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Ecoshoe: an Ecodesign tool to enhance environmental sustainability in the Footwear Industry

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ABSTRACT

The increased production in the footwear sector is directly related to excessive consumption, combined with the progressive reduction of the useful life of the footwear. Moreover, a great variety of materials can be employed in the manufacturing of a footwear component. The production of traditional materials, such as leather, cotton, synthetic fibers, and rubber, raises major environmental concerns. Furthermore, the *focal companies* of footwear delegate the manufacturing to small enterprises, resulting in difficulties in tracking the origin of raw materials and monitoring environmental and social impacts of the suppliers.

The goal of this study was to create an ecodesign tool, named Ecoshoe, to support companies and manufacturers of footwear estimating the potential reduction of environmental burdens by substituting traditional materials. Firstly, 71 companies were analyzed to develop a benchmark of the sector, through publicly available information. Secondly, a selection of traditional and alternative materials was modeled through the LCA methodology to evaluate their potential environmental impact. Finally, the Ecoshoe tool was created coupling the analyzed materials with the possible application of the ecodesign approach. The tool was tested for a classic and a casual shoe model evaluating the environmental benefits by materials replacement through scenarios.

The benchmark analysis revealed that companies provide less information on the adopted sustainability practices compared to intermediate price range and fashion companies which claim to be green. The LCA showed that the alternatives to the conventional tanning process present better performances in almost every impact category considered. The best alternatives to traditional textiles are healthy materials (DfHM) and recycled materials (DfRM). The tool showed that substituting the traditional materials can reduce the environmental impacts, outlining the contribution to the impacts of each footwear component. Limitations and opportunities for further development of the tool are discussed in the present thesis.

KEYWORDS

Footwear industry; Life Cycle Assessment; Ecodesign; Environmental Sustainability.

SOMMARIO

L'aumento della produzione nel settore calzaturiero è direttamente collegato al consumo eccessivo, combinato con la progressiva riduzione della durata utile della calzatura. Inoltre, una grande varietà di materiali può essere impiegata nella fabbricazione di una componente della calzatura. La produzione di quelli tradizionali, come la pelle, il cotone, le fibre sintetiche e la gomma, suscita grandi preoccupazioni ambientali. Inoltre, le *aziende focali* delegano la produzione a piccole imprese, con conseguente difficoltà nel tracciare l'origine delle materie prime e nel monitorare le pratiche ambientali e sociali dei fornitori.

L'obiettivo di questo studio è stato quello di creare uno strumento di ecodesign, denominato Ecoshoe, per supportare le aziende e i produttori di calzature nel valutare la potenziale riduzione degli impatti ambientali legata alla sostituzione dei materiali tradizionali. In primo luogo, sono state analizzate 71 aziende per definire un benchmark del settore, attraverso informazioni pubblicamente disponibili. In secondo luogo, una selezione di materiali tradizionali e alternativi è stata modellata attraverso l'Analisi del Ciclo di Vita (LCA) per valutare il loro impatto ambientale. Infine, lo strumento Ecoshoe è stato creato associando i materiali analizzati con l'approccio dell'ecodesign. Lostrumento è stato testato per un modello di scarpe classiche e casual valutando i benefici ambientali derivanti dalla sostituzione dei materiali attraverso alcuni scenari.

L'analisi di benchmark ha rivelato che le aziende di lusso forniscono meno informazioni sulle pratiche di sostenibilità adottate rispetto alle aziende di fascia di prezzo intermedia e a quelle che dichiarano di adottare pratiche sostenibili. La LCA ha mostrato che le alternative al processo di concia tradizionale presentano prestazioni migliori in quasi tutte le categorie di impatto considerate. Le migliori alternative ai tessuti tradizionali sono i materiali non nocivi (DfHM), e i materiali riciclati (DfRM). Lo strumento ha mostrato che la sostituzione dei materiali tradizionali può ridurre gli impatti ambientali, delineando il contributo agli impatti di ogni componente della calzatura. I limiti e le opportunità per un ulteriore sviluppo dello strumento sono discussi nella presente tesi.

Parole chiave

Industria calzaturiera; Analisi del ciclo di vita; Ecodesign; Sostenibilità ambientale.

PREFACE

This master thesis constitutes the final exam of the master course Environmental and Land Planning Engineering from *Polytechnics of Milan*.
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I would like to thank Politecnico di Milano for all these years, which made me grow a lot as a person, helping to make me a more aware citizen. I believe that the decision to enroll in the Faculty of Environmental and Land Planning Engineering was one of the best I have ever made.
During these years I have met many friends with whom I have been able to share part of this experience.

Acronyms

ALOP Agricultural Land Occupation Potential

DfC Design For Compostability

DfD Design For Disassembly

DfHM Design For Use Of Healthy Material

DfM Design For Maintenance

DfR Design For Recycling

DfRM Design For Use Of Recycled Material

DfRMV Design For Reduced Material Variety

EPD Environmental Product Declaration

EU European Union

FDP Fossil Depletion Potential

FEP Freshwater Eutrophication Potential

FSC Forest Stewardship Council

GHGs Greenhouse Gases

GOTS Global Organic Certified Standard

GRI Global Reporting Initiative

GWP Global Warming Potential

ISO International Organisation for Standardisation

LCA Life Cycle Assessment

LCI Life Cycle Inventory

LCIA Life Cycle Impact Assessment

LEED Leadership in Energy and Environmental Design

LWG Leather Working Group

MDP	Metal Depletion Potential
NGO	Non-Governamental Organization
NMVOCs	Non-Methane Volatile Organic Compounds
NMMO	N-methylmorpholine-N-oxide
OCS	Organic Content Standard
PCR	Product Category Rules
PEF	Product Environmental Footprint
POFC	Photochemical Oxidant Formation Potential
SDGs	Sustainable Development Goals
TAP	Terrestrial Acidification Potential
UN	United Nations
WDP	Water Depletion Potential

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Introduction

1.1 Problem definition

The rapid growth of human societies recorded in the last century, known as the great acceleration, brought significant prosperity but also accentuated major environmental issues [11, 12].
Nowadays, the human impact on the environment can no longer be denied. Some of the biggest biophysical systems regulating the earth climate, like the arctic sea ice, the amazon rainforest, and the coral reef, are approaching a tipping point, after which the changes could be irreversible [13].
The urgent problem posed by global warming requires a profound change in every aspect of the production system [14]. It is paramount to implement actions in order to mitigate the environmental burdens of society.

Among the most pollutant production sectors can be found the fashion industry [15]. In this sector, the footwear industry contributes significantly to the environmental impacts [16].
From 2010 to 2018, footwear production increased by 20.5% [17], with 24.2 billion pairs of footwear manufactured in 2018 [18]. The increased production is directly related to the excessive consumption of shoes, associated with the progressive reduction in the useful life of footwear [19]. Italians are the second greatest footwear consumers, just after Americans, with an average consumption of almost 7 pairs of shoes per year [20].
All of these trends have major consequences for the environment: increased production means more resources exploited and a greater amount of energy required, while increased consumption is reflected in a consequent greater waste stream that requires to be disposed of [19]. Considering that a shoe is made up by many different materials [21], from the ones used for the main components, like the upper, the outsole, and the liners, to the reinforcements applied and the glue used to assemble the shoe, all of these materials need to be treated and disposed of in different ways [19].
Furthermore, in manufacturing each shoe component, a great variety of materials can be employed. The production of the materials traditionally used, such as

leather, cotton, synthetic fibers, and rubber, raises major environmental concerns [19, 22]. Companies increasingly delegate the different stages of the manufacturing of their products to many different enterprises, often located in different parts of the world. For this reason, it is not always easy to keep track of the origin of the raw materials and to monitor the environmental performances of the suppliers [22].

1.2 STATE OF THE ART

In recent years, the fashion industry has undergone profound changes on the path to sustainability and eco-efficiency. These changes are linked to the growing pressure from consumers, public opinion, the scientific community, and policymakers [23]. According to *Chrobot et al., (2018)*, in the face of the urgent environmental and social challenges caused by climate change and the depletion of resources, it has become paramount to act to create a more sustainable future on a sectoral level [24]. Sustainability within the industrial processes in the footwear sector is therefore a key factor that is increasingly translated by the market through greater demand for transparency on production processes [25]. Companies of the footwear industry can reduce their environmental impact following the ecodesign approach when planning their products [26]. Ecodesign considers the environmental concerns in the designing stage of a product [27]. There are many ways to implement ecodesign and therefore reduce the environmental impact, e.g. by selecting more sustainable materials for each shoe component, with longer useful life, or making a product that it is easy to be disposed of or recycled [28].

one of the tool that allows to assess the environmental impact caused by the production of a certain material or service is the Life Cycle Assessment (LCA) [29]. In order to implement an LCA study, it is necessary to monitor not only the final shoe assembly process but also the extraction and processing of raw materials, manufacturing, and transport. Since these processes are frequently carried out by different companies, also located in different countries, the management of such data requires an interaction between companies that is not always possible. Furthermore, the extraction and processing of raw materials contribute significantly to the overall impact linked to the production of a shoe [24].

The ecodesign approach, coupled with the LCA, constitutes a fundamental way to reduce the impact and create a more sustainable product [28]. However, there is not any general ecodesign tool, but each company tries to create an ecodesign model on its own.

Nowadays, there are various other tools at a national and international level that support companies in the implementation of sustainability practices, including environmental certifications, both for products and companies, emission reduction targets, the use of more sustainable innovative materials, communication to the public, and so on [30]. However, such tools that aim to ensure the traceability of a company's sustainability level still appear poorly defined and structured [30]. In fact, driven by market demands, each company independently defines which actions to implement in its production process. Consequently, since there are no specific and preferential activities that allow to improve a production process throughout the supply chain from an environmental point of view, it is necessary to identify the actions most promoted by the companies in the sector and subsequently build a map of possible options and study its specific feasibility [22].

1.3 Objective of the study

According to the problems highlighted in *section 1.1*, the study focused on the environmental sustainability in the footwear sector. Its main goal is to create an ecodesign tool with the purpose of supporting the companies of the footwear sector in designing a more sustainable product by evaluating the substitution of the current material used in the shoe with an alternative one.
In order to achieve this goal the methodology approach used is characterized by the following procedure:

1. To create a benchmark to compare the performance of several companies of the sector, evaluating them under some criteria in order to bring out the most widespread best practices.
2. To evaluate the most used materials, identified in the benchmark, with an LCA study, assessing the environmental burdens of the production processes.
3. To link the materials to the relative ecodesign characteristics, i.e. if they are from recycling process, or produced in a more sustainable way.
4. To create a user interface to visualize the potential environmental impact reduction by substituting the material used in a shoe component.

The thesis is structured in the following way:

- Chapter 2 describes the current status of the footwear industry, the main environmental impact generated, and the initiatives carried out at governmental, industrial, and scientific levels.
- Chapter 3 defines the methods used to realize the benchmark, the Life Cycle Assessment of the materials considered, and how the tool is made.
- Chapter 4 presents the outcomes obtained concerning the benchmark of the companies of the footwear sector, highlighting the major differences between them, the impact generated by the materials, and an example of application of the tool in relation to different scenarios.
- Chapter 5 contextualizes the obtained results with the related scientific literature, indicating the main limitations of the conducted analysis.
- Chapter 6 summarizes the main outcomes of the study, and the future development needed.

2

STATE OF THE ART

In 2020, a value of 365.5 billion dollars was estimated for the global footwear market and it is expected that this value will continue to rise, reaching 530.3 billion in 2027, which corresponds to an annual increase of 6.4% [31]. In 2018, 24.2 billion pairs of footwear were produced [18], with an increase of 20.5% compared to 2010 [17].
Production takes place mainly in Asia, where 87.6% of global footwear is manufactured [32]. In Europe, even if only 3.2% of world production occurs, 13.6% of the total is consumed [32]. In particular, in Italy the per capita consumption levels are among the highest: 6.8 pairs of shoes per year [19, 20].
The aim of this chapter is to provide an overview of the current situation in the footwear industry. *Section 2.1* starts with pointing out the environmental impacts generated and how they are distributed along the life cycle of the product, and then listing the sustainability practices that can already be implemented at an industrial and institutional level. It also considers how these practices can be influenced by the consumers' perception. Concerning the scientific aspects covered in *section 2.4*, some of the LCA studies on footwear available in the literature were reviewed. Finally, *section 2.2* deals with the approach of ecodesign and how it can be applied to the footwear sector.

2.1 CURRENT STATUS OF THE ENVIRONMENTAL SUSTAINABILITY IN THE FOOTWEAR SECTOR

The manufacturing process of a shoe uses many raw materials and resources such as water and energy [17]. Despite the improvement of materials efficiency and the removal of some harmful substances used in production processes [19, 33], over the years there has been an increase in the impact on the environment [24], as a consequence of the increase in production and the progressive decrease in the useful life of footwear, as a result of the trend in consumer fashion [19, 26].
Furthermore, the absence of recycling and recovery systems for footwear at the end of life generates an increase in waste production and consequently an increase in the environmental impact [24, 34]. Considering also that the studies involving the characterization of waste combine footwear with clothing, making it difficult

to quantify the fraction generated by footwear [19]. LCA is one of the most used tools that allow to quantify the environmental impact of a product starting from the extraction of raw materials up to the disposal at the end of its life [24]. For a more detailed explanation of this tool, please refer to *section 2.1.3* of this thesis. In the case of footwear, the phases of the life cycle are [24]:

1. Extraction of raw materials needed for the production of the shoe;
2. Processing of raw material, such as spinning and weaving for textile and synthetic shoes and tanning for leather shoes;
3. Manufacturing of each component of the shoe;
4. Assembling of the footwear parts (sewing, gluing...);
5. Packaging production, including the extraction of the necessary raw materials and their processing;
6. Transport of products in relation to distribution, from the manufacturing site to the retail outlets;
7. Disposal, including collection and management of footwear at the end of the use phase.

According to *Chrobot et al., 2018* [24], the main impact categories to which the life cycle of the footwear industry contributes are:

- Climate change (or GHGs emissions);
- Freshwater withdrawal;
- Human health;
- Ecosystem quality;
- Resource depletion.

Considering the entire life cycle, and therefore the impacts related to each production phase, from the extraction of raw materials to the disposal of the product at the end of its life, it was estimated that in 2016 the overall contribution of the footwear industry to climate change was equal to approximately 3.29 billion tons of CO_2 [24]. In general, the manufacturing of components and the extraction of raw materials are the main drivers for the impact categories [24]. Moreover, the focal companies, i.e. the owner of the brand which manages the supply chain [35], increasingly delegate the different stages of the manufacturing of their products to many different small/medium enterprises scattered around the world [22, 26]. This reduces the possibility of interaction between the parties and consequently a control on the reduction of environmental impacts. For this reason, more and more efforts are being made in order to create a traceability system among the actors present in the supply chain [30]. The environmental impacts also depend on the type of materials used. It has been estimated that on average 40 different materials are present in a shoe [21], which are produced according to different production processes and require specific end-of-life treatments [19] [20]. The most common materials used by the footwear industry are: synthetic materials, leather and textiles present respectively in 57%, 25% and 18% of footwear [24]. For almost all impact categories synthetic materials contribute more than textiles and leather, this also due to the fact that they are present in 57% of footwear. According to *Chrobot et al., (2018)* [24], despite the fact that leather materials are present only in a quarter of footwear production, their impacts are relevant, ranging between 30% and 80%, depending on the impact categories considered [24] [17]. For this reason, in order to reduce the environmental impact, it is essential to choose innovative materials with better performance or products according to social sustainability practices in each component of the shoe, such as the use of recycled materials, or of natural origin [36].

2.1.1 Policy and initiatives in the footwear sector

There are numerous organizations operating at the international level to spread the adoption of sustainability practices in the fashion industry [37, 38, 39, 40]. Some of these organizations directly collaborate with fashion companies and institutions in order to reduce the negative environmental and social impacts and to contribute to the United Nations (UN) Sustainable Development Goals (SDGs) [37]. Regarding the aspect related to the disposal and the end-of-life treatment of textile and footwear waste, some changes are expected in terms of regulations. The European Union (EU) considers the management of textile and footwear waste a priority in its circular economy strategy, within the European Green Deal [41]. *The EU directive 2018/851* [42] indeed obliges all member states to collect their textile waste separately by 2025 [41]. In Italy this regulation has been anticipated by the *Legislative Decree 116* of *September 3, 2020* [43], which makes it mandatory to collect textile and footwear waste separately starting from 1st January 2022.

2.1.2 Consumers' perception and sustainable footwear

Consumers' sensitivity towards the issue of sustainability in the fashion sector has become increasingly important [44]. Indeed, from the results of a recent questionnaire conducted in 2020, about 50% of Italians believes it is important to buy sustainable clothing, footwear and accessories, 70% would like to know the ecological footprint of the products purchased and 80% would like to know the origin of the raw materials used for the products purchased [44]. Finally, considering the economic aspect, the global market for sustainable footwear, made with innovative and more responsible materials, is expected to grow at an annual rate of 5.8% from 2020 to 2027, reaching a value of 11.82 billion dollars in 2027 [45].

2.1.3 PRACTICES FOR TRACKING SUSTAINABILITY

At present, several tools at national and international level allow to support companies in the implementation of sustainability practices, including: sustainability reports, the LCA, the adoption of certifications and the selection of suppliers through a code of conduct, that are discussed in the following paragraphs.

SUSTAINABILITY REPORT

The drafting of a sustainability report is an important tool for taking into account the activities of the company, with reference to environmental, social and economic aspects, in order to communicate them in a transparent way to stakeholders and consumers [30].
At the moment, companies are not obliged to write a sustainability report. There isn't a unique standard covering the guidelines that a company must follow to write it. One of the most widespread standard is constituted by the Global Reporting Initiative (GRI) [46]. The aims of GRI are to improve the reliability and transparency of the environmental, social and economic practices implemented by a company [47, 48].
Within the report it is possible to quantify the targets to be achieved, such as reducing emissions or increasing the use of clean energy. The targets can then be referred to internationally recognized objectives such as the United Nations' SDGs.

LIFE CYCLE ASSESSMENT

Life cycle Assessment (LCA) is a tool that allows to quantify the environmental impacts of a product from the extraction of raw materials to the end of life [29], as reported in the diagram showed in *Figure 2.1*. At the international level, the principles of LCA are defined within the ISO 14040 standard [49].
The LCA is divided into the following four phases:

1. Definition of the goal and scope of the study;
2. Life Cycle Inventory (LCI);
3. Impact assessment;
4. Interpretation of results.

