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Life Cycle Assessment of a Product from the Textile Industry

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Abstract

The textile industry, that encompasses clothing items as well as home and technical textiles, is one of the oldest and currently among the largest and most polluting industries in the world. Due to the importance of this industry in Portugal, that represents 4 % of the Gross Domestic Product (GDP), as well as in the world, it's relevant to assess the environmental consequences inherent of the textile production, in order to improve its environmental performance.

The main goal of this dissertation is to assess and quantify the environmental impacts associated with the life cycle of a boxer, one of the main products made by IMPETUS, using the Life Cycle Assessment (LCA) methodology. A cradle to gate perspective was considered, including the life cycle stages of raw materials production, yarn, knit fabric and elastic manufacturing, and the making-up of the product. The information collected regarding the production of the boxer, the functional unit considered in the study, refers to the year 2021 and in the absence of this information the available literature and life cycle inventory databases were used. The environmental impact assessment was done using the software SimaPro and a new method was implemented combining the environmental impact categories of climate change (CC) by IPCC 2013 GWP 100a, eutrophication (ET) and fossil fuels depletion (AD) by CML-baseline 2001, water use (WU) by AWARE and freshwater ecotoxicity (FE) by UseTox. This was done to allow a comparison with the values estimated by the Material Sustainability Index (MSI) and Product Module (PM) tools of Higg Index, to verify the validity of the results provided by Higg Index.

The results obtained from SimaPro show that the stages with the most significant environmental impacts were the production and spinning of organic cotton followed by the dyeing, drying and heat setting processes. The organic cotton production and spinning is responsible for more than 50 % of the overall impacts in the ET category and more than 80 % for WU, whereas the dyeing process contributed to 19 % for the overall impacts in the FE category. For most processes, the biggest contributor to their impacts is energy use and the processes with the biggest contributions to the overall impacts occurred in ACATEL. The results provided by Higg Index were three times higher in the CC and AD categories, possibly due to the different percentage in renewable energy in the electricity mixes used. Three scenarios considering different percentages of renewable energy were analyzed, and the largest reduction of environmental impacts was observed in scenario 3, that combined in situ photovoltaic solar with external wind generation, with a 10 % and 8 % decrease in the CC and AD categories, respectively.

Keywords: Textile Industry, Life Cycle Assessment (LCA), Higg Index, Environmental Impacts, Boxer.

Resumo

A indústria têxtil, que engloba artigos de vestuário, têxteis de lar e têxteis técnicos, é um dos setores industriais mais antigos e atualmente, um dos maiores e mais poluidores do mundo. Dada a importância desta indústria em Portugal, onde representa 4 % do Produto Interno Bruto (PIB), é de extrema importância avaliar as consequências ambientais inerentes à produção de têxteis, de maneira a melhorar a *performance* ambiental do setor.

Esta dissertação tem como objetivo principal avaliar e quantificar os impactos ambientais associados ao ciclo de vida de um boxer, um dos principais produtos produzidos na IMPETUS, usando a metodologia de Avaliação do Ciclo de Vida. Uma perspetiva do berço à porta foi utilizada e incluiu a produção de matérias-primas, fabrico de fios, malhas e elásticos e confeção e embalamento do produto. As informações recolhidas, relativas à produção do boxer, que é a unidade funcional do estudo, referem-se ao ano de 2021, e na ausência dessas informações foram utilizadas as bases de dados e a literatura disponíveis. A avaliação do impacto ambiental foi realizada usando o software SimaPro, onde foi implementado um novo método que combinou as categorias de impacto ambiental das alterações climáticas (CC) pelo IPCC 2013 GWP 100a, eutrofização (ET) e depleção de combustíveis fósseis (AD) pelo CML-baseline 2001, uso de água (WU) pelo AWARE e ecotoxicidade (FE) pelo UseTox. Isto foi feito de modo a permitir a comparação com os valores estimados pelos módulos *Material Sustainability Index* e *Product Module* da ferramenta Higg Index, para verificar a validade dos resultados fornecidos pela mesma.

Os resultados obtidos no SimaPro indicam que as etapas com impactos ambientais mais significativos são a produção e fiação do algodão orgânico, seguida pelos processos de tingimento, secagem e termofixação. A produção e fiação de algodão orgânico é responsável por mais de 50 % dos impactos na categoria ET e mais de 80 % na WU, enquanto o processo de tingimento contribuiu com 19 % para a categoria de FE. O maior contribuinte para os impactos, na maioria dos processos, é o uso de energia e os processos com maiores contribuições para os impactos globais são os que ocorrem na ACATEL. Os resultados obtidos na *webtool Higg Index* foram três vezes maiores nas categorias de CC e AD devido às diferentes percentagens de energia renovável nos mixes energéticos utilizados. Três cenários com diferentes percentagens de energia renovável foram analisados, tendo-se observado a maior redução no cenário 3 que combina *in situ* solar fotovoltaico com energia eólica exterior à empresa, que apresentou uma redução de 10 % e 8 % nas categorias de CC e AD, respetivamente.

Palavras-chave: Indústria Têxtil, Avaliação do Ciclo de Vida, Higg Index, Impactos Ambientais, Boxer.

Declaration

I hereby declare, under word of honor, that this work is original and that all non-original contributions are indicated, and due reference is given to the author and source.

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Contents

List of Figures

List of Tables

Notation and Glossary

$m_{boxer\ in\ ACATEL}$	mass of fabric in1 boxer in the ACATEL steps	kg
$m_{boxer\ cutting}$	mass of fabric in1 boxer in the cutting stage	kg
$m_{boxer\ knitting}$	mass of fabric in 1 boxer in the knitting stage	kg
E	energy needed for 1 boxer	kWh
P	power of the machines	kW
Δt_{boxer}	time it takes to do the amount of fabric needed for 1 boxer	h
Δt_{1kg}	time it takes to do 1 kg of fabric	h
$m_{chemicals\ boxer}$	mass of chemicals used to dye 1 boxer	kg
$m_{chemicals\ in\ 418kg}$	mass of chemicals used to dye 418kg of fabric	kg
E_{418kg}	energy consumed (electricity) to dye 418 kg of knit fabric	kWh
$E_{steam\ boxer}$	steam used to dye 1 boxer	Mcal
$E_{steam\ in\ 418kg}$	steam used to dye 418 kg of knit fabric	Mcal
$E_{consumption}$	energy consumption of the machine per kg of fabric	kWh
$\Delta t_{operating\ adjusted}$	time of operation (adjusted) of both machines in 1 year	h
$\Delta t_{operating\ 1\ year}$	time of operation of both machines in 1 year	h
Em_{boxer}	pellet emissions resultant of making 1 boxer	kg CO_2.eq
$m_{pellets\ for\ 1\ item}$	mass of pellets consumed per clothing item made conventionally	kg
$Em_{pellets\ year}$	pellet emissions generated in average a year	kg CO_2.eq
$m_{pellets\ used\ annualy}$	mass of pellets used in an average year	kg
Δt_{ring}	time it takes to do 1 ring of elastic	h
$m_{waste\ boxer}$	mass of waste produced to make 1 boxer	kg
$m_{waste\ in\ 1\ year}$	mass of waste produced in 1 year of operation	kg
$m_{fabric\ handled\ 1\ year}$	mass of fabric handled by the company during 1 year of operation	kg
$V_{water\ boxer}$	volume of water needed to make 1 boxer	m^3
$V_{water\ in\ 1\ year}$	volume of water used by ACATEL in 1 year of operation	m^3
$V_{wastewater\ boxer}$	volume of wastewater produced to make 1 boxer	m^3
$V_{wastewater\ in\ 1\ year}$	volume of wastewater produced in 1 year of operation	m^3
P_{boxer}	perimeter of the boxer that is cut	m
l_{fabric}	length of the knit fabric that is going to be cut	m
w_{fabric}	width of the knit fabric that is going to be cut	m

List of Acronyms

GDP	Gross Domestic Product
EU	European Union
SDGs	Sustainable Development Goals
LCA	Life Cycle Assessment
ISO	International Organization for Standardization
LCT	Life Cycle Thinking
LCC	Life Cycle Costing
LSCA	Life Cycle Sustainability Assessment
S-LCA	Social LCA
FEM	Facility Environmental Module
FSLM	Facility Social & Labor Module
BRM	Brand & Retail Module
MSI	Material Sustainability Index
PM	Product Module
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
EPS	Environmental Protection Strategies
EF	Environmental Footprint
AD	Abiotic Depletion
LO	Land Occupation
CC	Climate Change
GWP	Global Warming Potential
FE	Freshwater Ecotoxicity
WU	Water Use
ET	Eutrophication
HT	Human Toxicity
VOCs	Volatile Organic Compounds
LHV	Lower Heating Value
EF	Emission Factor
BoM	Bill of Materials
GHG	Greenhouse Gas
PPA	Power Purchase Agreement

1 Introduction

1.1 Framing and presentation of the work

Since immemorial times, human beings have used several types of clothing to protect themselves from the elements and to increase their personal comfort. From a social standpoint, the textile industry is extremely important and necessary since everybody has a need for getting dressed. Clothes have the purpose of protecting the body from meteorological conditions and, socially speaking, it has a function of differentiating cultures, religions and even professions (Gabriel & Luque, 2020). Hence, the textile industry is one of the oldest industries in the world, and historically one of the first when considering consumer goods manufacturing (Retail Forum for Sustainability, 2013) as it was one of the most relevant sectors at the start of the industrial revolution. Nowadays, it is valued at 3 trillion dollars, which translates to 2 % of the world's Gross Domestic Product (GDP) (Fashion United, 2022) and the product category that includes all the different articles of clothing as well as accessories is, globally, one of the most sold, taking the 5th spot in a list of 11 categories (World Federation of Direct Selling Associations, 2020).

In Portugal, as of 2016, the textile industry was responsible for around 4 % of the GDP, and it showed its regional importance by being mainly located in Northern Portugal, where more than 76 % of the production is located, as can be seen in Figure 1 (Direção Geral das Atividades Económicas, 2018). The GDP related with the textile industry as well as the percentage of production in each location, should still, as of today, be around the same values.

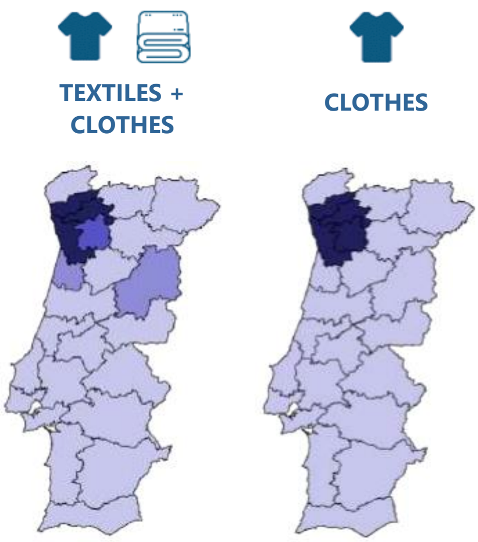

Figure 1. Territorial distribution of the production of textiles in Portugal (Cenit, 2017).

The textile industry encompasses, not just clothing items or apparel but also home textiles like curtains and bed linen and other technical textiles like seat covers (Lehner, Mont, Mariani, & Mundaca, 2020; Rasheed, 2020; Tudor, 2018). It should be noted that, within the scope of this dissertation, when the textile industry is mentioned, the focus is on the clothing section.

Due to the size and global scale of the supply chain involving the textile sector, including stakeholders from the agricultural sector (e.g., cotton farmers), industrial sector (e.g., producers of synthetic fibers such as polyester), among many others; the sustainability impacts are particularly important. There is a need to improve the sustainability of the textile sector, by tackling social challenges along the supply chain, when it comes to labor conditions, and the growing consumer demand for sustainable clothing, but also by tackling environmental issues (Moreau, 2021). These issues are of big concern, since, according to the UN alliance for sustainable fashion, this industry is responsible for around 2 - 8 % of the world's greenhouse gas emissions and the use of 215 trillion liters of water every year (Meier, 2021; UN alliance for sustainable fashion, n.d.). All these aspects combined make clear the need to act on this industry and the need to make it the most sustainable it can be.

The current line of production of this industry, which includes the whole production of the articles of clothing, the distribution and their use, is still nowadays very linear and therefore it entails a large quantity of waste and pollution (Ellen MacArthur Foundation, 2017). In fact, the textile industry is one of the most polluting in the world (Patwary, 2020).

As can be seen in Figure 2, all the stages in the production line of textiles put pressure on resources (e.g., water), create negative social impacts, pollute, and degrade the natural environment and also miss out on economic opportunities (Ellen MacArthur Foundation, 2017).

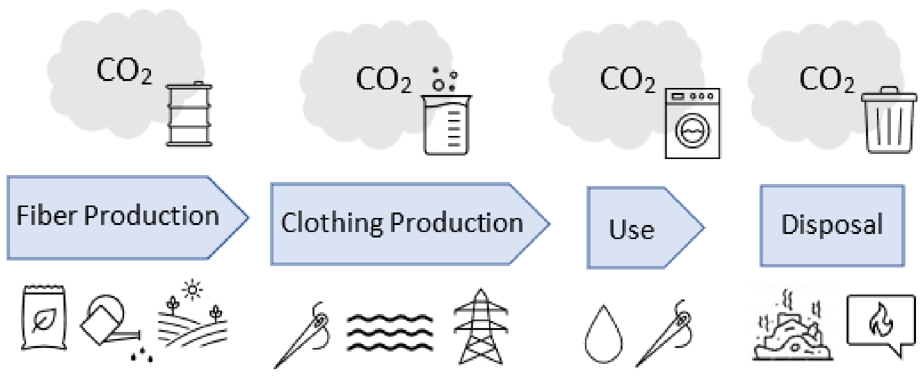

Figure 2. Examples of elements that have an impact in stages of the production line of textiles. Adapted from (Ellen MacArthur Foundation, 2017).

Therefore, every stage on the life cycle of clothing has, to some degree, a negative impact on the environment (Patwary, 2020). The relevant environmental factors of each stage in the line of production are further discriminated in Table 1.

Table 1. The environmental factors related to each stage of the life cycle of clothing. Adapted from (Federal Environment Agency, 2011; Patwary, 2020)

Life cycle stage	Environmental Factors
Production of natural fibers	Water demand Use of chemicals (pesticides, fertilizers…) Land use
Production of synthetic fibers	Use of petrochemicals (non-renewable) Energy demand Air emissions Wastewater
Yarn manufacturing	Energy demand Waste of fibers
Fabric manufacturing	Use of chemicals Energy demand
Pre-treatment, Dyeing, Finishing	Water and energy demand Use of chemicals Wastewater
Cutting, Assembly, Packing	Energy demand Waste of material
Use	Energy demand Microplastics
End of life (incineration or landfill)	Air Emissions Groundwater pollution

Specific politics and strategies to promote the sustainability of the textile industry were absent until very recently, since there were no clear regulations or targets directly related with the sector. In the last few years, several policies and strategies directly related to this industry were created worldwide. The European Union (EU), for example, came up with the "EU's strategy for sustainable and circular textiles" that was recently adopted, on March 30th 2022. Moreover, countries like Denmark, United Kingdom and France also came up with or improved their own regulations related with environmental claims, and France, also with a new labelling system (European Commission, 2021; Ministère de la Transition écologique, 2019; Moreau, 2021).

It is to note that the strategies and policies defined for the textile sector should be considered simultaneously with other sustainability related strategic plans, like the move to reduce the greenhouse gas emissions, being an example the "Fit for 55" plan (European Council, 2022).

Furthermore, the textile industry has great potential to contribute to the Sustainable Development Goals (SDGs) and impact all 17 of them (KPMG & Textile Exchange, 2018). SDG 12 represents a way to ensure sustainable consumption and production, giving the companies an opportunity to act on natural resources, chemical, and waste management all of which are present in the textile industry (UNECE, 2018). Alongside the producers, the consumers also have a significant role to play, being mentioned in target 8 of this SDG with regards of making sure they have the information to make sustainable choices (United Nations, n.d.) and being more conscious of products made in a more environmentally friendly way (Gabriel & Luque, 2020).

Therefore, there is a need to reduce the environmental impacts of the textile sector. To do this properly and understand what the real impacts are, in order to define the adequate improvements and/or changes in the production system, one must consider the full life cycle. Various methods and tools can be used, with the most used in practice being the Life Cycle Assessment (LCA) methodology (Watson & Wiedemann, 2019).

In this dissertation, the LCA methodology will be applied to a product manufactured in the company IMPETUS, considering specific aspects related with the product and the results being compared to those provided by Higg Index, a webtool that evaluates the environmental impacts of every stage of the product life cycle (Sustainable Apparel Coalition, 2020). Although both approaches are based in a Life Cycle Thinking (LCT) perspective, the Higg Index uses average data for the sector or data obtained in different conditions and circumstances which makes the results obtained inadequate to be used by IMPETUS.

1.2 Presentation of the company

IMPETUS Group started out as a small textile business that was created in 1973. Nowadays, it is comprised of several companies, and it has approximately 860 employees (693 in Portugal), reaching an annual production of 4,650,000 articles of clothing.

The company first started producing underwear and loungewear with a cut & sew method and nowadays, thanks to nearly 50 years of experience and a significant investment in technology, they have expanded their product range to include work attire and workout clothes, using the cut & sew method as well as a new without sewing method (seamless).

The company has several social and environmental commitments, such as fair work practices, safe working conditions, reduction of the environmental footprint and energy consumption which boils down to "Fashion, creativity and communication, but at the service of the community and the sustainability of the planet". Air emissions control, biomass use for hot water, built-in water treatment systems, investment in efficient machinery, use of photovoltaic panels to feed the electric and plug-in hybrid cars of the fleet and the use of eco-sustainable fibers are some of the accomplishments made so far.

IMPETUS has several environmental certifications such as Bluesign, Global Organic Textile Standard (GOTS), Global Recycle Standard (GRS), OEKO-TEX Standard 100 and Recycled claim standard (RCS).

There are several companies within the IMPETUS Group, including ACATEL, that is the company that does all the dyeing, printing and finishing processes of the pieces, being also a relevant company to this work.

1.3 Objectives of the work

The main goal of this study is to assess the environmental impacts of the different life cycle stages of a particular clothing product, in particular of underwear - boxer, finding the life cycle hotspots and purposing and analyzing scenarios of changes in the life cycle to improve the environmental performance.

A comparison between the results of the LCA study and the values of the environmental impacts predicted by the Higg Index tool will be done, in order to access how the results compare with each other.

1.4 Organization of the dissertation

This dissertation is divided in 5 chapters. The first one, the introduction, gives an overview of the key issues of the textile industry related to its sustainability, mentioning some key economic, social, politic and environmental aspects, the last ones being the main focus of this dissertation. The dissertation goals are described, the company description is made, and, at the end, the dissertation structure is presented.

The second chapter, context and state of the art, provides information on the life cycle stages of textile products, on what is the life cycle assessment (LCA) methodology, and describes the Higg Index mentioning similar tools as well. Furthermore, the LCA methodology, according to the

International Organization for Standardization (ISO) 14040 and 14044, is described in detail and lastly, a review of the main LCA studies of textile products that exist is made.

In chapter 3 there is a description on how the LCA methodology was applied in this study, in particular, the data sources and main hypothesis considered to obtain or estimate them, the functional unit, system boundaries and how the environmental impact categories are chosen.

Chapter 4 presents the results obtained using the software SimaPro and the MSI and PM tools of the webtool Higg Index, and a comparison of both set of results is conducted. The results are discussed, identifying the most important environmental impact categories and which stages of the life cycle are responsible for most of the impacts.

In the fifth chapter the main conclusions of the study are presented as well as some recommendations for future work.

2 Context and State of the art

The textile industry involves the entire production of textile products, from the extraction and/or production of the raw materials (like cotton and polyester) to the final disposal of clothing (Retail Forum for Sustainability, 2013). In all the parts of the supply chain there are environmental impacts, due to the natural process inefficiencies and incomplete resources utilization.

As can be seen in Figure 3 of the total amount of raw and other materials used, around 73 % of them are incinerated or go to landfill. Also, there is around a 12 % loss during the production (10 % of this in the factory with offcuts) and only 13 % of this material is in some way recycled after use.

