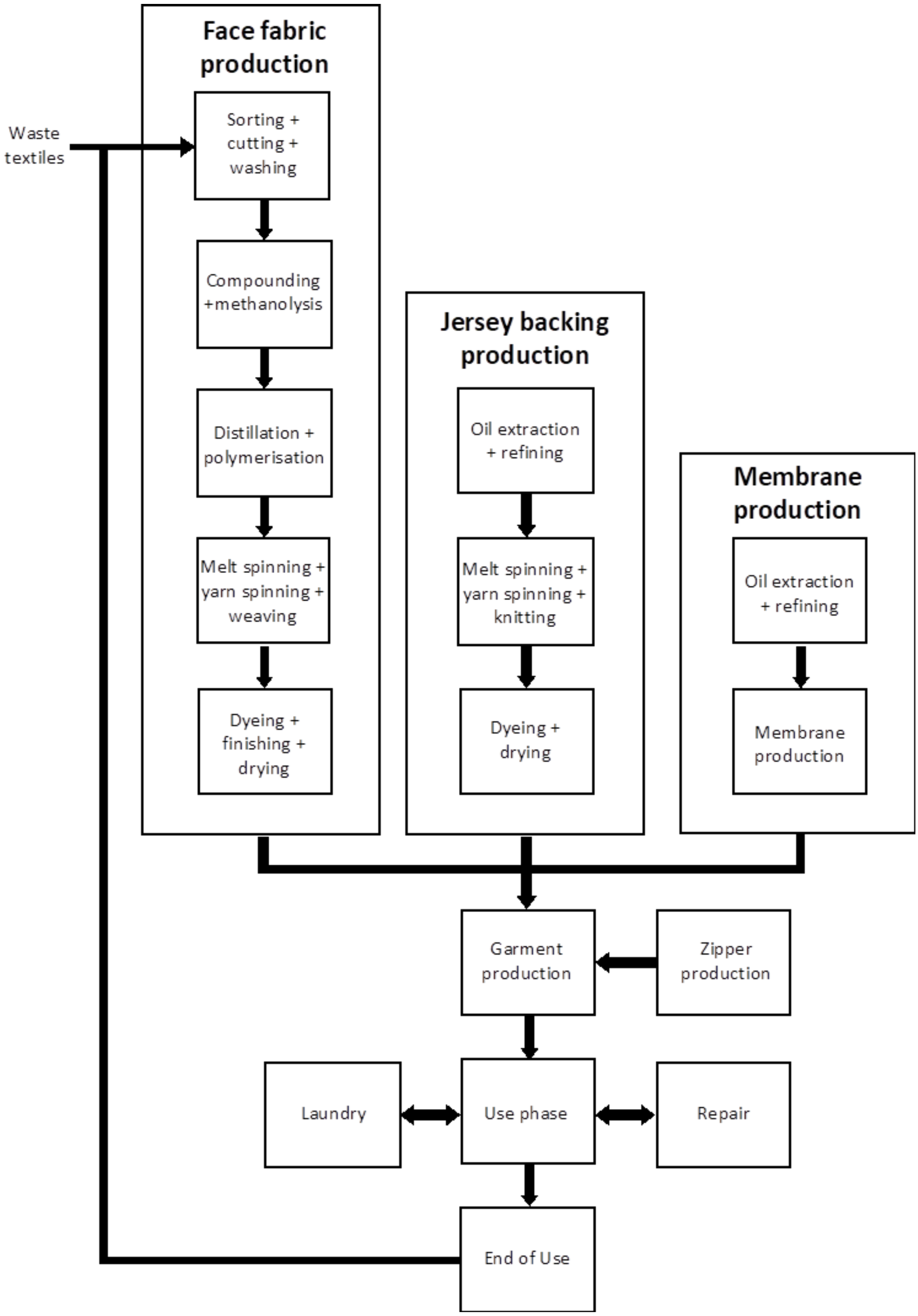

Figure 2 The figure shows the generic lifecycle of the representative jacket. In the flowchart, transports are represented by the black arrows outside boxes (Figure extracted from Böckin et al., 2020).

The flowchart was a generic representation of the processes to include in the assessment and it does not refer to any of the two specific business models.

Fig. 2 shows the traditional flowchart representing the technical system of a product. However, in order to investigate the business models a further step was necessary. By referring to Fig. 2 based on physical flows, then other two flowcharts were created to highlight actors involved, the interactions points and the monetary flows which characterized the two different business models (Fig. 3). In Fig. 3, the two flowcharts represent the sales model on the left and the rental model on the right, respectively.

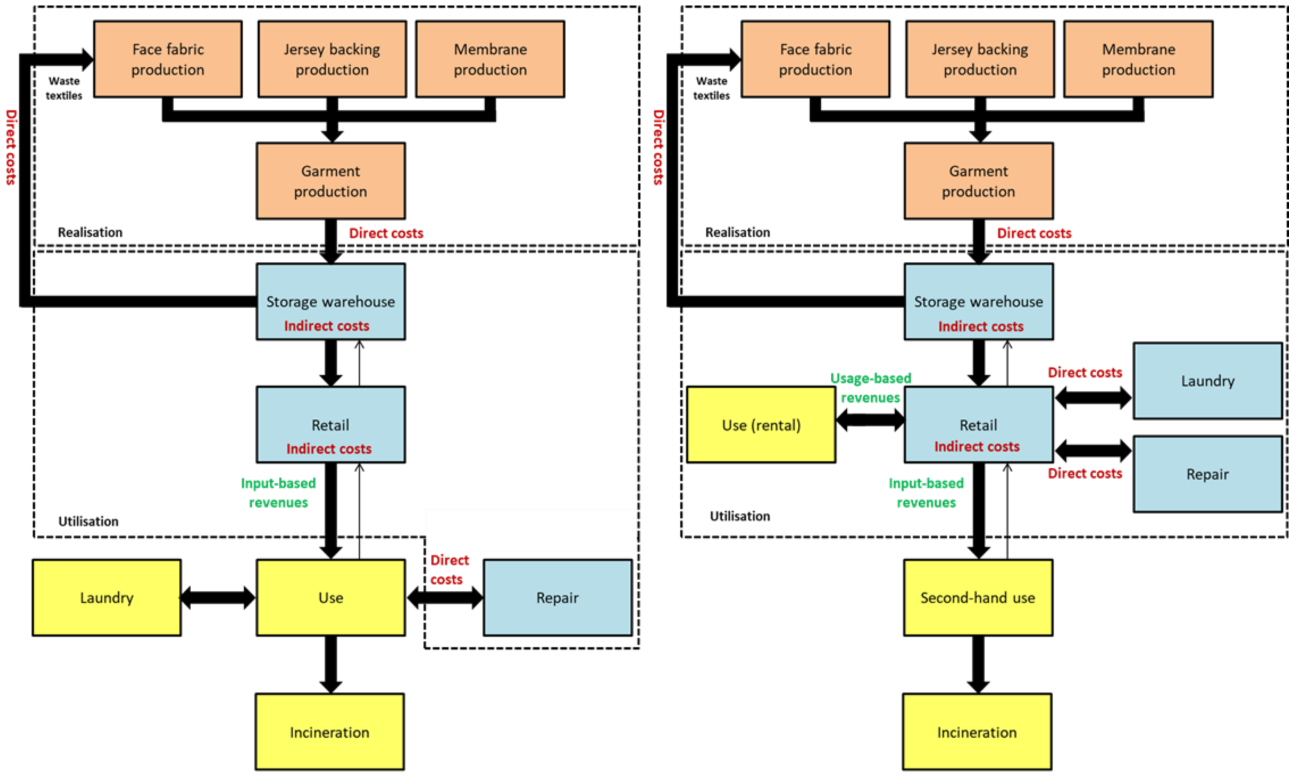

Figure 3 Life cycle flowchart showing the material flows in the two business models and the connected monetary flows that are associated with either a material flow or the activities in a process. The revenues are identified in green, conversely the costs in red (Figure modified from Böckin et al., 2020). The slim black arrows represent physical flows related to the returning of jackets from customers to the stores of the company and, from the store to the warehouse, when jackets are returned and collected in order to be recycled. When the collection of jackets for the recycling is not performed jackets are incinerated.

As it is visible from the flowchart, boxes are coloured differently. Red boxes stand for external suppliers that are involved during the textile production and the manufacturing production. Differently, the blue boxes symbolize phases where the company has the ownership of the product or is responsible for its handling (e.g. during the repair in the sales model the company is responsible for the reparation activities while it does not own the jacket). The yellow boxes represent the phases during which customers becomes owner of the product.

The change of colour of boxes is important because it indicates an interaction points where a product is exchanged between two different actors. The exchange of the product implies an economic transaction that may generate a cost or a revenue according to the company perspective. In addition, the identification of the borders within which the company has the responsibility over the product it is helpful to better identify indirect costs by considering the necessary activities to implement within the company for handling the product (e.g. costs necessary to store the products or to pay employees).

Once that monetary flows were identified by following the physical flows and by identifying the interactions points, costs and revenues were divided according do different categories as shown in Table 2.

Table 2 Categorisation and specifications about the cost structure and revenues streams for a representative jacket business model (Table modified from Böckin et al., 2020).

Monetary flows		**Cost variable name**
Interpretation/ subdivision	**Type**	
Production costs	Direct and variable costs (depend on volume of production)	C_{prod}
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}
End-of-Life costs	Direct and variable costs (depend on volume of collected jackets)	C_{EoL}
Input-based revenues	Product sale	RE_s
	Second hand sale	$RE_{r,2nd\ hand}$
Usage-based revenues	Rental service	RE_r

Production costs should be intended as aggregated type of cost that includes:

- Textile material production costs;
- Manufacturing costs;
- External distribution costs related to the transport of garments from the external suppliers to the central warehouse of the company where products are stocked.

Distribution costs deal with the transport activities necessary to transport jackets from the central warehouse to the company stores.

Overhead and employee costs are the only fixed or semi-fixed costs considered in this study. They depend on the number of stores and on the number of employee necessary to make the business model operative. In general, overhead costs are tied to activities to operate and administer the business model.

Maintenance costs are linked to the activities that the company performs to handle and maintain the products. Maintenance costs are divided in two sub-categories costs: laundry costs and repair costs.

End-of-Life costs represent the expenses that the company incurs to deal with end-of-life operations. In this case, the company was responsible to collect and store the old garments and transport them to the recycling plant.

Table 2 also represents the revenues that in the sales model revenues are only input-based, contrary, in the rental model revenues are both input and usage-based. Revenues were defined according to the specification given in section 3.2.3.

3.3.1. Definition of functional unit

The functional unit was established to be the profit defined as "a certain amount of profit π, over a business period, T, from the transactions of representative jackets for a company in the apparel sector" (Böckin et al., 2020). Adopting a profit-based functional unit means setting the economic performance as the basis of comparison of the business models.

Once that the cost structure and the revenue streams were identified a four-steps procedure was modelled in order to quantify the functional unit.

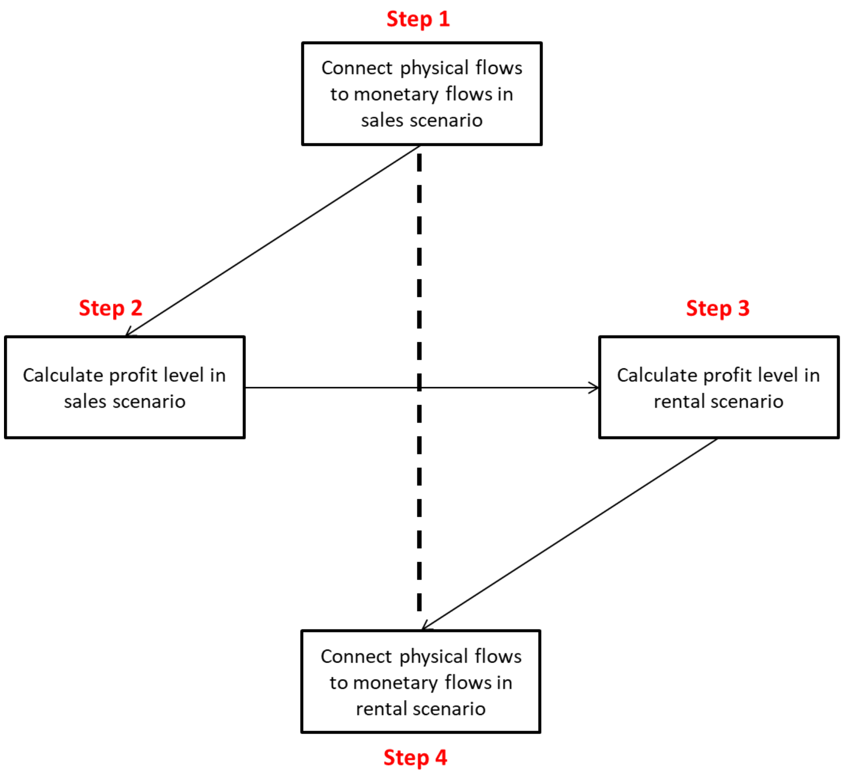

Figure 4 Procedure based on 4-step to find the number of transactions (t_r) and required replacement jackets (q_r) in the rental model, based on the monetary and physical flows in the sales model.

As it is visible from Fig.4, the procedure was based on a symmetrical and specular pattern.

During the first step, the physical and monetary flows were connected by taking into account the number of transactions that it is possible to achieve within a sales model and, the related number of jackets that it is necessary to produce. Determining the number of transactions and the number of products to produce allowed to calculate the total revenues and the total costs that characterise a sales model according to a company perspective. Indeed, direct costs and revenues were calculated in function of number of transactions or number of products to produce. During the second step, the profit was calculated as the difference between total revenues and total costs. In the third step, since the functional unit had to be the same for the two business models as required by ISO standards, we postulated the same level of profit as a starting point to analyse the sales and the rental models. Lastly, in the fourth step, once that the level of profit was set, the number of transactions and the number of garments to produce necessary to achieve the level of profit in the rental model were calculated. This enabled the identification of monetary and physical flows and connecting them.

However, if on a side, the quantification of monetary and physical flows of the sales model was easy to obtain, it was more complex procedure for the rental model.