In order to carry out an LCA, it is therefore necessary to quantify all the flows of materials and energy that contribute to the life cycle of a product. In the case of footwear it is necessary to collect data relating not only to the production of the footwear, but also that of the raw materials that make up the shoe [17]. The process is iterative and the data are not always made available by the producers.

There are different variants associated with LCA, depending on the system boundary considered. The main ones are classified as [17]:

1. Cradle to gate: A partial life cycle study, where the system boundary considered to study the product's impact is confined to the production stage of the product.
2. Cradle to grave: A complete life cycle study, where the system boundary is extended up to the end-of-life disposal stage.
3. Cradle to cradle: A category of cradle-to-grave assessment, where the end-of-life disposal stage is a recycling process, after which identical or new products are created.

In the footwear sector, several players contribute to the production of a pair of shoes: sole producers, laces producers, shoe manufacturers, etc. Hence, the quantification of the materials and energy consumption is sometimes challenging. As reported in *section 2.1*, the greatest impacts are generated by the first phases of the life cycle: extraction and processing of raw materials, manufacturing and assembly of components [24]. Considering the globalized character of many of the companies in the sector, and given that the early phases of the life cycle are carried out by factories located in countries very distant from each other and with different policies, makes it difficult to monitor and reduce their impact [30, 46].

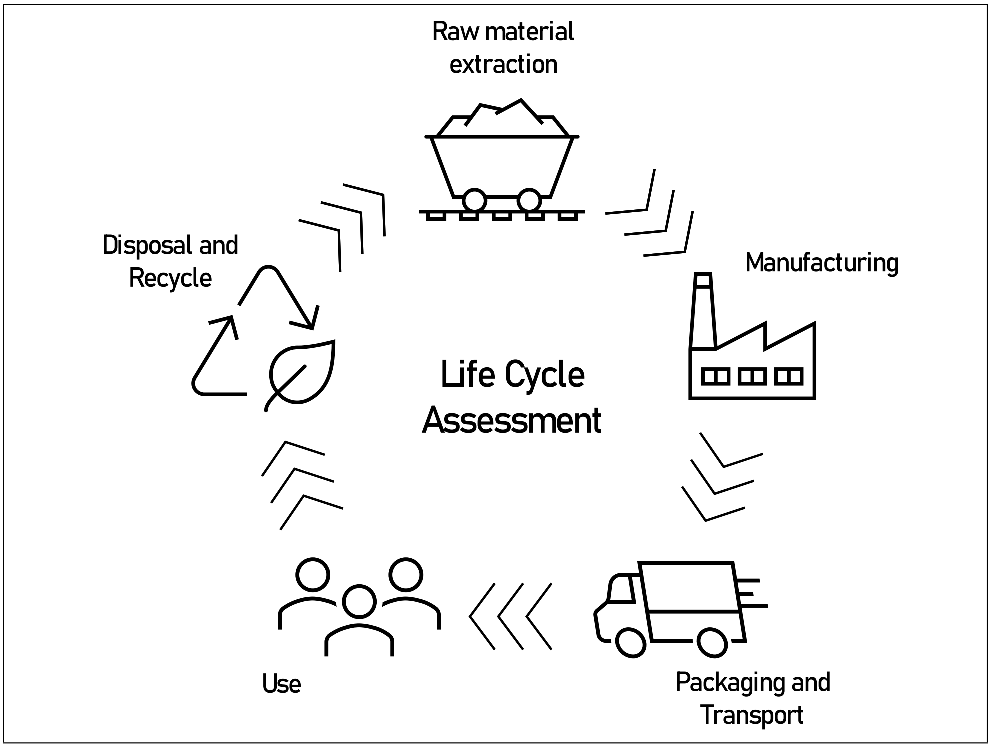


Figure 2.1: Life Cycle Assessment phases

CERTIFICATIONS

There are various type of certifications referring to social, environmental and economic aspects, and they can be applied to different levels: to the management system of a company, or to a specific process or product. Whatever type is considered, certifications can be defined as the confirmation, through an audit performed by independent and accredited auditors, of an organization's compliance with specific, agreed-upon rules or standards [48].
For these reasons, certifications are useful tools for companies to ensure compliance with certain conditions, in addition, they can select certified suppliers, to have a guarantee of conformity with certain standards, both environmental and social. [30].
Among the product certifications, the Environmental Product Declaration (EPD) constitutes a important solution to communicate the environmental performance of a product [50]. The EPD is a standardized environmental declaration, based on the LCA methodology, to assess the environmental impacts of a product. The standard ISO 14025 [51] defines the requirements for performing the LCA at the basis of the EPD, concerning every aspect of the assessment, like how to model the product system, how to select the system boundaries, or which impact indicators to consider. The requirements vary depending on which category the product belongs to, in line with the product category rules (PCR)[50].

CODE OF CONDUCT

Another possibility that can be directly implemented by a company is to require to its suppliers to comply to a Code of Conduct, respecting workers' rights and integrating environmental aspects [46].
For greater effectiveness it is necessary to carry out frequent checks and support suppliers in the implementation of sustainable practices.

2.2 ECODESIGN APPLIED TO THE FOOTWEAR SECTOR

Companies that aim at reducing the environmental impact of footwear production could consider the ecodesign as the operational approach to enhance environmental sustainability at the design stages of a product [36, 26, 52].
To put it briefly, ecodesign can be defined as the systematic introduction of environmental concerns during product design and manufacturing process [27, 53, 54, 55]. Implementing the ecodesign approach in the footwear sector means minimizing environmental impacts through the phases of the shoe's life cycle, without this leading to lower the quality of the product [54]. The ecodesign approach,

integrated with LCA, promotes a new reading of design and manufacturing techniques. It also allows relating the functions of the product or service with issues linked to the environment by reducing the environmental impact and increasing the presence of eco-efficient products, requiring less natural resources in their production phases [28].
The ecodesign approach can be applied in the following areas [28]:

- Selecting raw materials from renewable sources, recycled or recyclable;
- Reducing the consumption of materials in the production phase and selecting materials that generate less pollution or waste;
- Simplifying the constructive shape of products in order to reduce the weight and consumption of raw materials;
- Providing for product maintenance in the use phase in order to extend its lifespan;
- Using more efficient production system, in both terms of energy consumption and resource consumption;
- Using more sustainable distribution system and optimizing the schedule for the delivery of the products and materials;
- Selecting responsible materials for the packaging used for the product;
- Reducing the waste generated in the production phase, including the selection of materials that can be easily disassembled, disposed of, recycled, or recovered.

Since the companies in the footwear sector, very often, do not have direct control over the entire supply chain, actions cannot be implemented in all of the above-mentioned areas. However, they can act on the design of the product, and so on all the aspects concerning the materials used and their consumption.

Nowadays, the number of companies applying ecodesign principles to their shoes is increasing [27, 56, 57, 58, 59]. The developed strategies are focused on using non-hazardous materials, reducing the use of harmful chemicals, and using recycled materials [27]. However, the speed at which ecodesign practices are spreading is not enough to make the industry more sustainable and to adequately address current environmental problems [60]. This is mainly due to the fact that ecodesign is a multi-disciplinary approach. In order to reduce the environmental impacts, this must be first known and evaluated, through the LCA method, which needs a lot of resources to be performed, in terms of data, time and experts [60]. Knowledge regarding materials to use in a shoe should be needed, in order to select the most appropriate materials to perform a given function. Furthermore, to reduce the energy consumption of a certain production process, it is needed to understand how to improve its efficiency [53].

For all of these reasons, the implementation of the ecodesign approach results to be particularly difficult for the smaller companies, whose have fewer resources and are more oriented on the short-period goals [60].

2.3 Review on materials used in the footwear industry

As it was already mentioned in the previous section, companies that want to reduce the environmental impact should consider more sustainable materials in the designing phase of the product [28]. In the footwear industry, there are a great variety of materials that can be employed [21, 33]. The materials most commonly used are leather, synthetic textiles, like nylon and polyester, natural textiles, like cotton, and rubber [33]. In the following paragraphs are introduced the most traditional materials and some of the alternatives.

Leather

Leather can be considered as one the oldest material used to realize shoes and clothing [61]. Leather shows several properties making it a great material for shoe application, such as strength, elasticity, water vapor permeability, abrasion resistance and durability [62]. As reported in *section 2.1* the environmental impacts caused by the leather industry are relevant [24]. The phases that contribute the most to the overall environmental impact are agriculture and tanning [63]. The tanning phase is characterized by excessive use of chemicals causing severe pollution in the areas close to tanneries [19]. It was estimated that for each pair of leather shoes almost 3 kilograms of chemicals are used [29]. Nowadays, environmental concerns become more and more pressing, and society and market demand more and more action to make the production processes more transparent and sustainable [61].

Currently, there are increasingly more vegan bio-based alternative materials to leather [62, 64]. Materials such as Desserto [65], made from cactus, Pinatex [66], produced from pineapple leaves, or Appleskin, coming from apple waste, and many others [62]. *Meyer et al., 2021* [62] compared the physical properties of these new materials with the ones of leather, but without considering the environmental impacts. These materials can become very important in a circular economy since some of them came from vegetable waste [62]. However, none of these leather alternatives showed the same performance as leather, but they still remain a good substitute [62].

TEXTILES

Textiles are the most used material for footwear application, obtained from natural or man-made fiber [24]. The most used textiles of synthetic origin is polyester, made from polyethylene terephthalate (PET). Nylon is another widely used synthetic textile for shoe manufacturing, made from polyamide. Both these textiles are made from fossil source [19].

COTTON

Among the natural textiles, cotton is the most used fiber for textile production [6, 67]. It is mainly produced in tropical and subtropical regions [5], and the majority of the production occurs in Asia, where the 58% of the world production happens. India is the biggest producers (24%) followed by China (19%), USA (17%) and Brazil (11%) [68]. Cotton cultivation requires a large amount of water, so the irrigation needed is highly dependent on the rainfall that occurs in a given location [67, 69]. In fact, irrigation in Brazil covers less than 1% of the total water needs, while in Egypt it covers 77% of the total [70]. In conventional cotton cultivation it is used a great amount of pesticides [67]. It was estimated that 11% of the total pesticides consumption worldwide is employed in cotton cultivation, even though it covers only 2.4% of the total arable land [67, 69].
One of the alternative to the conventional cotton cultivation is represented by organic cotton. Organic cotton is cultivate without employing the use of artificial fertilizers and pesticides [67, 69, 71]. In order to certify the organic origin of cotton, the cultivation must comply with the organic farming regulation. According to the EU organic policy, organic farmers are encouraged to: use energy and natural resources responsibly, maintain biodiversity, preserve the regional ecological balance, enhance soil fertility, and maintain water quality [72]. There are two major certifications for organic farming: the Global Organic Certified Standard (GOTS) and the Organic Content Standard (OCS) from Textile Exchange a non-profit organization aiming to create a community in the textile supply chain promoting the use of more sustainable fibers [73]. GOTS defined the guidelines for both environmental and labor conditions, throughout the textile and apparel manufacturing supply chain using organically produced raw materials [74]. While OCS guarantee the organic content in a product [73].
In recent years, the market of organic cotton fiber is continuously growing. The larger producer is India covering 50% of the global production, while, China being second producing 12% of the total [73]. Despite the production growth, organic cotton still constituted only 0.95% of the cotton produced with conventional agriculture practices [73].

HEMP

Another textiles of natural origin that is increasingly used for footwear components is hemp. Hemp (*Cannabis Sativa L.*) has been cultivated for many centuries in different parts of the world for food and medical purposes but also to make textiles [75]. In the past century, there has been a decline in hemp production, due to the rapid development of synthetic fibers and cotton cultivation [76, 77], and the restriction of hemp cultivation in many countries due to its THC content, a psychotropic substance [75]. Hemp is a bast fiber, which means that the fiber is obtained from the outer part of the plant stem, and can be grown in a wide range of climatic conditions [5, 69]. In the European context, hemp can be considered as another alternative to cotton, where it can be grown widely, while cotton can be harvested only in the most southern part [78]. In addition, hemp needs less water than cotton, and can be grown without the use of artificial pesticides, thanks to its natural resistance to pests [69, 5, 77]. Hemp is also known for its bioremediation properties, and it can be used to decontaminate heavy metal polluted soils [5, 79]. For all of these properties, in recent years, hemp is considered more and more as an alternative sustainable fiber [5].

WOOL

Wool is not so commonly used for footwear application, but there are some brands using it [80]. Sheep farming constitutes an important agricultural activity for its products, such as wool, milk, and meat, but also for its role in cultural tradition [81]. The peak of global production of wool was recorded in 1990, after that, there has been a progressive reduction until reaching the minimum in 2020, with an overall reduction of 47% [68]. The major producer is China (19%) followed by Australia (16%), Europe (12%) and New Zealand (8%) [68].

RECYCLED TEXTILES

Most of the textile post-consumer waste is disposed of by incineration or landfill [7]. Recycling textile waste can be economical and environmentally convenient since the production of virgin fiber is avoided, but also the impacts related to the disposal [67, 7, 82].

One of the recycled material that is gaining more and more attention in recent years is econyl, being used by many companies of the footwear sector [83, 84, 56, 85]. Econyl is a recycled material recovered from nylon waste, like fishing nets retrieved from the ocean, or textile production waste [86].

Insoles and outsoles materials

Rubber is the most commonly used traditional material for insole and outsole [34]. It can be distinguished according to the different origin: natural, extracted from the rubber tree (*Hevea brasilensis*) or synthetic, obtained from hydrocarbon monomers [34].

An alternative to rubber is represented by cork. Cork is a natural renewable material, obtained from the bark of cork oak (*Quercus suber L.*) [87]. In footwear production it can be used for insole and outsole [88, 87]. It is antimicrobial, flexible and impermeable to liquid. Furthermore, cork forests are important reservoirs of biodiversity, acting also as carbon sinks [87]. The biggest producer is Portugal, covering the 34% of the global production, followed by Spain (27%), Morocco (18%), and Algeria (11%) [89].

2.4 LCA studies in the footwear industry

As already mentioned in *subsection 2.1.3*, LCA represents a fundamental tool to understand the environmental impact generated by a product, the life cycle stages that contribute the most to the overall environmental impact, and consequently identify the possible actions to reduce the impact [17]. Currently, there are some LCA studies evaluating the impact related to the production of shoes, focused more on evaluating the impact related to material, like leather, or on the end of life treatment [63, 20, 27, 34].

One of the first example of the LCA application in the footwear sector was a study on leather shoes conducted by *Mila et al., (1998)* [63]. The goal of this study was to identify the life cycle stage of a Spanish pair of leather shoe that contributed the most to the overall environmental impact [63]. The functional unit of an LCA study on footwear might be chosen taking into consideration the following two aspects (defined by *Perdijk et al., (1994)* [90]): firstly, the purpose of the shoes which is to protect the foot, secondly, the duration of the shoe, considering one year of standard use [63]. As an approximation of the best functional unit selected by *Mila et al., (1998)* was "1000 hours of protection of the feet". They obtain this number by estimating the number of hours a lady would wear her shoes during a year and assuming an average consumption rate of 3.7 pair of shoes per year [63].

They considered all the major life cycle stages, in a cradle-to-gate LCA, for the leather and textile component, including cattle rising, slaughtering, tanning, footwear manufacturing process, use, distribution, and waste management. The main outcomes from this study were that the agricultural phase in the footwear life cycle was the major contributor to global warming, acidification, and eutrophication, accounting for 40% of the total life cycle impact. While, the tannery production phase was mainly responsible for water-related impacts [63].

Another example of LCA study applied to footwear is represent by the project *LIFE GreenShoes4All* [91]. It is a project co-founded by the European Commission with the aim of spreading the Product Environmental Footprint (PEF) methodology for footwear and to develop efficient ecodesign, recycling and manufacturing solutions [91]. The PEF methodology intends to introduce some improvements compared to other existing LCA methods including, clear identification of the potential environmental impact categories to be looked at, data sets and minimum data quality requirements [92]. In the report *Ferreira et al., (2020)* [92], from the same project, they compared the environmental impact generated by five different models of shoes and of different materials used in the production, considering the different weights associated to the different types of shoe [92]. The study outlined that Climate Change was the most relevant environmental impact categories for the footwear production. The Global Warming Potential (GWP), measured in $kg_{CO_{2eq}}$, caused by a pair of shoe can vary from 6, for a pair of sandals, to 19 $kg_{CO_{2eq}}$ for a pair of high boot [92].

Serweta et al., (2019) [93] performed a similar comparative LCA study considering 7 different types of shoes, 4 of them for children of different sizes, 2 outdoor footwear for men and 1 women's footwear of ballerina type. The life cycle stages considered are the same of the report from *Chrobot et al., (2018)* [24]. However, they did not report calculation for the first two stages of extraction and processing of raw materials [93]. They indicated both the weight of the shoe model and that of the packaging used to contain them [93]. In the study it was highlighted the environmental impact generated by each stages of the life cycle, focusing only the GWP impact category. They found similar results to those obtained by *Chrobot et al., (2018)* with the phase of manufacturing of footwear component that is the major contributor to GWP for almost all of the model considered [24].

All of these LCA studies did not focused on the variability of the environmental impacts across different materials applied in the footwear sector. As concern this evaluation, a lack of studies has been observed. Nevertheless, this is crucial for companies in the footwear sector that aims at understanding the potential environmental impact reduction derived from substituting a material used in a component with an alternative material.

Currently, there is only one example of the EPD methods application in the footwear industry, represented by the model *Bellamont plus* from AKU [10]. In this EPD it was evaluated the environmental performance of an outdoor footwear, made with leather upper and liner, and rubber outsole. Considering an average estimated lifetime of the footwear of 3.5 years. The stages of extraction and preparation of the raw and semi-finished materials are the main contributor to the environmental impacts. The contribution of the early stages of the life cycle cover 85% of the overall impact [10].

Concerning materials that can be used in realizing shoes, there are several papers available in the literature that apply the LCA methodology to the production process of these materials. Some papers evaluated traditional materials, such as leather [1, 94, 61], cotton [95, 6], and polyester [95], other natural materials, such as hemp [5] and wool [6], and innovative materials, like Lyocell [8].