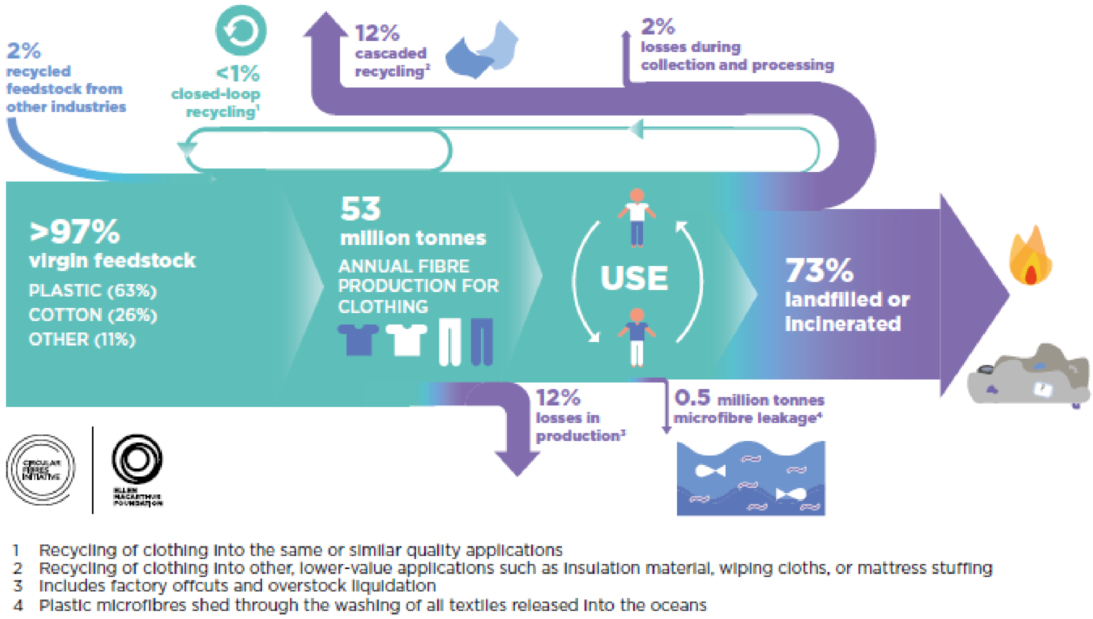

Figure 3. Material flows in the production line of textile products (Ellen MacArthur Foundation, 2017).

Each material or energy loss or inefficiency naturally contributes to the system overall environmental impact, as more energy and raw materials are necessary to compensate the losses. In this context, the life cycle assessment of textile products is essential to understand which are the stages of the product life cycle with the most significant environmental impacts and which materials or type of energy is responsible for them. This methodology can contribute to drive this industry towards sustainability by minimizing these impacts and possibly in the future, eliminate them (Baumann & Tillman, 2004; Hackett, 2015).

2.1 Life Cycle Assessment (LCA) and Higg Index

Life Cycle Thinking (LCT) is a framework where the environmental, social and economic impacts of a product during its entire life cycle are taken into consideration, contrary with what used to be the traditional focus on only the production and manufacturing, with the upstream and downstream processes being considered as externalities (Petit-Boix et al., 2017). Currently, the LCT perspective is at the heart of most of the ISO standards dealing with environmental management and related systems, such as ISO 14001, 14020 and 14031 (Wiloso et al., 2019).

When applying the LCT framework to a product, process or service, it is necessary to have methodologies to evaluate quantitatively the impacts in all the main dimensions of sustainability: environmental, economic, and social. In practice, the Life Cycle Assessment (LCA) methodology is the most commonly used, in particular, the one defined in ISO 14040 and 14044 (ISO 14040:2006; ISO 14044:2006).

LCA only considers the environmental impacts, but extensions to include other impacts exist, in particular: Life Cycle Costing (LCC) for the economic dimension and Social LCA (S-LCA) for the social aspects. When the three types are used simultaneously the study can be called a Life Cycle Sustainability Assessment (LSCA) analysis (Petit-Boix et al., 2017).

According to the ISO standards, LCA is a methodology that quantifies the environmental performance of products, processes, and services throughout the life cycle (Baumann & Tillman, 2004). Ideally, it should include the entirety of the life cycle (cradle to grave), encompassing the production or extraction of the raw materials, the manufacturing, distribution, use and at last, the final disposal (Bojarski et al., 2009).

This methodology can be used to help decision makers to identify potential improvements in the life cycle/supply chains and can be used to compare different supply chains of the same functional product (Gonçalves & Silva, 2021). LCA is also the methodological framework to measure other environmental impact indicators, like the environmental footprint, carbon footprint and water footprint (The Textile Institute and Woodhead Publishing, 2015), being the product environmental footprint (PEF), the GHG protocol and the water footprint some real examples of these (Hoekstra et al., 2011; Ranganathan et al., 2004; Zampori & Pant, 2019).

When it comes to applying LCA, the base guidelines, that have the principles and other requirements of this sort of study are laid out in the ISO 14040 and 14044. Several other standards are based on ISO 14040 and ISO 14044, like for example ISO 14021, 14024 and 14025 for environmental labels, ISO 14067 for carbon footprint and ISO 14046 that focuses on the water footprint (Pré sustainability, n.d.).

Usually, when applying the LCA methodology, to simplify the calculations, dedicated software is used, as process models can be very complex, and the Life Cycle Inventory (LCI) databases that come with the software simplify and speed-up the data gathering process. Moreover, as the impact evaluation methodologies can be very complex and computationally intensive, using LCA software makes the life of practitioners in the area simpler and allows them to focus on the process description and/or results analysis. Two of the most used and well-known commercial software for LCA are SimaPro and GaBi (Herrmann & Moltesen, 2015). Regarding the LCI databases, normally Ecoinvent is the one that is chosen, although specific LCI databases for specific sectors are also available. Figure 4 shows the general structure of LCA software when considering the life cycle of a product, process, or service, where commonly used LCI databases and impact evaluation methodologies can be seen.

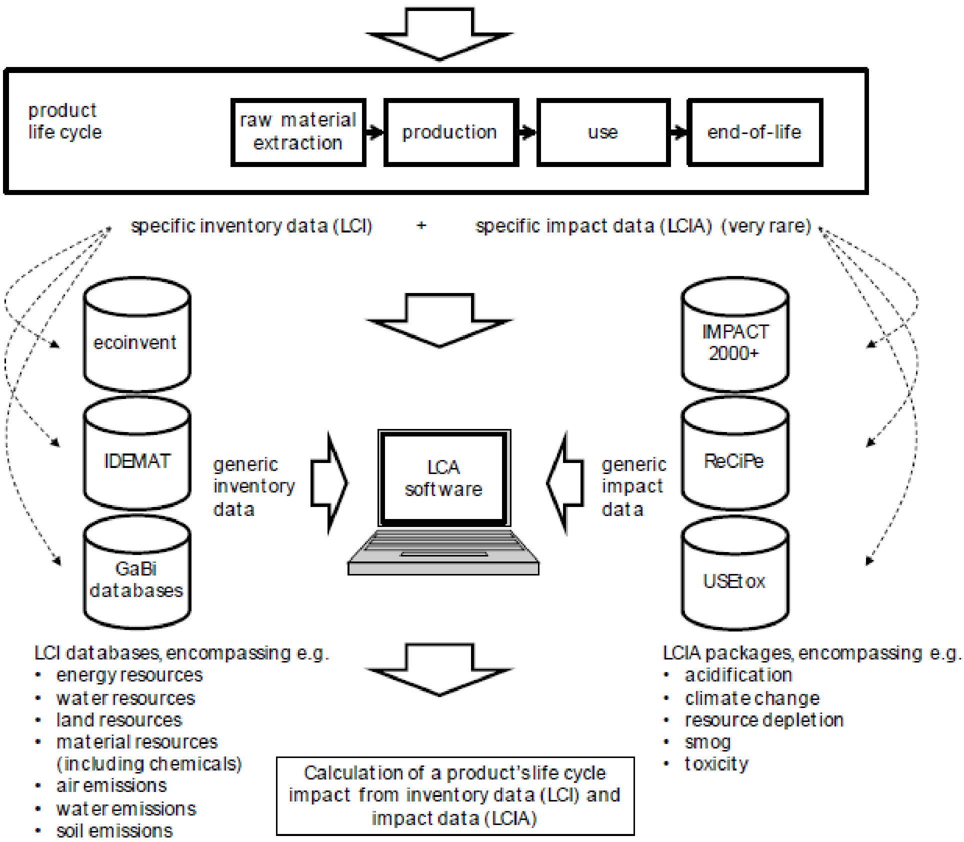

Figure 4. General stages of the product life cycle and examples of databases and life cycle impact assessment methods (Roos, 2016).

Besides the LCA software, nowadays, there is also web based tools that make it possible to do LCA online, like for example, BEES (https://ws680.nist.gov/Bees2), one click LCA (https://www.oneclicklca.com/) and Higg Index (https://higg.com/) (Mora et al., 2020). The webtools normally focus on particular sectors of activity, as for example the construction sector for BEES and one click LCA.

The Higg Index is a suite of tools created for the textile industry based on LCA, with the goal of evaluating the environmental and social impacts of footwear and apparel, taking into consideration the entire life cycle of the products, from raw materials extraction to the end of life (Chun et al., 2021). Higg Index is nowadays used by retailers, suppliers and brands and it is comprised of 5 tools that assess the social and environmental aspects of the supply chain in apparel production: the Higg Facility Environmental Module (FEM), Higg Facility Social & Labor Module (FSLM), Higg Brand & Retail Module (BRM), Higg Material Sustainability Index (MSI) and Higg Product Module (PM) (Sustainable Apparel Coalition, 2020).

Considering only the environmental impacts, The Higg PM measures the products impacts from cradle to grave, meaning it takes into consideration the use and end of life of the product. To do so, the Higg PM uses Higg MSI as a source making the Higg MSI the fundamental tool in the suite (Sustainable Apparel Coalition, 2020). The Higg MSI delivers a cradle to gate score that assesses the environmental impacts, from the production or extraction of the raw materials like cotton, polyester and leather to the textile formation, in 5 environmental impact categories (eutrophication, chemistry, climate change, resource depletion- fossil fuels and water scarcity) (Sustainable Apparel Coalition, 2020; Watson & Wiedemann, 2019).

2.2 LCA methodology

According to ISO 14040, the LCA methodology is comprised of four phases: Goal and Scope definition, Inventory Analysis, Impact Assessment, and Interpretation as can be seen in Figure 5.

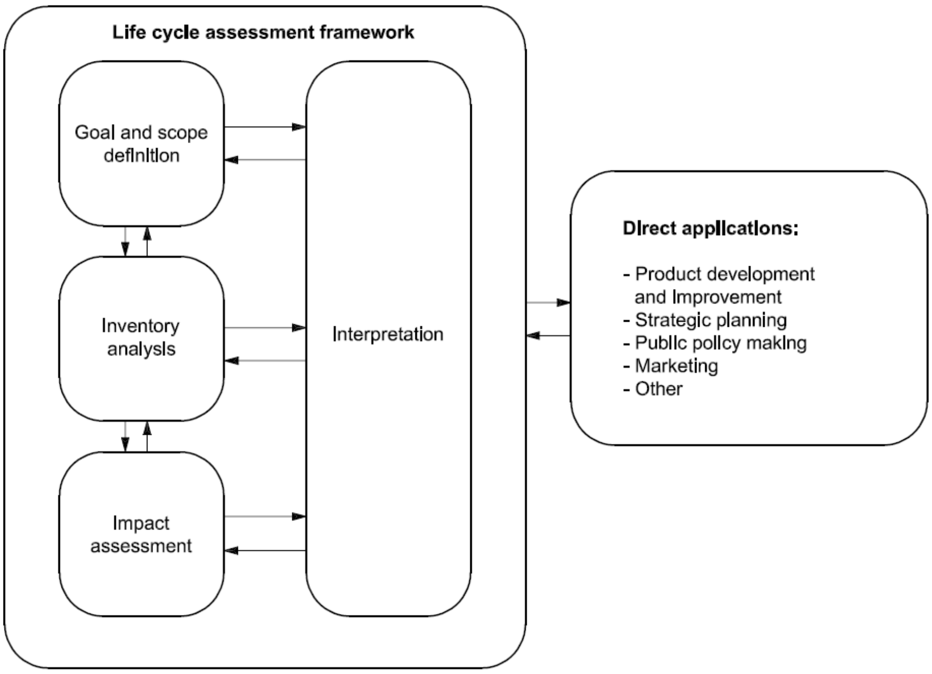

Figure 5. Phases in the LCA methodology (ISO 14040:2006).

In the first phase, the goal of the study is identified, stating the reasons for carrying it out and its intended application. The definition of the scope includes the functional unit and the system boundaries, along with all aspects that ensure that the depth of the study is sufficient to address the intended goals.

The second phase, Life Cycle Inventory Analysis (LCI), consists in the gathering of the necessary data regarding the inputs (materials, energy, water) and outputs (wastewater, residues and emissions) of the system being studied (Baumann & Tillman, 2004). Data and information from the real processes, primary data, is preferable but in many cases, it is necessary to complement it with data from LCI databases, the literature, or even from process simulators.

The Life Cycle Impact Assessment (LCIA) is the third phase of the LCA methodology, and it has the purpose of evaluating the environmental impacts based on the information gathered in the inventory phase. In this phase, a set of environmental impact categories are chosen, deemed representative of the expected main system impacts, or considering applicable regulations and/or standards. Then, an impact assessment methodology is chosen to calculate the values of the environmental indicators corresponding to the environmental impact categories that were selected. This phase has mandatory elements, such as classification and characterization and some optional elements like normalization, grouping and weighting.

The final phase of the LCA methodology, the interpretation, consists of combining the data from inventory analysis and from the impact assessment and analyze them, creating the way for conclusions and recommendations (ISO 14040:2006).

2.3 Limitations and Advantages of LCA and Higg Index

The LCA methodology presents some limitations that lead to difficulties when the method is being implemented. One of these limitations, and the most general one, as previously mentioned, is that LCA only quantifies the environmental performance of products, services, and processes, not taking into consideration the social and economic aspects (Dahllöf, 2003). As referred above, there are extensions for the economic (LCC) and social aspects (LCA), but they are still works in progress with no consensual methodology defined yet.

Also, in order to perform an LCA study there is a big need for data, which in most of the cases, is lacking and needs to be estimated either by searching in the existent literature or by simulating the process if possible. This limitation may lead to the possibility that the data that is searched is out of date or nonexistent, which can compromise the data quality (Dahllöf, 2003; ISO 14040, 2006).

An example of the data availability problem in the textile industry is cotton cultivation, since it is often unknown where the cotton is grown, there is a big range of values for the environmental impacts depending on where the cultivation happens, the variety of fertilizers that are used, if the culture was irrigated or not, among other factors (Dahllöf, 2003).

Another set of limitations of LCA are related with the LCIA, in particular, with the impact assessment methodology used, since it only addresses the issues specified in the goal and scope of the study. Thus, it is possible that it may not completely assess all the environmental problems of the product, service or process under study (ISO 14040, 2006). Furthermore, there is a vast quantity of impact assessment methods proposed in the literature, all with different models for the various environmental impact categories, making it very difficult to compare the results of different LCA studies when different evaluation methods were used.

It is quite challenging to conduct an LCA study of a clothing item since the supply chain is very lengthy and complex, incorporating many processes and activities, at all levels of production (The Textile Institute and Woodhead Publishing, 2015). The entirety of the supply chain needs to be taken into consideration, including raw materials extraction and since the raw materials are usually grown and processed in completely different parts of the globe, there is a big load of work related with data collection (Zoltkowski, 2022).

However, despite these limitations, LCA presents several benefits as it provides a complete picture of the product, service, or process in study (Chai, 2014). It also identifies hotspots, for example, in the production line of a certain product, making it easier to improve processes and achieve a better environmental performance. Moreover, LCA doesn't just consider one indicator, it provides a holistic view of the environmental impacts, avoiding the optimization of one environmental indicator without considering the others (Meer, 2018). Furthermore, LCA leads to the identification of opportunities for improvements in environmental performance and it helps with marketing, for example, by leading to the implementation of an ecolabelling scheme (ISO 14040, 2006).

When it comes to the Higg Index, its benefits are, like mentioned before, the fact that it considers both environmental and social impacts and that it is easier to use, as its internal databases and predefined life cycle stages significantly simplify the calculation and analysis of the results. Also, in the environmental section of the tool, an advantage is the fact that the Product Module considers the entire life cycle, from raw material extraction to end of life (Radhakrishnan, 2015).

However, Higg Index has some limitations to consider, such as the fact that Higg MSI only accounts for a cradle to gate perspective, as can be seen in Figure 6. Another limitation is that Higg MSI is not yet suitable for public disclosures, since it as no way to ensure that the scores are developed consistently. This is due mainly because it has 2 methods for submission of data: the input and output data at the process level or the LCIA results that were modelled independently (Watson & Wiedemann, 2019).

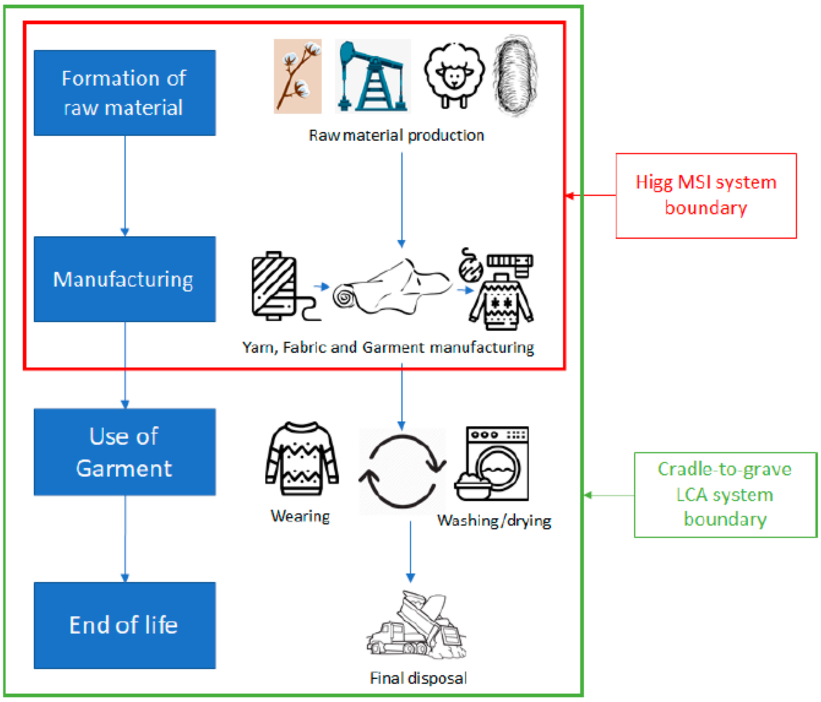

Figure 6. System boundaries for Higg MSI and cradle to grave LCA (Watson & Wiedemann, 2019).

Moreover, some inconsistencies with respect to compliance with ISO 14044 exist in Higg MSI, like the lack of sensitivity and uncertainty analysis and the lack of coverage when it comes to environmental impact category considered, that may not represent all the relevant environmental impacts. Also, there is no information about the choices made concerning methodological considerations (e.g., the choice of attributional or consequential LCA) or the reasons why certain life cycle stages were excluded (Watson & Wiedemann, 2019).

Furthermore, the social part of Higg Index is focused on costs like working hours, child labor and worker wages but does not consider the potential benefits such as employment and the opportunity for economic development (Luo, Song, Ding, & Wu, 2021).

2.4 Overview of LCA studies for textile products

There is a large quantity of LCA studies for fibers, like cotton, available in the open literature whereas fewer studies consider textile products, but still a fair amount can be found. Most of the articles found considered T-shirts or jeans as an object of study, whereas only two considered underwear. This represents a severe under coverage of underwear in the available literature, as far as the author knows. A review of life cycle inventory studies of clothing was done by Munasinghe et al. (2021), where out of the 57 articles considered, 8 were of actual textile products. The majority (4) were of t-shirts (one of which is already present in Table 2), and the rest were of a jacket, a bra, a sweater, and a blouse.

Table 2 presents an overview of the studies that were identified relative to textile products, mainly consisting of t-shirts, jeans, jackets, and underwear, presenting the main aspects of the LCA study.

Table 2. Overview of LCA studies of textile products.