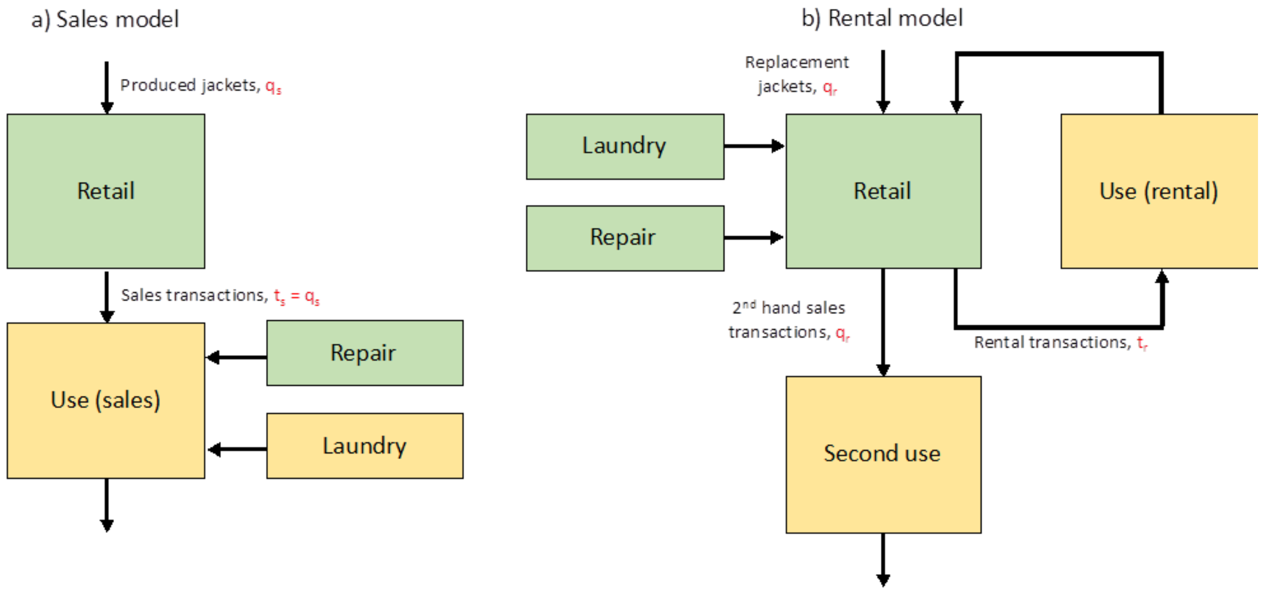

Figure 5 The image can be considered as a zoom on the retail and use phases already shown in flowcharts represented in Fig. 3. In this image, the attention is on the relation between the produced jackets and the number of transactions. Contrary to what happens in the sales model, in the rental model q_r and t_r are connected by a different relation. Figure extracted from the technical report (Figure extracted from Böckin et al., 2020).

As it is visible from fig. 5, in the sales model the number of transactions (t_S) corresponds to the same amount of products to produce (q_S) during a time T. Indeed, in the sales model it is expected that all the garments produced are sold. Contrary, in the rental model the number of transactions (t_r) does not correspond to the number of jackets produced (q_r) because the rental model operates according to a different logic. Indeed, in the rental model a garment is rented multiple times before to be removed from the rental service. New jackets are produced only when garments are excluded from the rental cycle. Therefore, before calculating profit and connecting costs and revenues with number of transactions or products to produce during an established time, it is necessary to understand what parameters affects the number of the transactions and the production of new garments in the rental model.

3.3.2. Rental model parameters identification and modelling

The stock of garments to rent is affected by the rental efficiency of the business model and by the average use days per rental transaction. The rental efficiency indicates the average share of stock that can be rented on any given moment in time and thus represents the amount of the stock that is available and that is not subjected to urgency to wash or repair garments, or to problematic related to imperfect renting (Böckin et al., 2020). Instead, the average use days represent the average period of time during which jackets are used by customers.

To explain how these two parameters affect the rental model an example is provided: assuming that the company acquires 50 jackets to perform a rental model and , during the first week of the rental service 10 jackets are rented, the company should be aware that during the second week the average share of stock is lower than 50 jackets. In fact, some jackets may be still rented while others need to be laundered or repaired. These aspects affect the number of possible transactions during the second week and, so on. In mathematical terms, this condition is expressed by the following formula:

Equation 1:

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

Where, t_r expresses the number of transactions; E_r the rental efficiency; U_r indicates the average use days per rental transaction and; Q_r and T represent the total stock of garments that the company owns and include in the rental service and the time period considered ,respectively.

In addition, the replacement rate is another parameter that affects the rental model in terms of product to produce. Indeed, once that garments are worn out, they are removed from the rental service implying the production of new jackets. Therefore, the number of products to produce depends on the total stock of garments and the rate of replacement according to the following formula:

Equation 2:

$$q_r = R_r * Q_r$$

where q_r represent the number of jackets that the company needs to produce during the time T and R_r is the rate of replacement of garments.

However, by considering Equation 1, it is also possible to connect $Q_r$and t_r in the following way:

Equation 3:

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

Consequently, on the basis of Equation 2 and 3, the relation between q_r and t_r can be expressed as Equation 4.

Equation 4:

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

However, t_r is also affected by the store size (SS) that can be defined as "the maximum capacity of the rental stock that each store can sustain" (Bockin et al., 2020). SS depends on number of stores (N_r) where the company wants to implement a rental service and the total stock of garments.The relation between N_r and t_r is expressed in the following formula:

Equation 5:

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

3.3.3. Connecting monetary flows with physical flows

Once that fundamental parameters of rental model were identified, it is possible to implement the four-steps procedure shown in Fig.4.

In **Step 1**, monetary flows of the sales model were connected to the physical flows by expressing costs and revenues in function of number of transactions or garments produced, respectively (t_s) or (q_s), as represented in Table 3. The monetary flows were divided according to the categorisation provided in section 3.4.

Table 3 Revenues and costs characterising the sales model. All the monetary flows are connected with the number of transactions or the number of garments produced with the only exception of overhead and employee costs that do not depend on change of quantities or volumes. Several help-variables are defined here, and the number 30 represents the days in a month, to convert between units of months and days (Table extracted from Böckin et al., 2020).

Monetary flows category	Monetary flows connected 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	$C_{emp} = k_{emp}*N_s*EPS*T/30$[4]
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	$C_{EoL}=k_{EoL}*q_s*CR$

In **Step 2,** monetary flows defined in Table 3 were included in a unique equation in order to calculate the profit, π_s, as the difference between revenues and costs (Equation 6).

[4] In our study, the time reference T was '30 days'. However, some of the costs considered referred to a month (e.g. employees and overhead costs). Therefore, the number 30 was included in formula to facilitate the possible conversion months/days in case the time frame differs from 30 days. For example, if T is established to be 45 days, then it is necessary to find how many months T is, which is 45/30 = 1,5 months.

Equation 6:

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

In **Step 3,** we postulated that π_r must be the same as in the sales model π_s and, thus $\pi_r = \pi_s$.

To conclude, in **Step 4**, costs and revenues were connected to t_r and q_r as shown in table 4.

Table 4 Revenues and costs characterising the rental model. All the monetary flows are connected with the number of transactions or the number of garments produced with the only exception of overhead and employee costs that do not depend on change of quantities or volume (Table extracted from Böckin et al., 2020).

Monetary flows category	**Monetary flows connected 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]	$C_{EoL} = k_{EoL} * q_r * CR$

Then, since we know the profit level, by referring to Equation 4 and 5, it is possible to calculate the number of rental transactions t_r by applying the following formula:

Equation 7:

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

Once that the number of rental transactions is calculated, it is possible to quantify the number of jackets to produce (q_r) by solving Equation 4.

[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

3.4. Establishing the goal and scope of the assessment

The aim of the assessment was to compare two different ways for a company to capture value from a product, and whether a rental model can lead to decouple environmental degradation from private profit. The object of the assessment was the business model of an apparel company for a represetative jacket while the time reference covers 30 days (one month). Data were collected through scientific literature researches, Ecoinvent (2019) database search, Web searches and online tools, personal communication with experts and representatives of the company. Generally, efforts to obtain specific data from the company about the setting up of business models were done in order to perform an assessment as more realistic as possible. Contrary, data about the technical processes stems from other researches (e.g. Roos et al., 2019) due to lack of site-specific data availability. Thus, in this case secondary data and processes were mainly used.

As far as concerned the impact categories to be assessed, the company was interested in investigating a wide range of environmental impacts. For this reason, we adopted the following midpoint impact categories (Table 5). In addition, to simplify the running of the sensitivity analysis impacts were also assessed through the weighted endpoint method ReciPe (H,A). The software used for the assessment was OpenLca.

Table 5 The table represents some of the impact categories considered in the assessment.

Mid-point indicators considered in the assessment
Climate change
Ozone layer depletion
Freshwater eutrophication
Marine eutrophication
Terrestrial eutrophication
Photochemical ozone creation
Respiratory effects, inorganic
Freshwater acidification

As far as concerned the definition of the functional unit, which is a fundamental element to establish during the goal and scope definition phase, a new method based on the systemic approach was developed according specifications provided in sections from 3.3.1 to 3.3.3. Values of variables and parameters that define business model will be provided in section 3.5.

3.5. Life Cycle Inventory

This section deals with the creation of the data inventory. Both monetary and physical flows involved in the business model based on the representative jacket were modelled as following described.

3.5.1. Monetary flows and business models parameters modelling

Many of data related to costs were directly provided by the company through personal communications such as in the case of reparations, laundry and overhead costs.

Reparations costs occur for the 4% of transactions both for the sales and the rental business model while costs for laundry occur after every transaction but only in the rental model[7]. Overhead costs are semi-fixed and depends on the number of stores. Production costs were obtained indirectly by considering the sales price of a jacket (which is established by the company) and establishing a mark-up margin based on evidences from the sector.

Employee costs are semi-fixed and depends on the number of stores, however, their modelling required a research in literature. From Business Sweden (2019) it emerged that in Sweden the average salary for a shop assistant is about 26200 SEK/month. Therefore, we estimated the costs of employee by summing at the average salary a 50% of surplus. 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. To conclude, the End-of-Life costs which represent the costs of transport by truck and cargo ship to send garments back to the suppliers in order to be recycled, they were estimated by summing costs related to transport via land modelled according to knowledge provided by Maibach et al. (2006) and by adopting the World Freight Rates (2020) as calculation tool. Indeed, World Freight Rates (2020) automatically calculates the route and the average expenses of transport by cargo-ship based on the characteristics of the product.

In the following Table 6, costs and business model parameters are summarized and quantified. Fundamental parameters such as the number of jackets to produce during the time T in the sales model (q_s) and the number of transactions (t_s) were defined at the beginning of the assessment. Contrary, for the rental model parameters such as t_r and q_r were derived according the equations presented in section (3.3.3). In addition, Table 6 shows the technical lifetime and the rental

[7] Costs related to the laundry were considered only in the rental model since in the sales model customers are responsible for the washing of garments.

lifetime of jacket, which were estimated by the representatives of the company according to their empirical experience.

Table 6 List of all the parameters (and their values and sources) used in the definition of the functional unit (Table extracted from Böckin et al., 2020).

General parameter values			
Symbol	**Name**	**Assigned value**	**Source**
T	Time	30 days	Defined
EPS	Number of employees per store	1	Provided by the company
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 3.3)
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 3.3.3)
q_r	Number of jackets produced during the period T	28 jackets	Derived (see section 3.3.2)
Q_r	Stock of product required to fulfil service in the rental model	308 jackets	Derived (see section 3.3.2)
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 3.3)
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	0,091	Derived (see section 3.3)
E_r	Rental efficiency	0,6	Provided by the company
U_r	Average use days per rental transaction	5 use days	Provided by the company

3.5.2. Physical flows modelling

Physical flows were considered by taking into account the flowchart shown in Fig. 2 which refers to the representative jacket. The three different layers of the jacket required three different production processes. The face fabric is partly composed by recycled polyester which is produced through a chemical recycling process in Japan. Contrary, both the jersey backing and the membrane are completely made of virgin polyester and required two different production processes that still occur in Japan. Once that the textile production is over, the three layers are laminated together and then sent in Estonia were the textile is manufactured and combined with zipper and the final jacket is produced. Generally, as far as concerned background processes, the electricity mixes were match to the location where processes happen while other the heat and other energy supply were modelled as generic global average for the textile production but as European average for all those processes that take place in Europe (Böckin et al., 2020). Ecoinvent (2019) was considered as main database.

In the following sub-sections, an overall description of the processes considered in the assessment is provided. The modelling choices based on the assumptions and choices made in Böckin et al., 2020 together with the sources considered are presented in Appendix A. In addition, it is also presented the mass balance sheets obtained by considering the yield of the processes included in the assessment.

3.5.2.1. Face fabric production

The polyester face fabric of the jacket is mainly produced through a chemical recycling process which is based on six phases namely washing, shredding, compounding, methanolysis, distillation and polymerisation. During the first two phases (washing and shedding) garments are washed and then shredded in many pieces. Then, during the compounding and the methanolysis stages, the PET-polymers are broken down into Dimethyl Terephthalate (DMT) first through a reaction with ethylene glycol and a sodium carbonate catalyst and subsequently by using methanol. The output of the compounding and methanolysis processes is a mixture of DMT and ethylene glycol that are separated through a distillation process. Lastly, through a polymerisation process, the mixture obtained from the distillation process is transformed in PET granules by means of an antimony catalyst. Once that the PET granules are produced the chemical recycling process of polyester is concluded.

However, in order to produce the polyester textile three further processes are necessary: the melt spinning, the yarn spinning and the weaving. During the melt spinning, the PET granules are melted, then through the yarn spinning and the weaving the polyester is transformed into a fabric and then dyed.

3.5.2.2. *Production of jersey backing and membrane*

The jersey backing is made of knitted polyester derived from synthetic fibres based on crude oil. Therefore, the two first processes for the production of the jersey backing are the extraction and the refining of the oil. Subsequently, a polymerisation process produces polymers in the form of PET granules.

As it happens for the production of the face fabric, also in the case of the jersey backing, once that PET are produced they are melted through a melt spinning process and transformed into fibres through a yarn spinning process. Contrary to what happens for the production of the face fabric, in this case fibres are knitted into a fabric.

The membrane is produced through the same processes, which, however, need different amounts of inputs compared to the jersey backing as it is shown in Appendix A.3.

3.5.2.3. *Production of other components*

The zipper is assumed to be made of virgin polyester and it generically and simply needs polyester granulate input.

3.5.2.4. *Garment production*

During the garment production, first, the face fabric and membrane are laminated together and subsequently, all layers are sewn together. Once that the layers are combined the jacket is finished with the addition of a virgin polyester zipper, and taping, by means of an 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.

3.5.2.5. *Transport*

The external transport from suppliers to the warehouse of the company covers the distance shown in the Table 7.

Table 7 Average distance covers to deliver jackets from the suppliers to the warehouse of the company and type of vehicle.

Location	Distance for one way trip (km)	Means of transport
Japan-Estonia	21655,74	Freight cargo ship
Estonia harbour- manufacturing company	3,1	Truck
Estonia-Sweden	497,42	Ferry
Sweden harbour- warehouse	38,8	Truck

Once that jackets are delivered to the warehouse of the company, they are internally distributed to the different stores by truck. The average distance between the warehouse and the stores is about 410 km.

During the use phase, transport average data were provided by the company according their empirical experience. The average distance between user residence and the stores is 5 km per trip. According to the data of the company, customers move to the store by using the type of transport shown in Table 8.

Table 8 Customers transport habits expressed in percentage.

Means of transport	Percentage
Public transportation	40%
Car	20%
Bike	20%
Walk	20%

In the sales model it is expected that customers perform one trip to buy the jacket and one trip to return to the residence while in the rental model trips are doubled since customers need to return the jackets after the use. In case of return of the jacket for the recycling, two additional trips are expected. It is important to note that all the distances may be over-estimated. Indeed, in this modelling all the impacts are allocated to the jacket, but in reality, it may be highly possible that customers during one trip pursue more than one purpose.