Regarding the alternative materials to leather introduced in the previous section (*2.3*), they were not . As of today the only LCA study available, evaluating leather alternatives, is the one conducted by *Yan, 2017* [96], where he compared the environmental impacts of conventional leather production with fruit leather. Fruit leather is a leather-like material made from fruit waste [96, 97]. He obtained that, in general, Fruit leather has lover environmental impacts than conventional leather [96].

To understand the true potential of these alternative materials, more LCA studies need to be conducted, comparing the results with those of the conventional leather.

MATERIALS AND METHODS

3

The final goal of this thesis was to create the *Ecoshoe tool*, a tool with the purpose to support companies of the sector in designing environmentally sustainable shoes. The realization of the tool was achieved by considering several types of ecodesign and the most common materials used in the industry emerging from the benchmark. These materials are then considered singularly by conducting an LCA study to assess their environmental impacts. *Figure 3.1* shows the general methodology implemented for the development of the ecoshoe tool. Consequently, this chapter is divided into 3 main sections: *section 3.1* describes the methods followed in the realization of the benchmark, *section 3.2* describes the LCA methodology adopted to model the materials considered and linked to the ecodesign, and finally, *section 3.3* outlines the methodology used in creating the *Ecoshoe tool*, and the selected scenarios are introduced.

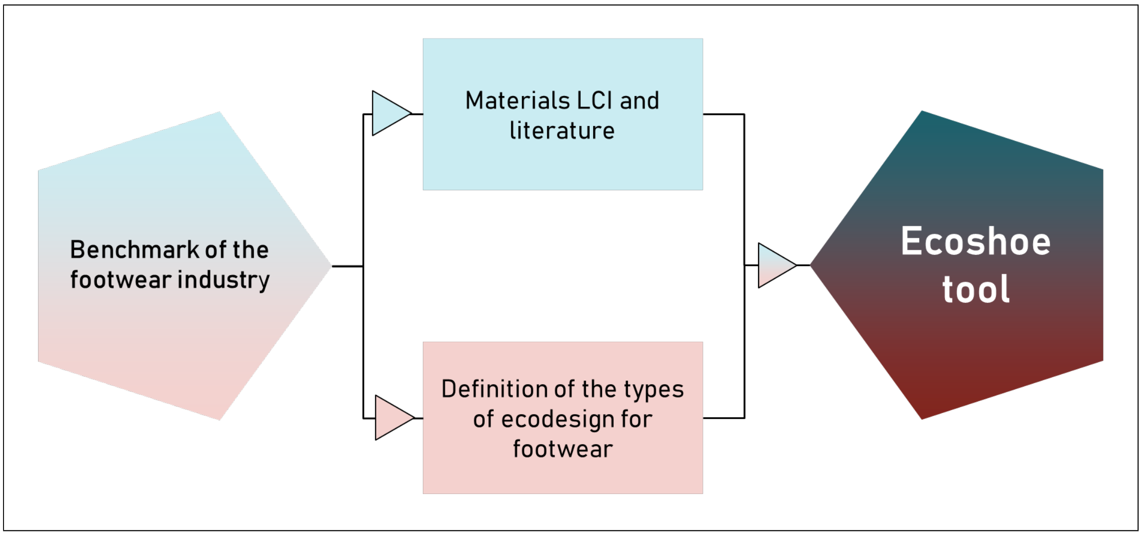


Figure 3.1: Methodology scheme for the development of the ecoshoe tool.

3.1 BENCHMARK OF THE FOOTWEAR INDUSTRY

This section describes the methodology used for the analysis of sustainability in the companies of the footwear sector. In particular, *paragraph 3.1.1* describes the selection criteria for brands and *paragraph 3.1.2* defines the sustainability aspects that were evaluated. *Paragraph 3.1.2.5* introduces an analysis of the production chain of the companies analyzed. Finally, *paragraph 3.1.3* describes the methodology introduced to compare the different brands.

3.1.1 BRANDS SELECTION

The first phase of the benchmark consisted in selecting a certain number of companies to constitute a sample sufficiently representative of the footwear industry. These brands, showed in *Table 3.1*, were selected among the most internationally relevant, and were then grouped into the following three categories:

- Luxury brands: companies that sell luxury products at a price range above 400 euros;
- Intermediate range: companies whose products have a price range between 60 and 300 euros, approximately;
- Green fashion: companies, generally small/medium-sized, which stand out for the creation of footwear models with a focus on sustainability.

The companies belonging to the luxury and intermediate categories have been selected through market analysis, in order to identify those with the greatest turnover or importance on a global level. In addition, in the selection of luxury brands, it was considered the list of companies that work with the *"Consorzio Maestri Calzaturieri del Brenta"* (ACRiB), which collaborates with the *Politecnico Calzaturiero*, present on the reference site [98].
The companies belonging to the green fashion category were identified through a search of the press review on sustainability on the internet [99], for non-Italian companies, or through a targeted search of Italian brands that define themselves as sustainable and that work exclusively on the national territory.

Table 3.1: List of selected brands subdivide by category

Category	Brands		
Luxury brands [31 brands]	Kering	Fendi	Valentino
	Gucci	Givenchy	Stella McCartney
	Bottega Veneta	Marc Jacobs	Vivienne Westwood
	Balenciaga	Christian Louboutin	Tods
	Yves Saint Laurent	Chloé	Moreschi
	Alexander McQueen	Dolce & Gabbana	Rossetti
	Prada	Armani	Santoni
	Miu Miu	Capri Holdings	OTB
	Church	Gianni Versace	Maison Margela
	Louis Vuitton	Jimmy Choo	
	Christian Dior	Salvatore Ferragamo	
Intermediate range [25 Brands]	VF corporation	Puma	Clarks
	Timberland	New Balance	FRAU
	Vans	Skechers	Geox
	North Face	Fila	NeroGiardini
	Nike	Scarpa	ECCO
	Converse	Vagabond	Diesel
	Adidas	Asics	Vibram
	Reebok	Camper	Levi’s
	Saucony		
Green fashion [15 Brands]	Allbirds	NAE	ACBC
	Able	Nisolo	Aku
	Baabuk	SAYE	Camminaleggero
	Christy Dawn	Darzah	Thaely
	8000Kicks	Ragioniamo con i piedi	Vivobarefoot

3.1.2 EVALUATION CRITERIA

The second step of the benchmark was to identify the criteria representative for the evaluation of the sustainability of each brand. Supply chain, Governance, certification and management of raw material, and shoe ecodesign were selected as the four criteria for the evaluation. Further description of each criteria is shown in table *Table 3.2* and in the following paragraphs.
The analysis carried out was based on the collection of information made public by companies up to September - October 2021.

Table 3.2: Evaluation aspect.

Aspect	Description
Supply chain	Control of the production chain through control systems, policies and private agreements with the various stakeholders with a view on sustainability.
Governance	System of coordinated actions towards sustainability, promoted by the company both internally and externally.
Certification and management of raw material	Pursuit and demonstration of sustainability levels through the use and application of sustainability certifications.
Shoe ecodesign	Pursuit and demonstrate sustainability levels through the use and application of sustainability certifications.

3.1.2.1 Supply Chain

Supply chain means the entire supply chain that is necessary to obtain the final product. In the footwear sector, the supply chain includes all those operations involving the supply of raw materials (e.g. leather, laces, rubber, etc.) and the subsequent production, assembly, and distribution of the footwear [30]. A single footwear may therefore be composed of different materials produced in different countries and only then sold within the brand of reference.

The sustainability concept is based on three pillars: social, environmental, and economic[100]. The economic one was not considered in this study. Concerning the environmental and social aspects, it is important to know and track this production from the suppliers of raw materials through to the final distribution. The attempt to track the supply of raw materials is done through communication to the public and attention to the selection of determined suppliers.

The hierarchical levels present in the supply chain, from a brand perspective, are referred to as tiers. For example, tier-1 refers to all the manufacturers of the finished footwear that supply directly to the main brand, while tier-2 represents the suppliers of the components needed by the footwear manufacturers, and so on, proceeding backwards in the supply chain [30]. Therefore, in the present analysis, the level of supply chain transparency by brands belonging to the Luxury and Intermediate range categories was assessed according to the information that the brands themselves make public. Specifically, the following three levels of transparency were identified:

1. Indication of the countries or geographical areas where production takes place;
2. Publication of a list of shoe manufacturers (defined as tier-1);

3. Publication of a list of shoe manufacturers (defined as tier-1) and raw material suppliers (defined as tier-2, tier-3, tier-4).

For brands in the green fashion category, these levels of transparency may not be applicable primarily for the following two reasons: on one hand, these companies are born with the aim to try and circumscribe the supply chain as much as possible, and this aspect was repeatedly highlighted on their websites. However, not all brands have certifications to prove their statement. On the other hand, a significant proportion of these companies are small/medium-sized businesses and therefore do not have management systems that make them comparable to large companies. Consequently, the following three main levels of assessment have been identified for this category of companies:

1. Presence of information regarding the production site;
2. Single producer of footwear, with no other external producers and therefore only raw materials suppliers;
3. Single producer and short supply chain, i.e. all located within a single country.

3.1.2.2 Governance

The governance of a company includes all the tools, rules, systems and processes that contribute to the efficient management of the company. From a sustainability perspective, governance plays a key role: it defines a series of actions, including sustainability goals, supply control, personnel management, activities and partnerships with other companies or Non-Governmental Organizations (NGOs) [30].

In recent years, the implementation of sustainability within corporate governance has been broken down into the United Nations' 17 Sustainable Development Goals (SDGs) [101].

The analysis of governance was especially relevant for large companies, which have a very networked structure, and headquarters and suppliers located in different countries. Similarly, for the *Supply chain* aspect, the analysis of Governance was conducted by identifying, for brands belonging to Luxury and Intermediate Range categories, different levels of information made public by individual companies:

1. Publicizing actions and initiatives linked to sustainability and/or activities related to the circular economy;
2. Presence of a sustainability report published periodically containing an outline of environmental, social and innovation aspects;

3. Presence of a sustainability report published periodically containing not only an outline of environmental, social and innovation aspects but also defining specific goals referring to the SDGs.

As described in the previous paragraph, brands that belong to the Green Fashion category are generally small/medium enterprises that therefore do not have a structured governance like large companies. Therefore, the assessment was not carried out considering the presence of a sustainability report. For brands classified as Green fashion, the assessment was therefore based on information regarding the practices followed and the presence of international partnerships with other companies and/or NGOs.

3.1.2.3 Certification and management of raw material

The company and product certification is a system that aims to control, manage and improve the efficiency of a production process. It can be distinguished in company certifications, which define standards and requirements at company level on different aspects and issues (e.g. quality, safety, environment) and product certifications, which define standards and requirements for a specific product, or raw material, on different aspects (origin, composition, tracking, etc.).

From a sustainability perspective, certification can help on the one hand to control the governance of a company through requirements and, on the other hand, can improve the selection and control of the production chain.

Table 3.3 shows the certifications considered in this study, reporting the characteristics and some of the requirements that a company must possess to be successful in obtaining them.

The evaluation of certifications and management of raw materials was carried out according to which and how many types of certification each company has. For this aspect, it was highlighted which certifications have been obtained and declared by the companies, both at company level and with regard to the supply chain, considering also the products manufactured, the presence of a list of substances not allowed, and a code of conduct that suppliers must sign in order to work with the reference brand. Similarly to the supply chain and governance analysis, also the analysis of this aspect was carried out considering only the information made public by individual companies.

Table 3.3: List of the certifications and their definition

Certification	Description
ISO 9001	Specifies requirements for a quality management system when an organization: a) needs to demonstrate its ability to consistently provide products and services that meet customer and applicable statutory and regulatory requirements, and b) aims to enhance customer satisfaction through the effective application of the system, including processes for improvement of the system and the assurance of conformity to customer and applicable statutory and regulatory requirements[102].
ISO 14001	Specifies the requirements for an environmental management system that an organization can use to enhance its environmental performance. ISO 14001:2015 is intended for use by an organization seeking to manage its environmental responsibilities in a systematic manner that contributes to the environmental pillar of sustainability[103].
ISO 45001	Specifies requirements for an occupational health and safety (OH&S) management system, and gives guidance for its use, to enable organizations to provide safe and healthy workplaces by preventing work-related injury and ill health, as well as by proactively improving its OH&S performance[104].
ISO 50001	Specifies requirements for establishing, implementing, maintaining and improving an energy management system, whose purpose is to enable an organization to follow a systematic approach in achieving continual improvement of energy performance, including energy efficiency, energy use and consumption[105].
LEED	Is the most widely used green building rating system in the world. Available for virtually all building types, LEED provides a framework for healthy, highly efficient, and cost-saving green buildings. LEED certification is a globally recognized symbol of sustainability achievement and leadership[106].
Fair Labor Association	Is a collaborative effort of universities, civil society organizations and socially responsible companies dedicated to protecting workers' rights around the world[107].
SA 8000	Provide a framework for organizations of all types, in any industry, and in any country to conduct business in a way that is fair and decent for workers and to demonstrate their adherence to the highest social standards[108].
LWG	Is a not-for-profit organisation responsible for the world's leading environmental certification for the leather manufacturing industry[109].
OEKO Tex 100	Is one of the world's best-known labels for textiles tested for harmful substances. It stands for customer confidence and high product safety[110].

FSC	Guarantees that the product has been made with raw materials deriving from responsibly managed forests. Companies that use FSC certified packaging are not considered but only those that use certified materials in the production of footwear, such as cellulose and wood[111].
B Corporation	Certified B Companies are a new kind of business that balances purpose and profit. They are legally required to consider the impact of their decisions on their workers, customers, suppliers, community, and the environment[112].

3.1.2.4 SHOE ECODESIGN

The fourth aspect of the analysis was the presence of any sustainable footwear models, according to the indications introduced in *section 2.4*. To make a sustainable product, it is necessary to design it taking into account the principles of ecodesign: to consider the entire life cycle starting from the choice of materials, and how they are obtained, until the end-of-life treatment [36]. It means, therefore, to consider in the design innovative materials, such as synthetic yarns obtained from the recycling of plastics or natural fibers, such as cotton and hemp, obtained from certified crops. In this study, the definitions of ecodesign shown in *Table 3.4* were considered [28].

Table 3.4: Typology and definition of ecodesign founded in the brands analized

Type of Ecodesign	**Acronym**	**Description**
Design for use of Recycled Material	DfRM	The shoe is made from recycled or reused materials
Design for use of Healthy Material	DfHM	The shoe is made with materials from responsible sources, such as certified suppliers, materials safe for human health, or use of natural materials, such as hemp and sugar cane
Design for Recycling	DfR	The shoe is designed so that it can be recycled into raw material to make new shoes or other products
Design for Compostability	DfC	The shoe is produced with biodegradable materials
Design for Reduced Material Variety	DfRMV	The shoe is designed from a few materials, up to a single material, in order to facilitate recycling
Design for Disassembly	DfD	The shoe is designed so that it can be easy to separate the components of which it is composed
Design for Maintenance	DfM	The shoe is made by providing that it can be repaired, in order to extend the phase of use and any reuse.

3.1.2.5 Supply chain analysis

The second part of the benchmark involved a preliminary analysis of the supply chain. As reported in *subsection 3.1.2*, tracking the supply of raw materials and monitoring and selecting suppliers are necessary aspects in the assessment of a brand's sustainability. Since information regarding the suppliers of many companies was not disclosed, it was not possible to analyze the characteristics of the suppliers themselves. Therefore, a preliminary analysis of the supply chain was carried out to identify the minimum requirements that brands require from suppliers in order for them to comply with their supply chain. These requirements mainly concern aspects linked to worker health and safety, quality of the raw materials used, emission control, etc. In order to explore the aspect of supplier and raw material management, preliminary consideration was given to Codes of Conduct, which companies make their suppliers sign where available and public. In fact, Codes of Conduct contain requirements on minimum working conditions for employees, monitoring of environmental aspects and any certifications required for raw materials [30].

It should be noted that this phase of analysis was also based on information made public by individual companies. *Table 3.5* and *Table 3.6* show the main requirements in the Codes of Conduct regarding worker conditions and environmental monitoring respectively.

Table 3.5: description of the aspects considered regarding the treatment of workers, present in the Code of Conducts.

Worker treatment aspect	Description
Child labor	Prohibit child labor under the age of 15/16, depending on the regulations in the country in which the provider operates; in any case, the minimum age of employment should not be less than the age at which compulsory schooling ends.
Modern slavery	Prohibit all forms of forced labor, every employee has the right to accept employment or resign freely.
Health and safety	Suppliers shall provide all workers with a safe and healthy working conditions.
Decent labor	Ensuring adequate pay and employment contracts, respecting working hours, and not exceeding the limits imposed by law.
Abuse and harrassment	Prohibit any form of corporal punishment, physical, sexual, verbal or psychological violence, or any other form of abuse.
Freedom of association	Respect the right of employees to collective bargaining and to establish or join freely chosen trade union bodies.
Equal treatment	Ensure equal pay and benefits between men and women for work of equal value.
No discrimination	Prohibit any form of discrimination on the grounds of sex, ethnicity, religion, age, disability, sexual orientation, political opinion, union membership, nationality, gender identity or social origin.

Table 3.6: description of the environmental aspects considered in the Code of Conducts.

Environmetal aspect	Descriprion
Emissions monitoring	Monitor greenhouse gas emissions and pollutants, report values periodically.
Energy consumption monitoring	Monitor energy consumption so that actions can be implemented to contain it.
Renewable energy	Prefer to use energy from renewable sources.
Transport	Prefer the use of alternative, less polluting transportation systems.
Responsible use of water	Reduce water consumption and avoid waste.
Waste management	Reduce waste generation and manage it properly.

3.1.3 Brands comparison

After the definition of the four criteria and the analysis performed for the 71 brands included in the study, the last phase of the benchmark consists in comparing the different companies using the evaluation criteria described in *subsection 3.1.2*. The purpose of this paragraph was therefore to provide a description of the methodology introduced.
Table 3.7 shows the four evaluation criteria (supply chain, governance, certifications and shoe ecodesign), and for each of the four criteria five levels of transparency were identified (from 0 to 4). A score from 0 (worst) to 4 (best) for each evaluation criterion was assigned to each company. This evaluation was functional to identify the most widespread good practices.
As reported above, it was stressed that the assessment was the result of the analysis carried out for the 71 companies examined on the basis of the information made public by the companies themselves. Therefore, this evaluation should subsequently be accompanied by a series of detailed interviews with each of them in order to fully characterize in detail the different practices.