Textile product	Location	LCIA Methods	Functional Unit	System boundaries	Source
Cotton t-shirt	China	CML 2001, UseTox	100 % cotton knitted dyed T-shirt	Cradle to grave	(Zhang et al., 2015)
Jeans	Sweden	ReCiPe 2016	1 pair of an average sized jean, over its full lifetime of 200 use cycles	Cradle to grave	(Hedman, 2018)
3 pack of men's cotton briefs (underwear)	UK	-	3 pairs of men's briefs in size medium used for 2 years	Cradle to grave	(Collins & Aumônier, 2002)
Polyester trousers	UK	-	1 pair of polyester trousers used for 2 years	Cradle to grave	(Collins & Aumônier, 2002)
Jacket	USA	ReCiPe	The use of the product for 5 years	Cradle to grave	(W. L. Gore & Associates, 2013)
Incontinence product (underwear)	Sweden	ReCiPe 2008 ; EPS	Hygiene function of 1 absorbent product with medium absorption capacity of medium size	Cradle to grave	(Willskytt & Tillman, 2019)
Polyester Jacket	Switzerland	Environmental Footprint (EF)	Use of a 3 layer-laminate jacket for a period of 4 years	Cradle to cradle	(Braun et al., 2021)
Cotton T-shirt vs Denim Jean	UK	ReCiPe 2008	Comparison of the production of 1 pair of Levi's jeans and 1 color dyed T-shirt.	Cradle to gate	(Hackett, 2015)

All the studies mentioned represent non-sustainable productions conditions, except for the polyester jacket, that is circular in the sense that it closes the textile loop, thus being a cradle-to-cradle study (Braun, Som, Schmutz, & Hischier, 2021).

The studies have a mix of primary and secondary data, most of them considering primary data (i.e., from the production site or manufacturer) for the production line and secondary data (i.e., from literature and statistic data sources) for the background, raw materials cultivation and extraction and use and disposal. Willskytt & Tillman (2019) are the exception, with most of the data being obtained from the literature.

Most of the studies consider the use and disposal phases, being cradle to grave, whereas Hackett (2015) takes the approach of cradle to gate only and Braun et al. (2021) considers the circular route, like mentioned before, being cradle-to-cradle.

Hedman (2018), Hackett (2015) and Braun et al. (2021) used SimaPro as the software to perform the LCA, whereas Zhang et al. (2015) used GaBi and Willskytt & Tillman (2019) used Open LCA. Both studies done by Collins & Aumônier (2002) were streamlined LCAs and were not clear on what software was used to perform the analysis.

Only two of the studies mentioned the methodological consideration in terms of attributional LCA instead of consequential LCA, whereas none of the other studies mentioned the choice. Yet, from the work analysis is clear that those studies are also of attributive nature, as the studies only did consider the environmental impacts directly linked to specific products, not the consequences of using them or of changes in existing products and/or their production processes.

In terms of environmental impact categories, W. L. Gore & Associates (2013) considered 18 of them, while Hackett (2015) only considered 5. The most common were abiotic depletion (AD), land use/occupation (LO), climate change (CC), water consumption/use (WU), eutrophication (ET) and human toxicity (HT).

According to Zhang et al. (2015), in the production of a cotton t-shirt, the dyeing process is the biggest contributor to the CC category, followed by the making-up-stage, that is comprised of the cutting, sewing, and package processes. These 2 stages and processes were also the biggest contributors to the abiotic depletion category whereas for the ET and WU, cotton cultivation was the significant stage.

Hackett (2015) had similar results to Zhang et al. (2015) when it comes to the climate change potential category, since the fabric assembly (yarn spinning, dyeing, weaving, and fabric finishing) is the most significant part for both the jeans and the cotton t-shirt. Also, in the water use and eutrophication categories since the biggest contributor is fiber cultivation. However, for this author, the abiotic depletion category suffered most from the packaging stage (in the jeans case) and from fiber production (in the t-shirt case). Hedman (2018) had similar results for the CC, WU and AD categories as Zhang et al. (2015).

Collins & Aumônier (2002) had, to produce the pack of 3 briefs, an energy consumption of around 13 kWh which is an average of 4,33 kWh per brief and an emission of 1,34 kg CO_2 eq. Also, in this study, the transport of clothing by suppliers and manufacturers was an insignificant part of the clothing life cycle with regards to energy consumption .

Other LCA studies not listed in Table 2 include the work of Baydar et al. (2015), that studied knitted and dyed cotton T-shirts from cradle to grave with Gabi software and database, the work of Bevilacqua et al. (2011) that analyses a 100 % Merino wool sweater from cradle to grave with SimaPro software and ecoinvent database, and the work of Muthukumarana et al. (2018) that studied a 100% cotton blouse from cradle to gate also with SimaPro software and ecoinvent.

When it comes to Higg Index, there is almost no studies in which the webtool is applied to textile products using the MSI and PM tools. The only studies found in the literature are presented in Table 3. The knitted t-shirt studies were conducted by the same authors one year apart. One of the studies mentions the brands of the knitted t-shirts that were compared whereas the other doesn’t disclose the brands, but they are very similar and can be considered to be the same study.

Table 3. Overview of studies of textile products done with Higg Index.

Textile product	Location	Year	Source
Knitted t-shirt	Bangladesh	2014 and 2015	(Islam & Khan, 2014) and (Khan & Islam, 2015)
Uniforms	USA	2015	(Cao et al., 2015)

Both Islam & Khan (2014); Khan & Islam (2015) and Cao et al. (2015) used the Product Module of Higg Index 1.0 to carry out their studies, scoring their products in the range 1-100.

Islam & Khan (2014); Khan & Islam (2015) considered 6 knitted men’s T-shirt size M made of 100 % cotton single jersey fabric from various brands, with the goal of comparing the product scores of each t-shirt to identify which ones were more sustainable.

On the study done by Cao et al. (2015), the authors tested a 65 % polyester 35 % cotton woven fabric automotive industry uniform to create a sustainable and usable automotive uniform. One of the conclusions of the study was that the product score would increase by around 5 points if the materials used changed from conventional to recycled polyester and organic cotton.

3 Materials and Methods

In the following subsections the LCA methodology used for this study, in accordance with the ISO 14040 and 14044, is described (ISO 14040, 2006; ISO 14044, 2006). The calculations related with the environmental impacts were done using the commercial software SimaPro (version 8.5.2) along with the database ecoinvent (version 3.5).

In this study, the results provided by SimaPro will be compared with the ones provided by the webtool Higg Index, in particular, the MSI and PM tools.

3.1 Goal and Scope of the study

The goal of his study is to assess the environmental impacts of a textile product, in particular, a boxer (men's underwear), to identify the environmental hotspots and to compare the results with those predicted using the webtool Higg Index. The hotspots analysis will give information about which life cycle stages, in the production of a men's boxer at IMPETUS, have the largest environmental impacts.

The functional unit is 1 men's boxer in dark blue, size medium (M) as shown in Figure 7. The company chose this piece of clothing to be the case study, as boxers represent a significant part of the products that are manufactured and sold, therefore being significant to the company environmental and economic performance.

Figure 7. Men's boxer in dark blue, size M.

The scope of the study is Portugal, since the electricity mix, transport conditions, among others considered are the Portuguese as much as possible. Whenever the Portuguese conditions were not possible, the European ones were used. The time coverage for this study is the current processes and machinery implemented at IMPETUS and the technological coverage, the best available technologies for the background processes, in particular, upstream.

In this study an attributional LCA approach was used since the focus are the environmental impacts originated by producing a unit of a specific product (Finnveden & Potting, 2014).

3.1.1 System boundaries and definition

The LCA study is cradle to gate, which means that the life cycle stages included go from raw materials production/cultivation to the boxer being packaged and ready to leave IMPETUS.

Some of these stages are considered to be in the background and others in the foreground of the study. Foreground systems consist of the processes that can be changed based on study results, whereas background systems are the remaining processes, that can be influenced by the foreground systems, but cannot be changed directly by the company (Baumann & Tillman, 2004). Primary data, which is data collected directly from the process, is usually used in the foreground systems and secondary data (data from literature) is used for background systems (Cucurachi, Giesen, & Guinée, 2018).

The system boundary for the knit fabric portion of the product, with the indication of the background and foreground processes, is shown in Figure 8. The transportation of elastane to spinning and after spinning to IMPETUS, the distribution, the use and the end of life were not considered in this study. They represent stages where there is large variability and uncertainty in the data, in particular, for the use phase, in which objective and representative scenarios are currently not possible to be defined. Moreover, due to time constraints and the goals defined by the company during the execution of this work, they were not considered.

As can be seen in Figure 8, the process starts with the cultivation of the organic cotton and the production of elastane, that are the raw materials used in the fabric of the boxer. Later, both fibers need to go through spinning, that is the process of turning them into yarn and in the case of the organic cotton the method applied is ring spinning and in the case of elastane is wet or dry spinning.

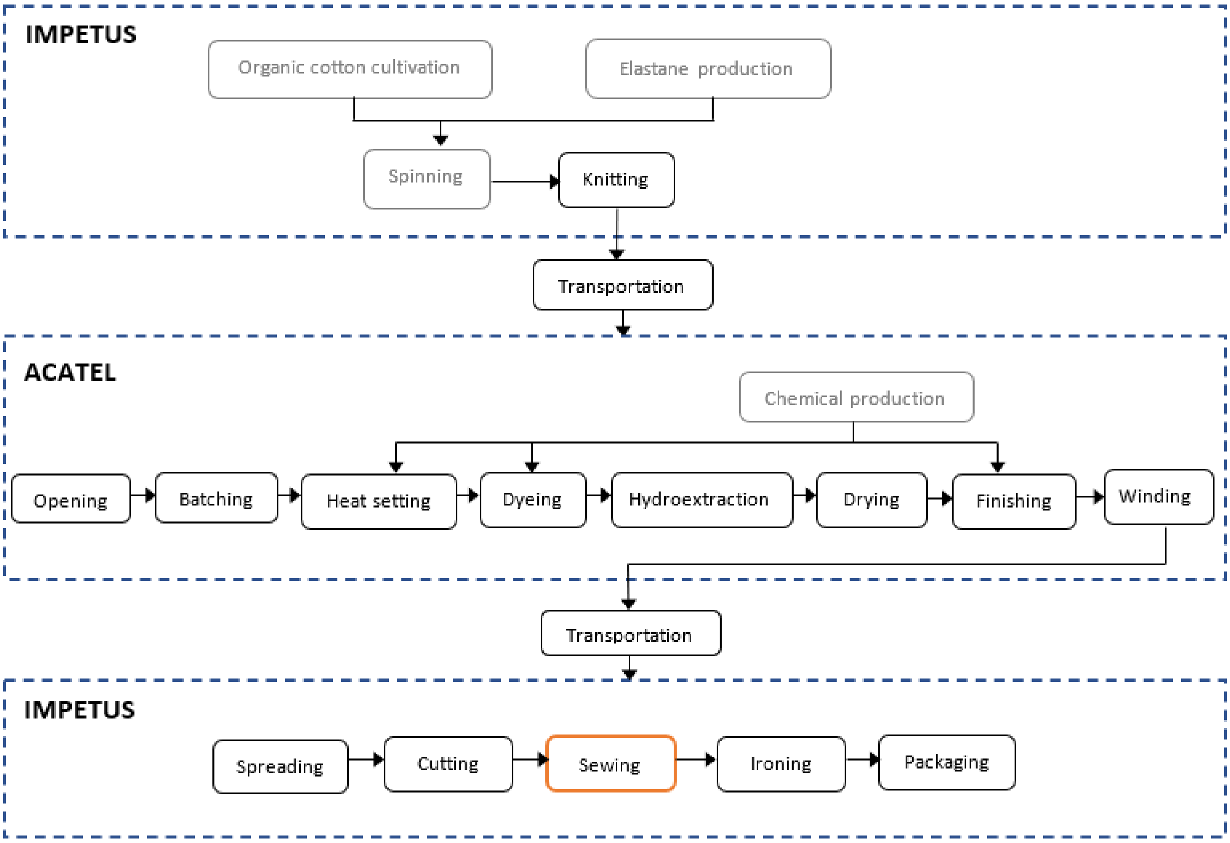

Figure 8. Background (grey) and foreground (black) processes considered in the life cycle of the product.

The next step is knitting, where yarn spools are fed into the machine, that, with the help of several hundred needles, as can be seen in Figure 9, makes the roll of knit fabric. After completion, the roll is ready to go to ACATEL to undergo the dyeing and finishing process. Please note that, when there is a mention of fabric in this study, it is always referred to knit fabric since it is what the company produces.

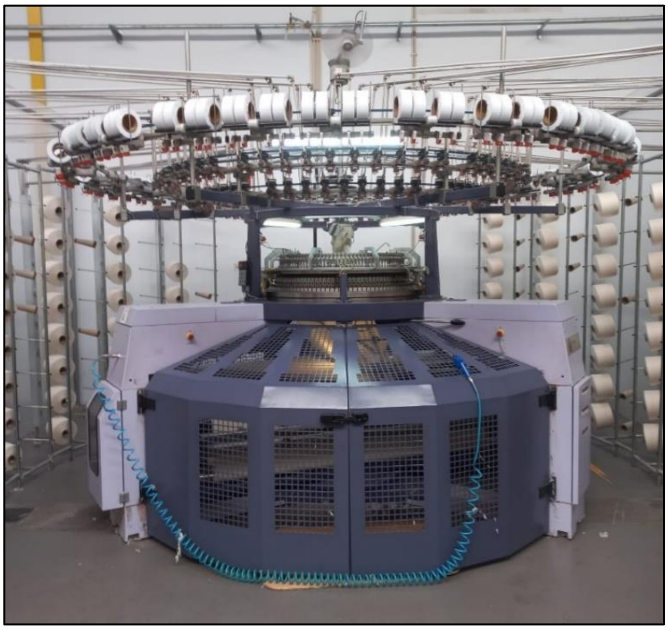

Figure 9. One of the knitting machines used at IMPETUS.

The knit fabric arrives to ACATEL in roll form, hence, it needs to be opened and then batched in order to undergo the next stages. Subsequently, the knit fabrics that have elastane in their composition, need to go through a heat setting process, in a Stenter Frame, presented in Figure 10, where the fabrics are treated with dry heat, at around 185 ºC, with the purpose of providing them with dimensional stability. Also, a chemical is added in the process in order to prevent the knit fabric from turning yellow due to the temperatures to which the fabric is subjected.

Figure 10. Heat setting machine used at ACATEL.

The now opened, batched and heat set knit fabric is ready for the dyeing process, that occurs inside jet dyeing machines. In these machines, both the fabric, the dyes and other auxiliar chemicals are mixed together with water, which causes the fabric to get the intended color in a fast and uniform way.

The knit fabric is wet as it goes out of the dyeing machine, hence, it needs to be squeezed in the rope opener presented in Figure 11, where it will lose most of the water it has. The remaining water, that cannot be removed mechanically (without heat), is removed in the drying machine, that operates at around 110-120 ºC.

Figure 11. Machine that squeezes the fabric in ACATEL.

Once dried, the knit fabric goes to the finishing stage that is comprised of 2 steps: the 1st being stentering and the 2nd sanforizing. In this first step softener is added to a vat at the entrance of the stenter, and then the softener is impregnated in the knit fabric through two squeezing rolls. Also in this step, around 4 cm of fabric is cut along each side of the knit fabric since the fabric rolls inwards and that creates problems in the cutting stage if not removed. The sanforizing step is done after the stentering and consists of steam being applied to the fabric, as can be seen in Figure 12, with the purpose of improving the shrinking aspect of the fabric and its touch.

Figure 12. Sanforizing machine used in ACATEL.

To end the process at ACATEL, the knit fabric is rolled in a winding machine and is ready to be transported back to IMPETUS where the final product will be made. After arriving at IMPETUS, the fabric is unwind and spread in a table, to go to the cutting stage. There, the fabric is cut, in automatic cutting machines, like those shown in Figure 13, where the maximum number of pieces are cut out of the fabric, having maximum efficiency and minimum waste.

Figure 13. Automatic cutting machines in IMPETUS.

After the fabric is cut in the desired shape, it moves to the next stage, the sewing stage, highlighted in orange in Figure 8 (and further down in Figure 14 as well), where the different pieces of fabric are sewn together using sewing machines. Also in this stage, the fabric portion of the boxer and the elastic band (accessory) are sewn together, making the final product.

The product is then ironed, in a machine powered by a boiler, and finally manually packaged using a specific box, hang tag and other accessories presented in Appendix A.

Alongside the process for the fabric production, there is also the production of the elastic band (accessory) that is attached to the fabric in the sewing stage, as previously mentioned. This elastic production is also done at IMPETUS and the process is shown in Figure 14.

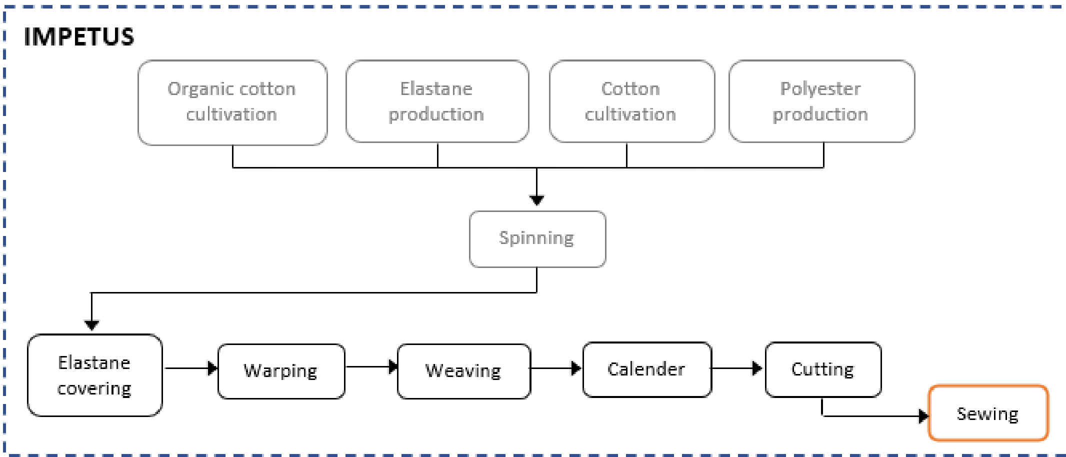

Figure 14. Processes in the production of the elastic band with foreground (black) and background (grey) processes.

This process begins with strands of elastane being covered, with polyester, in the yarn covering machine shown in Figure 15. This process ensures that the shiny aspect of the elastane strands do not appear in the final elastic and that the yarn becomes stronger while providing elasticity to the elastic band.

Figure 15. Strands of virgin elastane being lined with polyester yarn.

After, polyester spools as well as the spools of polyester coated elastane will go to the warping creels to be fed into the warping machine, where the yarns are aligned to form warping beams that are shown in Figure 16.

Figure 16. Warping beams that come out of the warping machine.

Once the warping beams are made, they are placed in their spot to feed the weaving machine, that is going to make the elastic recurring to several wire healds as can be seen in Figure 17.

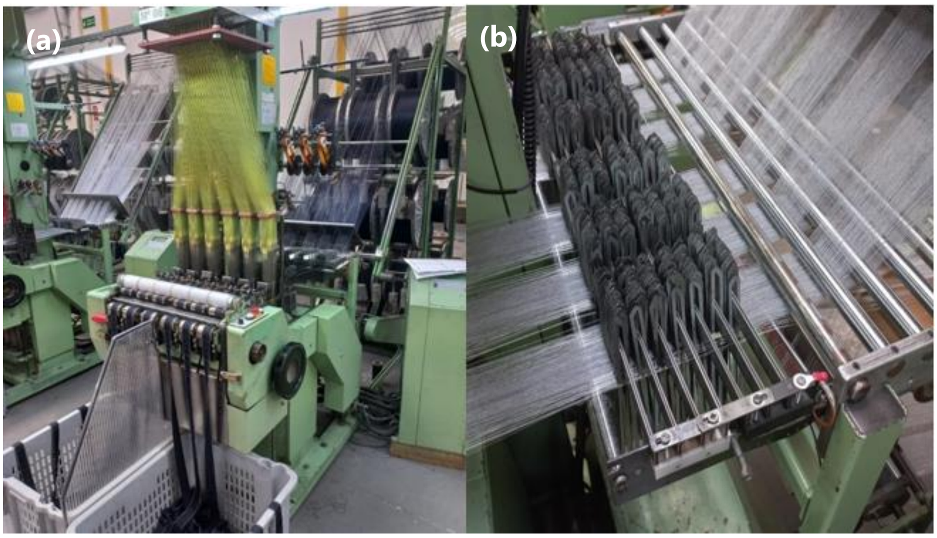

Figure 17. Weaving machine in IMPETUS (a) and the wire healds used (b).

The elastic then goes to 2 different calender machines, where in the first one it passes between the rollers at high temperatures (120 -145 ºC) and then, in the 2nd machine, again through high temperatures but also pressuring, as seen in Figure 18.

Figure 18. One of the calender machines used in IMPETUS for the elastics.

Finally, the elastic goes to the elastic band formation process, where the machine cuts it in ring form with the indicated waist size. The final elastic looks like what is presented in Figure 19.

Figure 19. Elastic band that will be sown to the knit fabric to make the boxer.