3.5.2.6. Use

During the use phase two main processes are considered: laundry and repairs. In the sales model, the users are responsible for laundry, but repairs are carried out via the company. In the sales model it is expected that on average a user washes each jacket 9 times during 5-year life length (Roos et al., 2015). Considering that in our study the jacket has a technical life time of 10 years, we estimated that a jacket is washed on average 0,15 times per month. Jackets are washed using a temperature of 40° C while, we assumed that the average load during wash of 60% (Roos et al., 2015).

Contrary, in the rental model jackets are washed after every transaction (case company, personal communication, Decembre, 2020). Also, in this case, we assumed that the laundry occurs at 40° C, however, contrary to what happens in the sales model, there is loading of 100%, because the company makes the effort to always wash full loads. 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 simplified manner as the electricity consumption of a tumble dryer, again according to Roos et al. (2015).

Regarding repairs, we assumed that reparation activities are the same both for the rental and the sales model. According to the company, reparation occurs at an average rate of 4% of every rental transaction. Assuming that every rental transaction corresponds to five use days on average (see Ur in Table 6, section 4.3), 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.

3.5.2.7. 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, but we assumed that the collection rate is 50%. The returned jackets are transported back to Japan in order to be recycled through the chemical recycling process. In this case, the End-of-Life was simple modelled as transport according the data shown in Table 9. The remaining 50% of jackets that are not collected are assumed to be incinerated via municipal waste management. The allocation of benefits from recycling was modelled via the mass balance.

Table 9 Average distance covers to deliver End-of-Life jackets from the company operating in Sweden to the supplier in Japan.

Location	Distance for one way trip (km)	Means of transport
Stores-Warehouse	410	Truck
Warehouse- Sweden harbour	38,8	Truck
Sweden-Japan	21650	Freight cargo ship

3.6. Results and interpretation

In this section, the results obtained from the quantification of costs and revenues and from the Life Cycle Impact Assessment are presented. Moreover, because our analysis was based on several assumptions, we carried out a sensitivity analysis to assess the robustness of our findings. Therefore, a summary of the main outcome of the sensitivity analysis is presented, while for further specifications is possible to look at the Appendix B.

3.6.1. Costs and revenues quantification

Establishing the profit as functional unit allowed to quantify costs and revenues generated by the two different business model. Fig. 6 shows how the sales and in the rental model present different cost and revenue amount and composition. In the sales model costs are mainly related to the production of garments, whereas in the rental model employee costs are the largest cost. It is also clear that the main revenues in the rental model are from rental transactions rather than 2nd hand sales.

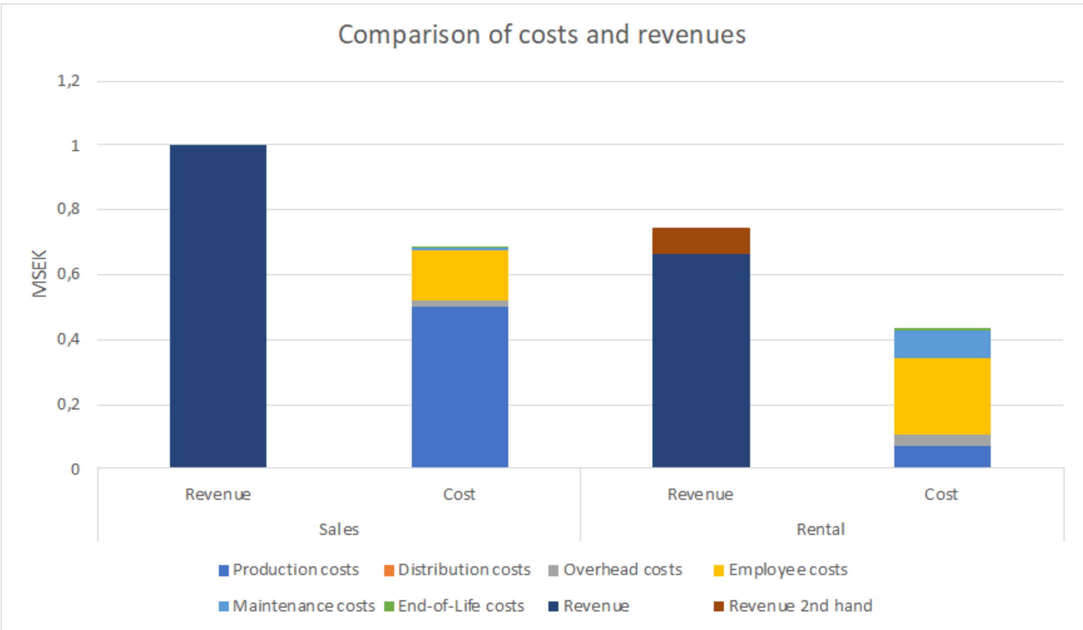

Figure 6 Economic performance of the sales model (on the left) and of the rental model (on the right). Revenues and costs are expressed in million SEK (MSKE). (Image extracted from the technical report)

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. Contrary, 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).

3.6.2. Assessment of the environmental performance of the two business models

From the life cycle impact assessment emerged that the rental model allowed to reduce impacts per amount of generated profit for many of the impact categories considered (Figure 7).

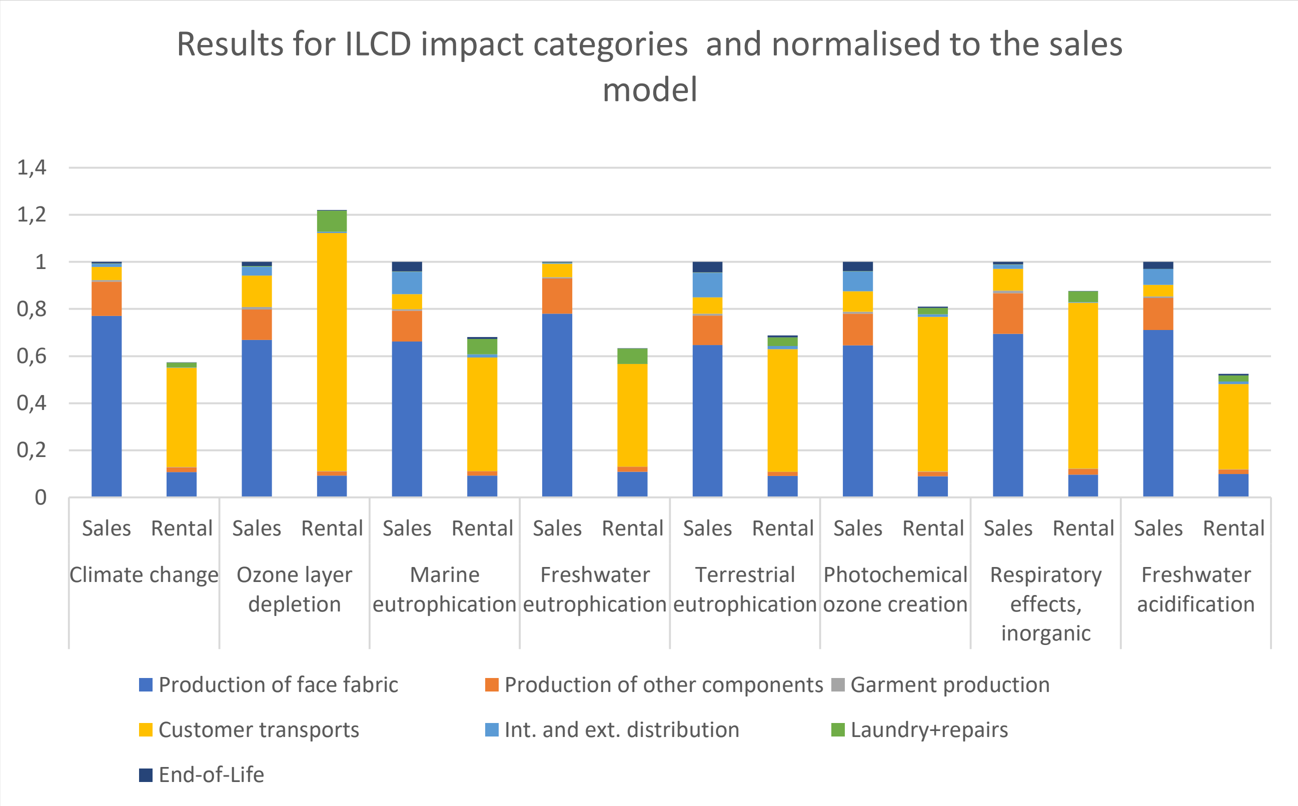

Figure 7 Impact assessment results per functional unit for eight different impact categories, normalised to the sales business model.

Starting from the climate change impact category, the rental model reduced by 43% impacts compared to the sales model. Similarly, marine, freshwater and terrestrial eutrophication showed reduced impacts in the rental model by 32%, 37% and 31%, respectively, while impacts related to the freshwater acidification were reduced by 48%. Photochemical ozone creation is reduced by 19% in the rental model, while respiratory effects are reduced by 12%. Contrary, the ozone layer depletion impact category was characterized by an increase of impacts of 22% compare to the sales model.

The reason why most of the impact categories presented a reduction of impacts in the rental model compared to the sales model was related to the lower production of jackets. Indeed, in the rental model, during one month, it is necessary to produce only 28 jackets while in contrast in the sales model the number of jacket produced is 200. However, Fig. 7 shows that the rental model shifts the impacts from the production to the use phase. Indeed, customers that rent jackets have to do many more travels to pick the jacket up and then return it.

Figure 8 represents impacts aggregated into the weighted endpoint indicator which summarizes the results previously obtained. As can be seen, from an overall perspective the rental model leads to reduced impacts by 33% compared to the sales model and the shift of impacts from the production to the consumption phase is observed.

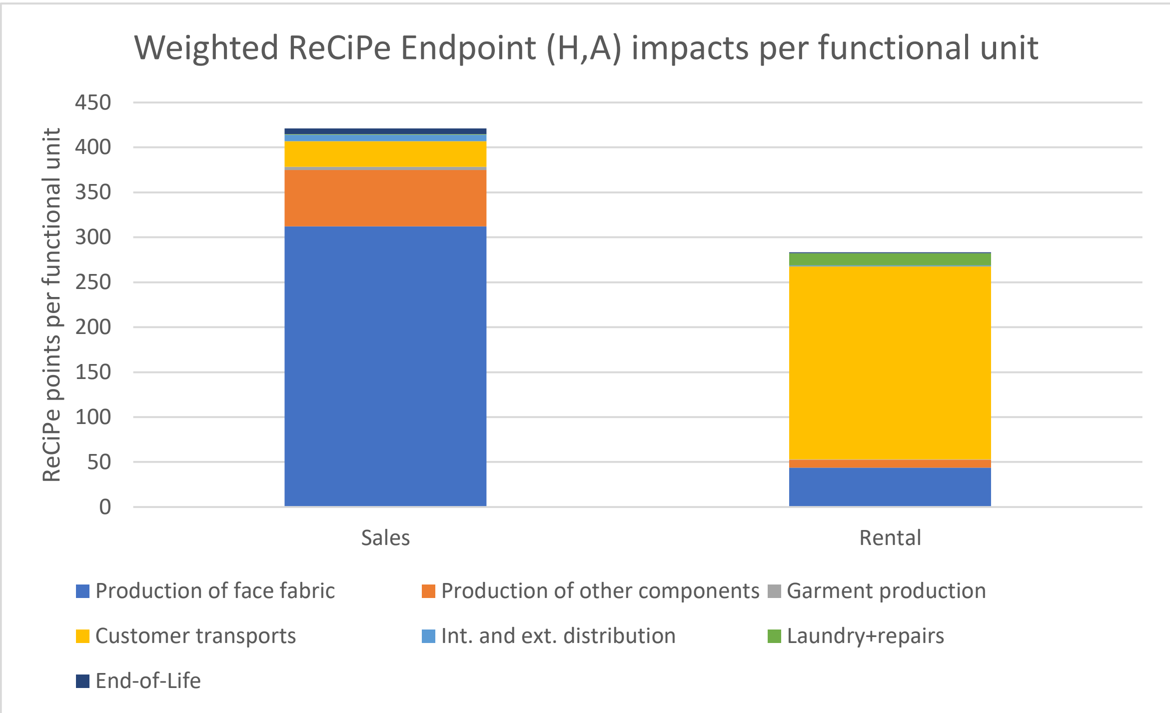

Figure 8 Weighted and aggregated results per functional unit in the sales and rental model by adopting the ReCiPe (H,A) as endpoint indicator.

Figure 8 represents the baseline scenario considered in the sensitivity analysis. The sensitivity analysis was performed by testing the dominant phases of the life cycle (customers transport, energy intense processes, laundry practices and production location) and the business model parameters (rental and sales prices, rental efficiency and hybrid rental services). From the sensitivity analysis emerged that on an overall level the results are robust, nevertheless, the two business models are particularly affected by some key parameters.

By considering the dominant phases, the sales model is strongly affected by the change of the location of the processes that are necessary to produce the textile. Indeed, the textile production processes imply a high consumption of energy. Therefore, the change of location in countries with low-carbon energy intensity (e.g. Sweden) allows the reduce the 33% of the environmental impacts (Appendix B).

Contrary, the rental model is strongly affected by the customers habits. The sensitivity analysis revealed that when all customers drive in order to pick the jacket up and then return it, the environmental performance of the rental model is strongly compromised with an increase of impacts about 241% (Appendix B). Conversely, when the totality of customers only use bike, the rental model allows to reduce the 64% of environmental impacts (Appendix B).

On the other hand, the choices made by the company to set up the rental model are fundamental in order to guarantee a good environmental performance (Appendix B). Establishing a too low price can in fact dramatically doubling the impacts of the rental model, since more rental transaction would be necessary in order to obtain the same level of profit and, consequently, also more jackets to be produce. Contrary, a higher rental price allows a reduction of impacts by 51% according to a reverse logic which requires fewer rental transactions and fewer jackets to replace. Although with a lower magnitude, also, the rental efficiency affects the rental model environmental performance due to the inability of the company to effectively use its own stock of jackets to generate profit, leading to a major number of transactions and jackets to produce. Lastly, also introducing in the rental model elements of product sales, increase impacts by the 74%. Higher impacts in the hybrid rental model are caused by the premature removing of jackets from the rental service, which impliesthe production of new jackets. This condition compromises the principles on which a use-oriented system is based making it closer to a product-oriented system where the ownership is sold (Böckin et al., 2020). In addition, the hybrid rental model loses the benefits that stem from the generation of rental revenues linked to the multiple rental transactions. Thus, to reach the same profit as the sales model, more rental transactions are required overall.

3.7. Discussions

From the results, it emerged that on an overall level the rental model allowed to reduce impacts according to the majority of the impact categories while maintaining at the same time the same level of profitability of the sales model. This result was achieved by renting multiple times the garments in order to generate more revenues in total compared with the sales model and by reducing at the same time the number of jackets produced. In addition, results proved that the rental model better contributes to achieve the decoupling of the private profit from the environmental degradation. Indeed, to achieve the same level of profit generated by one jacket in the rental model, 7.13 jackets are necessary in the sales model.

Despite the rental model proved to be a promising business model in order to reduce the environmental impacts, some key factors, such as the the business model set up and the transport of customers, can strongly affect the environmental performance of the rental model.