Table 3.7: Evaluation criteria to compare brands in the footwear sector

Marks	**Supply chain**	**Governance**	**Certification and management of raw material**	**Shoes ecodesign**
0	No information on the location of shoe production of shoes happen and on the origin of raw materials.	No reference to initiatives and/or projects related to the circular economy. There is no sustainability report or reference to SDG.	No information about certifications. No information on the control of raw materials.	No information about the use of sustainable materials in the production of footwear
1	Information on the continents/-nations of production of the shoe in terms of percentages.	Some references to activities related to sustainability on the website that do not directly concern production. There is no sustainability report (valid for medium/large companies).	Suppliers of selected raw materials but without certification. Presence of a Code of Conduct for suppliers related to the health and safety of workers (valid for luxury/intermediate companies). No evidence on the control over the ban on the use of hazardous raw materials.	No footwear produced from materials of responsible origin.

2	Single manufacturer of shoes or list of shoe manufacturers (Tier 1). No information on the supply of raw materials.	There are activities related to the circular economy that directly concern production. The sustainability report is present but without any reference to SDG or with undefined reference to SDG (valid for luxury/intermediate companies).	Selected suppliers of raw materials, some can be certified. Control over the prohibition of the use of hazardous raw materials. Presence of a Code of Conduct for suppliers related to the health and safety of workers (valid for luxury/intermediate companies).	1 shoe collection based on materials of responsible origin.
3	Single manufacturer of shoes or list of shoe manufacturers (Tier 1). Information on the supply of raw materials (Tier 2).	There are activities related to the circular economy that directly concern production. There are targets for reducing emissions. There is the sustainability report with clear reference to SDG, but targets and qualitative assessments (valid for medium/large companies).	Two out of three of the following conditions must be true: (1) Some raw materials from certified suppliers (2) choice of local suppliers (3) publication of the suppliers' minimum wage. Control over the prohibition of the use of hazardous raw materials. This Code of Conduct for suppliers related to the health and safety of workers (valid for luxury/intermediate companies).	More than a shoe collection based on products of responsible origin
4	Single manufacturer of shoes and short supply chain (i.e. same country of production of the shoe). Or, list of shoe manufacturers (Tier 1) and list of suppliers of raw materials up to Tier 3 / Tier 4.	There are activities related to the circular economy that directly concern production. There are targets for reducing emissions. Sustainability-related activities in partnership with other companies/NGOs/etc. There is the sustainability report with clear reference to SDG including targets and quantitative assessments (valid for medium / large companies).	All raw materials from certified suppliers and/or some certified shoes. Choice of local suppliers and publication of the minimum wage of suppliers. Control over the prohibition of the use of hazardous raw materials. Presence of a Code of Conduct for suppliers related to the health and safety of workers (valid for luxury/intermediate companies).	All models of shoes produced with materials of responsible origin

3.2 LCA METHODOLOGY FOR THE MATERIALS MAPPING

This section describes the LCA methodology that was needed prior the construction of the ecodesign tool. In particular, the LCA was developed for all the materials used for the production of a footwear. The materials were chosen among the most widely used in the footwear industry, obtained from the benchmark analysis described in the previous section (3.1). Firstly, the main footwear components were selected and several materials for each component were identified linking with ecodesign, if applicable (*section 3.2.2*). Secondly, the functional unit, the system boundaries and the LCIA methodology were defined (*section 3.2.3*). Finally, for each material, the LCIs are presented, and thus which production processes are considered, the source of the data, and the main assumptions made.

3.2.1 SHOE COMPONENTS

Shoes usually are made from different materials and many parts [21]. In this study are considered the main ones, such as upper, liners, laces, insole, and outsole. No other material was considered, such as glue, metal parts, and reinforcements, since it was decided it was best to consider the most characteristic components of a shoe and those that are most relevant in its composition, in terms of overall weight [88].

Upper. The upper, which can be considered the shoe's main component, is attached above the sole and covers the top and side of the shoe. There is a large variety of materials that can be used for this component. Traditionally the most used are leather, natural textiles, such as cotton, or synthetic ones like polyester [88]. The upper accessories, such as buckles, eyelets or any reinforcements, were not included.

Liner. This is the material inside the shoe that comes into contact with the entire foot, sides, top and heels, and it is attached to the inside of the upper [88]. The main purpose of the lining is to cover the inside seams of the shoe and lengthen the shoe's lifespan. It can be made from the same materials used for the upper, but in a different shape.

Laces. They close the shoe and tighten it up to fit to the foot. Shoelaces can be made from yarns of different materials, such as cotton, polyester, hemp, etc.

Insole. It is the part touching the bottom of the feet, it might be fixed or removable [88]. The materials that can be used vary from Ethylene-vinyl acetate (EVA), leather and rubber.

Outsole. It is the bottom part of a shoe that touches the ground during use. For this reason, it is the part that wears out the fastest [88]. The main material used for this part is rubber, synthetic or natural. An alternative can be represented by cork.

3.2.2 SELECTED MATERIALS

Table 3.8 shows the materials included in the study, classified according to the type of ecodesign and the type of shoe components in which they are used. The table also shows the section in which the material is described.
According to the types of ecodesign in *Table 3.4*, the following were considered for the footwear application: Design for use of Recycled Material (DfRM), Design for use of Healthy Material (DfHM), Design for Compostability (DfC) and, considering the whole shoe, Design for Reducing Material Variety (DfRMV). The latest one is linked to the variety of materials used, so it depends on how many different materials are selected in the production of the shoe. The other Ecodesigns, on the contrary, are related more to the use phase, like the Design for Maintenance (DfM), or to the disposal, like the Design for Recycling (DfR) and the Design for Disassembly (DfD). Some of the materials can be considered in more than one ecodesign, e.g. natural materials from responsible source can be classified as both DfHM and DfC.
The selected materials are subdivided into three main categories: leather, covering different type of leather production processes, textile, which includes all the materials from which it is possible to make the yarn and then the fabric, and then the materials used specifically used for insoles and outsoles.

Table 3.8: Selected materials related to the relative ecodesigns

Ecodesign	Materials	Type	Section	Upper	Liner	Laces	Insole	Outsole
Conventional materials	Wool	Textile	3.2.4.2	x	x			
	Conventional cotton	Textile	3.2.4.2	x	x	x		
	Nylon	Textile	3.2.4.2	x	x	x		
	Polyester	Textile	3.2.4.2	x	x	x		
	Chrome leather	Leather	3.2.4.1	x	x		x	x
	EVA	Soles	3.2.4.3				x	x
	Rubber	Soles	3.2.4.3				x	x
Design for use of Healthy Material	Hemp	Textile	3.2.4.2	x	x	x		
	Jute	Textile	3.2.4.2	x	x	x		
	Kenaf	Textile	3.2.4.2	x	x	x		
	Organic cotton	Textile	3.2.4.2	x	x	x		
	Viscose	Textile	3.2.4.2	x	x	x		
	Lyocell	Textile	3.2.4.2	x	x	x		
	Certified leather	Leather	3.2.4.1	x	x		x	x
	Vegetable leather	Leather	3.2.4.1	x	x		x	x
	Cork	Soles	3.2.4.3				x	x
Design for use of Recycled Material	Econyl	Textile	3.2.4.2	x	x	x		
	Recycled cotton	Textile	3.2.4.2	x	x	x		
	Recycled polyester	Textile	3.2.4.2	x	x	x		
	Recycled wool	Textile	3.2.4.2	x	x			
	Recycled rubber	Soles	3.2.4.3				x	x

3.2.3 GOAL AND SCOPE DEFINITION

For each material, an LCA study was conducted considering all production processes, from the raw material extraction to the final product ready to be used by footwear component manufacturers. Life Cycle Inventories (LCIs) were constructed using data available in the Ecoinvent database or, alternatively, from LCA studies in the literature. The Ecoinvent is one of the most widely used databases for LCA studies, it contains many reliable LCIs, covering several sectors [113]. In the present work, version 3.6 of the Ecoinvent database was used. It was considered for the location of the processes taken from the database, the generic case to the European level, so, when possible, were chosen providers with the code "RER". This decision was made in order to obtain more general results so that materials could be compared more consistently, as the results can vary greatly depending on the location considered.

The Life Cycle Impact Assessment (LCIA) is computed with the use of Brightway2. Brightway2 is a open source framework for LCA implemented in Python as a library [114].

The system boundary specifies which unit processes are part of the product system under study. For each material, the system boundaries considered comprise all the flows of energy, matters, and resources involved in every stage of the production system, from the raw material extraction to the manufacturing of the finished intermediate product that can be used by shoemakers.

To compare the environmental impact generated by the production of the different materials, every product system needs to be referred to the same functional unit. The functional unit is a quantified performance of a product system for use as a reference unit [49]. At this point of the analysis, the functional unit used to compare the materials is 1 kg of finished material ready to be used by the shoe manufacturers.

3.2.4 LIFE CYCLE INVENTORIES

3.2.4.1 LEATHER

The life cycle stages considered for the leather production are cattle breeding, slaughtering and storage of the hides, and the tanning process. Furthermore, regarding the tanning process, in this work, the following three types of process were considered: the conventional chrome tanning, certified tanning, from LWG certified tannery, and vegetable tanning. The system boundary is reported in *Figure 3.2*.

Leather production processes are not implemented in the database ecoinvent, hence the LCA study is based upon papers available in the literature that provide directly the inventory data [1, 94, 4]. In the following paragraphs are described the life cycle stages considered, the main assumptions, and where the data are taken from for implementing the LCA.

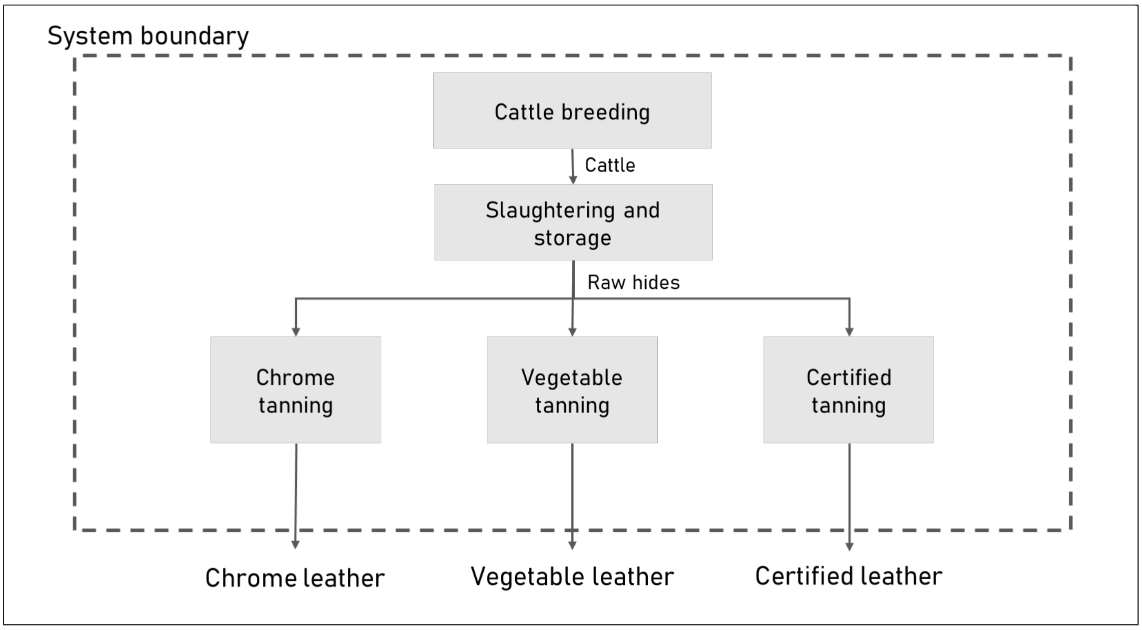


Figure 3.2: Life cycle stages and system boundary of leather production.

CATTLE BREEDING

The data related to this stage were adapted, considering the allocation factor, from the process "*market for cattle for slaughtering, live weight*" of the Ecoinvent 3.6 database. Hides, the raw material of leather, constitutes a by-product of the cattle industry [94, 63]. Some of the other products are meat, milk and manure used as fertilizer. Hence, the problem is how to consider the environmental impact associated with this phase and relate it to the hides, resulting in an allocation problem [63]. According to the ISO 14044 standard, related to the allocation procedure, whenever possible allocation should be avoided [115]. In this particular case, allocation cannot be avoided since data cannot directly be referred to the different products that are integrated in the process. Input and output flows have to be partitioned preferring a physical allocation, referring to how they are changed by quantitative changes in the products. If a physical relationship cannot be established, other allocation methods should be considered, e.g. according to the proportion of the economic value of the co-product [115].
It was found that most of the LCA studies available in the literature do not consider the cattle breeding phase into the system boundary, since they are comparative LCAs of different tanning systems [116] or data from different countries [1]. The only article that could be found in the literature that deals with this allocation problem is the one from *Mila et al., (1998)* [63]. It is useful in order to

fully understand the issue to follow the reasoning carried out by *Mila et al., (1998)*. They started from 2 extreme options: to consider hides to be the only product of the cattle industry and so allocate all of the environmental burdens to leather production, or to consider hides as waste and so free of burdens [63]. This two options can be considered true only in rare cases, like fur production for the first one, or dairy cattle for the second [63]. Since this study considered a more general case, it is necessary to choose an intermediate way. A solution is to consider an economic allocation taking into account the prices of the different products. *Mila et al., (1998)* considered an allocation factor of 7.69%, taken from the Catalan industry [63]. Since the paper is from 1998, this value could be outdated and also specific to the Spanish case, but still, it is not easy to quantify a new one. This value represents a critical aspect of the analysis since choosing a different could strongly affect the results [63]. The importance of this parameter it was evaluated in a sensitivity analysis, by varying the chosen value of +/- 5% (*section 4.12*.

Slaughtering and storage

Similarly to cattle breeding, hides and meat are the main output of the slaughtering process. Hence, allocation between the different product is needed [1, 94]. *Notarnicola et al., (2011)* in their study opted for an economic and mass criteria, selecting as allocation factor 8% for leather and 92% for meat and the other edible parts [1]. *Joseph et al., (2009)* have chosen instead 14% as allocation factor for the hides [94]. In this work, since the data used in the LCI are from *Notarnicola et al., (2011)*, referring to the Italian leather system, it was selected 8% as allocation factor [1]. The hides coming out of the slaughterhouse, need to be preserved and stored. The data used for the storage phase are referred to a system that uses salting as storage process [1]. In *Table 3.9* are reported the input and output flows from ecoinvent 3.6 for the stage of slaughtering and storage.

Table 3.9: LCI for the Slaughtering and storage stages, before economic allocation, from *Notarnicola et al., (2011)* [1]

Slaughtering	**Flow**	**Amount**	**Unit**	**Provider**
Input	cattle	15.532	kg	market for cattle for slaughtering, live weight, for leather production
	tap water	5.862	kg	market group for tap water
	heat	2.274	MJ	market for heat, district or industrial, other than natural gas
	electricity	0.146	kWh	market group for electricity, low voltage
Output	wastewater	5.858	L	market for wastewater, average
	Blood	0.65	kg	
	Manure and digestive tract	1.254	kg	
	Meat	8.058	kg	
	Other edible part	1.976	kg	
	Sick organ from slaughtered cattle	1.475	kg	
Storage	**Flow**	**Amount**	**Unit**	**Provider**
Input	tap water	0.237	kg	market group for tap water
	electricity	0.0155	kWh	market group for electricity, low voltage
Output	municipal solid waste	0.0161	kg	market group for municipal solid waste
	wastewater	0.237	L	market for wastewater, average
	Raw salted hides	1	kg	

Tanning process

Tanning constitutes the core process of leather production [61]. Tanning refers to all of the processes needed to transform raw hides into finished leather with determined properties, like stability in order to prevent degradation, abrasion resistance and elasticity [94, 117]. The final product of the tanning process is finished leather, but there is also an intermediate product: crusts. Hence, as for the previous step, it is needed to select an allocation method [1]. In the following paragraphs are discussed the tanning methods, all the intermediate processes considered and how the LCI was conducted.

Chrome tanning process

Nowadays, chrome tanning is the process most commonly used [118]. In this type of tanning process, the main reactant is chromium, in the form of basic chromium sulfate [117, 118, 1]. Chromium is the most effective agent for tanning leather, however it has some dangerous effects on human health [118].
As for the phases related to the slaughterhouse, for the chrome tanning the LCI refers to *Notarnicola et al., (2011)* [1]. In the aforementioned paper, the other intermediate operations considered, besides tanning itself, are draining, shaving, re-tanning, neutralization, dyeing, fat-liquoring, pressing, drying and trimming. The number of operations implemented in the process can vary depending on the tannery [1, 116].
Concerning the allocation between leather and crusts, it was chosen an economical allocation of 94.5% of the impact to leather, according to *Notarnicola et al., (2011)* [1]. The LCI data of the chrome tanning process is reported in *Table 3.10* before applying the allocation factor.