The inputs and outputs of the processes (flows of materials and energy through the system boundary) included in this life cycle study are presented in Figure 20.

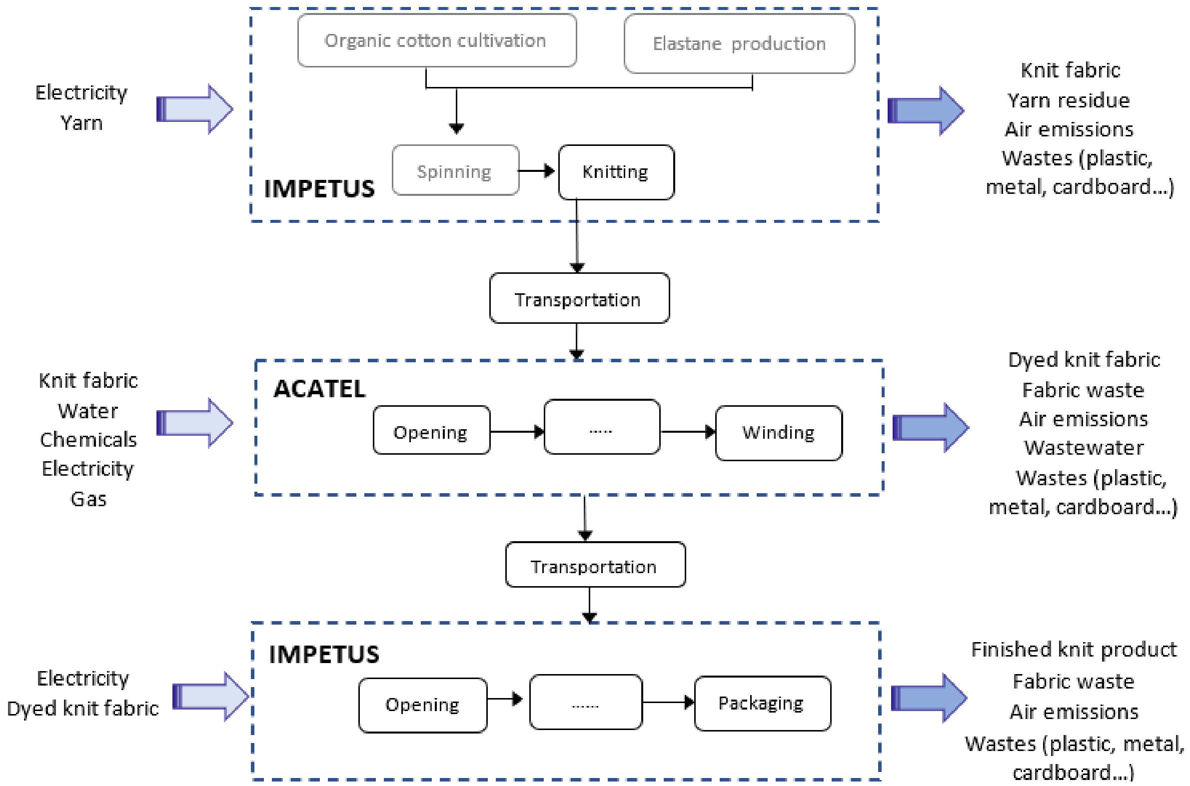

Figure 20. Inputs (left) and Outputs (right) of the process in study.

3.2 Inventory data and analysis

Fabric manufacturing, which includes all the processes from knitting to dyeing, finishing, cutting and packaging, are in the foreground. For them, site specific data was obtained, directly from IMPETUS, corresponding to primary data. Raw materials (organic cotton and elastane) production, chemicals production, packaging materials, washing agents, among others, are in the background. The inventory information for them was obtained from Life Cycle Inventory databases or from the literature, hence, mostly secondary data.

All the site-specific data, collected at IMPETUS and ACATEL refers to the year 2021 and represents the conditions of the companies at that time. This data still presents a certain level of uncertainty, but they are closer to the real values than the possible data that can be found in literature, as it is based on the specific operational conditions of the processes. Whenever necessary allocation procedures are done, in particular, when only the global production volumes and consumptions are available for a given process, an estimate is obtained by multiplying the total consumption, either material or energy, by the mass of a boxer produced. Although this calculation assumes that the consumptions and emissions linked to produce one boxer are directly proportional to the ones of producing several kilograms of knit fabric, as a first approximation is adequate.

The significant assumptions made and the inventory data that was collected for each stage of the life cycle are listed below.

- **Organic cotton cultivation, synthetic fibers production and spinning:**

The values for these background stages were obtained from the literature and the sources are presented in Table 4.

Table 4. Sources used for the secondary data that was needed.

Data	Source
Organic cotton production	(Thylmann et al., 2014)
Elastane Production	Ecoinvent 3.5
Polyester production	Ecoinvent 3.5
Spinning of organic cotton	(Van der Velden, Patel, & Vogtländer, 2014)
Spinning of elastane and polyester	(Roos, et al., 2019)

- **General assumptions for knit fabric manufacturing:**

The amount of knit fabric that one boxer has depends on what stage of the process the calculation starts. The mass value for the boxer in the cutting stage was taken directly from the cutting machine and the other values were calculated from that point, considering the average percentage of yarn waste provided by the company. The average waste values are presented in Table 5.

Table 5. Percentages of yarn waste in the process.

Stage of the process	Yarn waste (%)
Knitting	1 - 1.5
Whole ACATEL process (preparation-dyeing-finishing)	10 - 12
Cutting	14.24

From the percentage of yarn waste values (assuming always the highest value) and the starting point of the mass in the cutting stage, the mass of knit fabric in 1 boxer before ACATEL and in the knitting stage, were calculated using equations 1 and 2, respectively.

$$m_{boxer\ before\ ACATEL} = \frac{m_{boxer\ cutting}}{100 - 12} \times 100 \qquad [1]$$

$$m_{boxer\ knitting} = \frac{m_{boxer\ before\ ACATEL}}{100 - 1.5} \times 100 \qquad [2]$$

with $m_{boxer\ in\ ACATEL}$ being the mass of fabric in 1 boxer during the ACATEL steps, in kg, $m_{boxer\ cutting}$ the mass of fabric in 1 boxer in the cutting stage, in kg, and $m_{boxer\ knitting}$ the mass of fabric in 1 boxer in the knitting stage also in kg.

The starting value for the mass of knit fabric in 1 boxer is presented in Table 6, as well as the calculated values for the other stages. As expected, the values for Before ACATEL and knitting are larger, as it is necessary to compensate for the losses that occur in those steps.

Table 6. Mass of boxer in the fabric during different process stages.

Process stage	Mass of fabric in 1 boxer (kg)
Cutting	0.069
Before ACATEL	0.078
Knitting	0.080

- **Knitting:**

The electricity consumed by the knitting machine was obtained by knowing the power of the machine and the time it took to do the mass of knit fabric for the boxer, according to equation 3

$$E = P \times \Delta t_{boxer} \qquad [3]$$

where E is electricity needed for 1 boxer in kWh, P is power of the machines in kW, and Δt_{boxer} is the time it takes to do the amount of fabric needed for 1 boxer in hours. The value of P was obtained from the technical characteristics, in this case, of the knitting machine. The value for Δt_{boxer} was estimated from the time needed to obtain 1 kg of fabric, adjusted to boxer mass, as expressed in equation 4

$$\Delta t_{boxer} = \Delta t_{1kg} \times m_{boxer\ knitting} \qquad [4]$$

where Δt_{1kg} is the time it takes to do 1 kilogram of fabric in hours. The data related with knitting and the values used for the electricity calculations mentioned above, are presented in Table 7.

Table 7. Data related with the knitting machine.

Power (kW)	5.5
Time spent to do 1kg of fabric (min)	3.4
Time spent to do 1 boxer (min)	0.27
Electricity consumed for 1 boxer (kWh)	0.024

- **Transportation:**

The distance between IMPETUS and ACATEL was rounded to 10 kilometers. Although the fabric goes directly from IMPETUS to ACATEL, when it comes back from ACATEL it stops first in another facility, making the total distance around 25 kilometers per trip. Also, it was assumed that the truck, that is diesel fueled, would always be travelling at full capacity (3.5 ton).

The transport of the organic cotton is considered to be done by ship with a distance of around 11,000 km, since it is considered that the cotton was cultivated in India.

- **Unwinding and Spreading:**

These are mechanic machines that only use electricity, however, even though the power of the machines was available, the time it takes to unwind the knit fabric was not, and thus these steps were not considered. When compared to other processes like those involving heat, it is not expected that these two steps will have a significant energy consumption.

- **Heat setting:**

A chemical called "Tuboset" is added to the fabric to keep it from turning yellow due to the heat. Its composition is provided in the safety data sheet and all the chemicals were found in the ecoinvent life cycle inventory database in the SimaPro software used in this work.

The data related with the heat setting process and the values used for the energy calculations are presented in Table 8, as well as the results for electricity and natural gas consumption. The electricity needed for this stage, presented in the table below, was calculated in the same way as it was done for the knitting process, using equations 3 and 4.

Table 8. Data related with the heat setting machine.

Temperature (°C)	185
Water (kg/kg of fabric)	0.80
Quantity of Tuboset (g/L)	15
Power (kW)	120
Time spent to do 400 kg of fabric (h)	2
Time spent to do 1 boxer (h)	3.9×10^{-4}
Electricity consumed for 1 boxer (kWh)	0.047
Natural gas consumed in 2021 for this machine (m^3)	160,056
Quantity of fabric thermoset in 2021 (kg)	729,781
Natural gas consumed do to 1 boxer (m^3)	0.017

The natural gas consumed to thermoset 1 boxer was calculated by knowing the overall natural gas consumption, for this specific machine in 2021, the total amount of fabric thermoset in that same year and the mass of 1 boxer, assuming that the natural gas consumed is proportional to the boxer mass. The natural gas value was later converted from m^3 to MJ by multiplying the given value by its lower heating value (LHV) of 33.77 MJ/m^3 (Guo et al., 2017).

- **Dyeing:**

The quantity for each auxiliar and dye used in the dyeing process of the fabric for the boxer, is presented in Table 9.

Table 9. Quantity of chemicals used in the dyeing process.

	Chemicals in Dyeing	Quantity* (kg)	Quantity for 1 boxer (kg)
Auxiliars	Acetic acid	2.090	3.9×10^{-4}
	Toxal Tac	2.090	3.9×10^{-4}
	Albatex CO	4.180	7.8×10^{-4}
	Toxal JET/SO	4.180	7.8×10^{-4}
	Mazyme ECO	4.180	7.8×10^{-4}
	Toxal PV-DT	4.180	7.8×10^{-4}
	Centrifuged salt	146.3	0.027
	Sodium hydroxide, liq 50%	5.330	1.0×10^{-3}
	Sodium carbonate	10.45	2.0×10^{-3}
Dyes	Novacron deep night	12.54	2.4×10^{-3}
	Everzol red E	5.430	1.0×10^{-3}
	Everzol yellow 3R	6.900	1.3×10^{-3}

* for 418 kg of knit fabric

All the auxiliars have safety data sheets with their composition, however, the three dyes presented (Novacron deep night, Everzol red E and Everzol yellow 3R) do not, since dye manufacturers, due to confidentiality, do not disclose the substances used. The ecoinvent database does not have information on dyes used for textile products. Hence, the information regarding the 3 dyes used was obtained from (Roos et al., 2018). One of the chemicals used in the Toxal TAC formulation, was not considered in this study, since no information was available either in the databases or in the literature. In the case of the mazyme ECO, a general enzyme production life cycle inventory from the ecoinvent database was used.

The quantity of chemicals used for 418 kg of knit fabric in this stage, as well as the electricity and steam needed for that amount of fabric were known from the industrial practice. So, it is only necessary to adjust those values to the mass of the boxer, assuming a linear dependence, and that was done through equations 5,6 and 7

$$m_{chemicals\ boxer} = \frac{m_{chemicals\ in\ 418kg} \times m_{boxer\ in\ ACATEL}}{418} \quad [5]$$

$$E = \frac{E_{418kg} \times m_{boxer\ in\ ACATEL}}{418} \quad [6]$$

$$E_{steam\ boxer} = \frac{E_{steam\ in\ 418kg} \times m_{boxer\ in\ ACATEL}}{418} \quad [7]$$

, where $m_{chemicals\ boxer}$ is the quantity of chemicals used to dye 1 boxer in kg, $m_{chemicals\ in\ 418kg}$ is the quantity of chemicals used to dye 418 kg of knit fabric in kg, E_{418kg} is the electricity consumed to dye 418 kg of knit fabric in kWh, $E_{steam\ boxer}$ is the steam used to dye 1 boxer in Mcal and $E_{steam\ in\ 418kg}$ is the steam used to dye 418 kg of knit fabric in Mcal.

- **Hydroextraction:**

The electricity consumption related with the opening and hydroextraction process, as well as the consumption result for 1 boxer are presented in Table 10.

Table 10. Data related with the hydroextraction machine.

Power (kW)	27
Time spent to do 400 kg of fabric (h)	1
Time spent to do 1 boxer (h)	1.73×10^{-4}
Electricity consumed for 1 boxer (kWh)	0.00466

The electricity needed for this stage, presented in the previous table, was calculated following the same procedure considered for the knitting process, using equations 3 and 4.

- **Drying:**

The temperature range for this process was 110-120 ºC. In ACATEL they use 3 different drying machines and therefore it is necessary to use the average of the values for the 3 machines.

When it comes to the electricity and natural gas consumed by the machines, the values are already known per kilogram of fabric. Thus, it is only necessary to multiply the electricity consumption value with the kilograms of fabric in 1 boxer before it gets to ACATEL, as shown in equation 8:

$$E = E_{consumption} \times m_{boxer\ in\ ACATEL} \quad [8]$$

where $E_{consumption}$ is the electricity consumption of the machine per kg of fabric in kWh. The same equation was applied for the natural gas consumption in m^3.

The data regarding electricity and natural gas consumption per kilogram of fabric and for the quantity of fabric used in 1 boxer in the drying process is shown in Table 11.

Table 11. Data related to electricity and natural gas consumption in the drying process.

	Electricity consumption (kWh/kg)	Gas consumption (m^3/kg)	Electricity consumed for 1 boxer (kWh)	Gas consumed for 1 boxer (m^3)
Babcock dryer	0.347	0.150	0.0272	0.0120
Pentek dryer	2.03	1.17	0.159	0.0914
Mach5 dryer	0.476	0.160	0.0373	0.0125
Average	1	0.490	0.0746	0.0387

The natural gas values were later converted from m^3 to MJ in the same way as with the heat setting process, using the LHV of natural gas.

- **Finishing:**

1. Stentering

The chemicals used in the stenter as well as the information of operational pressure, temperature, and pH, are presented in Table 12.

Table 12. Data relating to chemicals, temperature and other parameters of the stentering process.

<table>
<tr><td></td><td>pH</td><td>4.5</td></tr>
<tr><td></td><td>Pressure (bar)</td><td>4</td></tr>
<tr><td></td><td>Temperature (°C)</td><td>130</td></tr>
<tr><td rowspan="4">Chemicals</td><td>Solusoft NUP (g/L)</td><td>30</td></tr>
<tr><td>Toxal BUF/4 (g/L)</td><td>1</td></tr>
<tr><td>Fluowet UD LIQ (g/L)</td><td>3</td></tr>
<tr><td>Aquifix FT (g/L)</td><td>20</td></tr>
</table>

Three of the chemicals have safety data sheets with their composition, and all the components can be found in the ecoinvent database. The exception was Aquifix FT, whose composition was not available in the safety data sheet and therefore this chemical was not considered.

When it comes to the electricity and natural gas calculations for the stentering process, they were done in the same way as the drying process using equation 8. The calculated values are presented in Table 13.

Table 13. Electricity and natural gas values for the stentering process.

Electricity consumption (kWh/kg)	0.090
Natural gas consumption (m^3/kg)	0.15
Energy consumed for 1 boxer (kWh)	0.0071
Natural gas consumed for 1 boxer (m^3)	0.012

Similar to the heat setting and drying processes, the natural gas value was converted from m^3 to MJ, by multiplying the value with the LHV of natural gas.

2. Sanforizing

The data related with sanforizing used for the energy calculations as well as the consumptions result are presented in Table 14.

Table 14. Data related with the sanforizing machine.

Power (kW)	15
Time spent to do 400 kg of fabric (h)	1.15
Time spent to do 1 boxer (h)	1.98×10^{-4}
Electricity consumed for 1 boxer (kWh)	0.00298
Steam consumed in 2021 for this machine (ton)	8458
Quantity of fabric sanforized in 2021 (kg)	1,183,119
Steam consumed do to 1 boxer (kg)	0.49
Steam consumed do to 1 boxer (Mcal)	0.27

The electricity needed for this stage, presented in the table above, was calculated using equations 3 and 4. The steam needed, in Mcal, was calculated using the latent heat vaporization of water of 540 kcal/kg (Coelho, 2017).

- **Winding:**

The data related with the winding process (last step in ACATEL) used for the electricity calculations as well as the electricity consumption result are presented in Table 15.

Table 15. Data related with the winding machine.

Power (kW)	4.5
Time spent to do 400 kg of fabric (h)	1
Time spent to do 1 boxer (h)	1.73×10^{-4}
Electricity consumed for 1 boxer (kWh)	7.76×10^{-4}

The electricity needed for this stage, presented in the table above, was once again calculated using equations 3 and 4.

- **Spreading and Cutting:**

The data for this step corresponds to the spreading of the fabric in the table before it goes to the cutting machine and includes both cutting machines at IMPETUS. All the values used to calculate the electricity consumed to cut 1 boxer as well as the estimated electricity values are presented in Table 16.

Table 16. Data related with the cutting stage.

Clothing pieces cut in 1 year	3,636,692
Operating time of the machines in 1 year (h)	2137.67
Power (kW)	33.20
Electricity consumed to cut 1 boxer (kWh)	0.020

The operating time of the machines was given for the months of December through May (6 months). The value for the entire year was extrapolated from that value, assuming that in the other 6 months of the year a similar operational performance occurs, corresponding to a doubling of the given value.

A correction was made to the month of August, in which most employees take vacations and the main company activities stop, as defined in equation 9

$$\Delta t_{operating\ adjusted} = \Delta t_{operating\ 1\ year} \times \frac{11}{12} \quad [9]$$

where $\Delta t_{operating\ adjusted}$ is the adjusted operating time of both machines in 1 year in hours, and $\Delta t_{operating\ 1\ year}$ is the operating time of both machines in 1 year in hours.

The electricity consumed to cut 1 boxer was then calculated using equation 10.

$$E = \frac{P \times \Delta t_{operating\ adjusted}}{3\ 636\ 692} \quad [10]$$

- **Sewing:**

When it comes to the electricity consumed in the sewing process, it was calculated in the same way as the knitting process using equations 3 and 4 and the values, obtained from the company and calculated, are presented in Table 17.

Table 17. Data related with the sewing stage.

Power (kW)	0.45
Time spent to do 1 boxer (min)	4.14
Electricity consumed for 1 boxer (kWh)	0.031

- **Ironing:**

The steam used in the ironing machine comes directly from the boiler. The chemicals added to the boiler were considered non-significant since they are used in small quantities due to the feed water already having low amounts of calcium and magnesium. Thus, the potential for deposits appearance in the boiler is very low.

The energy used in this particular machine was not available, but the global emissions of CO_2 in the boiler used to feed this machine were. Therefore, the calculation to make 1 boxer was done according to equation 11,

$$Em_{boxer} = \frac{m_{pellets\ for\ 1\ item} \times Em_{pellets\ year}}{m_{pellets\ used\ anually}} \quad [11]$$

where Em_{boxer} is the pellet emissions resultant of making 1 boxer in kg CO_2.eq, $m_{pellets\ per\ item}$ the mass of pellets consumed per clothing item made in the conventional way in kg, $Em_{pellets\ year}$ is the pellet emissions generated in average a year in kg CO_2.eq, and finally $m_{pellets\ used\ annually}$, the mass of pellets used in an average year in kg.

In Table 18 the values used for the calculation of the CO_2 emissions originated from burning pellets in the boiler to make 1 boxer are given.

Table 18. Mass and emission values for the burning of pellets in the boiler.

Mass of pellets per item made (kg)	0.02
Average Pellet emissions in 2021 (kg CO_2.eq)	209
Average mass of pellets used in 2021 (kg)	2875

The CO_2 emissions, to iron 1 boxer were 0.0017 kg CO_2. eq and they were calculated taking into consideration a characterization/emission factor (EF) of 72.61 (Defra, 2022) and the monthly pellet consumption.