Considering the business model set up, companies should be careful on how they set their prices, what efficiency they can achieve and whether they incorporate elements of product sales into their rental model. Usually these aspects are considered to the extent they contribute to achieve maintaining or increasing an established level of profitability. However, from the case study clearly emerged that they are also fundamental parameters to take into account in order to not compromise the environmental sustainability of the company. Therefore, companies that implement a rental business model should be aware that such parameters can have a double effect both on an economic and on an environmental perspective. For example, the establishing of the rental price should be based on a side on the willingness to pay of customers, their preferences but, on the other, it should also consider the number of transactions and the related number of produced jackets.

Moreover, the rental model was strongly affected by impacts related to customers transport in the use phase. The sensitivity analysis revealed that customers transport by bike can drastically improve the environmental performance of the rental model, conversely, the transport by car can strongly reverse the ranking of the most environmentally sustainable business model making the sales model the preferred choice. Consequently, it emerged that aggregated private choices can dramatically change the final assessment of the rental model which requires a higher collaboration between companies and customers in order to protect the environment. Thus, it becomes crucial to develop knowledge on customer behaviors to better manage and foresee collateral effects related to the business model. From their side, companies can try to orient and influence customers habits to more sustainable practices through communication programs and activities aimed at increasing environmental awareness. In addition, companies could also strongly contribute in monitoring of customers choices, reducing uncertainties or filling the gaps in the field of customers behaviors knowledge.

Other parameters that can affect the environmental performance of the company are related to the energy consumptions. Indeed, intensive laundry practices can reduce the environmental sustainability of the rental model. Similarly, when the production is based in low-carbon energy countries, impacts are hugely reduced, proving that the sales model can be even better than the rental model. Therefore, companies working in the apparel field could exercise pressures on their suppliers in order to use sustainable electricity.

Some limits of the study performed and inherent to the economic dimension of the two business models regard the absence of a long time perspective, which leads to not include considerations about the time-value of money and the related discounting operations. Therefore, the long-term economic risks that might affect the possibility of the company to implement a rental model were excluded from the analysis. In addition, only recurring costs and revenues were considered. This meant omitting investment, acquisition and design costs for example. In addition, customers preferences related to tangible and intangible values (Tukker, 2015), such as price differences and the sense of control over the product, respectively were not investigated. Regarding the customers preferences, Tukker (2015) also highlighted as in use-oriented system, customers behaviors may be characterized by a less-careful use of products when compared to ownership.

Another important gap is the absence of the toxicity effects related to the production of jackets. In the apparel field chemicals may play crucial part on human health and on the environment. However, toxic chemicals are poorly characterized in the LCA field due to the lack of data and of characterization factors (Roos et al., 2019) and this condition difficulty allows to properly assess the contribute of the textile industry in terms of impacts.

Lastly, another important limit regard the possibility that the technical lifetime of a jacket can be affected by the frequent laundry practices. Although, from literature emerged that garments in the outdoor sectors are less affected by washing than cotton T-shirt (Schellenberger, 2019).

3.7.1. Methodological insights

The study presented in this chapter is characterized by a methodological novelty related to the creation of a profit-based functional unit. In order to highlight what are the main strengths of this method, a comparison with more the conventional LCA and LCC simultaneous application is here provided.

In the Life Cycle Thinking field, applying simultaneously LCA and LCC is one common procedure to include in the assessment both the economic and the environmental dimensions of sustainability. However, by considering already existent studies in literature (Kaddoura et al., 2019; Zhang et al., 2018) it can be observed that such approach presents crucial limitations in terms of integration of the environmental and economic dimensions. Indeed, in the mainstream practice LCA and LCC are performed in parallel giving as outputs two independent results referred to the environmental and economic performance, respectively. Although, such application of LCA and LCC is useful to evaluate the overall performance of a company in the environmental and in the economic dimension, it does not allow to understand the link and the existing relations between physical and monetary flows. In other words, the parallel application of LCA and LCC do not enable to measure the magnitude of a change in one of the two dimensions and the consequent impact on the other. In some way, it is possible to say that the application in parallel of LCA and LCC answer to the logic of the interconnection of the three different spheres of sustainability. However, as it was already noticed, such representation of sustainability present the limits to consider the dimensions as separated.

In contrast to the parallel application of LCA and LCC, the method of the profit-based functional unit embodied the logic of the pyramid representation of sustainability. The profit-based functional unit enables to observe the interconnections between physical flows and monetary flows on a side, and, on the other, the feedback loops that occur once that a variable is change. The connection between physical and monetary flows was pursued through the identification of two relevant variables, the number of transactions and the number of jackets to produce within an established time frame in order to calculate the profit, while feedback loops were measured and presented through the sensitivity analysis. From the sensitivity analysis, it emerged how the change of business model parameters (e.g. price, rental efficiency) can strongly affect the environmental performance of a company. In addition, the results also show how the social behavior in terms of customer transport habits become relevant for a more sustainable environmental performance, opening the way for new debate on the consumption model and possible policies to implement to make consumption more sustainable and create awareness in customers. Therefore, the profit-based functional unit shows how the three different dimensions are not separated and how pursuing a sustainable transition requires multiple measures and actions that take into account not only technological processes but also economic parameters and social aspects, which entail the involvement of decision makers in the business and political field in order to orient customers towards to more sustaianable behaviours.

4. Assessing the level of circularity of a territorial system

4.1. The scientific background

Due to many environmental issues (e.g. climate change, loss of biodiversity, ocean acidification) that strongly compromise the ability to sustain life in the future, societies must develop alternative paradigm of production and consumption in order to operate within safe operating space commonly known as planetary boundaries (Rockstrom et al., 2009).

Contrary to the most traditional and applied linear paradigm, the Circular Economy (CE) concept seems to be promising in order to reduce the environmental impacts. Indeed, the core message of CE is to conserve the natural capital by "reducing wasteful resources through effective design and implementation of products and processes for improved resource-efficiency with circular material flow involving recovery, reuse, recycling and remanufacturing of products" (Jawahir & Bradley, 2016, p. 104).

In the scientific literature, despite the numerous definitions of the CE concept (Kirchherr et al., 2017; Korhonen et al., 2018), it is commonly accepted that CE and its traditional 3R principles, namely, reducing, reusing and recycling (Ellen Mac Arthur Foundation, 2017) can be applied on three different levels: micro, meso, macro (Prieto-Sandoval et al., 2018). At micro level, CE is applied on a company/industry level through pro-active behaviors that aim at improving the efficiency or the environmental performance of the company through the application of CE principles. At meso level, CE is applied within an industrial park according to industrial symbiosis practices. Lastly, at macro level, applying CE means encouraging the development of eco-cities, eco-municipalities or eco-provinces(Prieto-Sandoval et al., 2018).

However, the application of CE from theory to practice requires the intervention and the participation of national governments and local administrations (or other governmental or organizational bodies) in order to establish guidelines and policies for its advancement. This urgency was identified by Ghisellini & Ulgiati (2020) in their study about the CE transition in Italy. Similarly, Murray et al. (2017) pointed out as in China, which has a strong tradition in the CE field, the National Government actively participates in the elaboration of policies and programs for the implementation of circular measures. In addition, the Chinese Government, from 2007 is promoting a framework of indicators by referring to the 3R principles based on four main categories of indicators: resource output, resource consumption, integrated resource utilization, and waste disposal/pollutant emission (Geng et al., 2012). These categories then include different indicators in order to assess CE at macro and meso levels (Geng et al., 2012). Besides, Murray et al. (2017) highlighted as the National Development and Reform Commission, a Chinese Government agency, strongly encourages academic and policy experts to develop further CE indicators in order to broadly and comprehensively monitor CE both at macro and meso levels.

Among the possible different tools to assess the level of circularity of a system, LCA is seen as a promising methodology (Daddi et al., 2017) and it has already been used to assess the environmental performance of industrial parks (Dong et al., 2013; Singh et al., 2007; Boons et al., 2011) and wider geographical system (Eckelman and Chertow, 2009; Loiseau et al., 2014).

The aim of this research was to create a LCA-based set of indexes to apply to a territorial system in order to estimate the level of circularity, by referring to the impact categories traditionally considered in the LCA field.

4.2. Model development

In this research, LCA was not applied in a conventional way by following the ISO standards, but it was considered as a reference framework to develop the model through which the index of circularity is created based on several impact categories.

Particularly relevant for the study was the concept of impact category to be intended as "issues of concern to which LCI results may be assigned" (ISO 14040,2006). In this study, the impact categories recommended by the International Reference Life Cycle Data System (ILCD) are all considered as potential midpoint indicators to include in the assessment (Table 10). Impacts related to the same midpoint impact category that are caused by different sub-systems can be aggregated in order to calculate the overall level of impacts of a territorial system (described in section 4.2.1).

Table 10 Midpoint impact categories recommended by ILCD (European Commission, 2012)

Midpoint impact category
Climate change
Ozone depletion
Human toxicity, cancer effects
Human toxicity, non cancer effects
Ecotoxicity freshwater
Ecotoxicity marine and terrestrial
Particulate matters
Ionising radiation, human health
Ionising radiation, ecosystem
Photochemical ozone formation
Acidification
Euthrophication terrestrial
Euthrophication aquatic freshwater/marine
Land use
Resource depletion
Resource depletion – mineral and fossil fuels
Resource depletion – renewable

4.2.1. Description of ideal systems

The model is based on a two-steps procedure that investigates a territorial system delimited by geographical or administrative boundaries (e.g. related to property rights) in two different moment in time (t_0 and t_1). The territorial system includes different sub-systems that are responsible for the production of different products and services as final outputs. The sub-systems are investigated when they are fully operational at time t_0 and t_1.

At time t_0, the territorial system is named Q and, we assumed that all the sub-systems have a linear production and they are independent from each other. This condition implies that there is not recirculation of energy and materials, with the only exception of sub-systems working in series. In this last circumstance, the output of a sub-system can become an input for another. Consequently, all the inputs used in the production system come from outside the geographical boundaries of the territorial system.

At time t_1, the territorial system is named $\bar{Q}$ and appears as a black-box where the internal relations between the several sub-systems are unknown and only the inputs entering from outside the boundaries of the territorial system are trackable and quantifiable.

The environmental performance of Q and $\bar{Q}$ can be assessed by performing a LCA based on different impact categories shown in Table 7. The functional unit of the system is the whole annual production of the territorial system. The data inventory is created by considering all the inputs necessary to produce goods and services that are provided from outside the territorial borders during an established period of time. In this case, we assumed that the time frame is one year.
Aiming at clearly defining the nomenclature used in this study it is opportune to specify that the territorial system is investigated by considering:

- S_i , which refer to the several sub-systems that compose the territorial system. It is assumed that the sub-systems are the same during the time that pass from t_0 to t_1.
- O_j and $\bar{O}_j$, which represent the final products produced by the several sub-systems and that are expected to be the same for the territorial system at time t_0 and t_1 . The letter "j" refers to the different types of products and services that can be produced within the territorial system (e.g. food, public transport, renewable energies etc.);
- A_k and $\bar{A}_k$ represent the total impacts caused by the production of the final products at the two different points in time. The letter "k" indicates the several impact categories (shown in Table 11) through which impacts are calculated.

Table 11 Definition of variables considered for the elaboration of the circular index

Sub-systems	Outputs	Impacts categories
	Macro-system Q	
S_i 1 ↓ i n	O_j 1 ↓ j p	A_k 1 ↓ k m
	Macro-system $\bar{Q}$	
S_i 1 ↓ i n	$\bar{O}_j$ 1 ↓ j p	$\bar{A}_k$ 1 ↓ k m

4.2.2. First-step model

In a first phase of the model, Q is considered in order to calculate its environmental impacts. Therefore, the S_i (S_i, $i = 1, \ldots n$) sub-systems that characterized Q are considered together with their related final outputs O_j ($j = 1, \ldots, p$).

As it was already specified in section 4.3.1., the sub-systems work according to linear paradigm principles and they are completely independent from each other, with the only exception of sub-systems working in series (represented by o_{S1} in Figure 9).

Due to this condition of linearity, there is not recirculation of flows within the macro-system and all the input necessary for the production come from outside the geopolitical borders of Q.

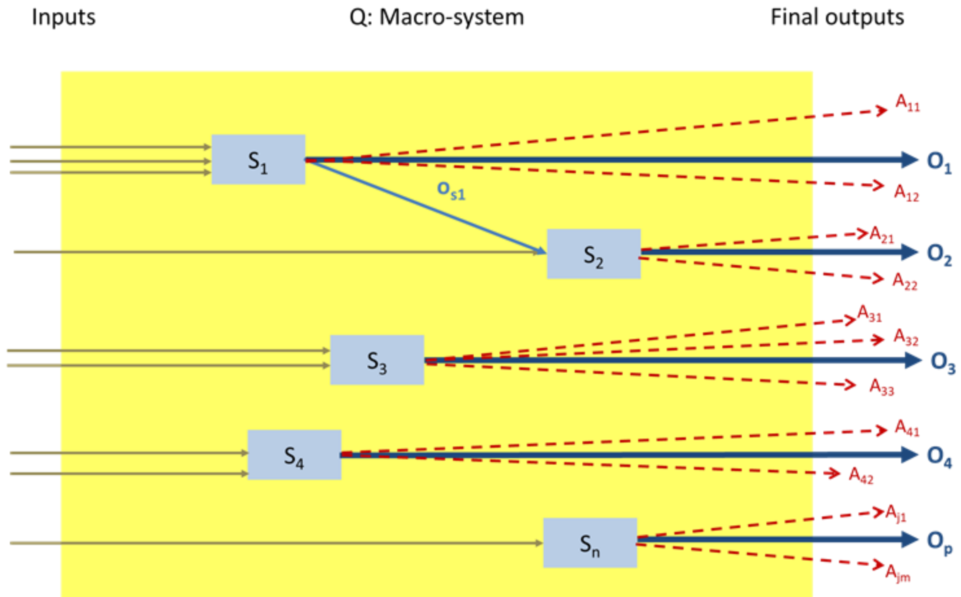

Figure 9 Sub-systems in a linear paradigm. The yellow box represents the boundaries of the macro-system Q which is made of a number of sub-systems S_i (i=1,..,n). The grey arrows on the left are external inputs to the production processes of the sub-systems which are independent of each other. For each process/sub-system, the outputs, O_j (j=1,…,p) - blue arrows – and related impacts, belonging to k impact categories - red dotted arrows – are shown on the right.. The blue thin arrow that connects S_1 and S_2 indicates that part of the production of S_1 is used as input in S_2.

Inputs related to the final products are collected in order to calculate the total impact A for the different k impact categories.

The total impact corresponds to the sum of all the A impacts of all O_j product for a determined k impact category and it can be calculated by the following formula:

$$\mathrm{A}_k = \sum_{j=1}^{p} A_{jk}$$

In other words, by focusing on the environmental loads of the inputs used for the production of the different O_j it is possible to calculate the environmental impact according to an established impact category. For example the production of the different O_1, O_2,… O_p products may be responsible for the increase of emissions that contribute to climate change or to acidification environmental issues. Once that impacts are calculated for each O_1, O_2,… O_p product, then it is possible to sum them up in order to calculate the total impact on climate change and acidification of the entire territorial system.

4.2.3. Second-step model

In the second-step of the model, the procedure adopted for the calculation of the total impact is the same and we assumed that $\bar{Q}$ is composed by the same sub-systems S_i and produces the same final outputs $\bar{O}_j$ that also characterized the territorial system at the time t_0.