Table 3.10: LCI for the chrome tanning process, before economic allocation, from *Notarnicola et al., (2011)* [1]

Type	**Flow**	**Amount**	**Unit**	**Provider**
Input	Raw salted hides	5	kg	from storage
	tap water	81.25	kg	market group for tap water
	electricity	1.4745	kWh	market group for electricity, low voltage
	heat	11.566	MJ	market for heat, district or industrial, other than natural gas
	ammonium sulfate	0.083	kg	market for ammonium sulfate, as N
	aniline	0.005	kg	market for aniline
	chromium oxide	0.4915	kg	market for chromium oxide, flakes
	enzymes	0.0115	kg	market for enzymes
	fatty alcohol	0.015	kg	market for fatty alcohol
	formic acid	0.0815	kg	market for formic acid
	methylamine	0.04	kg	market for methylamine
	petroleum wax	0.0005	kg	market for petroleum slack wax
	$NaHCO_3$	0.015	kg	market for sodium bicarbonate
	NaCl	0.233	kg	market for sodium chloride, powder
	NaHS	0.05	kg	market for sodium hydrosulfide
	sodium hydroxide	0.04	kg	market for sodium hydroxide, without water, in 50% solution state
	sodium sulfide	0.1125	kg	market for sodium sulfide
	solvent	0.032	kg	market for solvent, organic
	sulfuric acid	0.0465	kg	market for sulfuric acid
	Vegetable tannin	0.059	kg	from vegetable tannin production
	sodium phosphate	0.0035	kg	market for sodium phosphate
	formic acid	0.0135	kg	market for formic acid
	melamine resin	0.1635	kg	market for melamine formaldehyde resin
	sodium chloroacetate	0.0285	kg	market for sodium chloroacetate
	chemical, inorganic	0.445	kg	chemical production, inorganic
	chemical, organic	0.445	kg	market for chemical, organic
Output	wastewater	79.31	L	market for wastewater, average
	Crust	1.656	kg	
	Chrome leather	1	kg	

CERTIFIED TANNING PROCESS

Certified leather is considered to be the product of an LWG certified tannery. The tanning process considered is the conventional chrome tanning, but the input of energy and water consumption were changed according to the required level by the LWG certification [2]. LWG is a multi-stakeholder group that aims to enhance the environmental performances of the leather supply chain [109]. In order for a tannery to become LWG certified, it must comply to LWG guidelines, where its environmental performances are evaluated [2]. The LWG audit protocol reports the evaluation criteria, what is needed in order to be certified, and the level of certification: bronze, silver, or gold, depending on the score obtained [2]. The protocol evaluates several aspects, at both the organizational level, such as the traceability of the supply chain, and at the production level, evaluating the consumption of energy, the use of water, the greenhouse gases (GHG) emission, and the management of waste, hazardous substances and chemicals [2]. In this work, only the criteria that relate directly to production were considered, so the data used in the case of chrome tanning were adapted by considering the energy and water consumption required by the LWG protocol to become certificated [2]. Regarding the energy consumption, in the LWG protocol, there is no differentiation between heat and electricity, but it is reported only the overall value of consumption [2]. Thus, this value was partitioned between electricity and heat according to the fractions of the chrome tanning process from *Notarnicola et al., (2011)* [1]. In addition, since the water consumption is lower than in the case of chrome tanning, it was assumed that the amount of wastewater should also be lower, and the value is calculated taking into account the chrome tanning's proportion between water consumption and wastewater. In *Table 3.11* is reported the value assumed for the certified tanning, compared with the one of the chrome tanning case.

Table 3.11: Amount of energy, water and wastewater in the certified leather case, compared to the one of conventional chrome leather [2]

Flow	Chrome tanning	LWG certified tanning	Unit
electricity	1.47	0.28	kWh
heat	11.57	2.24	MJ
tap water	81.25	30	kg
wastewater	79.31	29.28	L

VEGETABLE TANNING PROCESS

Vegetable tanning constitutes an alternative to the conventional chrome tanning that allows to avoid the discharge of some dangerous pollutants [118]. In this type of process, chrome is substituted with tannins of natural origin, sourced from different plants [118, 4]. The tannins most commonly used are Mimosa bark, extracted from *Acacia mearnsii*, and Quebracho heartwood, extracted form *Schinopsis balansae* [119, 3]. There are also other sources for vegetable tannins, like chestnut bark [119] and spruce bark [119, 3]. The vegetable tanning process includes a pre-treatment step followed by the actual tanning process. Since ecoinvent does not provide data, the LCI was based according to the following literature:

- Vegetable tannins production: based on the data from *Carlqvist et al., (2020)* [3]
- Pre-treatment: this stage is based on the data provided by *Notarnicola et al., (2011)*, up to the pickling stage [1].
- Vegetable tanning process: based on the data provided by *Baquero et al., (2021)* [4].

This may be a critical aspect of the modeling because different systems were combined. The LCI data for the production of tannins are reported in *Table 3.12*, the data for the pre-treatment are in *Table 3.13* before applying the economic allocation between leather and crusts, and those for the vegetable tanning are reported in *Table 3.14*

Table 3.12: LCI for the production of vegetable tannins from spruce bark, adapted from *Carlquist et al., (2020)* The study is referred to the production of cationized tannins used in wastewater treatment, for the vegetable tanning application it was considered the intermediate product before the cationization phase is applied, reported in the study and referred as *Dry extract* [3]

Type	**Flow**	**Amount**	**Unit**	**Provider**
Input	Diesel	1.39	MJ	market for diesel, burned in agricultural machinery
	Electricity	1.48	kWh	market group for electricity, low voltage
	Ethanol	11.32	kg	ethanol production from wood
	Heat	141.49	MJ	market for heat, district or industrial, other than natural gas
	Heavy fuel oil	0.75	MJ	market for heavy fuel oil, burned in refinery furnace
Output	Polymethyl methacrylate	0.124	kg	market for polymethyl methacrylate, beads
	Tap water	105.66	kg	market group for tap water
	Transport	0.046	t*km	market for transport, freight, lorry >32 metric ton, EURO5
	Wastewater	0.104	m^3	market for wastewater, average
	Vegetable tannins	1	kg	

Table 3.13: LCI for the pre-treatment stage of the vegetable tanning process. The values were adapted from *Notarnicola et al., (2011)*, and they include all the stages up to the pickling phase [1].

Type	**Flow**	**Amount**	**Unit**	**Provider**
Input	Raw salted hides	1.147	kg	from storage
	ammonium sulfate	0.0190	kg	market for ammonium sulfate, as N
	chemical, inorganic	0.0023	kg	chemical production, inorganic
	chemical, organic	0.0576	kg	market for chemical, organic
	electricity	0.0477	kWh	market group for electricity, low voltage
	enzymes	0.0026	kg	market for enzymes
	fatty alcohol	0.0034	kg	market for fatty alcohol
	heat	0.456	MJ	market for heat, district or industrial, other than natural gas
	methylamine	0.0092	kg	market for methylamine
	sodium bicarbonate	0.0034	kg	market for sodium bicarbonate
	sodium chloride	0.0534	kg	market for sodium chloride, powder
	sodium hydrosulfide	0.0115	kg	market for sodium hydrosulfide
	sodium hydroxide	0.0092	kg	market for sodium hydroxide, without water, in 50% solution state
	sodium sulfide	0.0258	kg	market for sodium sulfide
	solvent	0.0073	kg	market for solvent, organic
	sulfuric acid	0.0107	kg	market for sulfuric acid
	tap water	11.906	kg	market group for tap water
Output	wastewater	0.0113	m3	market for wastewater, average
	Pickled leather	0.677	kg	

Table 3.14: LCI for the vegetable tanning process. The values were adapted from *Baquero et al., (2021)* [4]

Type	Flow	Amount	Unit	Provider
Input	Pickled leather	0.677	kg	from pre-reatment
	acetic acid	0.0027	kg	market for acetic acid, without water, in 98% solution state
	Acrylic binder	0.0271	kg	market for acrylic binder, without water, in 34% solution state
	EDTA	0.0027	kg	market for EDTA, ethylenediaminetetraacetic acid
	Electricity	0.4787	MJ	market group for electricity, low voltage
	Formaldehyde	0.0203	kg	market for formaldehyde
	Formic acid	0.0156	kg	market for formic acid
	Heat	0.2707	MJ	market for heat, district or industrial, other than natural gas
	Naphthalene sulfonic acid	0.0847	kg	market for naphthalene sulfonic acid
	Phenolic resin	0.0542	kg	market for phenolic resin
	Polyester-complexed starch biopolymer	0.0271	kg	market for polyester-complexed starch biopolymer
	Sodium formate	0.0034	kg	market for sodium formate
	Sodium tripolyphosphate	0.0054	kg	market for sodium tripolyphosphate
	Tap water	6.3	kg	market group for tap water
	Vegetable oil methyl ester	0.0542	kg	market for vegetable oil methyl ester
	Vegetable tannin	0.2710	kg	from vegetable tannin production
Output	Wastewater	0.0067	m3	market for wastewater, average
	Vegetable tanned leather	1	kg	

3.2.4.2 TEXTILES

Currently, textile materials are the most widely used in the manufacturing of footwear [24]. Textiles are all those materials from which the yarn can be obtained starting with natural or man-made fiber. The processes to produce the finished fabric are different depending on the material considered [95, 6, 5] and on the producer's choices [5]. In order to align the production process of every textile material, it was decided to relate the production to a common process scheme considering four main operations (*Figure 3.3*):

1. Fiber production: the product of this stage is the fiber, that can be distinguished according to its origin. It can be natural, or cultivated, like cotton and hemp, farmed like wool, or synthetic, like polyester and nylon. Thus, this phase is material-specific and is covered in more detail in the sections devoted to each one of them.
2. Yarn production: in order to obtain the yarn, fibers are subjected to the spinning process. The energy consumption of this stage can vary depending on the thickness of the yarn: the thinner the yarn, the higher the energy consumption [95].
3. Bleaching and dyeing: both operations are needed to give to the yarn the desired color.
4. Textile production: weaving and knitting are the two main techniques to create the fabric [95, 6].

The following paragraphs describe the life cycle stages of the textiles considered in the study, the data used and the assumptions made. Firstly, main assumptions are provided for the yarn production, bleaching and dyeing, and textile production. Secondly, detailed description of the modeling of each material is provided. All the data source and the selected process in ecoinvent for the production of the textiles, for each material and production stage, are summarized in *Table 3.15*. In the following paragraphs, the materials are treated individually, highlighting the characteristics of each production stage and how the modeling was built.

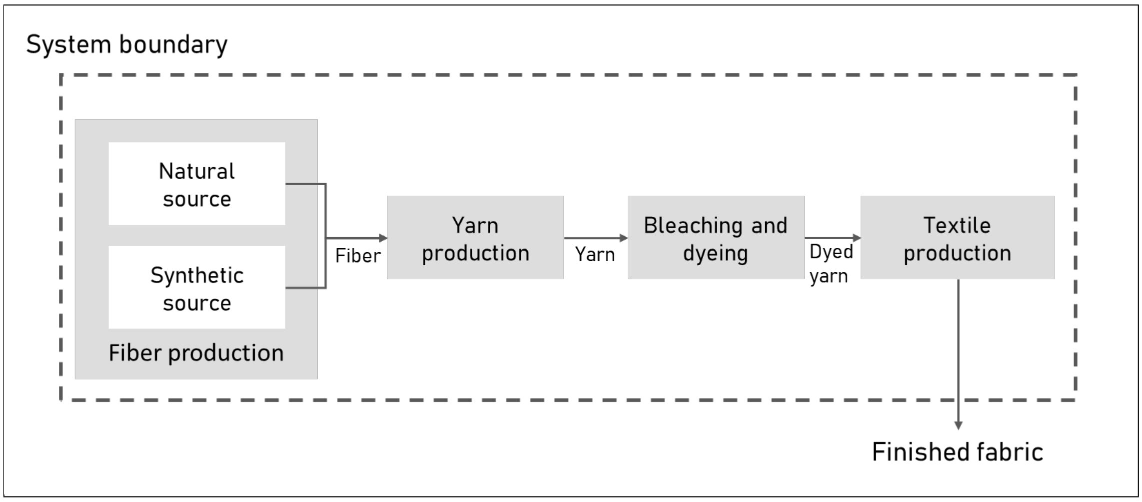


Figure 3.3: Life cycle stages and system boundary of textiles production.

Table 3.15: Data source for the textile materials considered. The E means that the data are from ecoinvent.

Materials	Fibre production	Yarn production	Bleaching and dyeing	Textile production
Conventional cotton	E: market for fibre, cotton	E: yarn production, cotton, open end spinning	E: bleaching and dyeing, yarn	E: textile production, cotton, weaving
Organic cotton	E: market for fibre, cotton, organic	E: yarn production, cotton, open end spinning	E: bleaching and dyeing, yarn	E: textile production, cotton, weaving
Recycled cotton	Liu et al., (2020) [7]	E: yarn production, cotton, open end spinning	-	E: textile production, cotton, weaving
Lyocell	Guo et al., (2021) [8]	E: yarn production, cotton, open end spinning	E: bleaching and dyeing, yarn	E: textile production, cotton, weaving
Viscose	E: market for fibre, viscose	E: yarn production, cotton, open end spinning	E: bleaching and dyeing, yarn	E: textile production, cotton, weaving
Kenaf	E: market for fibre, kenaf	E: yarn production, kenaf	E: bleaching and dyeing, yarn	E: textile production, kenaf
Jute	E: market for fibre, jute	E: yarn production, jute	E: bleaching and dyeing, yarn	E: textile production, jute
Polyester	E: market for fibre, polyester	E: yarn production, cotton, open end spinning	E: bleaching and dyeing, yarn	E: textile production, cotton, weaving
Recycled polyester	recycled polyester fibre production, finished	E: yarn production, cotton, open end spinning	E: bleaching and dyeing, yarn	E: textile production, cotton, weaving

Nylon	E: market for nylon 6-6	E: yarn production, cotton, open end spinning	E: bleaching and dyeing, yarn	E: textile production, cotton, weaving
Hemp	Van Eynde, H. (2015) [5]	Van Eynde, H. (2015) [5]	E: bleaching and dyeing, yarn	Van Eynde, H. (2015) [5]
Wool	E: sheep production, for wool	Cardoso, A. (2013) [6]	Cardoso, A. (2013) [6]	E: textile production, cotton, weaving
Recycled wool	Liu et al., (2020) [7]	E: yarn production, cotton, open end spinning	-	E: textile production, cotton, weaving
Econyl	Econyl EPD, upstream [86]	Econyl EPD, core [86]	E: bleaching and dyeing, yarn	E: textile production, cotton, weaving

YARN PRODUCTION

Yarn production includes all the required operations in order to obtain the yarn starting from the fiber. This phase was modeled using the ecoinvent or literature data, if available. In case of unavailable data in literature for the specific material, the ecoinvent process *"yarn production, cotton, open end spinning"* was used, assuming that it did not change according to the material modeled. Indeed, major differences in this processes are associated to the desired thickness of the yarn [95] and in the fraction of fiber lost in the process [120]. Yarn production of Hemp was modeled starting from input data taken from *Van Eynde, H. (2015)* [5]. The modeling of wool yarn production is based on data provided by *Cardoso A., (2013)* [6]. The thickness of the yarn can be defined through the unit of measure dtex (grams/10 km) [95]. Typical values for footwear application may vary from 467 dtex to 667 dtex [121]. In the selected ecoinvent process the thickness was not reported, but it can be deducted by starting from the value of the consumed energy reported in the process and comparing it to literature values. The amount of energy consumption in the ecoinvent process is 1.65 kWh that, according to *Van der Velden et al., (2014)* [95], corresponds to a thickness of about 573 dtex that is in the range of shoe application. Yarn thickness also varies depending on the shoe component considered. The fiber loss in the selected process is about 15%, which corresponds to a typical value for cotton [120]. This is made to vary by selecting a specific percentage for the different materials considered.

BLEACHING AND DYEING

The bleaching and dyeing phases were modeled with ecoinvent process *"bleaching and dyeing, yarn"*, related to dyeing of cotton yarn. Similarly to yarn production, bleaching and dyeing processes were assumed to be the same for all the textiles considered, except in the case of wool, for which this phase is based on the data from *Cardoso A., (2013)* [6]. The process consists of a pre-treatment, where the yarn is washed and bleached to remove the natural color and any traces of impurities, followed by the actual dyeing.

Textile production

Weaving is the chosen technique for the final step in the textile production. Weaving consists in interlacing two sets of yarns, the warp and the weft, and it does not change with the material considered [120]. Similarly to the previous phases, also for the textile production was assumed, for the majority of the materials, the ecoinvent process *"textile production, cotton, weaving"*. In the selected process it is included the warp sizing step. The warp is processed with a sizing agent, maize starch, in order to protect the warp during the weaving operation [5]. Also, for this phase, the energy consumption varies depending on the considered yarn thickness. In the ecoinvent process, the data are referred to a yarn thickness of 200 dtex. However, by repeating the same procedure made for the yarn production, and considering the same relationship between yarn thickness and energy consumption in *Van der Velden et al., (2014)* [95], the resulting yarn thickness is about 462 dtex. This value results to be slightly lower compared to the correspondent value obtained in the yarn production phase, and close to the minimum value of the footwear application range (467-667 dtex).

Conventional cotton

For conventional cotton, there are several LCA study concerning its cultivation, which analyze specific cases [6, 5, 69, 67]. Since the agricultural practices implemented can vary widely, depending on the area considered in relation to different climatic conditions, in this study the ecoinvent process was considered related to the global average. The process includes cultivation and ginning. Ginning is the process of separating lint from the seed and other plant residues. Ginned cotton is then ready to be spun into yarn [6].

Organic cotton

The production of the organic cotton was modeled using ecoinvent process *"market for fibre, cotton, organic"*, while the subsequent phases are considered to be the same of the conventional cotton case.

HEMP

In literature, there are few papers evaluating the environmental impact of the production of hemp, and the only one providing data is the study from *Van Eynde, H. (2015)* [5]. In the present work, the LCI is based on the data available in the aforementioned paper related to the Chinese production system [5]. The production stages reported in *Van Eynde, H. (2015)* [5] are adapted to the scheme considered in *Figure 3.3* as follows:

1. Fiber production: this phase includes the cultivation of the plant according to the alternative good agricultural practices in *Van Eynde, H. (2015)*, and scutching. The LCI data are reported in *Table 3.16*. Scutching is the process where the fiber is obtained starting from the stem. There are two outputs from the process: scutched hemp fiber, and shivs, considering an economic allocation factor of 52.8% for hemp fiber [5].
2. Yarn production: this phase includes the actual spinning process and the pretreatment constituted by degumming, carding and drawing. The degumming stage is referred to also as cottonization, where the fibers are boiled in an alkaline solution in order to remove all the lignin and pectins [5]. In the carding stage, the degummed fibers are disentangled and arranged in a parallel orientation, dividing the longest fibers, used to create pure hemp yarn, from the shortest ones that are blended with other fibers [5]. An economic allocation is applied between long and short fibers, allocating 25% of the impacts to the long fibers. The aggregated fibers are called slivers. In the drawing stage, different slivers are combined to obtain a new mixed sliver, this reduces the linear density of the sliver and a preliminary twist is applied, the resulting output is called roving [5]. The technology considered for the actual yarn production is ring spun. The roving is spun using a rotating spindle that twists the fiber and creates the yarn. The thickness of the yarn considered in this case is 625 dtex [5]. *Table 3.17* reported the LCI data of the yarn production phase, subdividing the inputs and outputs between the included stages.
3. Bleaching and dyeing: as described in *section 3.2.4.2*, this phase was modeled starting from the ecoinvent process *"bleaching and dyeing, yarn"*.
4. Textile production: this phase includes the warp sizing and the actual weaving process. The operations applied are similar to the ones considered in the ecoinvent process [5]. LCI data are reported in *Table 3.18*.