- **Packaging:**

This step is done manually, and as the environmental impacts of manual labor are extremely hard to quantify and no data was available for the electricity consumption in this stage, the energy was not considered in this step. The carton box that holds the boxer has a small window made of plastic that was not taken into consideration due to the little weight of it compared with the rest of the box. The mass of each product used in the packaging of the boxer is shown in Table 19.

Table 19. Mass of the materials used in packaging.

Materials used in packaging	Mass of the material per produced boxer (g)
Carton box	32.2
Label on the box	0.38
Label on the hang-tag	0.11
Hang tag (carton)	1.61
Plastic pin	0.030
Carton to fold the boxer	7.9
100% polyester label	0.19
100% cotton label	0.11

All the packaging materials life cycle inventory data came from the ecoinvent database with the exception of the labels for the box and for the hang-tag, which came from (Edwards & Parker, 2010).

- **Elastic manufacturing stages (Elastane covering + Warping + Weaving + Calendering + Cutting):**

The elastic composition was 74 % cotton, 20 % polyester and 6 % elastane, and it uses both organic and conventional cotton. However, as the distinction between the two was not possible, and since the organic cotton is used in a bigger quantity, it was assumed that the 74 % cotton was all organic cotton.

The electricity calculations for the first 4 steps in the elastic production were done using equations 3 and 4, knowing that the mass of elastic in the boxer is 0.022 kilograms. For the last stage in the production line of the elastic, the cutting and sewing stage, the calculation was simpler since there was only the need to multiple the power of the machine for the time it takes to do 1 ring of elastic, following equation 12

$$E = P \times \Delta t_{ring} \quad [12]$$

where Δt_{ring} is the time needed to do 1 ring (1 elastic waist) in hours.

The values used for the electricity calculations for all the steps in the elastic production as well the electricity results are presented in Table 20.

Table 20. Data related with the steps in elastic production.

Stage	Power (kW)	Time spent to do 1kg (min)	Time spent to do 1 elastic (min)	Time spent to do 1 ring (min)	Electricity consumed for 1 boxer (kWh)
Elastane covering	25.2	21	0.059	-	0.025
Warping	4	0.03	0.0010	-	4.4×10^{-5}
Weaving	2.4	14.2		-	0.013
Calender	16	21.9	0.48	-	0.043
	6.5				0.035
Cutting	0.6	-	-	0.33	0.0033

For the calender stage, there are two values of power since the elastic goes through 2 different machines and it goes through one of them 1 time and the other 2 times. The time spent in the machine where the elastic passes 2 times was considered to be 2/3 of the overall time in the calender and the remaining of the time (1/3) was allocated to the other machine.

- **Other assumptions:**

All the electricity provided for IMPETUS and ACATEL is medium voltage. Presently, 100% of the electricity is obtained from the grid even though there is production of electric energy with solar panels. The amount of energy produced by photovoltaic was deducted from the overall energy consumed from the grid.

The amount of energy sold by IMPETUS in the year 2021 from the photovoltaic panels was 176, 579 kWh and the electricity consumed from the grid in that same year was 3,321,586 kWh. Therefore, the photovoltaic percentage is assumed to be 5 % of the total energy consumed by IMPETUS.

The spot cleaning of the clothing pieces with the pressurized air gun, when there are oil stains, was not considered due to low occurrence.

The air emissions in both facilities were not considered, since, even though both companies monitor Volatile Organic Compounds (VOC's) values, there is no possible way to allocate these values to the specific processes and consequently to the functional unit.

Concerning the composition of all the chemicals and formulations present in Appendix B, it was assumed to be the maximum of the intervals provided in the safety data sheets. The ones with a presence of 0,1 % or less were not considered in this study, thus representing a cut of criteria.

The company uses compressed air, however, despite consumption being relevant, there is no way to consider it, as no information is available concerning the quantities used and for what machines.

In Table 21 the quantity of fabric produced at IMPETUS and handled at ACATEL in the year of 2021 is presented.

Table 21. Quantity of knit fabric produced and/or handled in the companies.

	At IMPETUS (kg)	At ACATEL (kg)
Quantity of fabric produced/handled	825,574	2,793,881

These values were used to calculate the amount of waste generated for 1 boxer and the amount of water spent and wastewater produced to make 1 boxer, trough equations 13, 14 and 15 respectively

$$m_{waste\ boxer} = \frac{m_{boxer\ in\ ACATEL} \times m_{waste\ in\ 1\ year}}{m_{fabric\ handled\ in\ 1\ year}} \quad [13]$$

$$V_{water\ boxer} = \frac{m_{boxer\ in\ ACATEL} \times V_{water\ in\ 1\ year}}{m_{fabric\ handled\ in\ 1\ year}} \quad [14]$$

$$V_{wastewater\ boxer} = \frac{m_{boxer\ in\ ACATEL} \times V_{wastewater\ in\ 1\ year}}{m_{fabric\ handled\ in\ 1\ year}} \quad [15]$$

where $m_{waste\ boxer}$ is the mass of waste produced to make 1 boxer in kg, $m_{waste\ in\ 1\ year}$ is the mass of waste produced in 1 year of operation in kg, $m_{fabric\ handled\ in\ 1\ year}$ is the mass of fabric handled by the company during 1 year of operation in kg, $V_{water\ boxer}$ is the volume of water needed to make 1 boxer in m^3, $V_{water\ in\ 1\ year}$ is the volume of water used by ACATEL in 1 year of operation in m^3, $V_{wastewater\ boxer}$ is the volume of wastewater produced to make 1 boxer in m^3 and $V_{wastewater\ in\ 1\ year}$ is the volume of wastewater produced in 1 year of operation in m^3.

The results for the water that is needed, and the waste and wastewater that are generated to make 1 boxer are presented in the next chapter, alongside the energy values for each stage. The water and wastewater were only taken into consideration in ACATEL since, in IMPETUS water is not used in the mentioned processes.

3.3 Environmental impact assessment

The selected impact categories for this study were eutrophication, freshwater ecotoxicity (chemistry), climate change, resource depletion - fossil fuels and water use, since they are the ones also calculated in the webtool Higg Index (Sustainable Apparel Coalition, 2020) and therefore allow for the comparison between the tool and SimaPro. A description of each environmental impact category and the corresponding physical units is given in Table 22.

Table 22. Significance and units of the environmental impact categories (Hillege, 2019).

Environmental Impact Category	Description	Units
Climate Change	Indicator of the possibility of global warming due to greenhouse gases emissions.	kg CO_2. eq
Water use	Indicator of the amount of water used, based on water scarcity factors.	m^3
Resource depletion – fossil fuels	Indicator of the natural fossil fuel resources depletion.	MJ
Eutrophication	Indicator of the increase of nitrogen or phosphor in freshwater ecosystems due to emissions of compounds that contain those nutrients.	kg PO_4^-. eq
Freshwater Ecotoxicity (chemistry)	Impact of toxic substances on freshwater organisms.	CTU_e

To ensure an objective comparison between the results of this LCA study and the values calculated by Higg Index, the same environmental impact calculation methodologies were used for each environmental impact categories. In Table 23 the methods for each of the categories are shown.

In SimaPro, a new LCIA method was created in order to combine the 5 different categories and methods needed for this study, as the combination of methodologies is not available in the standard version of the software.

Table 23. LCIA methods for each of the environmental impact categories.

Environmental Impact Category	LCIA method
Climate Change	IPCC 2013 GWP 100a
Water use	AWARE
Resource depletion – fossil fuels	CML-IA baseline 2013
Eutrophication	CML-IA baseline 2013
Freshwater Ecotoxicity (chemistry)	Usetox

3.4 Higg Index

When using Higg Index, first it's necessary to add all the materials that are going to be needed to make the product, a process that is done using the MSI tool. In this study, the boxer has 2 major materials: the fabric and the elastic each one made of several different materials. The fabric is 95 % organic cotton and 5 % elastane, and those materials and quantities need to be added to the MSI tool by picking the elastane fabric and organic cotton fabric from the library and specifying the composition percentages making a custom material.

Once a material is chosen, for example the elastane yarn for the knit fabric, the processes that it undergoes until it becomes the final fabric, like knitting and dyeing, need to be selected from the tools databases. Also, the method of transportation and the transport distances between each stage of the life cycle can too be defined.

Besides the fabric and the elastic, the packaging materials also need to be added to the MSI tool alongside their mass to make custom packaging materials. For example, the plastic pin is introduced by choosing the material (plastic) and then entering the mass of the pins, for which various options are available.

All the possible custom options in the MSI tool, like custom materials and trims and packaging are presented in Figure 21, as well as the example materials that are included in the database for the custom materials. Custom materials in this case, are the actual materials in study, composed of 1 or more of the example materials in the intended percentages. For example, cotton fabric was one of the example materials as well as elastane fabric and one of the custom materials created for the boxer was a knit fabric composed of 95 % cotton fabric and 5 % elastane fabric.

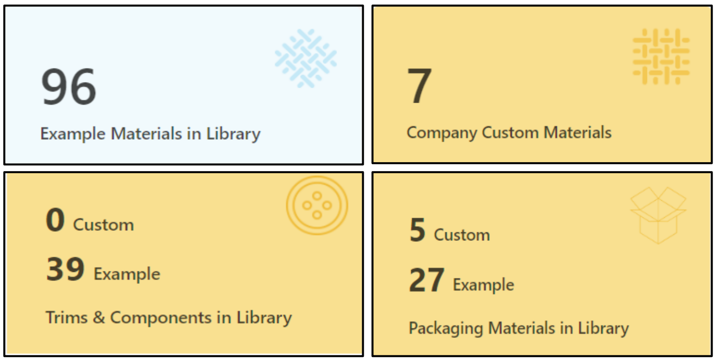

Figure 21. Options to create custom items in the MSI dashboard.

When choosing the processes that the yarn goes through until it becomes fabric, the dyeing step was not considered in the elastane yarn since elastane yarns used in this boxer are not dyed, only the organic cotton is dyed.

The environmental impact category of chemistry evaluated in Higg Index only accounts for freshwater ecotoxicity, not including human toxicity. One of the reasons for this is that the Sustainable Apparel Coalition considered ecotoxicity to have higher orders of magnitude than human toxicity for all the MSI processes (Sustainable Apparel Coalition, 2020).

There were some limitations encountered when the tool was being used and they will be detailed below as well as in the next chapter.

The PM tool evaluates the 5 environmental impact categories already mentioned, where 4 of them are straight forward, but the one related with chemistry is not well defined. The chemistry category is said to be a semi-quantitative category since it considers the freshwater ecotoxicity from Usetox as previously mentioned, but also qualitative modifiers which are the certifications the product has. This makes the comparison between results, for the chemistry impact category, not accurate since SimaPro doesn't have those qualitative aspect that changes the values.

The webtool Higg Index required the perimeter of the boxer that is cut and the length that is sewn. When it comes to the sewing stage the value of meters of sewing thread used were already known. However, the perimeter of the boxer needed to be calculated and that was done through equation 16.

$$P_{boxer} = \frac{l_{fabric}}{20} \times 4 + \frac{w_{fabric}}{20} \times 4 = \frac{4l_{fabric} + 4w_{fabric}}{20} \qquad [16]$$

where P_{boxer} is the perimeter of cutting in the boxer in meters, l_{fabric} is the length of the knit fabric that is going to be cut in meters and w_{fabric} is the width of the knit fabric that is going to be cut in meters.

4 Results and discussion

In this chapter the results are presented and discussed, focusing on the life cycle inventory and the environmental impact assessment. Furthermore, a comparison between SimaPro and Higg Index results is done, and a few electricity scenarios are studied.

4.1 Life Cycle Inventory

In the following tables the energy, water, wastewater and waste values are presented for all the processes involved in the production of a boxer.

In Table 24 the energy values needed to make 1 boxer, for each of the life cycle stages considered, are presented.

Table 24. Energy values to produce 1 boxer in the considered life cycle stages.

Process stage	Electricity (kWh)	Steam (Mcal)	Natural gas (MJ)	Pellets (kg)
Fabric				
Knitting	0.024	-	-	-
Heat setting	0.047	-	0.581	-
Dyeing	0.029	0.035	-	-
Hydroextraction	0.0047	-	-	-
Drying	0.075	-	1.305	-
Stentering	0.0071	-	0.397	-
Sanforizing	0.0030	0.27	-	-
Winding	0.00078	-	-	-
Cutting	0.020	-	-	-
Sewing	0.031	-	-	-
Ironing	-	-	-	0.02
Elastic				
Warping	4.4×10^{-5}	-	-	-
Weaving	0.013	-	-	-
Calender	0.043	-	-	-
	0.035	-	-	-
Cutting	0.0033	-	-	-

The water and wastewater values used and produced, respectively, in ACATEL in the year 2021, and the corresponding values needed and produced to make 1 boxer (the functional unit considered in this LCA study) are presented in Table 25.

Table 25. Water and wastewater values for ACATEL in general with all the processes.

Water consumed in a year (m^3)	467,639
Wastewater produced in a year (m^3)	437,322
Water consumed for 1 boxer (m^3)	0.0130556
Wastewater produced to make 1 boxer (m^3)	0.0122092

The plastic, metal and carton waste produced in both companies in a year and the values for the production of 1 boxer are presented in Table 26.

Table 26. Waste quantities from ACATEL and IMPETUS.

Waste type	At IMPETUS in a year (kg)	At ACATEL in a year (kg)	At IMPETUS for 1 boxer (kg)	At ACATEL for 1 boxer (kg)
Plastic	290	4,530	2.42×10^{-5}	1.26×10^{-4}
Metal	9,260	13,180	7.74×10^{-4}	3.68×10^{-4}
Carton	55,730	19,920	4.66×10^{-3}	5.56×10^{-4}

4.2 Environmental impact assessment

4.2.1 SimaPro

When using SimaPro, most materials, chemicals, water and energy options (corresponding to the background processes) are available in the life cycle inventory Ecoinvent V3.5 database. The LCI inventories that were not available were easily added from the literature to the software. In this case, the study conducted only took into consideration the mandatory stages of the LCIA (classification and characterization), since these steps already provide the contribution of each life cycle stage, and/or also each material, chemical or energy associated with the production of 1 boxer.

The analysis of the results starts with a discussion of life cycle process system environmental impacts. The total values for each environmental impact category, provided by SimaPro, are presented in Table 27. IMPETUS produced, in 2021, 150,587 boxers and therefore, the environmental impacts in the climate change category from boxer production during that operational year were 92,761 kg CO_2 eq. This value is relevant from a company reporting point of view, as generally, the Greenhouse Gas (GHG) Emission reduction goals are defined in terms of global emissions.

Table 27. Final impact results for each environmental impact category studied in SimaPro.

Environmental Impact Category	Results
Climate Change (kg CO_2 eq)	0.616
Eutrophication (kg PO_4 eq)	0.00085
Water use (m^3)	2.334
Resource depletion- fossil fuels (MJ)	7.103
Freshwater ecotoxicity (PAF.m^3.day)	1481.08

The contribution, in percentage, of each process considered in the boxer life cycle for each of the 5 environmental impact categories studied is presented in Figure 22.

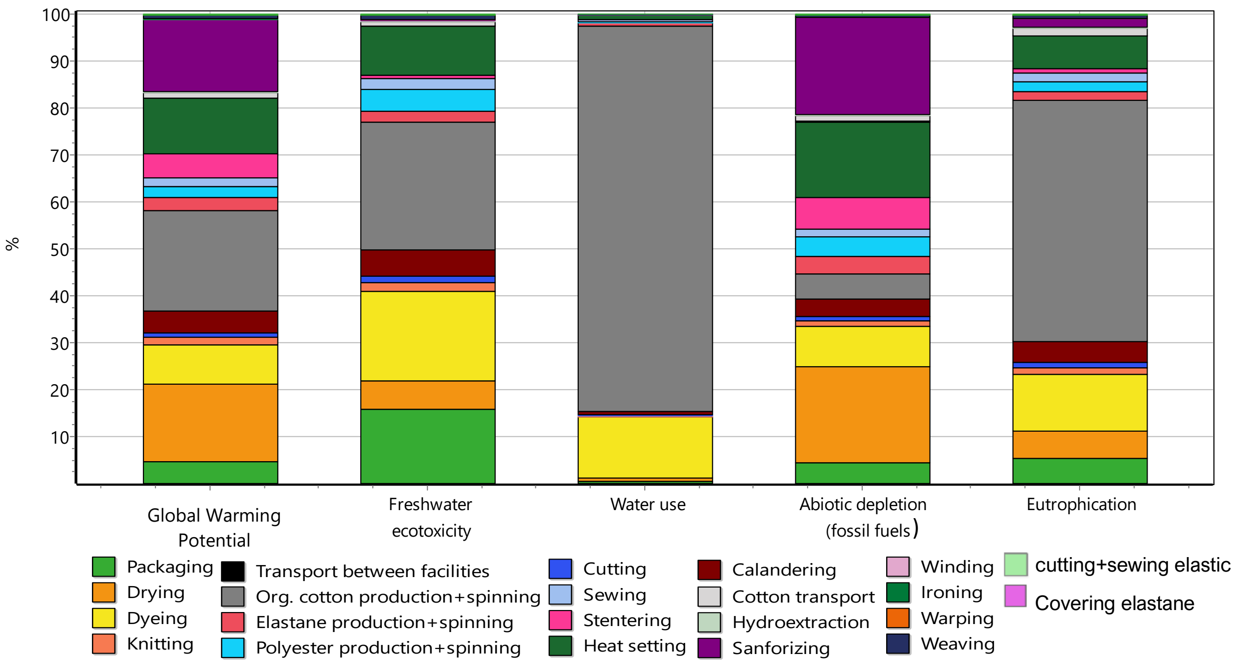

Figure 22. Contribution of each process in the life cycle of the boxer for the environmental impact categories studied.

On one hand, the processes with the biggest contribution for the environmental impacts are organic cotton production and spinning, dyeing, drying and heat setting, as can be seen in Figure 22. On the other hand, it is possible to see that some of the stages in the life cycle of the boxer, in particular, knitting, transports, warping, weaving, cutting and sewing the elastic, covering elastane, hydroextraction, winding, ironing, cutting and sewing have a low contribution to the overall impacts when compared to other processes. Therefore, in Figure 23, the previously mentioned processes are aggregated in a process called "others", to better visualize the results.

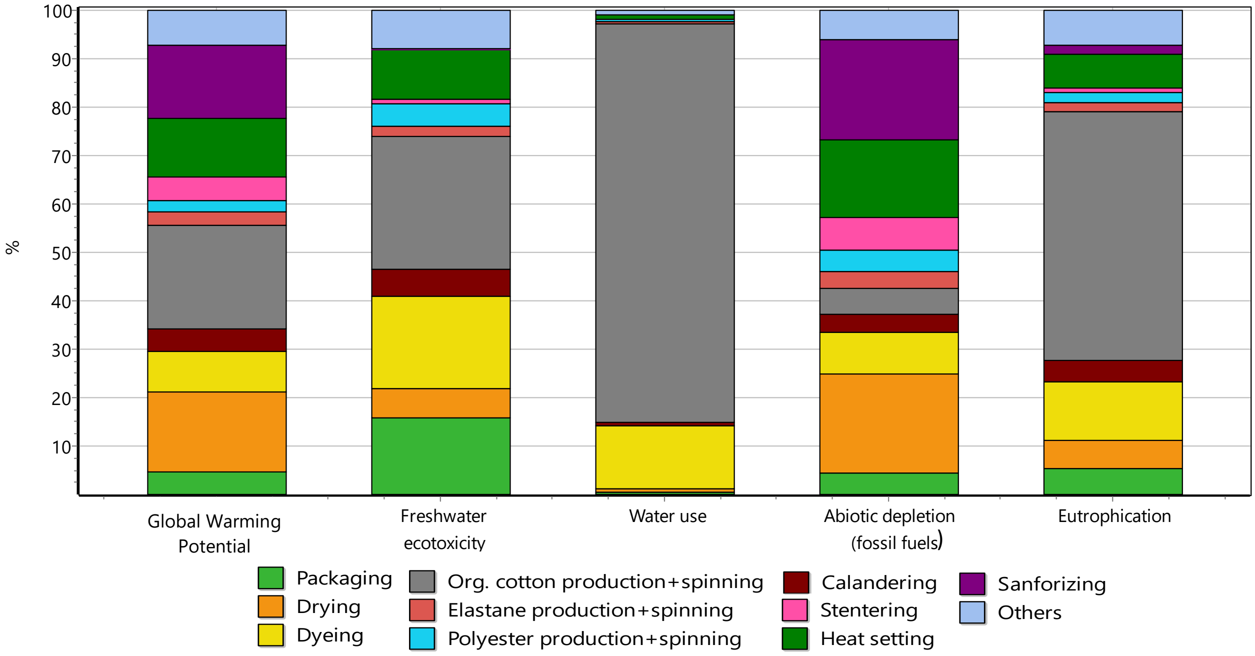

Figure 23. Contribution of the processes in the life cycle of the boxer for the environmental impact categories studied.