However, contrary to the previous situation, we assumed that, at t_1, $\bar{Q}$ appears as a black-box that does not allow to investigate how the different S_i are connected (Figure 10). Therefore, it is impossible to understand what kind of paradigm (e.g. linear or circular) of production is applied.

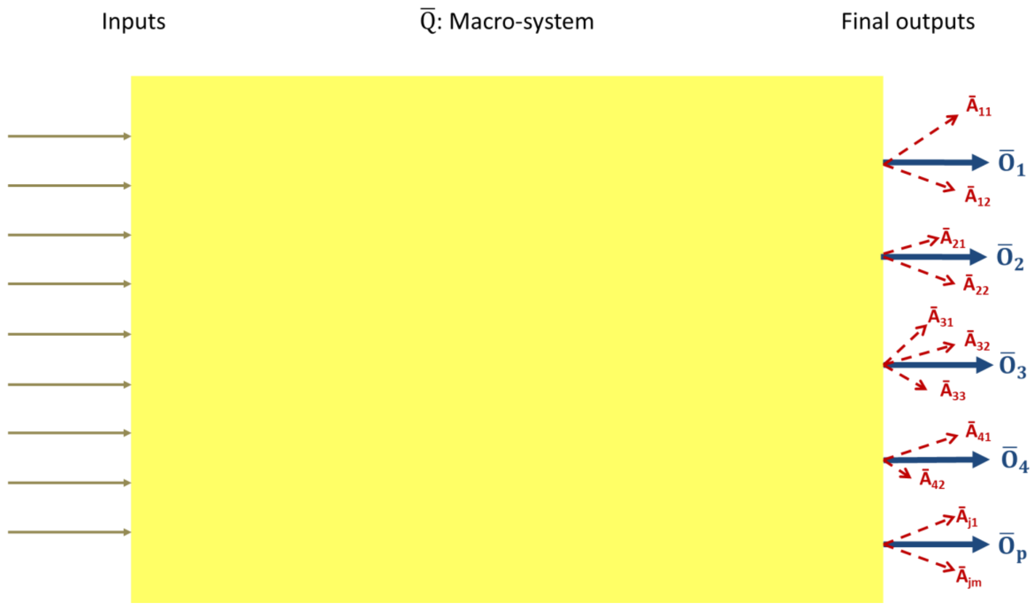

Figure 10 Macro-system representation as a black-box. The yellow box represents the boundaries of the macro-system $\bar{Q}$. The maco-system is still composed by sub-systems but we cannot see them. On the left, all the grey arrows represent the external inputs exploited during the production processes of the several sub-systems. The outputs, $\bar{O}_j$ (j=1,…,p)- represented by blue arrows - are visible on the right together with their respective impacts embodied in the red dotted arrows. Each red dotted arrow represents the impact that contribute to one of the $\bar{A}k$ (k=1,…, m) impact categories.

To calculate the total impacts related to the $\bar{O}_j$, also in this second step, the identification and the quantification of all the external inputs entering in the territorial system is necessary.

Then, the environmental loads of the inputs are converted through the different characterization factors in the different impact categories. Once that impacts referred to the different $\bar{O}_j$products are calculated, it is possible to sum up all the impacts in order to calculate the overall impact $\bar{A}_k$ per each impact category according to the following formula:

$$\bar{A}_k = \sum_{j=1}^{p} A_{jk}$$

Once that two total impacts, A_k and $\bar{A}_k$, are calculated, they are compared since they refer to the same sub-systems and the same final outputs produced within Q and $\bar{Q}$ during one year.

From the comparison of the two total impacts it is possible observing that if the total impacts of $\bar{Q}$ are lower than the one of Q, it means that some kind of circular principles has been adopted. In fact, since total impacts of Q and $\bar{Q}$ are strictly dependent on the external inputs that come from outside the territorial system, it is reasonable to assume that if the inputs that feed $\bar{Q}$ are lower than the one that feed Q it means that, at time t_1, the territorial system has implemented circular strategies that reduce impacts maintaining at the same time the same production amount of outputs $\bar{O}_j$.

By considering the total impacts $\bar{A}_k$ and A_k indicators, it is also possible to create an index based on the following formula:

$$C_k = \frac{A_k - \bar{A}_k}{A_k}$$

Where C_k represents the index of the level of circularity and it can vary between 0 and 1. When C_k tends to 0 it means that the sub-systems mainly work according to linear principles. Conversely, when C_k is close to 1, it means that sub-systems are applying circular principles. In the reality, C_k cannot achieve the value of 0 and 1, it can only tend to these extremes. Indeed, the only situation where C_k is equal to 1 is when $\bar{A}_k$ is zero. However, all production processes causes impacts and therefore this situation cannot occur in the reality. At the same way, $\bar{A}_k$ and A_k can hardly lead to the same level of impacts because the assessment is performed when the system is fully operative (at the end of the year) and circular measures should be already implemented compared to the situation at time t_0.

Once that all the indexes referred to each k category are calculated, it is also possible to obtained an aggregated index ($C_{aggregated}$) that on an overall perspective shows the level of circularity achieved within the territorial system.

4.3. Discussions

Historically, CE was pursued according three main principles usually refer as 3Rs: reduce, reuse and recycle. Jawahir & Bradley (2016) provide specifications about the over mentioned principles as following described as follow:

- Reduce refers to the reduction of use physical resources during the pre-manufacturing, manufacturing phase and the reduction of emissions and waste in the use stage.
- Reuse regards the utilisation of the product as it is (without destroying it) to reduce virgin materials to produce newer products and components.
- Recycle involves the process of converting material that is usually treated as waste, into new materials or products, maintaining its value.

According to Moraga et al. (2019), in literature, the 3R principles framework could be investigated by assessing five common different strategies focusing on function, product, component, material and embodied energy. From their literature review emerged that indicators used so far to assess CE are weak to assess circularity by encompassing all the different strategies. Most of the indicators focus on materials by considering the recycling process, while indicators focusing on functions are absent (Moraga et al., 2019). A similar conclusion was also achieved by Elia et al. (2017) whopropose a taxonomy established on index-based method type, which can refer to a single synthetic indicator or to multiple indicators and, on the parameters to be measured such as: material and energy flows (separately); land use and consumption; other life cycle based indicators. From their research it emerged that none of the indicators and the methodologies enables to assess and monitor all the different circular principles applied (Elia et al., 2017).

At political level, different frameworks based on several indicators exist. The Chinese Government, from 2007 is strongly encouraging CE and in order to assess the level of implementation it has developed a framework of indicators by referring to the 3R principles (Reduction, Reuse and Recycling) (Geng et al., 2012). Geng et al. (2012) describe the China's national circular economy Evaluation Indicator framework, as based on four main categories of indicators: resource output, resource consumption, integrated resource utilization, and waste disposal/pollutant emission. These categories then include different indicators in order to assess CE at macro and meso levels.

However, it may be possible to claim that the final goal of CE considering the environmental dimensions is to reduce pressures on the Earth System. Therefore, a complementary set of indicators that mainly focuses on the impacts rather than on the specific strategy to evaluate the territorial system may be helpful to assess the contribute that CE can offer in terms of environmental conservation and possibly human well-being.

With this perspective, in our work, the CE definition is close to what Murray et al. (2017) intend for CE: "an economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximise ecosystem functioning and human well-being". According to Moraga et al. (2019) this should be intended as a *sensu latu* definition that emphasises the sustainability and the effects of CE strategies on the environment.

The set of indexes based on the impact categories does not refer to a particular principle of CE but to some extent it is sensitive to all of them. Indeed, the set of indexes shows the effect in terms of environmental impacts of the implemented different strategies on a territorial system.

Since in our model, impacts are assessed by strictly considering inputs that come from outside the territorial system and the related outputs, if $A_k = \bar{A}_k$, it means that impacts entirely rely on external physical inputs. Conversely, if $A_k > \bar{A}_k$ it means that circular strategies occur. At the same time, the index $C_{aggregated}$, gives the percentage of circularity achieved within the territorial system. $C_{aggregated}$ can be considered as a synthetic indicator useful to monitor the CE level within a system and to include in the elaboration of local policies.

$C_{aggregated}$ is also a good tool to assess the efficacy of possible measures applied to the system (both the whole territorial system and every single system that compose it). Indeed, in literature is highlighted that some circular strategies adopted could be potentially environmentally unsustainable compared to more traditional linear solutions (Life Cycle Initiative). $C_{aggregated}$ is calculated starting from the set of indexes referred to each impact category. Therefore, it is possible to focus on each impact category index in order to observe how circular measures contribute to reduce or increase impacts. For example, if the index that refer to the resource depletion midpoint indicator shows a decrease of impacts in terms of used resources tending to one, it may indicate that within the territorial system a major recirculation or reduction of resources occur. Contrary, if the index that is based on the climate change shows a huge increase of impacts and tend to zero, it may refer to a condition where processes implemented strongly contribute to increase emissions compared with the situation assessed the year before. The method may be helpful to identify priorities in terms of need to reduce impacts related to a particular impact category that poofs that the environment is strongly affected by a determined environmental issue.

Besides, the $C_{aggregated}$ index may give also some information about the level of connections between the sub-systems. Indeed, it is reasonable to assume that C_k tends closer to 1, when i) each sub-system implements circular principles and ii) sub-systems implement a circular network to apply strategies of circularity outside their boundaries. In other words, in an ideal scenario where sub-systems have achieved all the complete circularity within their production systems, in order to further implement the circularity within the territorial system they need to collaborate by encouraging strategies such as recovering of materials and energy. Therefore, the $C_{aggregated}$ index is sensitive both to the implementation of strategies referred to site-specific production systems and to the increase of interconnections within the territorial system.

The main limits of the model regard the dataset necessary to assess the overall impacts and the fact that it is time consuming. In fact, the inventory construction should be done scrupulously in order to have a high level of accuracy in mapping the different sub-systems that insist on an area and to collect data to create a dataset of all the inputs that enter in the territorialsystem. The problem of availability of data is common to all the sustainability studies, including CE issues. The need of data, especially environmental, since economic and social ones have a long history of records, is one of the main "needs" to really pursue sustainability (and circularity): without the necessary data it is extremely difficult to plan policies in any direction (Bastianoni et al., 2019). Another limit regards the interpretation of impacts referred to the different impact categories. Indeed, due to the absence of knowledge about the strategies implemented, it may be difficult to properly interpret changes in the magnitude of impacts (negative or positive) for the different impact categories. Although, this method may be complementary with other indicators framework developed (e.g. the one provided by the Chinese Government) leading insights in the highlighted issues.

However, in order to stressed out possible new strengths or limitations, further empirical studies are necessary.

4.3.1. Possible applications

CE can be promoted by encouraging the implementation of circular strategies or by aiming at reducing impacts. The method suggested in this study could be consider a synthetic index to include in policies for the monitoring of CE. Indeed, the index can be considered representative of a trend towards CE of a territorial system and a tool of control for decision makers and organizations.

Indeed, local administrations may implement year by year programs for the monitoring by encouraging the screening of the sub-systems that act within a territory, the tracking of inputs and outputs and the reduction of impacts by means of circular strategies.

Despite the efforts to implement such a kind of monitoring are huge and important issues have to be faced such as the collection of data, successful experiences of similar programs of monitoring exist in literature.

For examples, the Province of Siena, from 2007, autonomously started to control and monitor the greenhouse gas emissions produced on its territory, giving life to the REGES Project “Project for the verification and certification of Reduction of Greenhouse Gas Emissions for the Province of Siena " (Bastianoni et al., 2014). The purpose of an emissions inventory is to monitor the progress of emissions into the atmosphere over time and to verify the pursuit of objectives of reduction that a given territory identifies in the different areas of its own environmental policy.

Similarly, applying the method developed in this study will lead to know the status of impacts on a local scale caused or improved by circular strategies helping to design, mitigate,-compensate scenarios and to intervene with effective measures in the context of specific territorial areas.

5. The social life cycle assessment and the concept of well-being

For many years, social sustainability was the most neglected dimension of sustainable development due to intents to prioritize environmental and economic issues in the political debate (Colantonio, 2009).

However, recently, political initiatives and laws are encouraging decision makers from the political arena and organizations to pursue social sustainability programs in parallel with the most traditional economic and environmental one.

Through a directive, the European Union establishes that public-interest companies with an average number of 500 employees need to include in the management report a non-financial statement that provides information about both environmental and social performance of the companies (European Commission, 2014). Similarly, the adoption of the Sustainable Development Goals require pro-active behaviors in order to achieve the sustainability in all its three dimensions by creating socio-cultural changes in the societies aiming at reducing negative social and environmental impacts.

Although, at this date, attempts to promote the social sustainability are many, the "understanding of this concept is still fuzzy and limited by theoretical and methodological constraints stemming from its context and disciplinary-dependent definitions and measurements" (Colantonio, 2009).

Chiu (2003) observed that in the literature, three main different interpretations of social sustainability can be identified. According to the first interpretation, the social sustainability is equated with the ecological sustainability and therefore, as happens with the latter, constraints also exist for social sustainability that limit its development. Constraints are identified with the social norms, which need to maintain specific social relations, customs, structure and values. The second interpretation considers the social sustainability as a necessary condition to support the ecological sustainability. Within this perspective, values and rules of a society can determine and affect the conservation of the natural capital and the equal allocation of it among different generations (present and future). The third interpretation is more people-oriented and intends social sustainability as the well-being of people of present and future generations. According to Chiu (2003), the last interpretation of social sustainability is the most common in literature.

Investigating and assessing the social sustainability in terms of well-being is the main interpretation adopted in the SLCA field. Indeed, as it is reported in the UNEP/SETAC Guidelines (UNEP/SETAC, 2009), SLCA ultimate goal is to promote improvement of social conditions throughout the life cycle of a product and thus, human well-being is a central concept to be explored and defined. However, a clear definition of well-being is not stated within the UNEP/SETAC Guidelines. For this reason, in the last years, SLCA practitioners are encouraging the involvement of social scientists in order to increase knowledge about the well-being concept, provide richer descriptions of social topics and contribute to new possible frameworks and methods to assess such a complex concept (Arvidsson et al., 2015).

The aim of this study is to compare how differently the UNEP/SETAC Guidelines and the social sciences deal with the concept of well-being providing new insights and possible new approach for the assessment of well-being.

5.1. Social life cycle assessment and limits

SLCA is a systematic process based on the assessment framework used in the LCA and provided by the ISO standards (ISO 14040,2006), which aims at assessing potential positive and negative social impacts of products throughout the life cycle including all the phases from extraction of raw material to final disposal (UNEP/SETAC, 2009).

SLCA finds its origin in the concept of sustainable development and in the theories of the Corporate Social Responsibility (CSR) (Sakellariou, 2018). CSR indeed provides a reason for companies to pursue and contribute to sustainable development by considering a wide range of stakeholders when decisions must be made and, remembering that companies have obligations towards the latter (UNEP/SETAC,2009). In other words, with CSR, companies acquire awareness about their social responsibility and try to solve social issues by considering needs of stakeholders respecting their rights. One heritage of CSR in the SLCA is the core idea that in order to pursue the well-being the assessment framework must be strongly established on relevant stakeholder categories that are affected by the conduct of the company at any life cycle stage.