Table 3.16: LCI for the hemp cultivation and scutching, adapted from the good agricultural practices in *Van Eynde, H. (2015)* [5], before economic allocation between hemp fiber and shivs.

Type	Flow	Amount	Unit	Provider
Input	diesel	1.186364	MJ	diesel, burned in agricultural machinery
	electricity	0.397222	kWh	market group for electricity, low voltage
	metolachlor	0.000977	kg	market for metolachlor
	phosphate rock	0.045455	kg	market for phosphate rock, as P2O5, beneficiated, dry
	potassium fertiliser	0.036364	kg	market for potassium fertiliser, as K2O
	urea	0.040909	kg	market for urea, as N
	Occupation, annual crop	4.545455	sqm*a	Resource in land
Output	Ammonia	0.442186	kg	Emission to air
	Benzene	0.000192	g	Emission to air
	Cadmium	0.001045	g	Emission to soil
	Carbon dioxide, fossil	0.0645	kg	Emission to air
	Carbon dioxide, non-fossil	0.082136	kg	Emission to air
	Chromium	0.027	g	Emission to soil
	Copper	-0.0065	g	Emission to soil
	Dinitrogen monoxide	0.207727	kg	Emission to air
	Lead	-0.00786	g	Emission to soil
	Methane, fossil	0.003395	g	Emission to air
	Metolachlor	0.487727	g	Emission to air
	Metolachlor	0.487727	g	Emission to water
	Nickel	-0.00555	g	Emission to soil
	Nitrate	0.053941	kg	Emission to water
	Nitrogen oxides	0.003626	kg	Emission to air
	NMVOC	0.00048	kg	Emission to air
	PAH	6.59E-05	g	Emission to water
	Particulates	0.045773	g	Emission to air
	Phosphate	0.0004	kg	Emission to water
	Sulfur dioxide	0.026586	g	Emission to air
	Zinc	-0.00464	g	Emission to soil
	Zinc	2.64E-05	g	Emission to air
	biowaste	0.590909	kg	market for biowaste, garden waste
	Hemp shivs	2.5	kg	
	Scutched hemp fibers	1	kg	

Table 3.17: LCI for the hemp yarn production, before economic allocation between long and short fiber in the *Car* stage, adapted from *Van Eynde, H. (2015)* [5]. - Deg = Degumming; - Car = Carding; - Dra = Drawing; - Spi = Spinning.

Type	**Stage**	**Flow**	**Amount**	**Unit**	**Provider**
Input	Deg	Scutched hemp fibres	7.8156	kg	from hemp cultivation and scutching
	Deg	Steam	80.96	MJ	market for heat, from steam, in chemical industry
	Deg	Electricity	7.49	kWh	market group for electricity, low voltage
	Deg	Deionized water	234	kg	market for water, deionised
	Deg	Caustic soda	0.875	kg	market for sodium hydroxide, without water, in 50% solution state
	Deg	Hydrogen peroxide	0.374	kg	market for hydrogen peroxide, without water, in 50% solution state
	Deg	Soda ash	0.257	kg	market for soda ash, dense
	Deg	Penetrant: Polyoxyethylene ether	0.023	kg	chemical inorganic
	Car	Electricity	3.273	kWh	market group for electricity, low voltage
	Dra	Electricity	1.08	kWh	market group for electricity, low voltage
	Spi	Electricity	4	kWh	market group for electricity, low voltage
Output	Deg	Sodium ions	0.503	kg	Emission to water
	Deg	Soda ash	0.257	kg	Emission to water
	Deg	Polyoxyethylene ether	0.023	kg	Emission to water
	Deg	COD environmental emission	0.25	kg	Emission to water
	Car	Fibre waste	0.323	kg	
	Car	Carded degummed short fibres	3.273	kg	
	Spi	Fibre waste	0.08	kg	
	Spi	Hemp yarn	1	kg	

Table 3.18: LCI for the hemp textile production adapted from *Van Eynde, H. (2015)* [5].

Type	**Flow**	**Amount**	**Unit**	**Provider**
Input	Dyed hemp yarn	1.05	kg	from bleaching and dyeing
	Potato starch	0.0456	kg	market for potato starch
	Steam	4.56	kg	market for steam, in chemical industry
	Electricity	5.458889	kWh	market group for electricity, low voltage
Output	COD	0.003648	kg	Emission to water
	Fibre waste	0.05	kg	
	Fabric	1	kg	

KENAF AND JUTE

Kenaf and jute fibers are obtained from plants of the same family, the *Malvaceae*. Like hemp, fibers are obtained from the stem of the plant, and present very similar characteristics [69]. The entire production process of both the textiles are inventoried in the ecoinvent database. The selected processes are reported in *Table 3.15*. The production of both textiles follows the same stages:

1. Fiber production: this phase includes the cultivation of the plant and the retting. Retting consists in the immersion of the plant bundles into water: after several days of immersion, the fiber gets loose from the stalk and is extracted [113].
2. Yarn production: this phase includes softening, carding, drawing, and spinning. The only different phase compared to the hemp process, modeled in the previous paragraph, is the softening phase that is needed to soften and split up the raw fibers. The ecoinvent processes considered were *"yarn production, kenaf"* and *"yarn production, jute*. In these processes, it is not reported the yarn thickness, however, there were not enough available elements to make some assumptions, and the processes are considered as they are.
3. Dyeing and Bleaching: the process was modeled following the description provided in *section 3.2.4.2*.
4. Textile production: the considered processes, *"textile production, kenaf"* and *"textile production, jute"*, are analogous to the hemp one, including warp sizing and weaving.

Wool

The majority of the data at the basis of the LCA study were taken from *Cardoso A., (2013)* [6]. The life cycle stages in the production of wool textiles were adapted according to the scheme considered, and modeled as followed:

1. Fiber production: this phase was modeled according to the ecoinvent process *"sheep production, for wool"*. This process is specific to wool, already taking into account the allocation between wool and meat. The output of this phase is greasy wool.
2. Yarn production: this phase includes scouring and spinning. Scouring consists in washing wool using detergents in order to remove the impurities, the main one being grease. The removed grease is then turned into lanolin that constitutes a by-product of production. After scouring, the wool undergoes other steps, such as carding and combing. The output of this operation is the wool top which is ready to be spun into yarn [6]. Data were taken from *Cardoso (2013)* [6]. This study considered four suppliers, one from China and three from Italy. An average amount was considered in this study [6]. *Table 3.19* shows the LCI data for this phase.
3. Bleaching and dyeing: unlike the other materials, in the case of wool the dyeing process was specified in *Cardoso A., (2013)* [6]. Similar to the previous phase, data are referred to three different suppliers, so also for this operation were considered the average values. The LCI data are reported in *Table 3.20*
4. Textile production: since in *Cardoso A., (2013)* [6] the reference product considered was dyed yarn, for this stage was considered the weaving process of cotton, as described in *section 3.2.4.2*.

Table 3.19: LCI for the wool yarn production, including scouring and spinning stages, before economic allocation between lanolin and wool top in the *scouring* stage, adapted from *Cardoso A., (2013)* [6].

Type	Flow	Amount	Unit	Provider
Input	Sheep fleece in the grease	1.18	kg	sheep production, for wool
	Chemical, organic	1.03E-01	kg	market for chemical, organic
	Corrugated board box	8.27E-02	kg	market for corrugated board box
	Electricity	4.717	kWh	market group for electricity, low voltage
	Heat	25.0	MJ	market group for heat, district or industrial, natural gas
	Lubricating oil	3.04E-02	kg	market for lubricating oil
	Paraffin	8.42E-03	kg	market for paraffin
	Polyethylene	1.20E-01	kg	market for polyethylene, high density, granulate
	Polyethylene terephthalate	9.74E-03	kg	market for polyethylene terephthalate, granulate, amorphous
	Polypropylene	4.17E-02	kg	market for polypropylene, granulate
	Steel	7.41E-03	kg	market for steel, low-alloyed
	Transport, lorry	0.717	t*km	market group for transport, freight, lorry, unspecified
	Transport, sea	28.9	t*km	market for transport, freight, sea, container ship
	Water	5.41E-02	m3	Resource in water
Output	Ammonium	4.86E-03	kg	Emission to water
	BOD5	8.97E-03	kg	Emission to water
	Chloride	3.80E-02	kg	Emission to water
	COD	3.09E-02	kg	Emission to water
	Nitrite	2.67E-05	kg	Emission to water
	Nitrate	4.00E-04	kg	Emission to water
	Nitrogen, organic bound	3.28E-04	kg	Emission to water
	Suspended solids	1.06E-04	kg	Emission to water
	Phosphorus	7.18E-05	kg	Emission to water
	Municipal solid waste	0.0215	kg	market group for municipal solid waste
	Wastewater	0.0487	m3	market for wastewater, average
	Wool yarn	1	kg	

Table 3.20: LCI for the dyeing of wool yarn, adapted from *Cardoso A., (2013)* [6].

Type	Flow	Amount	Unit	Provider
Input	Wool yarn	1.025	kg	from wool yarn production
	Electricity	1.634	kWh	market group for electricity, low voltage
	Water	0.244	m3	Resource in water
	Ttransport, sea	8.47	t*km	market for transport, freight, sea, container ship
	Transport, lorry	0.109	t*km	market group for transport, freight, lorry, unspecified
	Heat	24.29	MJ	market group for heat, district or industrial, natural gas
	Corrugated board box	3.11E-02	kg	market for corrugated board box
	Polyethylene terephthalate	1.12E-02	kg	market for polyethylene terephthalate, granulate, amorphous
	Polyethylene	2.77E-03	kg	market for polyethylene, high density, granulate
	Polypropylene	6.26E-03	kg	market for polypropylene, granulate
	Steel	8.76E-03	kg	market for steel, low-alloyed
	Kraft paper	3.68E-04	kg	market for kraft paper, bleached
	Chemical, organic	4.17E-02	kg	market for chemical, organic
	Chemical, inorganic	2.72E-02	kg	market for chemicals, inorganic
Output	Ammonium, ion	1.23E-04	kg	Emission to water
	BOD5	7.26E-05	kg	Emission to water
	Chloride	4.88E-04	kg	Emission to water
	Chromium, ion	2.90E-07	kg	Emission to water
	COD	2.18E-04	kg	Emission to water
	Copper, ion	1.45E-07	kg	Emission to water
	Iron, ion	7.12E-06	kg	Emission to water
	Lead	1.45E-07	kg	Emission to water
	Mercury	1.45E-08	kg	Emission to water
	Nickel, ion	1.45E-07	kg	Emission to water
	Nitrate	3.33E-03	kg	Emission to water
	Phosphorus	2.71E-03	kg	Emission to water
	Sulfate	2.90E-06	kg	Emission to water
	Zinc, ion	7.26E-07	kg	Emission to water
	Wastewater, average	0.2407	m3	market for wastewater, average
	Municipal solid waste	0.0365	kg	market group for municipal solid waste
	Dyed wool yarn	1	kg	

RECYCLED COTTON AND WOOL

The recycling process constitutes the fiber production stage in the scheme considered (*Figure 3.3*). The output of the recycled process is the recycled fiber. For both cotton and wool, the same recycling process was assumed. The recycling process consists of the following stages:

1. Waste collection: it is assumed that the collection of clothing waste is made by truck, considering an average distance of 100 km [7].
2. Separation: the waste is divided according to color, in this way the dyeing process can be avoided [67, 7].
3. Washing: the fabric waste, before being broken, is first washed and then dried [7].
4. Breaking: the fabric is broken using some chemicals, the resulting output is the recycled fiber [7].

The LCI data concerning the recycling of the fibers are reported in *Table 3.21*. The subsequent phases, i.e., yarn production and textile production, are conducted according to the respective material. For bleaching and dyeing, it is not needed [67, 7].

Table 3.21: LCI for the recycling of post-consume textile waste, adapted from *Liu et al., (2020)* [7].

Type	Flow	Amount	Unit	Provider
Input	electricity	0.135345	kWh	market group for electricity, low voltage
	tap water	1.2E-05	kg	market group for tap water
	cleaning consumables	0.005172	kg	market for cleaning consumables, without water, in 13.6% solution state
	sulfuric acid	0.004397	kg	market for sulfuric acid
	iron sulfate	0.005172	kg	market for iron sulfate
	polyaluminium chloride	0.001112	kg	market for polyaluminium chloride
	polyacrylamide	6.9E-05	kg	market for polyacrylamide
	sodium hypochlorite	0.009052	kg	market for sodium hypochlorite, without water, in 15% solution state
	urea	3.45E-05	kg	market for urea, as N
	sodium hydroxide	8.62E-05	kg	market for sodium hydroxide, without water, in 50% solution state
	hydrochloric acid	0.000284	kg	market for hydrochloric acid, without water, in 30% solution state
	sodium hydrogen sulfite	4.83E-05	kg	market for sodium hydrogen sulfite
	transport	0.125	t*km	market group for transport, freight, lorry, unspecified
Output	COD	0.001445	kg	Emission to water
	Ammonium	1.24E-05	kg	Emission to water
	Phosphorus	1.18E-05	kg	Emission to water
	Aniline	6.47E-06	kg	Emission to water
	Suspended solids	0.000249	kg	Emission to water
	BOD5	0.000249	kg	Emission to water
	Chlorine	8.97E-07	kg	Emission to water
	AOX	1.69E-06	kg	Emission to water
	Chromium VI	9.48E-08	kg	Emission to water
	Nitrogen	5.48E-05	kg	Emission to water
	Sulfide	9.91E-07	kg	Emission to water
	Antimony	8.62E-09	kg	Emission to water
	Recycle fiber	1	kg	

Lyocell and viscose

Lyocell and viscose are both obtained from wood pulp, but are distinguished by the different method used for dissolving the pulp [8]. Viscose is produced through a conventional manufacturing process [122], involving several chemical operations [8]. For the viscose production, it was considered the available process in ecoinvent starting from sulfate pulp, obtained from sustainable forest management. Lyocell is the first of a new generation of cellulosic fibers produced in a more responsible way [123, 124]. For lyocell, the LCA study is based on the data provided by *Guo et al., (2021)* [8]. In the Lyocell fiber production, wood pulp is dissolved with a solution of *N-methylmorpholine-N-oxide (NMMO)*, an organic compound of the family of the amine oxide [8, 123, 124, 125]. NMMO is a replacement of the carbon disulfide (CS_2) used in the traditional viscose production [125]. The fiber is directly obtained from the NMMO solution without the need of any other treatments [8, 124]. Furthermore, water and the NMMO solution are recycled within the process, where the NMMO recovery rate is greater than 99% [124, 126].

The lyocell production process requires fewer operations compared to the conventional viscose process [124, 125].

Theoretically, in lyocell production, there are a great variety of materials that can be used as raw material other than wood pulp, like paper grade pulp, cotton, and even waste paper [124]. However, the same raw material of viscose was considered for lyocell too, i.e. sulfate pulp. The environmental impact considering other types of input can be evaluated in future studies. Regarding NMMO in ecoinvent, its production is not inventoried, so as an approximation it was considered the generic *amine oxide*. All the input and output flows are reported in Table 3.22. As for the subsequent phases, the same process of the cotton case were considered. Also, the fraction of fiber loss during the yarn production was assumed as the same value of cotton, since no specific value was found in the literature for these materials.

Table 3.22: LCI for lyocell fiber production, adapted from *Guo et al., (2021)* [8].

Type	**Flow**	**Amount**	**Unit**	**Provider**
Input	Amine oxide	0.04	kg	market for amine oxide
	Electricity	1.8	kWh	market group for electricity, low voltage
	formaldehyde	0.003	kg	market for formaldehyde
	Hydrochloric acid	0.15	kg	market for hydrochloric acid, without water, in 30% solution state
	Lubricating oil	0.003	kg	lubricating oil production
	Sodium hydroxide	0.2	kg	market for sodium hydroxide, without water, in 50% solution state
	Steam	0.01	kg	market for steam, in chemical industry
	Water, softened	0.01025	kg	market for water, completely softened
Output	Wastewater, average	0.0200	m3	market for wastewater, average
	Municipal solid waste	0.3000	kg	market group for municipal solid waste
	Lyocell fiber	1	kg	

Polyester

Polyester is one of the synthetic fibers considered in this work and, among them, it is the most consumed for textile manufacturing [120]. For the fiber production stage, it was considered the ecoinvent process *"market for fibre, polyester"* related to global average production. The input considered in the production of polyester fiber is polyethylene terephthalate (PET) in the granulate form. PET is obtained from hydrocarbons, a non-renewable source [34] Concerning the yarn production phase, it was considered the same process of cotton, but the fraction of fiber loss was changed to 4% according to *Moazzem et al., (2018)* [120]. For bleaching and dyeing, and textile production were considered the same processes of cotton.

Recycled polyester

For recycled polyester can be theoretically considered the same production phases of recycled cotton and wool. But, in this case, in order to differentiate the analysis, it was decided to consider, instead of post-consumer textile waste, recycled raw material for manufacturing the polyester fiber. Hence, for the production of recycled polyester were simply taken the same process used for the production of virgin polyester, substituting the virgin polyethylene terephthalate with the recycled one (rPET). In particular, the flow *"polyethylene terephthalate, granulate, bottle grade, recycled"* was considered, related to the production of PET from recycled PET bottles. The subsequent stages, i.e. yarn production, bleaching and dyeing, and textile production, were modeled similarly to polyester.

Nylon

Nylon is another synthetic fiber considered, which is made from non-renewable resources, i.e. polyamide [19]. Nylon is usually manufactured in fibers that can be spun and then weaved into fabrics. It has high resistance to wear, heat, and chemicals. The production can vary according to the form of the product, which can be fibers, filaments, bristles, or sheets [127]. For the fiber production phase, it was considered the process of production from ecoinvent concerning the manufacturing of nylon 6-6. From the process description reported in ecoinvent it was not clear which was the form of the output, so it was assumed to be in the fiber form. In this way the subsequent phases follow the same reasoning made for polyester, assuming the same fraction of fiber loss since they are both synthetic fiber, and were not found any specific values for nylon.