As shown in Figure 23, the organic cotton production and spinning has a significant weight in the overall impacts of producing 1 boxer. This process is responsible for around 21 % of the total impact in the CC category, 27 % in FE, 51 % in eutrophication, 5 % in AD and 82 % in the water use category. As cotton production is partly an agricultural process, with the corresponding consumption of irrigation water, this conclusion was expected has the processes in IMPETUS and ACATEL are not particularly water intensive.

The second major contributor to the overall impacts is the dyeing process which is responsible for around 12 % of the total impacts in the ET category, 8 % in the CC and AD categories, 13 % in WU and 19 % in FE. The drying process, being the third biggest contributor to the environmental impacts, is most noticeable in the AD category with 20 % of the weight and CC with 17 %, the later as a result of the energy consumption in the process. Furthermore, the heat setting process also has some impact, especially in the AD and CC categories with a contribution of 16 % and 12 % respectively. The packaging stage stands out in the FE category with a contribution of 16 %.

For the dyeing and heat setting processes, a more detailed analysis of the impacts was conducted, due to their significance in the overall impacts and the variety of inputs used in the processes, such as materials, chemicals, energy and water. In Figure 24, the contribution of each material, chemical, energy and water used in the dyeing process is presented.

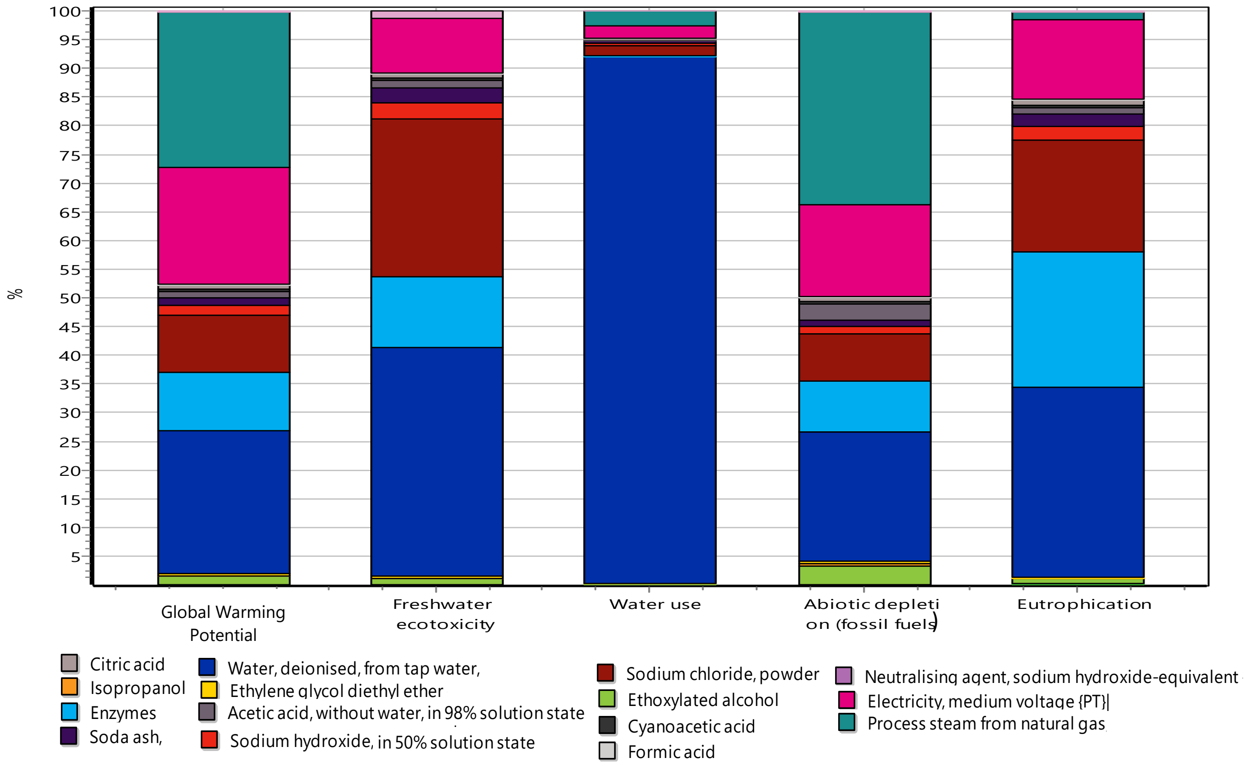

Figure 24. Contribution of each chemical, water and energy for the impacts of the dyeing process.

As can be seen in Figure 24, the deionised water used is the biggest contributor to the overall impact of the process, followed by sodium chloride production, process steam, electricity, and enzyme production.

For the rest of the processes, the biggest contributor to their impact was always electricity, natural gas, or process steam and in the packaging stage, the carton production had around 80 % of the contribution. A simplified version of Figure 24, with the chemicals, energy and water aggregated in classes, is presented in Figure 25.

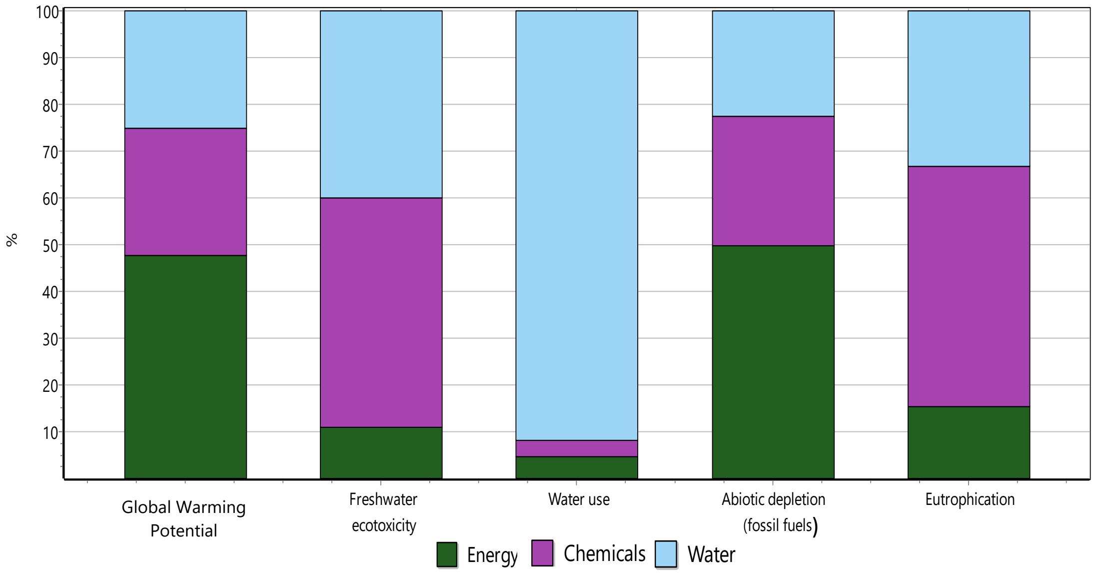

Figure 25. Contribution of each class of inputs for the impacts of the dyeing process.

Figure 25 shows that, in the dyeing process, the energy is responsible for the biggest impacts in the CC and AD categories with 48 % and 50 % contribution respectively. When it comes to the FE and ET categories, the chemicals used have most of the impacts with 49 % and 51 % respectively. The water is, as expected, the biggest contributor to the water use with 92 % of the impacts in that category. These results show that, no factor is dominant in all environmental impact categories (with the exception of water use), and to improve the overall environmental performance of the dyeing process one should propose improvements in various aspects, not just one, as for example the use of renewable energy.

The heat setting process involves the inputs of energy and chemicals, and the contribution of each to the environmental impact categories is shown in Figure 26.

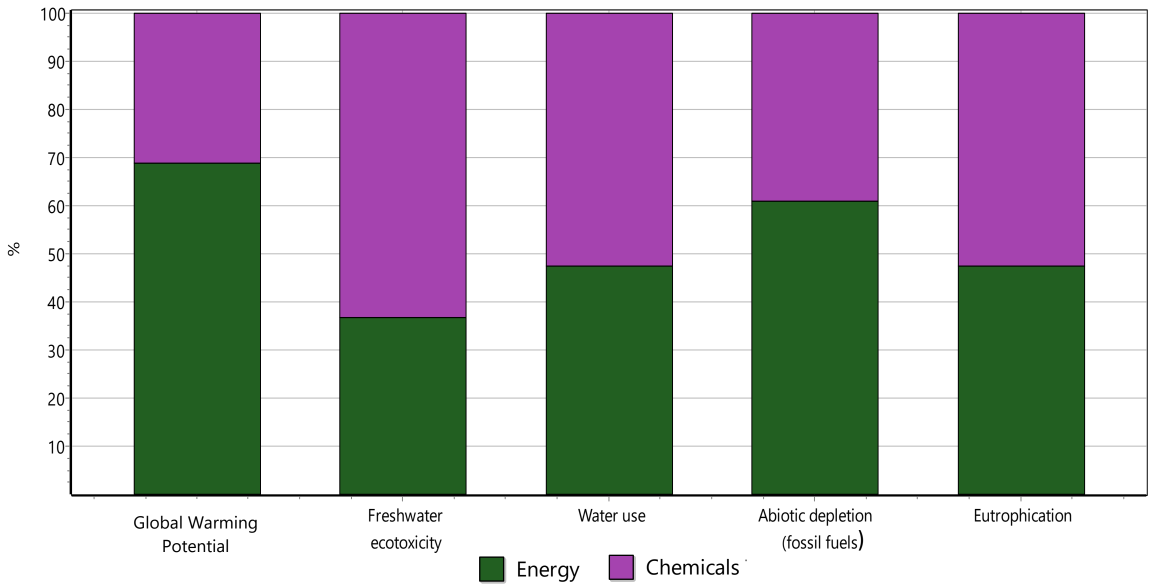

Figure 26. Contribution of each class of inputs for the impacts of the heat setting process.

As can be seen in Figure 26, the contribution for both energy and chemicals in the heat setting process is very similar, since none of the inputs is significantly more relevant than the other. As expected, energy is the largest contributor to the CC and AD categories with 69 % and 61 % respectively. In the WU and ET categories, the chemicals and energy have quite similar in values, being around 50 % each and in the FE category the chemicals have the majority of the impact with 63 % contribution.

Now aggregating the processes to the company they occur in, and aggregating all the raw materials, a general contribution of each to each environmental impact category is obtained and the results can be seen in Figure 27.

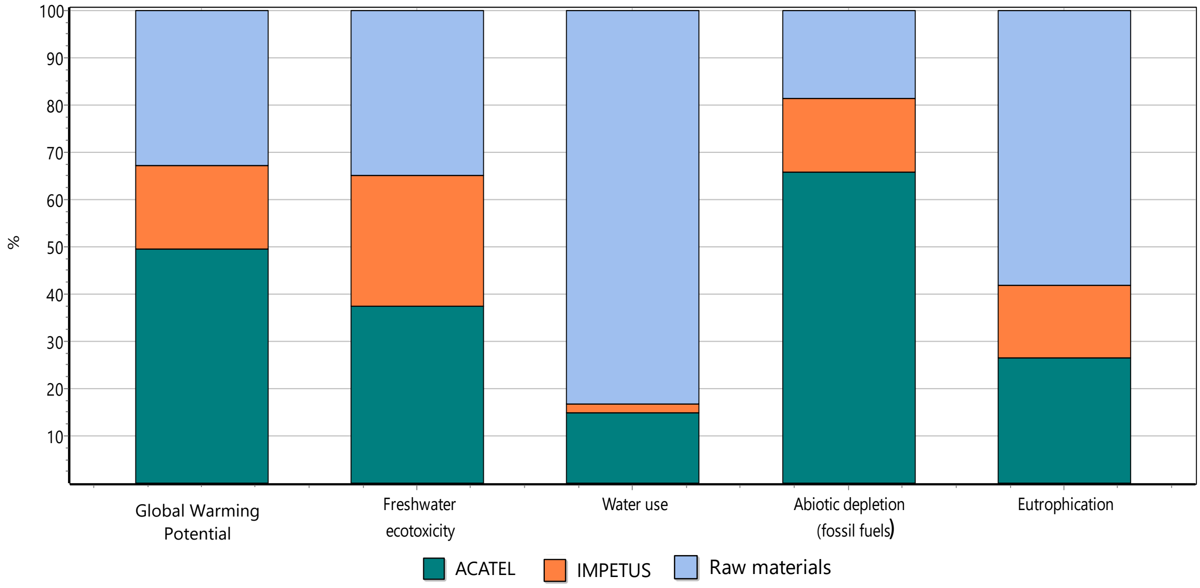

Figure 27. Contribution of each company and the raw materials to each environmental impact category.

The largest contributor to the CC category was ACATEL with around 50 % contribution due to a largest energy consumption in that company, as more process need to be heated, for example, for drying. For the ET category it was raw materials with 58 %, due to the utilization of fertilizers in the cotton cultivation The most well-balanced category was FE with ACATEL, IMPETUS and the raw materials having 37 % , 28 % and 35 % weight, respectively. In the water use category the raw materials had the biggest impact with 83 % of the total, due to the organic cotton production being very water intensive. When it comes to the AD category, ACATEL was the biggest contributor with 66 %, mainly due to the energy consumption, specifically natural gas.

Now aggregating all the impacts for all environmental impact categories, the overall contribution of each company as well as the raw materials production and spinning to produce 1 boxer is graphically presented in Figure 28.

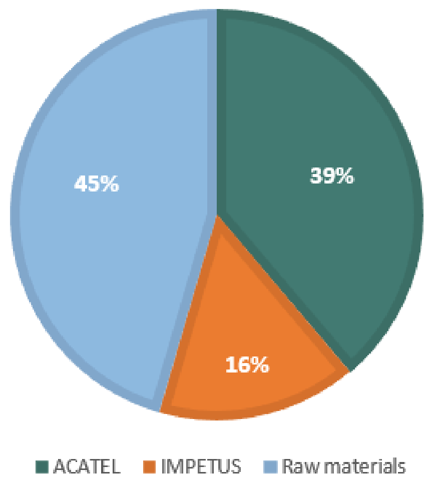

Figure 28. Contribution of each company and the raw materials to the overall impacts of the boxer production.

It can be seen in Figure 28, that the production and spinning of raw materials is the largest contributor to the overall impacts of making 1 boxer with a 45 % contribution. Comparing both companies, ACATEL is the biggest contributor to the overall impacts in the production of a boxer, with 39 % contribution, since it includes 3 of the most impactful processes, the dyeing, drying and heat setting. The processes that occur at IMPETUS consume mainly electricity which ends up not having a significant impact in comparison with the raw materials and ACATEL, accounting for 16 % of the overall environmental impact.

To conclude the results analysis, the relative importance of the environmental impacts for 1 kilogram of each raw material used in the boxer are presented in Figure 29.

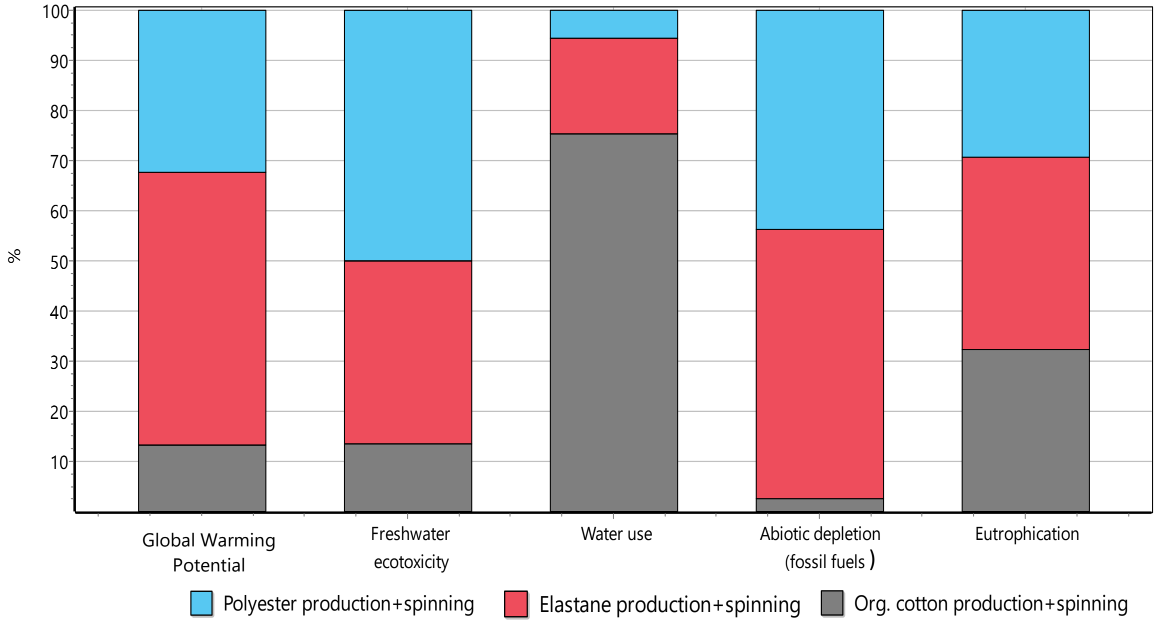

Figure 29. Contribution of 1 kg of each raw material in the environmental impact categories studied.

As can be seen by Figure 29, the production and spinning of elastane has the biggest impact in the environmental impact categories of Climate Change (CC), Abiotic depletion-fossil fuels (AD) and Eutrophication (ET), whereas polyester production and spinning have the biggest impact in freshwater ecotoxicity (FE) and the production and spinning of organic cotton in water use (WU).

However, since the quantity of organic cotton used in the boxer is much larger than the quantity of elastane and polyester, organic cotton ends up having the biggest impact in all categories when the real quantity used is considered as it can be seen in Figure 30.

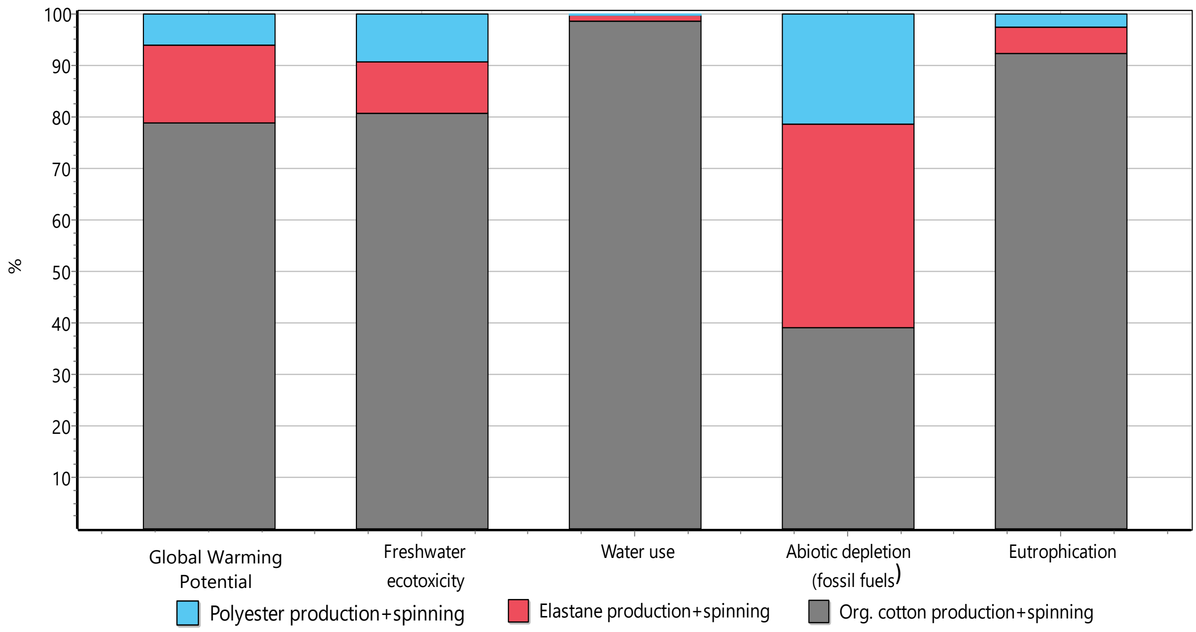

Figure 30. Contribution of each raw material in the environmental impact categories studied.