A stakeholder category is defined as a group or a cluster of stakeholders that share interests referred to a product system along the life cycle of a product (UNEP/SETAC, 2009). Commonly, the Guidelines consider five main groups of stakeholders: workers, local community, society, consumers and value chain actors. All these stakeholder categories are investigated by considering impacts categories to be intended as social issues of interest for the stakeholders and the decision makers. Some of the most common social issues covered in the UNEP/SETAC Guidelines regard health and safety, human rights, working conditions, socio-economic repercussions, cultural heritage and governance (UNEP/SETAC, 2009). In order to be better investigated, the impact categories are operationalized in different subcategories in the attempt to comprehensively cover all the constituent elements that determine them. For example, referred to the "worker" stakeholder, the human rights impact category could be divided into forced labour, equal opportunities, child labour and freedom of association subcategories. Fig. 13 shows a categorization of subcategories related to the different stakeholder categories suggested by the UNEP/SETAC (2009).

Stakeholder categories	Subcategories
Stakeholder "worker"	Freedom of Association and Collective Bargaining Child Labour Fair Salary Working Hours Forced Labour Equal opportunities/Discrimination Health and Safety Social Benefits/Social Security
Stakeholder "consumer"	Health & Safety Feedback Mechanism Consumer Privacy Transparency End of life responsibility
Stakeholder "local community"	Access to material resources Access to immaterial resources Delocalization and Migration Cultural Heritage Safe & healthy living conditions Respect of indigenous rights Community engagement Local employment Secure living conditions
Stakeholder "society"	Public commitments to sustainability issues Contribution to economic development Prevention & mitigation of armed conflicts Technology development Corruption
Value chain actors* not including consumers	Fair competition Promoting social responsibility Supplier relationships Respect of intellectual property rights

Figure 11 Stakeholder categories and subcategories of relevant social issues (figure extracted from UNEP/SETAC, 2009)

The UNEP/SETAC Guidelines establish that one way to assess the social impacts of a process is to apply a Performance Reference Points to compare the performance of a company by referring to international standards or conventions in order to attest the minimum level of performance, or a basic requirements (Ramirez et al., 2014) in compliance with standards and conventions considered. Therefore, social indicators should be operationalized in order to match social aspects considered in the standards, laws, and conventions.

Despite the assessment framework is a starting point for the assessment of social impacts, so far some limits and gaps were identified by practitioners in the field. Jorgensen et al. (2008) highlighted as one limit regards the possibility to relate social impacts to the processes of a production system. According to Jorgensen et al. (2008), this limit stems from the different causal link between processes and impacts that exist in the environmental and in the social dimensions. Indeed, environmental impacts arise due to the nature of processes, which can compromise or benefit the environment according to natural, ecological, chemical, biological laws or mechanisms that can be explained scientifically. Contrary, the mechanisms that rule within the causal link between processes and social impacts are unknown or unexpected and for this reason is difficult to relate impacts to a process Jorgensen et al. (2008). Indeed, the social dimension presents different characteristic compared to the environmental one, in particular according to Lehtonen, (2004) it can be considered:

- Bipolar by referring both to individual and collective levels;
- Reflexive, meaning that the perceptions and the interpretations of the objective social conditions change the behavior of individuals and social collectives, influencing the objective conditions;
- Immaterial, indicating the immaterialness of social phenomena, which can hardly can be assessed by quantitative measures.

A second relevant issue regards the identification and the choice of subcategories and social indicators to include in the assessment and to operationalize in order to assess the well-being of different stakeholders. Indeed, selecting one indicator rather than another indirectly may lead to shape and define the well-being according to different aspects. According to Baumann & Arvidsson (2020) one of the problems of the social assessment framework suggested by the UNEP/SETAC Guidelines is that is based on the theoretic framework of CSR. Establishing the assessment on the stakeholder categories may lead to oversimplify the reality by dividing it into stakeholder categories. A second relevant problem identified by practitioners in the SLCA field is that the assessment framework is too tied to political values, conventions or subjective value systems (Baumann & Arvidsson, 2020; Soltanpour et al., 2019; Ramirez et al., 2014; Hosseinijou et al., 2014). According to Colantonio (2009) such an approach, where targets and thresholds rely on system values and political objectives, can be speculative and not based on scientific criteria and it can lead to wrong conclusions in the assessment.

Moreover, Kuehnen & Hahn (2017) highlighted as researchers in SLCA field face issues relate to the choice of social indicators to include in the assessment due to lack of clear rules referred to the selection of indicators. More in detail, Kuehnen & Hahn (2017) show that, according to different scholars (Boukherroub et al. 2015; Gualandris et al. 2015; Baumann et al., 2013; Hassini et al., 2012; Webb, 1974; Price, 1972) the selection of indicators is based on common sense or arbitrary factors which lead to inconsistencies in the results and are not based on theoretical and conceptual constructs. As result, Kuehnen & Hahn (2017) observed that in the industrial ecology filed, on 141 reviewed articles that aimed to incorporate a life-cycle or supply chain perspective, most of the researchers only focused on the worker stakeholder category and mainly consider health-related indicators. Orienting the well-being assessment towards only one stakeholder category may lead to further over-simplifications of reality.

Similarly, Iofrida et al. (2018) investigated which of the two paradigms applied in social sciences (post-positivism-oriented and interpretivism-oriented paradigms) are commonly used in SLCA literature so far, and arrived at two relevant questions: “how and why are indicators chosen?” and “Which theoretical basis underpins the assessment process?”. These questions are still without an answer, thereby stalling the debate on an epistemological level (Iofrida et al. 2018). Iofrida et al. (2018) also highlighted that many researchers doing SLCA require to broad knowledge outside the literature boundaries of SLCA in order to acquire knowledge on social phenomenon but, at this date, little response was found to this request.

In order to contribute to new knowledge in the SLCA and advancing the assessment framework in its theoretic foundations, the main findings of two extended abstracts (Goffetti et al., 2020; Goffetti & Baumann, 2020) are here presented in order to show how social sciences approach the concept of well-being and in its assessment in contrast to conventional SLCA.

5.2. Method

In Goffetti et al. (2020) a preliminary literature review was performed. Based on our knowledge on the literature concerning the well-being definition and conceptualization, a list of articles eligible for the review was generated. Moreover, we included additional articles in the review from parent and child citations, that is, articles that cited or were cited by the articles included for the review.

In Goffetti & Baumann (2020), one of the dimension of well-being identified in Goffetti et al. (2020) is deepened, analysied and compared with the most conventional SLCA method based on the UNEP/SETAC Guidelines.

5.3. Well-being in social sciences

In Goffetti et al., (2020) a preliminary review of the concept of well-being in the different social sciences was performed by considering studies performed in the sociological, geographical, economic, psychological and anthropological field. The goal of the study was to understand how the well-being is shaped according the different social sciences in order to identify common aspects and differences with the notion of well-being suggested by the UNEP/SETAC Guidelines.

What emerged from the study is that well-being is characterized by a higher complexities compared to what is manifested in the UNEP/SETAC guidelines (Goffetti et al., 2020). Indeed, it appears that in social sciences, the well-being can be considered as an individual or a collective concept and it is affected by a broad variety of mechanisms.

In literature, the well-being appear as a multi-dimensional concept. According to White (2009), well-being foundations are based on material, relational and subjective dimensions (White, 2009). These dimensions of well-being describe and refer to different needs that humans tend to satisfy. For example, the material dimension refers to the material goods that people necessitate (e.g. foods, clothes). Contrary, the relational dimension deals with more intangible needs such as the ones related to the social relations or the human capabilities and attitude to life (White, 2009). These dimensions can be investigated by considering externally observable factors and adopting an objective approach; or, by eliciting the self-perceptions and opinions related to a matter of interest/issue, which belong to a more subjective dimension of well-being (Western & Tomaszewski, 2016; White, 2009). The material, social and human dimensions of well-being and their objective and subjective aspects can interact in different ways by contributing to shape well-being in different forms.

The idea that well-being can be intended as an individual concept is present in different social sciences. For example, in sociology, according to the social construction theory, individuals create and elaborate "mental representations of reality, using collective notions as building blocks" (Veenhoven, 2008, p.47). In this sense, well-being is a variable concept that depends on the individual experiences, the cultural context and the social comparison. Individuals could perceive a lower well-being when they perceive that there is a difference between how the see their lives and how they would like the life would be (Veenhoven, 2008).

The idea that social comparison may affect the status of the subjective well-being is also present in the Economics of Happiness, a new branch of the economic studies that notice how although the income of individuals increases, the well-being and the happiness of individuals decrease (Bartolini, 2010). In some studies of the Economics of Happiness, it seems that if on a side individuals are able to satisfy their material needs thanks to an increase in income, on the other side, there is an increasing trend that proves that the level of social and human well-being is decreasing (Bartolini, 2010). This condition is caused by an increase in the working hour and job-related stress that hamper the possibility of individuals to live relational goods. In parallel, the level of income achieved difficulty allows to acquire all the material goods necessary to fill the material gap that separate individuals by social groups that are seen as reference target to reach in order to be satisfied (Bartolini, 2010). From this perspective, objective measures of well-being (such as income, job position, or the possession of goods) are not enough to assess the overall level of well-being but also subjective measures are necessary.

Contrary to the individual constructivism, in sociology, the holistic perspective suggests that the starting point to achieve well-being is the society and its institutions and thus it may be possible to investigate the societal quality to observe how a society is capable to resolve possible conflicts that arise due to technological, institutional, and natural changes (Soltanpour et al., 2019). Thus, contrary to the individualistic perspective, in the holistic one the starting point to assess the well-being is the society (Soltanpour et al., 2019). One of the main exponents of the holistic perspective is Durkheim, which claimed "the group think, feels and acts entirely differently from the way its members would if they were isolated. If therefore we begin by studying these members separately, we will understand nothing about what is taking place in the group" (Durkheim, 1895/1982). Therefore, measuring the level of the societal quality could be seen as an alternative to the individual well-being. However, independently of which sociological perspective (individualistic or holistic) is adopted, what emerged is that well-being both in the sense "sum of individuals" or "independent entity" depends on the human actions, the interactions and the relations that occur within a society and between individuals (Soltanpour et al., 2019).

In addition to the different approaches of considering the well-being as an individual or a collective issue, from other social sciences (physiology, geography and anthropology) emerged that the relations with the context where individuals or collectivities are located can strongly influence the well-being. For example, according to Prilleltensky (2015), a researcher in the Critical Community Psychology (CCP), the overall well-being can be affected by the social and collective contexts, and it should be intended as "a positive state of affairs, brought about by the simultaneous and balanced satisfaction of diverse objective and subjective needs of individuals, relationship, organizations and communities" (Prilleltensky et al., 2015). For this reason, in order to assess the overall well-being, Prilleltenski et al. (2015) suggest a multi-dimensional framework based on the interpersonal, community, occupational, physical, psychological and economic well-being in order to better explored the well-being nature by referring to the context (Arcidiacono & Di Martino,2016).

Similarly, geographers approach to the well-being in terms of quality of life that defines the "conditions of the environment in which people live (air and water pollution, or poor housing, for example), or to some attribute of people themselves (such as health or educational achievement)" (Pacione, 2003). According to this perspective, the quality of life should be investigated by considering the relation between persons and environment, spaces and places.

The concept of places acquires even more relevance when it is necessary to investigate the bound between places and the variations of predominant cultures, values and norms (Diener & Lucas, 2000). Indeed, there is a link between well-being, places and cultures and values and this link is investigated by anthropologists. According to Ferraro & Barletti (2016) cultures and places are fundamental to shape what well-being means according to a population. By considering the anthropological approach, it is also important to notify that the adoption of an ethnocentric approach could lead to promote prejudice and bias in the evaluation of the well-being (Mathews and Izquierdo, 2009).

5.4. The community well-being

Section 5.2 highlights that the well-being concept could be intended as a multi-dimensional and umbrella concept (Gasper, 2007), which depends on individuals' perceptions and building blocks, but that according to other perspectives it could be strongly influenced by the context, the culture and the collectivity. This aspect was highlighted in particular in the Critical Community Psychology, in the geographical and anthropological fields.

One relevant dimension of well-being appeared to be the community well-being (Prilleltensky et al., 2015; Wiseman & Brasher, 2008). Therefore, a focus on how community well-being is provided in this section in order to identify possible alternative assessment framework applied in the social sciences. This section is based on the work of Goffetti & Baumann (2020).

As it happens for the individual well-being, also in the case of community well-being definitions are multiple and highlight different aspects and dimensions. For example, Forjeaz et al. (2011) defined the community well-being as the "satisfaction with the local place of residence taking into account the attachment to it, the social and physical environment, and the services and facilities". Alternatively, the community well-being could be seen as "the combination of social, economic, environmental, cultural, and political conditions identified by individuals and their communities as essential for them to flourish and fulfil their potential" (Wiseman & Brasher, 2008). As it is visible the two definitions point out different aspects: in the first case, the accent is on a state condition of satisfaction that implies a subjective perspective (McCrea et al. 2016); in the second case, the accent is more on the constituent multi-dimensions of community well-being and on the need for the community to flourish indicating that the time frame refers to future. Somehow, from these two definitions it may be possible to claim that community well-being should be intended as state condition in the future.

McCrea et al. (2014), by investigating rural communities, strongly contributed in the development of a comprehensive framework to investigate the community well-being based also on researches by other scholars. Their study provided many insights related to the well-being concept.

According to McCrea et al. (2014), the well-being reflects a specific 'status' as a given condition in time that can be compromised by many different external pressures, which affect its final status. Indeed, the external pressures may affect the community resources which are fundamental for the flourishing of the community itself. By adopting the framework of Flora and Flora (2013), McCrea et al. (2014) suggested that the community resources should be divided into seven different types of capitals: natural, cultural, human, social, political, financial and built capital. The impact of a process or of an external pressure on one or more of the community capitals can affect the level of well-being in one or more of its constituent dimensions which are social, economic, environmental, physical, political, health and place attachment (Fig. 12).