ECONYL

This material was modeled directly from the environmental impact results provided in the 2020 Environmental Product Declaration (EPD) of Aquafil S.p.A referred to the econyl yarn [86]. In this thesis ReCiPe was considered as the impact assessment method to compute the results. The description of the method is reported in *paragraph 3.2.5* at the end of the section. Since the impacts reported in the EPD were computed with another impact assessment method, CML2001, they must be converted into ReCiPe impact categories, according to the relative units. The ALOP category was not computed in the EPD, since it is not relevant for this material. The conversion factor between the two impact assessment models is reported in Table 3.23.

According to the usual scheme considered for textiles (*Figure 3.3*), the upstream phase reported in the EPD corresponds to the fiber production phase, while the core phase was considered for the yarn production phase. The downstream phase was not included because it was out of the scope of this study. Regarding the last two phases, the same processes selected for nylon and polyester were considered.

Table 3.23: Conversion between CML 2001 and ReCiPe impact categories for the production of Econyl

CML 2001	**ReCiPe**	**Conversion factor [ReCiPe/CML2001]**
GWP total	GWP100	1
Abiotic Depletion Potential - fossil fuel	FDP	0.0236 [128]
Abiotic Depletion Potential - elements	MDP	0.46
Acidification Potentials	TAP100	1
Photochemical Ozone Creation P.	POFP	1.69
Eutrophication Potentials	FEP	0.326
Water scarcity potential	WDP	1

3.2.4.3 OUTSOLES AND INSOLES MATERIALS

This section describes the modeling of the materials used for the production of insoles and outsoles. The materials taken into account for these shoe components are EVA, rubber, recycled rubber, and cork. Leather can also be used for these components, the modeling of this material was treated in *paragraph 3.2.4.1*. For the soles material the production systems are divided into two main phases: raw material production and soles production (*Figure 3.4*).

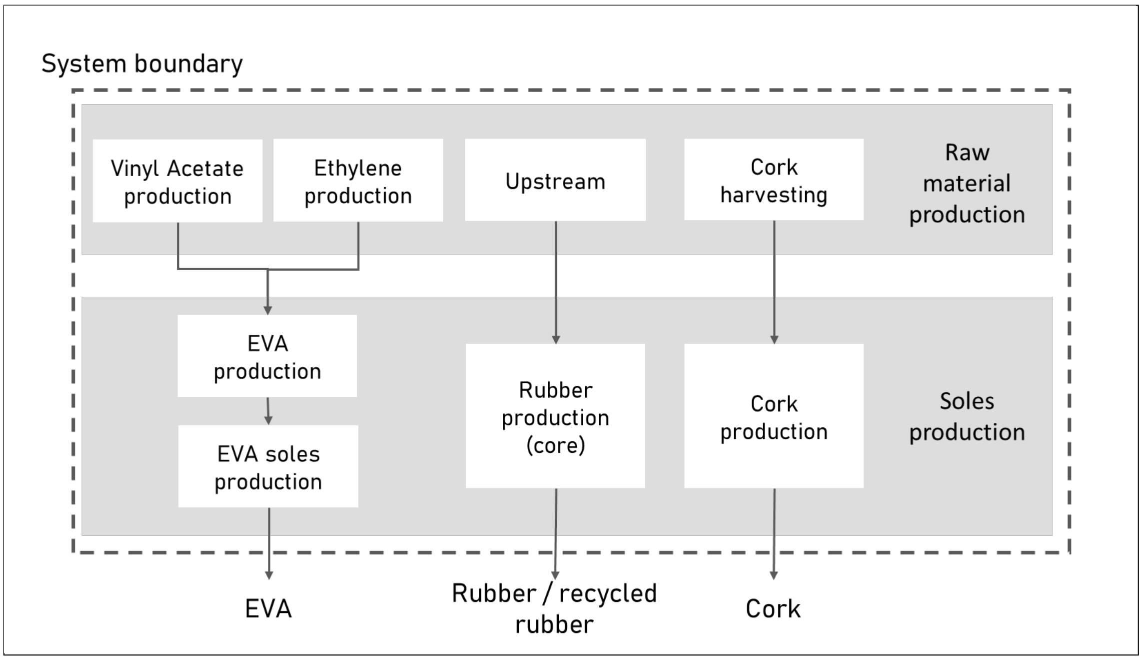


Figure 3.4: Life cycle stages and system boundary of the materials used for the insoles and outsoles.

RUBBER AND RECYCLED RUBBER

The rubber sole considered in this study is based on the EPD from Vibram S.p.A related to the TRONT Fourà model [129]. This model is made of synthetic rubber (72.4%), natural rubber (5.7%), and other chemical compounds [129]. The life cycle stages reported in the scheme in *Figure 3.4* are referred to the EPD considering for the raw material production the upstream stage of the EPD, while the soles production stage is represented by the core stage of the EPD. As for the econyl case, the impacts in the EPD were computed with EPD method so they had to be converted to the ReCiPe units.

Recycled rubber is referred to as the rubber just introduced with the assumption of a 30% of recycled content. The recycled fraction came from reused scrap materials in the manufacturing process. Thus, impacts are simply reduced by a factor of 30% compared to traditional rubber.

EVA

EVA stands for Ethylene Vinyl Acetate and it is one of the most common materials used for the insole of the shoe. It is a copolymer obtained from the two polymers Ethylene and Vinyl acetate [34]. The LCI of EVA is based on the process available in ecoinvent named *"ethylene vinyl acetate copolymer production"*. This process constitutes the preliminary phase of soles production. For the actual production of the sole was assumed the core stage of the rubber sole production from Vibram's EPD. These two processes combined constitute the soles production stage reported in *Figure 3.4*. The raw material production phase is constituted by the production of ethylene and the one of vinyl acetate, represented to the ecoinvent processes *"market for ethylene, average"* and *"market for vinyl acetate"*, respectively.

CORK

The life cycle stages considered for the production of cork in accordance with the usual scheme (*Figure 3.4*) are:

1. Cork harvesting: corresponding to the raw material production phase, this stage is represented by the ecoinvent process *"cork forestry"*, including manual harvesting with a period of 9 years, the transport of the workers to the forests, and the transport of raw cork.
2. Cork production: correspond to the soles production stage, since there were not any datasets in ecoinvent specific to the production of cork soles, it was decided to consider the process *"cork slab production"*. However, this assumption is an approximation of the model, since it is referred to cork slab used as insulator material.

3.2.5 IMPACT ASSESSMENT METHOD AND IMPACT CATEGORIES

To compute the environmental impact, first it is necessary to select the impact assessment method [115]. The impact category represents the major environmental issues of concern specific to the subject of the study [115]. The selected impact assessment method is ReCiPe Midpoint (H) V1.13 no LT. Midpoint means that the method computes the impact at the point after which the environmental mechanism is identical for all environmental flows assigned to that impact category [130]. The H in the method name stands for hierarchist and it is one of three possibilities to consider future cultural perspective. The hierarchist option consider the medium time frame, and it is the most widely used, the other alternatives are the individualist (I), which considers the short term interests, characterized with technological optimism regarding human adaptation, and egalitarian (E), which takes into account the longest time frame, being the most precautionary perspective [130]. The ReCiPe method comprehends 18 impact indicators. The most relevant categories for the purposes of this thesis were selected in accordance with the product categories rules (PCR) for leather [131] and textiles materials [132], and from the general guidelines for the EPD [133]. From the PCR guidelines the recommended impact categories are [130]:

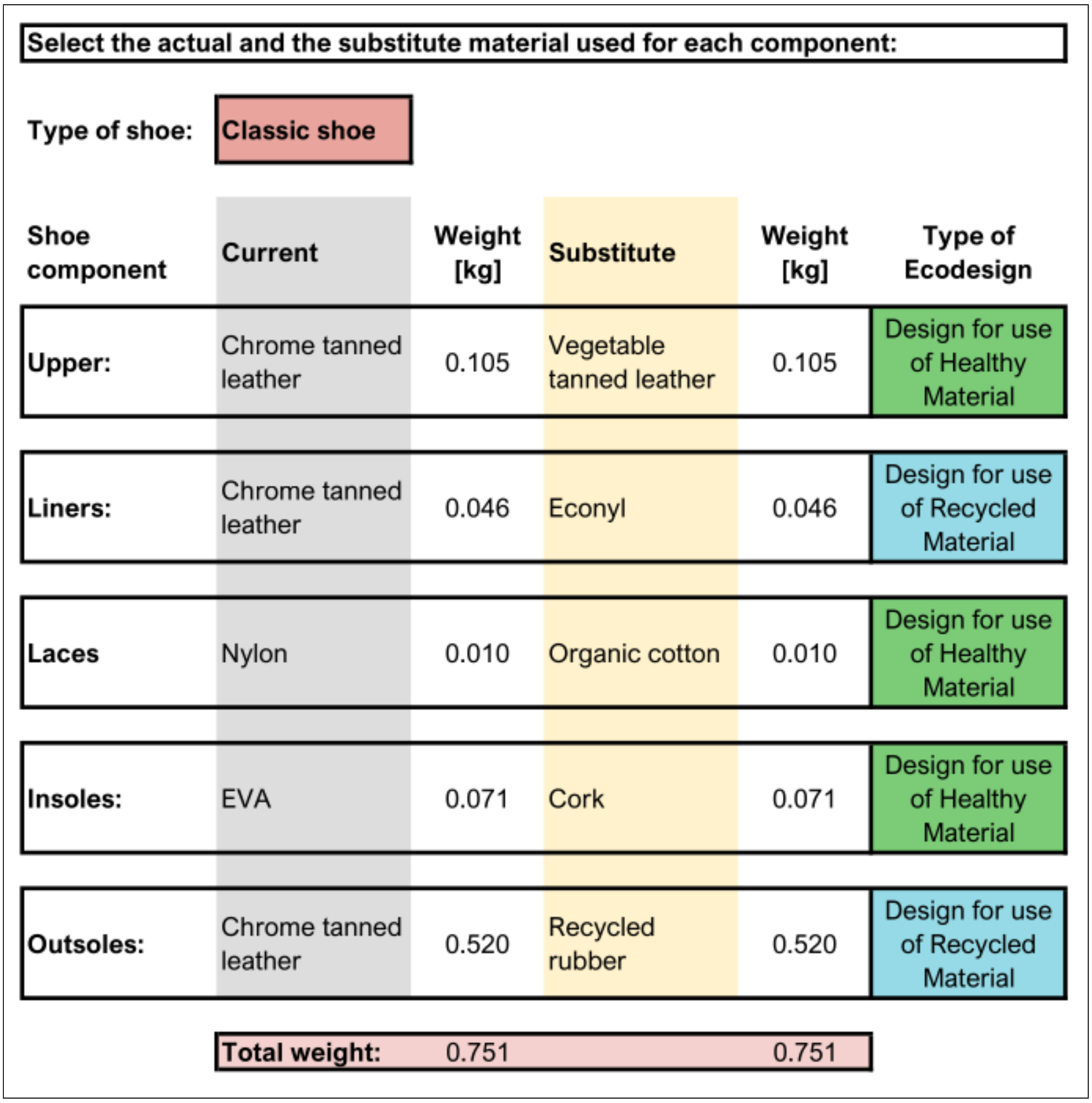
- Global Warming Potential (GWP): evaluates the contribution to climate change, assessing the emissions of greenhouse gases (GHGs). The time horizon considered in the hierarchist perspective is 100 years. It is measured in kilograms of CO_{2eq}.
- Fossil Depletion Potential (FDP): evaluates the exploitation of fossil resources in terms of kilograms of oil equivalent. The characterization factor of a fossil source is computed as the ratio between the energy content of the fossil source and the one of crude oil, used as reference.
- Freshwater Eutrophication Potential (FEP): evaluates the potential contribution to eutrophication, measured as kilograms of phosphorous equivalent. This phenomenon is mainly caused by the discharge of nutrients into the soil or into freshwater bodies rising the levels of nutrients, i.e. phosphorus and nitrogen, linked to the use of fertilizers in agriculture. The increase in nutrients determines the fast growth of algae and cyanobacteria, using more and more oxygen and blocking sunlight. At a certain point plants begin to die becoming food for microbes, and thus increasing the competition for oxygen, till the water becomes deoxygenated.
- Metal Depletion Potential (MDP): evaluates the exploitation of abiotic resources. It is measured in kilograms of iron equivalent.
- Photochemical Oxidant Formation Potential (POFP): evaluates the potential ozone formation in the troposphere. Ozone is not directly emitted but is

formed as a result of a reaction between NOx and Non-Methane Volatile Organic Compounds (NMVOCs). Ozone can have a negative impact on human health, causing respiratory problems. This impact is measured in kilograms of $NMVOC_{eq}$.

- Terrestrial Acidification Potential (TAP): evaluates the potential impacts on the acidity of the soil. For plant species is defined an optimum in the acidity level, changing this value can lead to a shift in species occurrence. Them main contributors are NOx, NH_3, or SO_2. The unit of measure considered is kilograms of SO_{2eq}.
- Water Depletion Potential (WDP): evaluates the water consumption of the product system under study. It is measured in cubic meters of water.
- Agricultural Land Occupation Potential (ALOP): evaluates the potential impact on land use occupation. This impact category is not recommended by the PCRs, but it was included since it can be particularly relevant for all the materials derived from agricultural practices, like cotton, wool, and leather. The unit of measure is square meter per year, considering annual cropland.

3.3 ECOSHOE TOOL METHODOLOGY

This section aims to present the Ecoshoe tool, its main goals, and how it works. Subsequently, some scenarios related to the models of the shoe and the materials composition are introduced, as application examples of the tool's operation.
The main goal of the Ecoshoe tool is to support a company or a footwear manufacturer in designing their shoes in a more sustainable way. The idea behind the tool is that the user can evaluate the potential environmental impacts reduction, coming from the replacement of a traditional material used in a shoe component with an alternative one. The tool is based on the LCIAs results of the materials considered, described in the previous section (3.2). The user interface of the ecoshoe tool is shown in *Figure 3.5*. Firstly, the user, the shoe manufacturer, or the designer, chooses the *Type of shoe*. Secondly, the user needs to insert the details of the current shoe, in terms of material composition and weight. Finally, the user selects the alternative materials for each shoe component in two ways. On one hand, the user can select the desired ecodesign and accordingly select the alternative materials that satisfy the requirements. On the other hand, the user can choose the alternative materials with subsequent identification of the related *Type of ecodesign*. The user can select alternative materials to substitute one or more shoe components. Ideally, the weights of the substituted materials are automatically updated from the current ones, according to the different weight densities. The tool also provides the user with the ecodesign corresponding to the specific substitute material selected.
The interface is then linked to an interactive visualization of the results, implemented in *Microsoft Power BI* [134]. The visualization combines as input the shoe composition selected for the current and substitute case in the Ecoshoe interface, and the LCIA results of the materials computed with brightway2. Through Power BI the user can directly compare the scenarios, considering both the whole shoe and the single components.



Select the actual and the substitute material used for each component:

Type of shoe: Classic shoe

Shoe component	Current	Weight [kg]	Substitute	Weight [kg]	Type of Ecodesign
Upper:	Chrome tanned leather	0.105	Vegetable tanned leather	0.105	Design for use of Healthy Material
Liners:	Chrome tanned leather	0.046	Econyl	0.046	Design for use of Recycled Material
Laces	Nylon	0.010	Organic cotton	0.010	Design for use of Healthy Material
Insoles:	EVA	0.071	Cork	0.071	Design for use of Healthy Material
Outsoles:	Chrome tanned leather	0.520	Recycled rubber	0.520	Design for use of Recycled Material
	Total weight:	0.751		0.751	

Figure 3.5: Ecoshoe user interface.

3.3.1 SCENARIOS

The scenarios considered are an example of tool application. The shoe models considered are:

- Classic shoe: a typical classic male shoe, usually made with leather.
- Casual shoe: usually made with textile materials for the upper and liner, and with rubber soles.

In order to effectively compare the different scenarios, the selection of the materials composition must also take into consideration other aspects, such as the average lifetime of a shoe. This aspect could change according to the materials used [34]. For this reason, materials whit similar characteristics were considered in selecting the scenarios composition.

At the current stage of the tool development, the weights of the shoe components considered do not take into account the different weight densities of the materials. This simplification was made since there is not enough information in the literature regarding the weight of components linked to the specific material; this information should be included in future developments of the tool.

Classic shoe

The classic shoe model composition refers to an actual model from the company *Camminaleggero*. The data related to the composition of the shoe model were provided by the *"Laboratorio calzaturiero sperimentale per la produzione di calzature su misura, STIIMA CNR"*. For this model were considered two scenarios: a traditional one, and an alternative one considering healthy materials. The scenarios' specifications are:

- Traditional scenario: it was considered to be made with conventional chrome leather for the upper, liner, insole, and outsole, and with conventional cotton laces.
- Substitution scenario: named DfHM according to the ecodisign reported in *Table 3.4*, which was considered to be made with healthy materials, that is with vegetable leather instead of chrome leather, and with laces made of organic cotton.

The scenarios are summarized in *Table 3.24*, reporting, for each shoe component, the selected materials and the relative weights.

Table 3.24: Scenarios definition and components weights for the classic shoe model. Values taken from the data sheet of the model *"Urban derby"* from *"Camminaleggero"* [9]

Shoe component	**Traditional**	**DfHM**	**Weight [kg]**
Upper	Chrome leather	Vegetable leather	0.092
Liner	Chrome leather	Vegetable leather	0.052
Laces	Conventional cotton	Organic cotton	0.003
Insole	Chrome leather	Vegetable leather	0.048
Outsole	Chrome leather	Vegetable leather	0.52

Casual shoe

Regarding the casual model, due to lack of information in the LCA studies available in the literature, the weight of shoe components was retrieved from the EPD of the *"Bellamont plus"* model from Aku [10]. This EPD provided the weight for every shoe component. However, since the footwear model is an outdoor shoe, to consider a realistic composition for the casual case, the component weights of

Aku's shoe were broken down according to the typical weight of a casual model available on the market. From the EPD was obtained that the shoe components Since for this shoe model there were more materials available, three scenarios were considered: a traditional one and two alternative scenarios made with healthy materials and recycled materials,

- Traditional scenario: polyester for the upper, liner, and laces, EVA for the insole and rubber for the outsole.
- DfHM: the healthy materials scenario was considered to be made of kenaf for the upper and liner, laces made of jute, and cork for the insole and outsole.
- DfRM: the recycled materials considered in the composition of the shoe are econyl for the upper, recycled wool for the liner, recycled polyester for the laces, and the insole and outsole made of recycled rubber.