As can be seen by Figure 30, out of the 3 raw materials used in the boxer, the production and spinning of organic cotton has the biggest impact in all the environmental impact categories that were studied. The organic cotton production and spinning, from the evaluation of only the raw materials, accounts for around 80 % of the CC and FE categories, 39 % of AD , 92 % of ET and 98 % of WU.

4.2.2 Higg Index

The utilization of the webtool Higg Index faced some hurdles when applied to the case under study. For example, only one type of elastane yarn from 1 manufacturer is available, hence that one had to be chosen even though it wasn't the real one used by the company. Also, not all yarn counts are present in the database of MSI, thus the closest value had to be chosen resulting in changes in the impact assessment.

Furthermore, the boxer is made up of knit fabric and an elastic band, and Higg Index does not have the options to take into account the narrow fabric weaving, that is the weaving of the elastic bands, making it very difficult to have a real value of the overall impact assessment of the boxer, and rendering the comparison with the values predicted with SimaPro not completely objective.

The MSI and PM tools of Higg Index also have pre-established average values for the percentage of yarn residue in each stage of the life cycle that cannot be changed. This is an inconvenience, since the values presented and the real ones provided by IMPETUS are not the same and, in some cases, not even close, situation that may lead to unrealistic results.

In the packaging materials, no carton option for the box , hang-tag and others is available, so cardboard had to be chosen instead. Also, there were no tag and label options which is considered a significant flaw since the tool is specific for the textile industry where those materials are commonly used.

Also, Higg does not allow for geographic variety since it doesn't have the option to choose in which country the production takes place. Hence, the tool doesn't allow, for example, to use different energy mixes specific to specific regions or countries. Furthermore, the platform itself also presented challenges in the sense that it was difficult to navigate at times.

The PM tool, like previously mentioned, accounts for the retail, distribution, use (product care) and end of life of the product, and it is not possible to remove those stages from the calculation. Therefore, the results provided by Higg Index are higher than they should be, since they take into consideration the values presented in Figure 31.

Impact Areas	Global Warming	Eutrophication	Water Scarcity	Resource Depletion / Fossil Fuels	Chemistry
Total	5.09 kg CO2 eq	0.003 kg PO4--- eq	3.05 m3	62.7 MJ	1.99 units
Bill of Materials	1.19 kg CO2 eq	9.739e-4 kg PO4--- eq	1.51 m3	14.0 MJ	1.99 units
Finished Goods Processes	0.427 kg CO2 eq	1.338e-4 kg PO4--- eq	0.122 m3	4.53 MJ	0 units
Packaging	0 kg CO2 eq	0 kg PO4--- eq	0 m3	0 MJ	0 units
Logistics	0.016 kg CO2 eq	1.717e-5 kg PO4--- eq	1.621e-4 m3	0.222 MJ	0 units
Retail	0.444 kg CO2 eq	1.293e-4 kg PO4--- eq	0.180 m3	5.44 MJ	0 units
Product Care	2.92 kg CO2 eq	0.001 kg PO4--- eq	1.23 m3	38.5 MJ	0 units
End of Use	0.101 kg CO2 eq	6.308e-5 kg PO4--- eq	0.006 m3	0.048 MJ	0 units

Figure 31. Environmental impacts for all the stages considered in the Product module of Higg Index.

The values in Figure 31, are the impacts considered by the PM tool in each phase of the production line and use of 1 boxer. Only the values from the Bill of Materials (BoM), that is basically a complete list of all the raw materials, parts and components required to make the product, and from the Finished Goods Processes were considered, with the values from the packaging, logistics, retail, product care and end of use being disregarded.

The values calculated of the environmental impacts form cradle to gate, in Higg Index are presented in Figure 32.

	Impact Areas Global Warming	Eutrophication	Water Scarcity	Resource Depletion / Fossil Fuels	Chemistry
Bill of Materials	1.19 kg CO2 eq	9.739e-4 kg PO4--- eq	1.51 m3	14.0 MJ	1.99 units
Finished Goods Processes	0.427 kg CO2 eq	1.338e-4 kg PO4--- eq	0.122 m3	4.53 MJ	0 units

Figure 32. Environmental impacts, from the PM tool, of the stages that were considered in the LCA study.

As can be seen by Figure 32, in Higg Index, most of the total impacts come from the bill of materials, which was expected, since this is the category that includes all processes apart from cutting and sewing (product assembly). The impact values for the two stages considered were added and the results, for a cradle to gate analysis, are presented in Table 28.

Table 28. Final results, provided by Higg Index, for each environmental impact category.

Environmental Impact Category	Results
Climate change (kg CO_2 eq)	1.61
Eutrophication (kg PO_4 eq)	0.001
Water use (m^3)	1.64
Resource depletion- fossil fuels (MJ)	18.5
Chemistry (units)	1.99

These results provided by Higg Index are aggregated, in the sense that, it is not easy to know how the various processes contribute to the overall environmental impact. The results consider processes like spinning, knitting, dyeing, etc., but at the end only the overall impact is known and in order to know the contribution of each process there is a need to go back to the MSI tool and see each material in detail.

4.2.3 Comparison between results

4.2.3.1 SimaPro vs Literature

The results obtained in SimaPro were compared with some of the available results from the literature in relation with textile products. Some constraints limit the comparison made, namely: the different methodologies considered in the LCIA, the different boundaries of the system, the difference between textile products and geographic specificities such as electricity mixes.

Comparing the obtained results with the only similar study about underwear, done by Collins & Aumônier (2002), an emissions result of 1,34 kg CO_2. eq was obtained, which is around double the value obtained in this study. Also, like in this study, the transportation in the life cycle of underwear, was considered irrelevant.

Now comparing the results with other studies, that consider other products besides underwear, Hackett (2015) and Zhang et al. (2015), some conclusions can be made regarding the stages in the life cycle of textiles with the largest impacts. Hackett (2015) and Zhang et al. (2015) showed that fiber production was the significant stage in the ET and WU categories, being in accordance with this study. Also, in this study, the biggest contributors to the CC category where spinning, heat setting, drying and dyeing, being in accordance with the results obtained by Hackett (2015), since the author concluded that, to the CC category, the biggest contributors were the processes in fabric assembly (yarn spinning, dyeing, weaving, and fabric finishing).

4.2.3.2 SimaPro vs Higg Index

In the comparison of the SimaPro results with the results provided by Higg Index, only the overall results will be compared, since Higg Index does not discriminate the percentage or value of the impacts for each individual process. The Chemistry impact category will not be directly compared with the freshwater ecotoxicity results by SimaPro since Higg Index also makes qualitative changes to the chemistry value altering the results in ways that are not known, rendering the comparison not objective.

In Table 29 the results from both SimaPro and Higg Index are presented, for all 5 environmental impact categories.

Table 29. Comparison between the SimaPro and Higg Index results.

Environmental Impact Category	SimaPro	Higg Index
Climate change (kg CO_2 eq)	0.62	1.61
Eutrophication (kg PO_4 eq)	0.0009	0.001
Water use (m^3)	2.33	1.64
Resource depletion- fossil fuels (MJ)	7.10	18.5
Freshwater ecotoxicity/Chemistry (PAF.m^3.day /units)*	1481	1.99

* These categories were not compared due to Higg Index also making qualitative changes to the value of chemistry as previously mentioned.

It can be seen that the values predicted by Higg Index are significantly higher for the impact category of climate change and resource depletion – fossil fuels, slightly lower for water use and very similar for eutrophication.

The reason for the higher values in Higg Index could be related with the elastic portion of the boxer, since, as previously mentioned, Higg only considers weaving of fabric and not narrow fabrics and the fabric weaving machines have considerable larger capacities when compared to those available at IMPETUS, leading to larger emissions values and larger impacts. Also, the yarn waste percentages may also play a role, since the values presented in Higg Index and the real ones provided by IMPETUS were different, in some processes, not even close as for example the knitting process with 6,5 % waste in Higg Index and 1,5 % in IMPETUS.

Also, the electricity mix might be significant in the difference of results since the boxer production is energy intensive. In SimaPro, the Portuguese electricity mix was used, whereas in Higg Index the weighted average of major textile producing countries was considered (Sustainable Apparel Coalition, 2020). The climate change and resource depletion – fossil fuels categories are 2.6 times bigger in Higg Index which can be explained, like mentioned before, by the electricity mix used, since in Portugal, the mix is comprised of around 60 % renewable energy and the global average is at 26 % (REN, 2022; Ritchie et al., 2022)

4.3 Analysis of different electricity scenarios

Based on the results of the previous sections, it is possible to conclude that the environmental impacts of the generation of energy, in particular electricity, is one of the main drivers of the process environmental performance. Moreover, it is one of the aspects that can be easily modified by the company, either by the installation of local renewable energy generations systems, or through the acquisition of renewable energy from a certified supplier, via for example a Power purchase agreement (PPA) (Enel X North America, 2021) .

Thus, three electricity mix scenarios were studied in this dissertation. The first corresponds to 75 % of electricity coming from the grid and 25 % from photovoltaic, that is going to be the reality of the company in 2023. The second scenario is with a 100 % solar renewable energy source and the third scenario with 75 % wind energy and 25 % solar energy. All these percentages were applied to the processes that occur in IMPETUS but not to those in ACATEL.

The same methodology executed in the base scenario was applied to all 3 energy scenarios and the results are presented in Figure 33. The same life cycle inventory as well as methodology applied to the base scenario was considered to the 3 energy scenarios. The results are presented in Figure 33, where the results for each environmental impact category was normalized by the largest value of the base and additional scenarios.

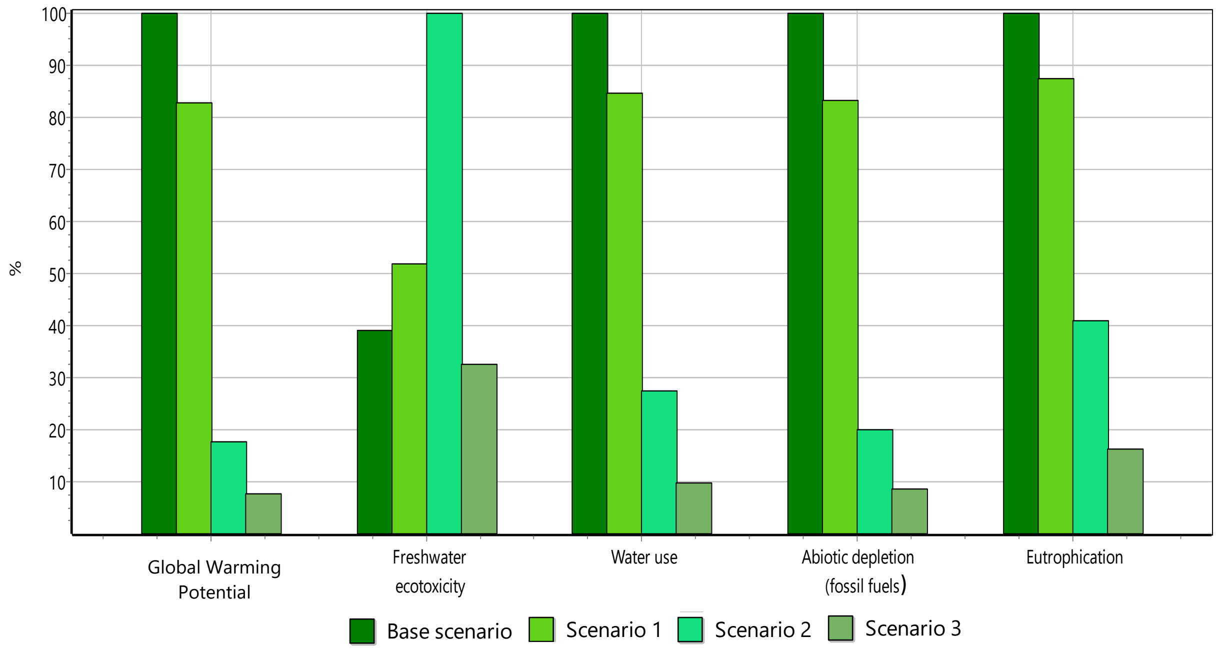

Figure 33. Comparison of the different electricity scenarios.

It is possible to conclude that the base scenario, the current situation at the company, presents the biggest environmental impacts in all categories, apart from freshwater ecotoxicity. Moreover, the larger the percentage of solar energy, the larger the value of FE, with scenario 2 having the biggest impact in that category. This is due to production of solar panels , in particular of the silicon needed to produce them, according to Bezerra et al. (2018). Moreover, (Rashedi & Khanam, 2020) andLieberei & Gheewala (2017) considered also that the electrical cables and supporting equipment also has significant environmental impacts, through the utilization of metals such as copper and chromium in solar panels.

Scenario 3, with 75 % wind energy and 25 % solar energy, is the best in all the environmental impact categories studied, having the lowest environmental impacts. These results are just valid for processes in IMPETUS, where the scenarios are applied. In the overall production of the boxer, the changes are presented in Table 30.

Table 30. Results for each electricity scenario in the 5 environmental impact categories studied.

Environmental Impact Category	Base scenario	Scenario 1	Scenario 2	Scenario 3	Decrease from base to 3 (%)
Climate Change (kg CO_2 eq)	0.616	0.603	0.563	0.557	9.6
Eutrophication (kg PO_4 eq)	0.00085	0.00083	0.00079	0.00077	9.4
Water use (m^3)	2.334	2.328	2.307	2.301	1.4
Resource depletion- fossil fuels (MJ)	7.103	6.982	6.619	6.55	7.8
Freshwater Ecotoxicity (PAF.m^3.day)	1481.08	1555.12	1777.8	1465.81	1.0

As can be seen in Table 30, from the base scenario to scenario 3, there is a decrease in the CC, ET and AD categories, of around 10 % , 9 % and 8 % respectively. The WU and FE categories only suffered a decrease of around 1 %. The impact is smaller as expected, and this is only considering the processes that occur in IMPETUS, being expected that when the ACATEL processes are considered those values would have an even bigger decrease. The FE category increased in scenario 1 and 2 since the percentage of solar energy also increased, as explained above.

This analysis allowed to infer that the use of wind energy is the best in terms of environmental impacts in all the environmental impact categories studied and that solar energy is best when compared to the electricity mix for all categories apart from freshwater ecotoxicity.

5 Conclusions

This study, done in a company, evaluated the environmental impacts associated with the production of one piece of underwear, a men's boxer, using the Life Cycle Assessment methodology. Each individual process in the products life cycle was considered, corresponding to a total of 24 processes. After identifying each input and output for all the processes, the environmental impact assessment was done using SimaPro, and a new method that was implemented by combining each of the 5 environmental impact categories and methods considered by the webtool Higg Index. The reason to develop the new method was to allow for the comparison of the values estimated by SimaPro, with the values from the Material Sustainability Index (MSI) and Product Module (PM) tools of the webtool Higg Index. Lastly, a scenario analysis was made regarding electricity and its source, having 3 scenarios be analyzed and compared with the company's current situation.

One of the main conclusions of the LCA study of a boxer was that the most significant processes for the environmental impacts, were the organic cotton production and spinning, dyeing, drying and heat setting. The organic cotton production and spinning was responsible for more than 50 % of the overall impacts in the ET category and more than 80 % for WU, whereas the dyeing process contributed 19 % for the overall impacts in the FE category. The drying process is responsible for 20 % and 17 % of the impacts in the AD and CC categories and heat setting for 16 % contribution to the AD category. All these processes, apart from the organic cotton production and spinning, do not occur in IMPETUS, but in ACATEL, making this company the most impactful out of the two. The organic cotton production and spinning, even though it doesn't occur directly in IMPETUS or ACATEL, being an upstream process, had the biggest environmental impacts in the life cycle of the boxer.

The comparison between the SimaPro results and the literature, validates the results of this study, with Collins & Aumônier (2002) obtaining a similar value of CO_2 emissions. Moreover, Hackett (2015) obtained the same significant stages in the CC category and Hackett (2015) and Zhang et al. (2015) also in the ET and WU categories. Some of the remaining results, in all the mentioned studies, presented values in the same order of magnitude as the ones obtained in this study.

Regarding Higg Index and the comparison with SimaPro, the results were similar in the ET category, but the CC and AD categories had results around 3 times higher than those obtained using SimaPro. This can be due to the differences in the energy mixes considered, especially how much renewable energy is considered. Based on the results obtained, it was concluded that the tool is helpful in providing companies with reasonable estimates of the environmental impacts of their textile products. However, as certain choices are not available in the webtool, as for example, the geographic location or options for specific processes, the prediction could be far from reality, potentially penalizing companies like IMPETUS that is investing strongly in using renewable energy.

From the electricity scenario analysis, it was concluded that the use of photovoltaic (solar energy) leads to larger environmental impacts in the FE category, but a reduction in all the remaining categories rest. Also, it is concluded that wind energy is a better option in terms of environmental impacts in all the environmental impact categories studied. Either way, all scenarios had a general improvement in the results when compared to the current situation experienced at the company.

5.1 Improvements and future work perspectives

Taking into account the results of the previous sections, it is clear that an improvement that could be implemented in IMPETUS and also ACATEL is the utilization of renewable/lower environmental impact energy sources, since the whole production is very energy intensive. A change to renewable energy sources such as solar or wind for electricity and biomass for the natural gas used for heating would bring great improvements. This applies specially to ACATEL, that is the biggest contributor of the environmental impacts out of both companies. All the electricity scenarios should be considered as potential improvements to reduce the overall environmental impacts.

The consumption of dyes, auxiliaries and other chemicals could be improved through the usage of dyes with a higher level of fixation, chemicals obtained from renewable sources, or recycled if possible. Naturally, these improvements should be evaluated not only by the potential to improve the process environmental performance, but its feasibility in terms of process and product quality.

For future work, as a start, the system boundaries should be expanded to account for the distribution, use and end of life of the product (either disposal, recycling or other options) making it a cradle to grave approach. For this to happen, there is a need to make an effort to obtain real and trustworthy information and data. Also, the materials, dyes and other chemicals not included in this study due to lack of information, should, in later studies, be included when information regarding them is accessible in literature or in life cycle inventory databases. The steps not considered in this study, like unwinding and spreading, should be included in later studies to confirm they are in fact non-significant to the overall impact. Moreover, an analysis to compare the impacts of different boxer sizes, the impacts of different colored boxers or even boxers with printing patterns (to see if the printing stage is impactful) could be accomplished. Furthermore, a sensitivity analysis of this work should be conducted in order to account for the variability and uncertainty in the data and many process parameters, and a better allocation of waste or even energy should be done. Finally, the scope of the study should be adjusted, in order to assess the environmental impacts of all products produced by IMPETUS, as for example pajamas and workout attire.

References

Baumann, H., & Tillman, A.-M. (2004). *The Hitch Hiker's Guide to LCA: an orientation in life cycle assessment methodology and application*.

Baydar, G., Ciliz, N., & Mammadov, A. (2015). Life cycle assessment of cotton textile products in Turkey. *Resources, Conservation and Recycling*, *104*, 213–223. https://doi.org/10.1016/j.resconrec.2015.08.007

Bevilacqua, M., Ciarapica, F. E., Giacchetta, G., & Marchetti, B. (2011). A carbon footprint analysis in the textile supply chain. *International Journal of Sustainable Engineering*, *4*(1), 24–36. https://doi.org/10.1080/19397038.2010.502582

Bezerra, Jordy. L., Antônio, M., Lira, T., & Aparecida Da Silva, E. (2018). *Avaliação do ciclo de vida aplicada a painéis fotovoltáicos*.

Bojarski, A. D., Laínez, J. M., Espuña, A., & Puigjaner, L. (2009). Incorporating environmental impacts and regulations in a holistic supply chains modeling: An LCA approach. *Computers and Chemical Engineering*, *33*(10), 1747–1759. https://doi.org/10.1016/j.compchemeng.2009.04.009

Braun, G., Som, C., Schmutz, M., & Hischier, R. (2021). Environmental consequences of closing the textile loop-life cycle assessment of a circular polyester jacket. *Applied Sciences (Switzerland)*, *11*(7). https://doi.org/10.3390/app11072964

Cao, H., Dickson, M. A., Cobb, K., Carper, M., Scudder, C., & Wong, C. (2015). Applying a sustainability performance measurement tool in designing and developing automotive employee uniforms. *International Journal of Fashion Design, Technology and Education*, *8*(2), 78–86. https://doi.org/10.1080/17543266.2014.992051

Cenit. (2017). *Têxtil e Vestuário no Contexto Nacional e Internacional*.