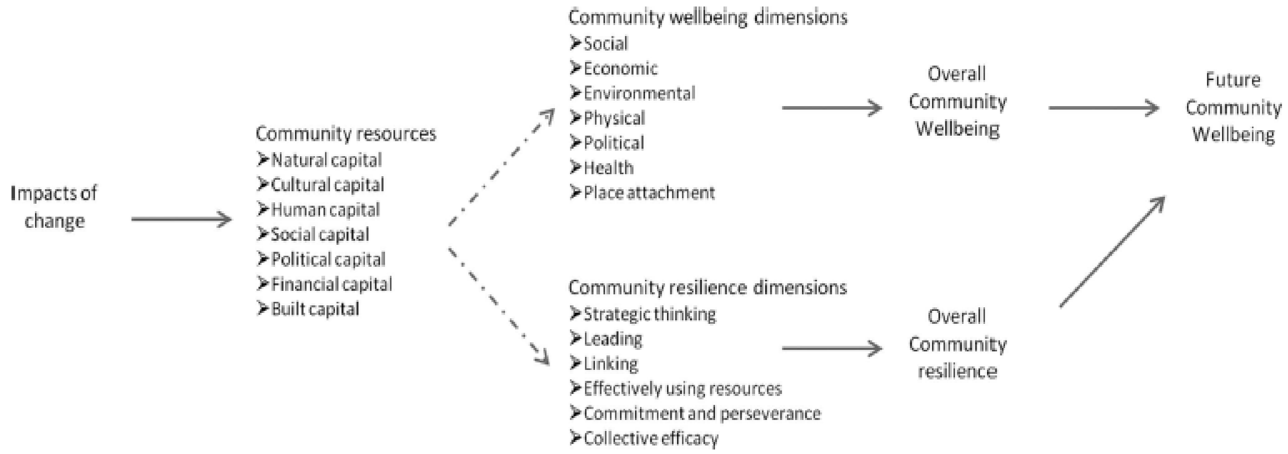

Figure 12 Framework developed by McCrea et al. (2014). The framework puts in relation the concept of community resources, community well-being and community resilience by specifying their constituent dimensions in order to explain how they contribute to determine the future community well-being (Figure extracted by McCrea et al., 2014)

However, in order to understand what the future community well-being will be, according to McCrea et al. (2014), it is necessary to introduce a new concept: the community resilience. The community resilience is intended "a type of community functioning in response to change, and occurs over time". Therefore, the community resilience should be intended as a process implemented by the community to respond to a change in order to maintain or enhance the community well-being in the future. The dimensions that compose the community resilience are divided into strategic thinking, leading, linking, effectively using resources, commitment and perseverance, collective efficacy and all these dimensions indicate competences, capacities or abilities that the community can implement in practical terms in order to enhance the well-being. Also, the community resilience dimensions could be affected by external pressures on the community resources, however, the way in which a community reacts and mobilizes can influence the future well-being.

The strengths of the framework suggested by McCrea lie on the comprehensive inclusions of all the capitals necessary for a community to flourish, the dynamic perspective and the importance of mechanisms and actions performed by a community to response to a change. The framework is not based on strict categories and allows to explain different outcomes of well-being in the future according to the different mechanisms implemented. Moreover, it allows to the relation of well-being to the context and an identification of the capitals or factors fundamental to maintain or improve the level of well-being.

5.5. Discussions

Although the study presented in this chapter is still at an embryonal stage and requires to be deepened and expanded with a more systematic literature review, some first findings can be identified. What emerged from the study presented is that the SLCA based on the UNEP/SETAC guidelines are affected by three main limitations in the measurement of well-being.

The first limit regards the lack of attention about the multidimensionality of the well-being concept. Indeed, from social sciences emerged that the concept of well-being is fluid, multidimensional and complex. The different dimensions of well-being can be investigated according to objective and subjective approaches. However, the subjectivity of well-being has been neglected so far in the UNEP/SETAC guidelines. Sometimes, objective indicators (e.g. the level of income; the presence or the absence of pathologies; incidents etc.) may lead to false results about the individual level of well-being. Indeed, the individual well-being could be affected by subjective factors which are strongly dependent on the context and its social, societal, the environmental, and cultural attributes. In SLCA literature, Jørgensen et al. (2010) pointed out that when well-being is defined in the individual area of protection, researchers should include subjective indicators in the assessment to improve the validity.

The second limit identified is related to a poor characterization of the relations between individuals or societies to the (cultural, environmental, social, political) context where they are located. By considering sociological theories, Soltanpour et al. (2019) already highlighted as in the SLCA field the subject of the assessment should not be the actors themselves but rather the relations between them. Similarly, here it is pointed out that, from the wider field of social sciences emerged that also relations with the environment, the culture and places are important. Therefore, when SLCA practitioners wants to investigate the social impact of a process or of a company, they should not only focus on the stakeholders but also on how processes impact on the context providing a change of the constituent dimensions of well-being. In the SLCA field, first attempts to introduce capitals in the assessment were done by Salvi et al. (2017) and (Goedkoop et al., 2018). For example, Salvi et al. (2017) introduced in the social assessment the "Environment" as relevant stakeholder to consider, while Goedkoop et al. (2018) applied the five-capital approach by identifying human, social, physical, economic and natural capitals that can hamper or encourage the well-being. Although, these two approaches show a more comprehensive approach that tries to include also context characteristics in the assessment, they are still based on normative list and rigid categories. Therefore, they should evolve and be developed in order to identify relevant interconnections to shape and measure the well-being.

The third limit regards the static approach adopted by the UNEP/SETAC Guidelines, which does not allow to investigate the mechanisms of response of individuals and societies once that a change occurs. Indeed, every pressure or process determine a change on the context, and the assessment of the future well-being should be investigated according to a dynamic perspective that also consider the duality of the directions of impacts.

From the identification of these limitations emerged that SLCA should be further implemented by integrating knowledge and methods from the social sciences, which proved to be more systemic in the investigation of the well-being compared to the UNEP/SETAC Guidelines.

In the social science field, one possible framework suggested to investigate the well-being on a community is the one presented by McCrea et al. (2014). Their framework proved to be systemic to the extent the authors (i) better considered the interconnections between actors, context and multidimensions of the well-being; (ii) adopted a system perspective which is broaden compared to the technological one commonly applied in SLCA; (iii) took into account the time dimension and the dynamisms that characterize social changes. McCrea et al. (2014) considered the capital resources that underlie both the well-being and the resilience of a system to investigate how actors react to an external pressure in the attempt to enhance the well-being in the future. The framework based on the community resilience could possibly be translated and replicated in the life cycle field. Indeed, it may be possible to connect community resources (and capitals) to what normally are defined as inputs in the life cycle methodologies. More in particular, the different community resources may be considered potential inputs for a production process. Thus, they have to be taken into account in the SLCA inventory and treated as flows to follow along the life cycle phases. The community resilience framework may help to understand the mechanisms that occur in the community once that capitals are affected by external disturbances (Goffetti & Baumann, 2020). Besides, it will better identify what kind of responses, and thus resilience mechanisms are adopted in order to react to a change. This would contribute to develop the socio-ecological model necessary for developing impact assessment methods by taking into account a dynamic perspective and a context-related approach that allows to select relevant indicators for assessing the well-being (Goffetti & Baumann, 2020).

Such a framework may on one hand increase complexity, but on the other hand, it will lead to investigation into what kind of responses and actions may lead to higher level of well-being. This would highlight the relevant relations and connections between the different dimensions of (individual or collective) well-being and the context .

Therefore, the development of a more systemic rationale based on the investigation of the relations between well-being and the context (e.g. environmental, cultural, political, social) may contribute to advance the assessment framework suggested by UNEP/SEATC by encouraging the adoption of a more multi-dimensional and systemic approach. Indeed, the UNEP/SETAC guidelines are too anchored to the subdivision in stakeholder categories and related subcategories inherent to political values, while they are missing the complexity and the dimensions that characterized the well-being according to both the individualistic and holistic perspective. Similarly, the UNEP/SETAC framework scarcely enables to consider the relations between the different subcategories and the context where a company operates. Within this perspective, a more systemic approach focused on the interconnections between actors and the context and, on the mechanisms of responses could contribute to discover or better understand the possible existent social causal links between processes and social impacts, which, at this date are unknown, as it was highlighted by Jorgensen et al. (2008). In addition, such an approach may promote a more scientific assessment of well-being untied from ethnocentric and political or values perspectives.

To conclude, stregthening the systemic approach within the SLCA may be crucial to advance the LCSA. Since SLCA deals with more qualitative and interpretivist approaches, it still appears more isolated compared to the more positivist and quantitative-based approach that characterize LCA and LCC, making difficult for these three methodologies to communicate within the LCSA (Stamford, 2020). Although, investigating the system of the interactions between several dimensions may lead to better understand the socio-ecological dynamisms opening to new methods and approaches to design integrated impact assessment methods according to a LCSA perspective.

However, future research should be oriented to acquire more knowledge and theories around well-being from the social sciences. In addition, more practical research should explore the possibility to couple more conventional methods ususally applied in the life cycle field with methods commonly used in social sciences to assess the well-being, aiming at identifies possible combined approach to improve the validity of the assessment. A first starting point could be to translate, combine and test the framework suggested by McCrea et al. (2014) within the SLCA field.

6. Conclusions

The main goal of this dissertation was to understand how the adoption of a systemic approach may contribute to advance the development of the LCSA framework in terms of new methods and tools to broad the scope and the object of the analysis and deep the relations within a system.

In Chapter 3 shows that, by adopting a systemic approach, it was possible to create a profit-based functional unit based on the connection of physical and monetary flows and on the identification of the socio-technical mechanisms (in terms of interactions points). The LCA performed by adopting the profit as functional unit proved to be a robust method to measure the cause-effect relations between the economic and environmental elements of different business models. Indeed, the profit-based functional unit allows to reveal the interdependencies between monetary and physical flows, enabling to improve or correct not only technical or design aspects referred to production system or a product (as happens in the mainstream practice of LCA) but also business model parameters such as the price or the rental efficiency. Furthermore, the method allows researchers to better investigates which actors are responsible for the environmental impacts by investigating the relation between physical, monetary flows and interaction points. For example, in the sales model, it emerged that the company was the main responsible in the production of impacts, whereas, in the rental model, costumers' habits were the cause of the main impacts. In the LCSA, a conventional praxis is to simultaneously apply LCA and LCC in parallel to obtain economic and environmental evaluations of a company or a system. Although, the application of LCA and LCC contributes to assess the environmental and the economic performances of the system investigated, the results achieved at the end of the life cycle impact assessment stage remain separated. Consequently, it is not possible to connect the dimensions that compose the sustainability. Contrary, the profit-based functional unit method presented in this dissertation better identify and measure the interconnections between the different dimensions of sustainability in the assessment starting from the goal and scope identification stage. Indeed, the profit-based functional unit internalizes socio-economic aspects (in addition to the physical or technical ones). Consequently, in addition to broad the object and the scope of the analysis (by considering not only the production process, but also the socio-technical and managerial mechanisms that characterized a business model), the method presented enables to observe and quantify the relations between the economic and the environment dimension of sustainability and the role of the key actors involved within the business model. Therefore, the developed method besides being a robust tool that companies and LCA practitioners can use to assess the environmental sustainability of a business model without compromise the economic performance, can also be a tool for decision makers in the public sector to elaborate policies, programs or sensitive campaigns to increase the awareness of customers regarding their actions.

In Chapter 4, a synthetic index to estimate the level of circularity of a territorial system was created by adopting a holistic and systemic approach based on an LCA framework. The territorial system was considered as a whole, which implies that the assessment of impacts (according to several impact categories) was strongly based on the inputs entering in the territorial system and the output that is produced while it was delinked by the production systems that operate within the territorial systems. The index allowed to theoretically estimate an overall level of circularity of the territorial system sensitive both to site-specification implementation of circular measures within each production system and, to the increase level of interconnections of the subsystems. Despite the level of details referred to each production system is lower compared to what normally happens in the mainstream LCA practice, a broaden level of the object of the assessment of the level of circularity of a system was obtained by indirectly grasping the increase of the interconnections between the several production systems revealed by the change in the amount of the inputs entering in the territorial system related to the whole annual production. Such synthetic index may be used by decision makers in the public and private sectors to elaborate political goals or environmental programs based on thresholds. With regard to the advancement of the LCSA, the method presented in this chapter may help researchers to explore the impact of the interconnections within the environmental dimension by expanding the perspective from a local to a more global dimension.

In Chapter 5, it emerged that so far, in the SLCA field, there is a lack of systemic approach in the assessment of the well-being. Indeed, the UNEP/SETAC Guidelines are too tied to the stakeholder categories' structure and do not allow to grasp the existent relations and interconnections between individuals or societies and the context. However, from social sciences emerged that such relations are fundamental in order to grasp and shape the concept of well-being according to people living in a determined area values and perceptions. In addition, in order to foresee possible future level of well-being is also necessary identifying mechanisms of responses of individuals or communities when a pressure occurs. Therefore, UNEP/SETAC Guidelines should evolve through more flexible structure allowing to identify relevant relations on which the well-being concept is built. Such a kind of approach should be considered a pre-condition in order to broad the scope of the assessment and include social impacts within the LCSA framework. In addition, determining what kind of relations between environmental, economic and social dimensions of well-being exist may be also useful to advance integrated assessment in the life cycle field.

Thus, on an overall level, the three studies proved that the adoption of the systemic approach can enable the identification of relevant interconnections, in terms of physical and monetary flows, sub-systems circular relations and, individual, societies and contexts. Such interconnections affect one or more dimension of sustainability and for this reason they need to be integrated in the LCSA. Moreover, their identification has practical effects on a more operative and methodological perspective. Indeed, cross-dimensional interconnections allows to: (i) quantify and predict the potential impacts occurring in a given dimension when measures or policies are applied to another one; (ii) broaden the scope of LCSA; (iii) deepen the relations between different dimensions. Furthermore, the adoption of the systemic approach enables to assess a system by evaluating the environmental performance of the existent interconnections between the sub-system rather than specific entities, leading to shift the perspective of the assessment from site-specific to local, regional or global levels.

However, future studies can be oriented to integrate within the profit-based functional unit also aspects related to the social dimension in addition to the economic and environmental ones aiming at including within the assessment all the three dimensions of sustainability. Moreover, the method could be further implemented by considering other economic performance indicators (instead of profit) and by adopting a money time-value perspective and a more dynamic approach within the assessment through discounting practices. The index to measure the level of circularity requires more empiric studies in order to test its robustness and investigate its results by taking into account possibly trade-off between different impact categories. Lastly, more studies in the social sciences fields are encouraged to further implement the SLCA according to a more systemic perspective to easily promote its integration within the the LCSA.

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Appendix A: Modelling of physical flows

Here, the modelling choices done to assess the life cycle of a representative jacket are presented. These tables were extracted from Böckin et al. (2020) and are the outcomes of the modelling choices made in OpenLCA. The following tables shows, all physical inputs used the process for amount of product, as well as the outputs in terms of emissions and waste.

In addition, the mass balance sheets of the life cycle of one jacket is also presented in the last section of the Appendix A.

In some cases, in OpenLCA, the modelling of the amount of flows was done by using local or global parameters (parameters used only in one process or in several processes, respectively). The parameters are presented and described in in Table A 1.

Table A 1:

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)
Repairs_T	0.06666664	Number of repairs during time T
q_rental	28	Number of replacement jackets produced during time T
t_rental	1107.8	Number of rental transactions during time T

Appendix A.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		0.1	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		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)
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 density	4.3E-7	kg		European average value, based on industrial survey	Ecoinvent (2019)
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		1.357690686 30604E-4	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - CO	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		5.607748784 44612E-5	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - IN	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		5.325081733 04272E-5	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - ZA	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		1.026799375 92291E-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 = 0.63769 (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-	Emission to water/fresh	3.0E-7	kg			Roos et al. (2019)

one	water					
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 A.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, organics		4.0E-10	Item(s)	market for chemical factory, organics | chemical factory, organics | Cutoff, U - GLO		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		0.0106818798905516	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%	Weighted average of reported input	Ecoinvent (2019)

				solution state | Cutoff, U - GLO		
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, unspecified natural origin		0.00279463700762329	m3		Weighted average of reported input	Ecoinvent (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/unspe	9.90817322912507E-10	kg		Weighted average of	Ecoinvent (2019)

	cified				reported emissions	
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	Ecoinvent (2019)

					reported waste	
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	4.8E-9	kg			Roos et al.

	to air/high population density					(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		0.03	kg	market for hydrogen peroxide, without water, in 50% solution state		Roos et al. (2019)

50% solution state				| hydrogen peroxide, without water, in 50% solution state | Cutoff, U - RoW		
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	Emission	6.0E-4	kg			Roos et al.

ethoxylate	to water/fresh water					(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 (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 A.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		0.05549994 21428199	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		6.12426586 651359E-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		0.00744986 723522292	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		2.19550075 103395E-4	kg	market for cobalt | cobalt | Cutoff, U - GLO	Weighted average of reported input	Ecoinvent (2019)
compressed air, 600 kPa gauge		0.34598626 1722217	m3		Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.02216570 27196663	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RLA	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.00346170 434504085	kWh	market for electricity, medium	Weighted average of reported input	Ecoinvent (2019)

				voltage | electricity, medium voltage | Cutoff, U - AU		
electricity, medium voltage		0.06466667 56538316	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - US	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.15487608 3916439	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RAS	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.01068187 98905516	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RAF	Weighted average of reported input	Ecoinvent (2019)
electricity, medium voltage		0.00510509 698409366	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		6.29884163 21517E-4	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - NZ	Weighted average of reported input	Ecoinvent (2019)
heat, from steam, in chemical industry		1.85538221 940177	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		2.17465665 147622E-4	kg	market for manganese | manganese | Cutoff, U - GLO	Weighted average of reported input	Ecoinvent (2019)
natural gas, high pressure		0.00615497 651058913	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		4.52832967 790106E-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		7.53838835 152195E-4	m3	market for natural gas, high pressure | natural gas, high pressure | Cutoff, U - JP	Weighted average of reported input	Ecoinvent (2019)
natural gas, high pressure		0.01443281 11469741	m3	market for natural gas, high pressure | natural gas, high pressure | Cutoff, U - RoW	Weighted average of reported input	Ecoinvent (2019)
nitrogen, liquid		0.03458956 06327028	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, unspecified natural origin		0.00279463700762329	m3		Weighted average of reported input	Ecoinvent (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		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	5.34348379342779E-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	3.92535574831055E-5	kg		Weighted average of reported emissions	Ecoinvent (2019)

	water/unspecified					
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 (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		0.875	kg	Refining (for membrane) - JP		Mass balance

(membrane)						
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	1.0E-6	kg		European average value, based on	Ecoinvent (2019)

	water/surface water				industrial survey	
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 - CO	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)

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,	EcoSpold01Location=UCTE	Ecoinvent (2019)

				medium voltage | Cutoff, U - RAF		
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 polymerised | Cutoff, U - GLO	Typical values, based on a European and a Swiss study	Ecoinvent (2019)
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		1.07124956535 68E-4	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - CY	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		5.85050847208 448E-4	kg	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - IN	EcoSpold01Location=CH	Ecoinvent (2019)
waste plastic, mixture		0.00141646517 489072	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 A.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 A.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						
Flow	**Emission category**	**Amount**	**Unit**	**Provider**	**Description**	**Source**
Product						
Jacket		1.0	Item(s)			
Inputs						
Adhesive		0.014507	kg	Adhesive - EE	Adhesive for taping	Willskytt et al. (2019)
Cut laminate		0.701	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 -		Willskytt et al. (2019)

				GLO		
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 A.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		0.00499813	t*km	market for transport, freight, lorry 16-32 metric ton, EURO6 |	Weight to be transported: 0.80615	Searates and Google Maps

ton, EURO6				transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RER	kg (see mass balance) Distance: 6.2 km	
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			Searates and Google Maps

Appendix A.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		200*CR	Item(s)	EoL transportation of one jacket	CR (collection rate) = 0,5	
Internal transportation of one jacket		200.0	Item(s)	Internal distribution		
Sales transaction		200.0	Item(s)	Sales transaction - SE		
Jacket		200.0	Item(s)	Sewing and finishing - EE		
transport, passenger car, EURO 5		Customer_transport_car *200 *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 *200 *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 *200 *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		200.0	Item(s)	External distribution	EoL transport	
Outputs						
waste yarn and waste textile		200*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_rental *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_rental *CR	Item (s)	EoL transportation of one jacket		
Internal transportation of one jacket		q_rental	Item (s)	Internal distribution		
Rental transactions		s_rental	Item (s)	Rental transaction - SE		
Repaired jacket		repairs_T *q_rental	Item (s)	Repair - SE	Repair of 2nd hand jackets	
Jacket		q_rental	Item (s)	Sewing and finishing - EE	Production of q jackets	
transport, passenger car, EURO 5		Customer_transport_car *q_rental *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_rental * 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_rental *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_rental * 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_rental *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_rental * 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_rental	Item (s)	External distribution		
Outputs						
waste yarn and waste textile		q_rental *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						
Flow	**Emission category**	**Amount**	**Unit**	**Provider**	**Description**	**Source**
Product						
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 A.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 (from Roos et al., 2015)	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	Energy use for drying, from weight of one	Roos et al. (2015)

				| Cutoff, U - SE	jacket * energy requirement per kg dried laundry (from 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 A.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 A.10 Mass balance of one jacket

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

Appendix B: Sensitivity Analysis

The sensitivity analysis presented in this Appendix is based on the results of Böckin et al. (2020).

The weighted ReCiPe (H,A) Endpoint indicator was chosen as basis to perform the sensitivity analysis. The criteria considered to perform the sensitivity analysis are shown in Table B1.

Table B 1 Parameters tested through the sensitivity analysis and their resulting effect on the final impacts expressed in percentage (Table modified from Böckin et al., 2020).

Sensitivity category	Parameter that was changed (default value)	How the parameter was changed	% change sales	% change rental
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

Considering the sensitivity analysis performed on the dominant phases emerged that in the sales model the change of the density of fiber of the face fabric from 150 to 75 dtx can improve the environmental performance by reducing impacts by the 20%. Indeed, a lower density of fibers requires a lower energy intense process during the production of the textile.

Similarly, locating the production in countries characterized by a low carbon energy supply (e.g. Sweden) can dramatically reduce impacts by the 33%. Contrary, countries with an high carbon energy supply (e.g. China) may lead to increase impacts by the 15%. On the other hand, the density of fibers and the energy consumption mix little affect the rental model impacts which present lower changes compared to the sales model (Table B1).However, the rental model proved to be strongly affected by other modelling choices such as the transport of customers, the laundry practices.

Considering the customers transport, data available were uncertain and were mainly based on an estimation of the different customer habits according to empiric evidences provided by the company. In order to test to what extent different habits can affect the two business models, we assumed two extreme type of transport habits: in the first scenario, customers only move by using bikes while, in the second scenario, customers use private cars. Having customers that only use bikes gave an 6% and 64% decrease of results in the sales and rental model respectively. Instead having all customers driving 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.

Also the laundry practices strongly affect the rental model because garments are washed after every rental transactions. In the baseline scenario laundries occur with fully loaded machine at 40 degrees. Conversely, in the sensitivity analysis, we assumed that laundry was doubled (assuming that customers wash the jackets before to return them), the washing temperature was increased at 60 degrees, the machines were assumed to be half-loaded and the electricity mix was defined to be a mix of the United States. A situation of intensive laundry practice contribute the make worst the rental model compared to the sales model. Indeed, the sales model is not affected by a change of the laundry while the rental model impacts increase by the 17%.

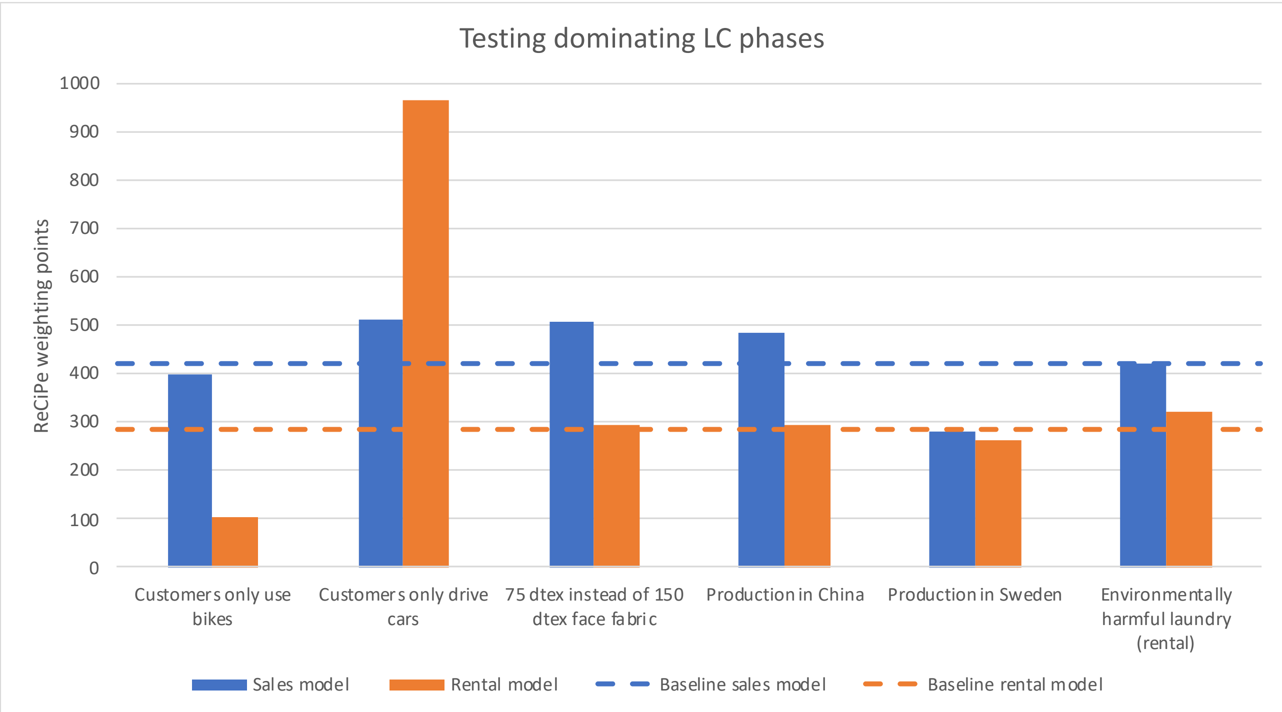

Figure 13 Sensitivity analysis of the dominant phases, in ReCiPe weightening points. Dashed lines represent the baseline scenario.

In the baseline scenario it was established that the rental price was 600 SEK. Through the sensitivity analysis, the rental price is firstly decreased by 50% and then increased by the same percentage. From Fig. 14 emerged that the rental price parameter can strongly affect the environmental performance of the rental model. Indeed, impacts are almost doubled when the rental price is lower while an higher rental price decrease impacts by 51%. The rental price is an important variable because it affects the number of transactions necessary to achieve the established level of profit. A lower rental price implies many more transactions and consequently more replacement jackets and more transport and laundry activities. Additionally, also the sales price was tested. The sales price affects impacts according to a reverse logic compared with the rental price. Indeed, at a 50% decrease and a 50% increase of the sales price result in a 78% decrease and a 74% increase in impacts for the rental model, respectively.

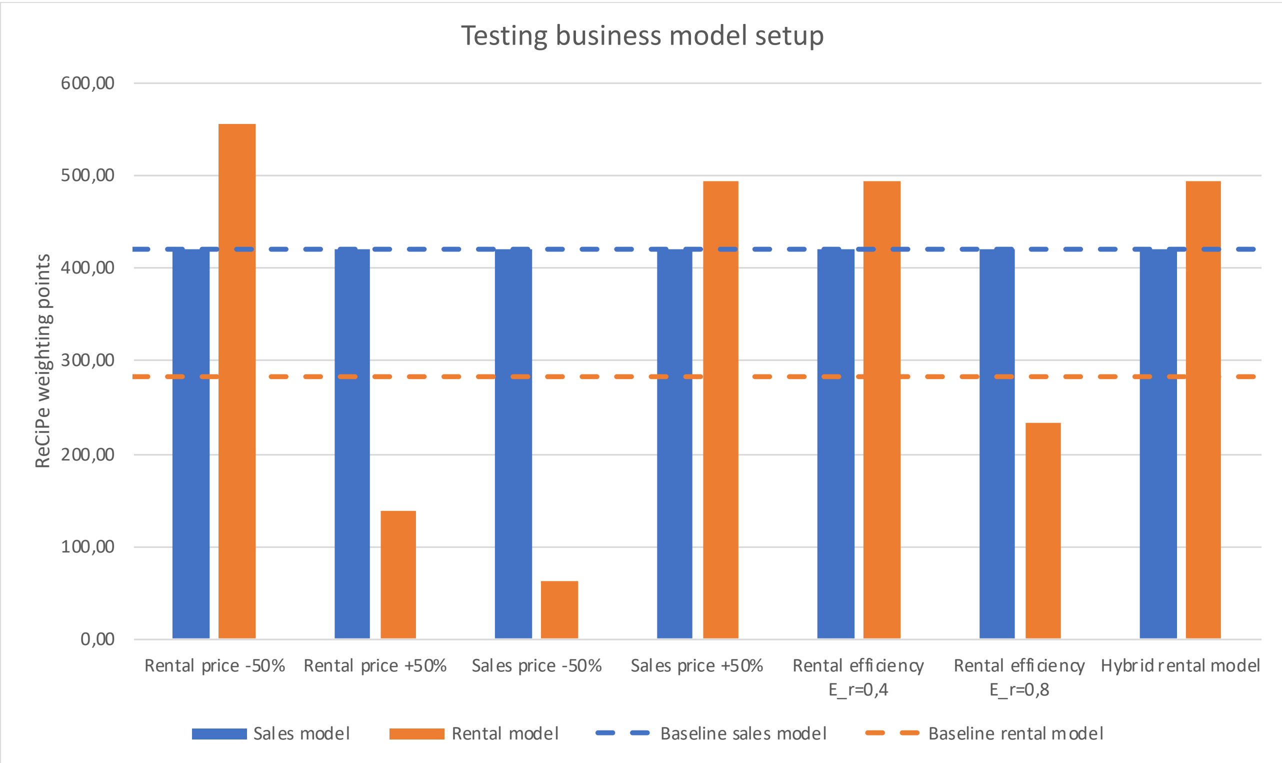

Figure 14 Sensitivity analysis of the business model parameters, in ReCiPe weightening points. Dashed lines represent the baseline scenario.

As already specified in section 3.3.1, the rental efficiency (E_r) indicates that not all the jackets that are included in the rental stock can be rented at any time because of urgencies related to laundry and repairs. From Table B1, the rental efficiency is estimated to be 60% in the baseline scenario. Through the sensitivity analysis, the rental efficiency was changed to be 40% and 80% leading to an increase of 74% and a decrease of 18% of impacts in the rental model, respectively. Lowering the rental efficiency affects and reverse the ranking between the sales and the rental model because the company cannot utilise their stock of jackets in compliance with the demand of customers and thus, more replacement jackets are necessary to sustain an higher number of transactions.

To conclude, through the sensitivity analysis was tested the chance of introducing in the rental model an element of product sales determining a hybrid business model. Specifically, in such a hybrid model the company offers rental customers to purchase the jacket at the end of the rental period (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.

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