Chai, C. (2014). *Life Cycle Assessment: an Introduction to Concepts and Applications*. Retrieved April 09, 2022, from https://www.azocleantech.com/article.aspx?ArticleID=516

Chun, E., Joung, H., Lim, Y. J., & Ko, E. (2021). Business transparency and willingness to act environmentally conscious behavior: Applying the sustainable fashion evaluation system "Higg Index." *Journal of Global Scholars of Marketing Science*, *31*(3), 437–452. https://doi.org/10.1080/21639159.2021.1904784

Coelho, P. (2017). *Tabelas de termodinâmica* (4th ed.).

Collins, M., & Aumônier, S. (2002). *Streamlined Life Cycle Assessment of Two Marks & Spencer plc Apparel Products*. https://researchingsustainability.files.wordpress.com/2012/01/streamlined-lca-of-2-marks-spencer-pls-apparel-products.pdf

Cucurachi, S., Giesen, C., & Guinée, J. (2018). Ex-ante LCA of Emerging Technologies. *Procedia CIRP*, *69*, 463–468. https://doi.org/10.1016/j.procir.2017.11.005

Dahllöf, L. (2003). *Life Cycle Assessment (LCA) applied in the Textile Sector: the Usefulness, Limitations and Methodological Problems-A Literature Review*.

Defra. (2022). *Greenhouse gas reporting: conversion factors 2021*. Retrieved May 29, 2022, from https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021

Direção Geral das Atividades Económicas. (2018). *Indústria Têxtil e Vestuário: Sinopse*.

Edwards, C., & Parker, G. (2010). *An environmental comparison of paper and plastic labels*.

Ellen MacArthur Foundation. (2017). *A NEW TEXTILES ECONOMY: REDESIGNING FASHION'S FUTURE*. http://www.ellenmacarthurfoundation.org/publications

Enel X North America. (2021). *Understanding Renewable Energy Agreements*. https://www.enelx.com/n-a/en/resources/ebooks-white-papers/understanding-ppas-and-vppas

European Commission. (2021). *EU strategy for textiles - Roadmap*. https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12567-Sustainable-products-initiative

European Council. (2022). *Fit for 55*. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

Fashion United. (2022). *Global fashion industry statistics - International apparel*. https://fashionunited.com/global-fashion-industry-statistics/

Federal Environment Agency. (2011). *Environmental standards in the textile and shoe sector*. www.umweltbundesamt.de

Finnveden, G., & Potting, J. (2014). Life Cycle Assessment. In *Encyclopedia of Toxicology*. (Third Edition, pp. 74–77). Academic Press. https://doi.org/10.1016/B978-0-12-386454-3.00627-8

Gabriel, M., & Luque, M. L. D. (2020). *The UN Sustainable Development Goals for the Textile and Fashion Industry: Sustainable Development Goal 12 and Its Relationship with the Textile Industry* (M. A. Gardetti & S. S. Muthu, Eds.). Springer. https://doi.org/10.1007/978-981-13-8787-6_2

Gonçalves, A., & Silva, C. (2021). Looking for sustainability scoring in apparel: A review on environmental footprint, social impacts and transparency. In *Energies* (Vol. 14, Issue 11). MDPI. https://doi.org/10.3390/en14113032

Guo, H., Liko, B., & Neill, W. S. (2017). Effect of diesel injection split on combustion and emissions performance of a natural gas - Diesel dual fuel engine at a low load condition. *ASME 2017 Internal Combustion Engine Division Fall Technical Conference, ICEF 2017*, *1*. https://doi.org/10.1115/ICEF2017-3584

Hackett, T. (2015). *A Comparative Life Cycle Assessment of Denim Jeans and a Cotton T-Shirt: The Production of Fast Fashion Essential Items From Cradle to Gate.* Master Thesis in the University of Kentucky. https://uknowledge.uky.edu/mat_etds/9

Hedman, E. A. (2018). *Comparative Life Cycle Assessment of Jeans.* Master Thesis in the KTH Royal Institute of Technology. https://kth.diva-portal.org/smash/get/diva2:1221104/FULLTEXT01.pdf

Herrmann, I. T., & Moltesen, A. (2015). Does it matter which Life Cycle Assessment (LCA) tool you choose? - A comparative assessment of SimaPro and GaBi. *Journal of Cleaner Production*, *86*, 163–169. https://doi.org/10.1016/j.jclepro.2014.08.004

Hillege, L. (2019, June 7). *Impact Categories (LCA) – overview*. https://ecochain.com/knowledge/impact-categories-lca/

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2011). *The Water Footprint Assessment Manual*.

Islam, M., & Khan, M. R. (2014). Environmental Sustainability Evaluation of Apparel Product: A Case Study on Knitted T-Shirt. *Journal of Textiles*, *2014*. https://doi.org/10.1155/2014/643080

ISO 14040. (2006). *Environmental management-Life cycle assessment-Principles and framework*.

ISO 14044. (2006). *Environmental management-Life cycle assessment-Requirements and guidelines*.

Khan, M. R., & Islam, M. (2015). Materials and manufacturing environmental sustainability evaluation of apparel product: knitted T-shirt case study. *Textiles and Clothing Sustainability*. https://doi.org/10.1186/s40689-015-0008-8

KPMG, & Textile Exchange. (2018). *Threading the needle: Weaving the Sustainable Development Goals into the textile, retail, and apparel industry*. https://textileexchange.org/wp-content/uploads/2022/03/Textile-Exchange-kpmg-threading-needle-report.pdf

Lehner, M., Mont, O., Mariani, G., & Mundaca, L. (2020). Circular economy in home textiles: Motivations of IKEA consumers in Sweden. *Sustainability* , *12*(12). https://doi.org/10.3390/su12125030

Lieberei, J., & Gheewala, S. H. (2017). Resource depletion assessment of renewable electricity generation technologies—comparison of life cycle impact assessment methods with focus on mineral resources. *International Journal of Life Cycle Assessment*, *22*(2), 185–198. https://doi.org/10.1007/s11367-016-1152-3

Luo, Y., Song, K., Ding, X., & Wu, X. (2021). Environmental sustainability of textiles and apparel: A review of evaluation methods. In *Environmental Impact Assessment Review* (Vol. 86). Elsevier. https://doi.org/10.1016/j.eiar.2020.106497

Meer, Y. van der. (2018). *Life Cycle Assessment: Benefits and limitations*. http://fibrenet.eu/index.php?id=blog-post-eleven

Meier, L. (2021). *Synthesis Report on United Nations System-wide Initiatives related to Fashion*. https://unfashionalliance.org/wp-content/uploads/2021/10/UN-Fashion-Alliance-Mapping-Report_Final.pdf

Ministère de la Transition écologique. (2019). *Les allégations environnementales*. https://www.ecologie.gouv.fr/allegations-environnementales

Mora, T. D., Bolzonello, E., Cavalliere, C., & Peron, F. (2020). Key parameters featuring bim-lca integration in buildings: A practical review of the current trends. *Sustainability*, *12*(17). https://doi.org/10.3390/su12177182

Moreau, P. (2021). *What's new in the EU's sustainable textile strategy consultation?* https://www.ohanapublicaffairs.eu/2021/06/27/du-neuf-dans-la-consultation-sur-la-strategie-textile-durable-de-lue/

Munasinghe, P., Druckman, A., & Dissanayake, D. G. K. (2021). A systematic review of the life cycle inventory of clothing. In *Journal of Cleaner Production*. Elsevier . https://doi.org/10.1016/j.jclepro.2021.128852

Muthukumarana, T. T., Karunathilake, H. P., Punchihewa, H. K. G., Manthilake, M. M. I. D., & Hewage, K. N. (2018). Life cycle environmental impacts of the apparel industry in Sri Lanka: Analysis of the energy sources. *Journal of Cleaner Production*, *172*, 1346–1357. https://doi.org/10.1016/j.jclepro.2017.10.261

Patwary, S. (2020). Clothing and Textile Sustainability: Current State of Environmental Challenges and the Ways Forward. *Textile & Leather Review*. https://doi.org/10.31881/TLR

Petit-Boix, A., Llorach-Massana, P., Sanjuan-Delmás, D., Sierra-Pérez, J., Vinyes, E., Gabarrell, X., Rieradevall, J., & Sanyé-Mengual, E. (2017). Application of life cycle thinking towards sustainable cities: A review. In *Journal of Cleaner Production* (Vol. 166, pp. 939–951). Elsevier . https://doi.org/10.1016/j.jclepro.2017.08.030

Pré sustainability. (n.d.). *Life Cycle-Based Sustainability — Standards & Guidelines*. Retrieved March 24, 2022, from pre-sustainability.com

Radhakrishnan, S. (2015). The Sustainable Apparel Coalition and the Higg Index. In *Roadmap to Sustainable Textiles and Clothing* (pp. 23–57). Springer Science & Business Media. https://doi.org/10.1007/978-981-287-164-0_2

Ranganathan, J., Corbier, L., Schmitz, S., Oren, K., Dawson, B., Spannagle, M., Bp, M. M., Boileau, P., Frederick, R., Vanderborght, B., Thomson, H. F., Kitamura, K., Woo, C. M., Naseem, &, Kpmg, P., Miner, R., Laurent, S., Koch, J., Bhattacharjee, S., … Camobreco, V. (2004). *The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard*.

Rashedi, A., & Khanam, T. (2020). Life cycle assessment of most widely adopted solar photovoltaic energy technologies by mid-point and end-point indicators of ReCiPe method. *Environmental Science and Pollution Research*, *27*(23), 29075–29090. https://doi.org/10.1007/s11356-020-09194-1

Rasheed, A. (2020). Classification of Technical Textiles. In S. Ahmad, A. Rasheed, & Y. Nawab (Eds.), *Fibers for Technical Textiles* (pp. 49–64). Springer International Publishing. https://doi.org/10.1007/978-3-030-49224-3_3

REN. (2022). *Electricity Generation by Energy Sources in Mainland Portugal in 2022*. https://www.apren.pt/en/renewable-energies/production

Retail Forum for Sustainability. (2013). *Sustainability of textiles*. http://ec.europa.eu/environment/ecolabel/

Ritchie, H., Roser, M., & Rosado, P. (2022). *Electricity Mix*. https://ourworldindata.org/electricity-mix

Roos, S. (2016). *Advancing life cycle assessment of textile products to include textile chemicals: Inventory data and toxicity impact assessment*. https://publications.lib.chalmers.se/records/fulltext/246361/246361.pdf

Roos, S., Holmquist, H., Jönsson, C., & Arvidsson, R. (2018). USEtox characterisation factors for textile chemicals based on a transparent data source selection strategy. *International Journal of Life Cycle Assessment*, *23*(4), 890–903. https://doi.org/10.1007/s11367-017-1330-y

Roos, S., Jönsson, C., Posner, S., Arvidsson, R., & Svanström, M. (2019). An inventory framework for inclusion of textile chemicals in life cycle assessment. *International Journal of Life Cycle Assessment*, *24*(5), 838–847. https://doi.org/10.1007/s11367-018-1537-6

Sustainable Apparel Coalition. (2020). *Higg Materials Sustainability Index (MSI) Methodology*. http://apparelcoalition.org/the-higg-index/

The Textile Institute and Woodhead Publishing. (2015). *Handbook of Life Cycle Assessment (LCA) of textiles and clothing* (S. S. Muthu, Ed.). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100169-1.02001-3

Thylmann, D., Souza, F. d', Schindler, A., & Deimling, S. (2014). *Life Cycle Assessment (LCA) of Organic Cotton-A global average*.

Tudor, L. (2018). Change in Textile and Clothing Industry. *Industria Textila*, *69*(1), 37–43. https://doi.org/10.35530/it.069.01.1449

UN alliance for sustainable fashion. (n.d.). *The Clothing and Textile Industry Today*. Retrieved March 13, 2022, from https://unfashionalliance.org/

UNECE. (2018). *Fashion and the SDGs: what role for the UN?* https://unece.org/DAM/RCM_Website/RFSD_2018_Side_event_sustainable_fashion.pdf

United Nations. (n.d.). *SDGs: 12 Ensure sustainable consumption and production patterns*. Retrieved March 13, 2022, from https://sdgs.un.org/goals/goal12

van der Velden, N. M., Patel, M. K., & Vogtländer, J. G. (2014). LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. *International Journal of Life Cycle Assessment*, *19*(2), 331–356. https://doi.org/10.1007/s11367-013-0626-9

W. L. Gore & Associates. (2013). *Life Cycle Assessment of a GORE branded waterproof, windproof and breathable jacket*. https://www.gore-tex.com/sites/default/files/assets/Gore_LCA_summary_report.pdf

Watson, K. J., & Wiedemann, S. G. (2019). Review of methodological choices in LCA-based textile and apparel rating tools: Key issues and recommendations relating to assessment of fabrics made from natural fibre types. In *Sustainability* (Vol. 11, Issue 14). MDPI. https://doi.org/10.3390/su11143846

Willskytt, S., & Tillman, A. M. (2019). Resource efficiency of consumables – Life cycle assessment of incontinence products. *Resources, Conservation and Recycling*, *144*, 13–23. https://doi.org/10.1016/j.resconrec.2018.12.026

Wiloso, E. I., Nazir, N., Hanafi, J., Siregar, K., Harsono, S. S., Setiawan, A. A. R., Muryanto, Romli, M., Utama, N. A., Shantiko, B., Jupesta, J., Utomo, T. H. A., Sari, A. A., Saputra, S. Y., & Fang, K. (2019). Life cycle assessment research and application in Indonesia. In

International Journal of Life Cycle Assessment (Vol. 24, Issue 3, pp. 386–396). Springer . https://doi.org/10.1007/s11367-018-1459-3

World Federation of Direct Selling Associations (WFDSA). (2020). *Global Sales by Product Category*. https://wfdsa.org/wp-content/uploads/2021/06/Product-Report-2020.pdf

Zampori, L., & Pant, R. (2019). *Suggestions for updating the Product Environmental Footprint (PEF) method*.

Zhang, Y., Liu, X., Xiao, R., & Yuan, Z. (2015). Life cycle assessment of cotton T-shirts in China. *International Journal of Life Cycle Assessment*, *20*(7), 994–1004. https://doi.org/10.1007/s11367-015-0889-4

Zoltkowski, A. (2022, January 27). *What on Earth Is a Clothing Supply Chain?* https://goodonyou.eco/what-is-a-clothing-supply-chain/

Appendix A – Pictures of the packaging materials used

In Figure A-1 the carton box in which the boxer is packaged at IMPETUS is presented.

Figure A-1. Carton box used for the boxer.

The carton used to fold the boxer and for the hang-tag, in the packaging stage of the life cycle, are both shown in Figure A-2.

Figure A-2. Carton to fold the boxer (a) and Hang-tag used (b).

The plastic pins, in the color black, used to secure the hang-tag on to the boxer are presented in Figure A-3.

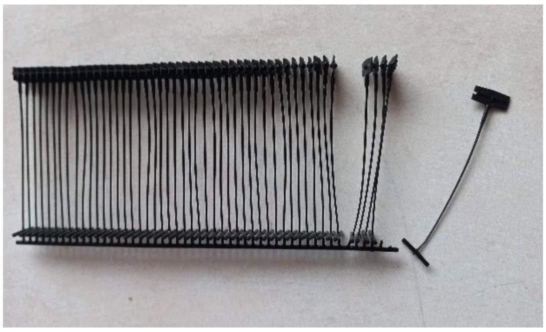

Figure A-3. Plastic pins used to put the hang-tag on the boxer.

Figure A-4 shows an example of the labels that are placed in the carton box and in the hang-tag, despite not being particularly for the boxer.

Figure A-4. Example of the sticky labels put on the hang tag (left) and on the box (right).

The labels that are sewed to the boxer, with the relevant information for the consumer and mandated by the applicable regulations, are presented in Figure A-5.

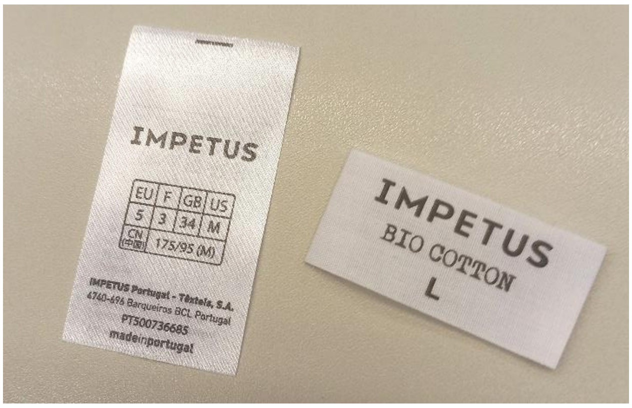

Figure A-5. Labels that are sewed to the boxer.

Appendix B – Chemical composition of the dyestuff and auxiliars

The chemical composition of all dyestuffs and auxiliars used in the heat setting, dyeing and finishing steps of the life cycle of the boxer are shown in Table B-1.

Table B-1. Chemical composition of the dyestuff and auxiliars used in ACATEL.

Tuboset			
Diethylene glycol butyl ether	C13 Alcohol ethoxylate	Adipic acid	Triethylene glycol monomethyl ether
Albatex CO			
Oxirane, methyl- mono (hydrogen sulfate), C9-11-alkyl ethers, sodium salts	C13 Alcohol ethoxylate		
Mazyme ECO			
Cellulase	Lyase	Lipase	Benzisothiazolinone
Toxal Jet SO			
C13 Alcohol ethoxylate	Diethylene glycol monobutyl ether	Isopropanol	Benzisothiazolinone
Toxal PV-DT			
Nitrilotriacetic acid	Sodium hydroxide	Benzisothiazolinone	
Toxal TAC			
Citric acid	Hydroxy ethylidene diphosphonic acid (HEDP)	Formic acid	3:1 mixture of Methylchloroisothiazolinone and Methylisothiazolinone
Novacron deep night			
White mineral oil (petroleum)	Reactive black 5		
Everzol Red			

Everzol Yellow			

SOLUSOFT NUP			
C13 Alcohol ethoxylate	Triethylene glycol	3:1 mixture of Methylchloroisothiazolinone and Methylisothiazolinone	
TOXAL BUF/4			
Formic acid	3:1 mixture of Methylchloroisothiazolinone and Methylisothiazolinone		
FLUOWET UD LIQ			
C11 Alcohol ethoxylate			

The chemicals presented in red, in Table B-1, were not considered since they represent less than 0.1 % of the product composition, and there is no information in the Ecoinvent LCI database and the literature about them.

Appendix C – Environmental Impact Assessment results by SimaPro

In Table C-1 the environmental impact results, for each individual process and environmental impact category studied, are presented.

Table C- 1. Environmental impact results for each environmental impact category studied and for each process considered.

	Climate Change (kg CO_2 eq)	**Freshwater ecotoxicity (PAF.m^3.day)**	**Water use (m^3)**	**Abiotic depletion - fossil fuels (MJ)**	**Eutrophication (kg PO_4 eq)**
Packaging	0.0284	233.44	0.00998	0.307	4.52×10^{-5}
Drying	0.101	95.832	0.0171	1.45	4.70×10^{-5}
Dyeing	0.0514	286.06	0.303	0.613	1.02×10^{-4}
Knitting	0.00889	26.226	0.00519	0.0834	1.21×10^{-5}
Cutting	0.00709	20.938	0.00414	0.0666	9.68×10^{-6}
Calendering	0.0282	83.278	0.0165	0.265	3.85×10^{-5}
Org. cotton prod. +spinning	0.132	404.25	1.92	0.379	4.33×10^{-4}
Elastane prod. +spinning	0.0168	33.590	0.0150	0.254	1.58×10^{-5}
Polyester prod. +spinning	0.0151	69.344	0.00659	0.312	1.83×10^{-5}
Sewing	0.0113	33.315	0.00659	0.106	1.54×10^{-5}
Stentering	0.0304	13.021	0.00157	0.473	7.09×10^{-6}
Heat setting	0.0725	156.66	0.0222	1.14	5.86×10^{-5}
Transport between facilities	0.00100	1.8829	7.42×10^{-5}	0.0144	5.69×10^{-7}
Cotton transport	0.00627	11.814	0.000545	0.0847	1.34×10^{-5}
Hydroextraction	0.00169	4.9969	0.000988	0.0159	2.31×10^{-6}
Sanforizing	0.0941	3.0047	0.000128	1.47	1.50×10^{-6}
Winding	0.000282	0.83275	0.000165	0.00265	3.85×10^{-7}
Ironing	0.00165	0	0	0	0
Warping	1.60×10^{-5}	0.047207	9.33×10^{-6}	0.000150	2.18×10^{-8}
Weaving	0.00454	13.406	0.00265	0.0427	6.20×10^{-6}
Cutting elastic	0.00120	3.5405	0.000700	0.0113	1.64×10^{-6}
Total	0.616	1481.1	2.33	7.10	0.000850