The scenarios are summarized in *Table 3.25*, reporting the selected materials for each component and the relative weights.

Table 3.25: Scenarios definition and components weights for the casual model. The shoe component weights were adapted to the casual case from the EPD of Aku [10].

Shoe component	**Traditional**	**DfHM**	**DfRM**	**Weight [kg]**
Upper	Polyester	Kenaf	Econyl	0.105
Liner	Polyester	Kenaf	Recycled wool	0.046
Laces	Polyester	Jute	Recycled polyester	0.017
Insole	EVA	Cork	Recycled rubber	0.071
Outsole	Rubber	Cork	Recycled rubber	0.190

RESULTS

4

This chapter aims to present the main results obtained. It is divided into three main sections, following the scheme of *chapter 3*. *Section 4.1* reported the main outcomes from the benchmark analysis of the 71 brands of the footwear industry, showing the differences between the three categories considered for all the four evaluation criteria. *Section 4.2* reported the LCIA results for the materials considered, evaluating the different impacts among the three material categories (leather, textiles, and soles). Finally, *section 4.3* covered the outcome of the Ecoshoe tool application, comparing the different scenarios.

4.1 BENCHMARK RESULTS

As previously mentioned, this section shows the results coming from the benchmark of the footwear industry, in accordance with the methods described in the *section 3.1.2*. For the detailed evaluation of each brand, please refer to the *appendix A*.

4.1.1 SUPPLY CHAIN

This section describes the results of the supply chain analysis for the 71 companies. In particular, it shows the level of transparency in communication to the public regarding the tracking of raw materials and the production of footwear itself.

Figure 4.1 shows the comparison between the Luxury and Intermediate Range categories. There are companies that do not report information regarding the supply of raw materials and they are the 14% of Luxury companies and 8% of Intermediate Range companies.

A second class of companies reports detailed information both on production sites (tier 1) and on the supply of raw materials (tier 2 and above), concerning 54% of companies in the intermediate range. Finally, around 64% of Luxury companies provide general information on countries of production, without giving evidence of production sites.

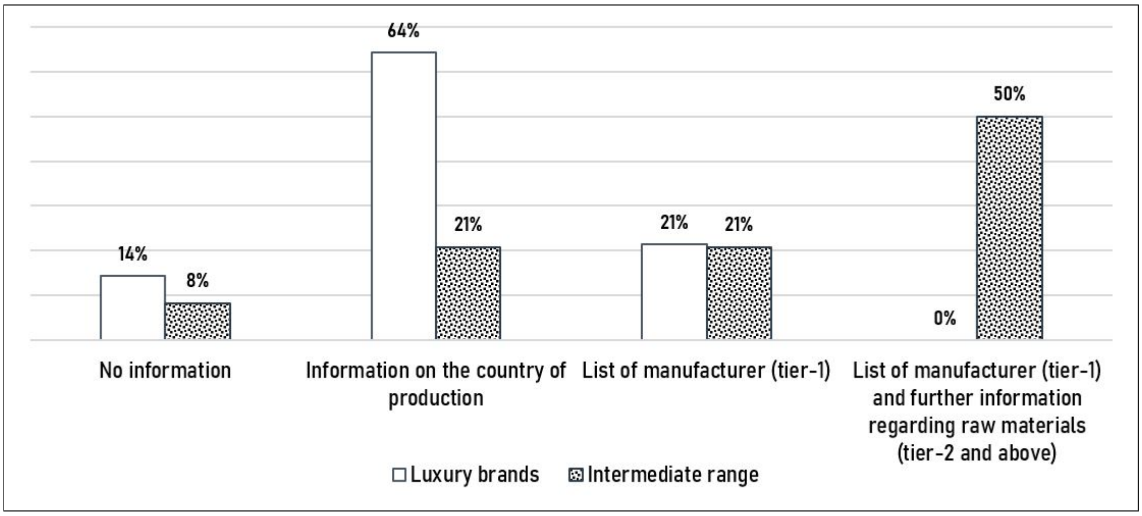


Figure 4.1: Supply chain analysis. Comparison between the statements of Luxury and Intermediate range companies in terms of footwear production and raw material supply in 2021.

Figure 4.2 shows the results for companies that are part of the Green Fashion category. For the latter, as described in *section 3.1.2*, a slightly different treatment has been made with respect to the other two categories described above. These companies, generally of small/medium size, which they claim to produce and sell a sustainable product, pay more attention to the type of raw material and especially to the origin of the raw material. In fact, these companies very often have few and/or localized producers, and therefore an evaluation such as the one carried out for the Luxury and Intermediate Range categories was ineffective and irrelevant.
based on desktop benchmark, 47% of the brands in this category have localized production and a supply of raw materials that comes from the same country in which the footwear is produced. However, 7% provide no information at all (*Figure 4.2*).

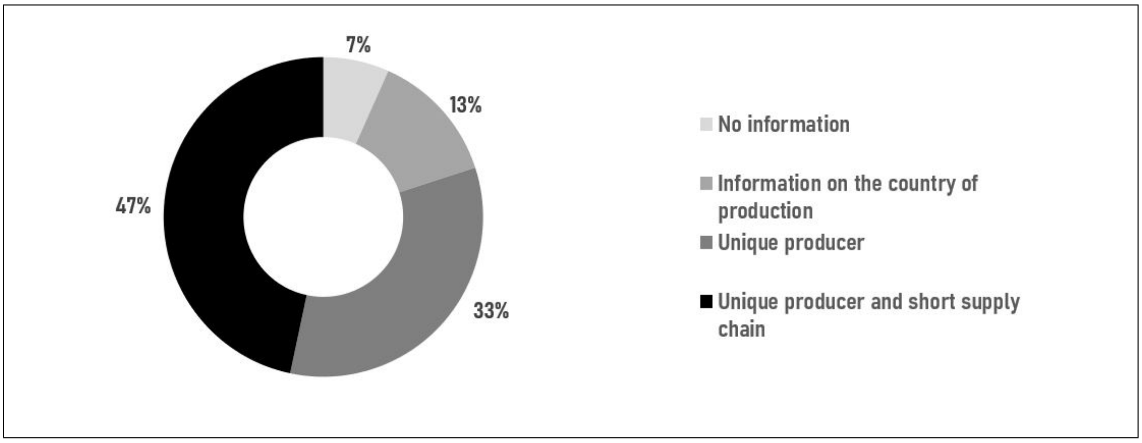


Figure 4.2: Supply Chain Analysis. Transparency analysis of 2021 declarations regarding traceability of raw materials and footwear production for companies in the green fashion category.

4.1.2 GOVERNANCE

This section describes the results of the governance analysis for the 71 companies. In particular, it shows the level of communication to the public regarding activities in the field of sustainability, actions aimed at reducing emissions, monitoring the main drivers of sustainability, etc.

Figure 4.3 shows the comparison between Luxury companies and Intermediate range companies. It can be seen that 61% of Luxury companies does not prepare, and therefore do not publish, any sustainability report, but only indicates some activities/actions in the area of sustainability, while 11% does not provide any type of information on their website. Moreover, among the Luxury companies that present a report, in half of the cases there are references to the SDGs, even if they are of qualitative type, i.e. they report generic objectives without quantifying them and setting a target to be reached.

On the other hand, 43% of Intermediate range companies have a sustainability report containing quantitative targets linked to the SDGs, and the 8% do not provide any kind of information on their website.

As for the companies belonging to the Green fashion, it was found that almost all of them, 12 out of 15 companies, provide information on their website about the sustainable practices pursued, while the remaining three are also part of numerous international initiatives and projects.

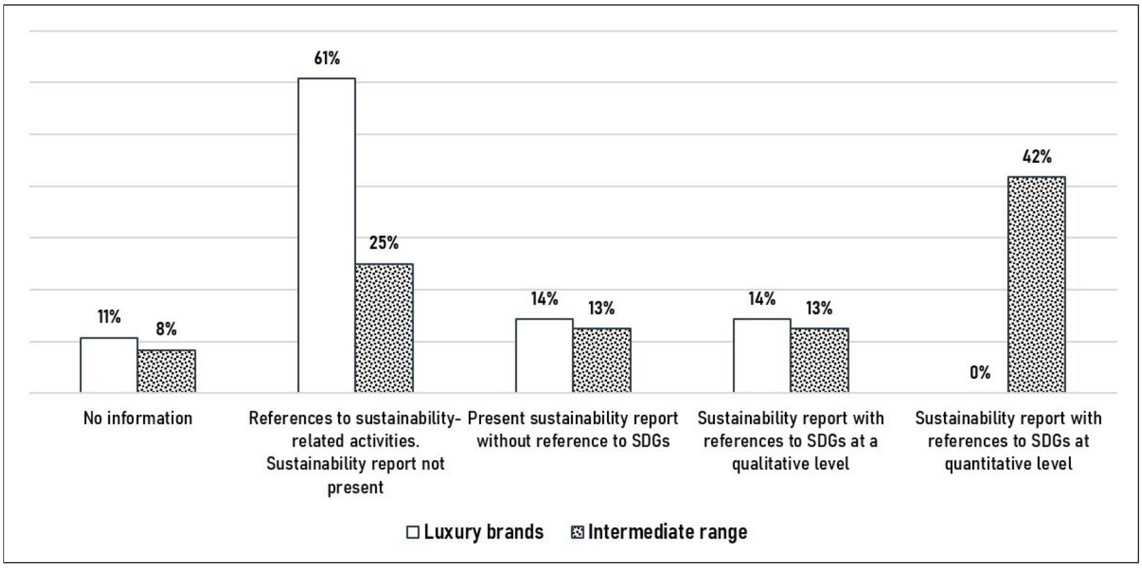


Figure 4.3: Governance analysis. Comparison of statements in 2021 by Luxury and Intermediate range companies in terms of level of communication of actions, objectives and monitoring of sustainability aspects.

4.1.3 Certification and management of raw material

The results described in this paragraph show the most widespread certifications among the companies analyzed. In addition, the analysis also identified some of the certifications held by suppliers working for the brands analyzed. For more details on the definition of the certifications, please refer to *Table 3.3* in *section 3.1.2*.

Figure 4.4a shows the most common certifications owned by companies, differentiating between Luxury and Intermediate range. In *Figure 4.4b*, instead, are reported the certifications owned by the suppliers of the respective companies of Luxury and intermediate range. At a general level, comparing the companies' certifications and the certifications of the relative suppliers, it can be observed in a preliminary way that the first type shows mainly corporate certifications while the suppliers realize mainly product certifications. Suppliers' product certifications have the purpose of guaranteeing a certain quality and keep the traceability of the raw materials. Considering that the analysis of the certifications of the suppliers is limited to the information contained in the web sites of the companies it cannot be excluded that the suppliers possess other types of certifications (also of business type) that do not emerge from the carried out analysis.

Observing the *Figure 4.4a* it emerges that LEED certification is the most diffused certification for both categories. However, the percentage of companies that do not declare any type of certification, either on the report, if present, or on the website is substantial (54% of Luxury companies and 21% of the Intermediate range).

Looking at *Figure 4.4b* LWG and OEKO Tex 100 certification, which aim to certify leather and fabric respectively, are the most common in both categories.

Figure 4.5 shows the most common certifications for companies in the Green fashion category. Some of the certifications are in common with the other two categories, however, the most widespread is the B-corporation Certification. Also for this category, the share of companies that do not declare any certifications is consistent (29%).

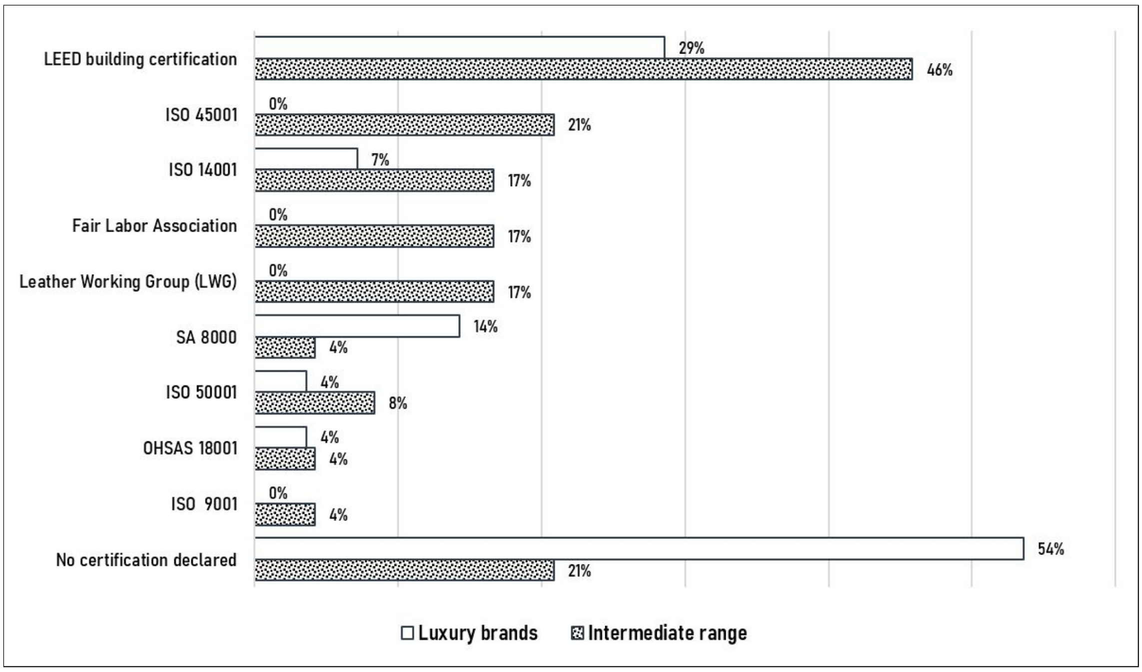
4.1.4 SHOES ECODESIGN

The fourth criterion through which the companies were analyzed concerns the development of new types of footwear designed from an ecodesign perspective. In general, footwear models have been identified that can preliminary fall under the definition of sustainability. Starting from the definitions of ecodesign (*Table 3.4*), to every model of footwear individualized, has been associated a typology of ecodesign.

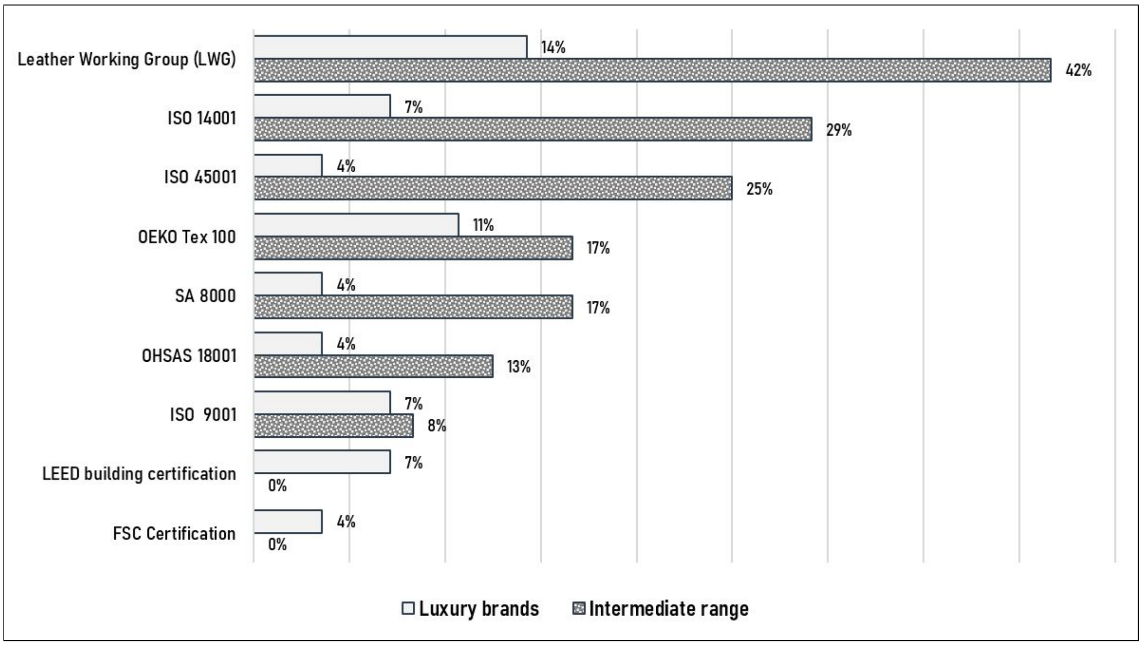
Figure 4.6 shows for every company the number of models of footwear that can fall in the definition of sustainability. From the analysis carried out it emerged that 61% of the companies belonging to the Luxury category did not declare any footwear model that could be ascribed to sustainability practices. Regarding this result it is noted that the analysis concerns models currently on the market with a declared focus on sustainability and therefore, the result should not be read as "61% of Luxury companies do not produce sustainable models of footwear". In addition, several companies may have produced models referable to sustainability practices in the past, while the analysis is referred to 2021 only. However, these models could also refer to experiments linked more to the concept of fashion than of sustainability. In fact, it turns out that only 11% of Luxury companies make more than one model of sustainable footwear.

For those in the intermediate range, the value rises to 58% and, having been chosen precisely for this characteristic, almost all of the green fashion companies produce sustainable models.

Figure 4.7 shows how the identified sustainable footwear is distributed among the ecodesigns, as previously classified, differentiating them by type, whether casual or classic. casual are mostly (59%) made from recycled materials, such as recycled nylon or recycled plastic, while classic shoes are mostly made from non-harmful or responsibly produced materials, such as leather from LWG-certified tanneries or materials of natural origin like hemp, wool or sugarcane soles.



(a) Company



(b) Supplier

Figure 4.4: Analysis of certification and management of raw materials. Comparison of the certifications declared in 2021 obtain directly by the companies belonging to the Luxury and Intermediate Range category (a) and by their suppliers (b).

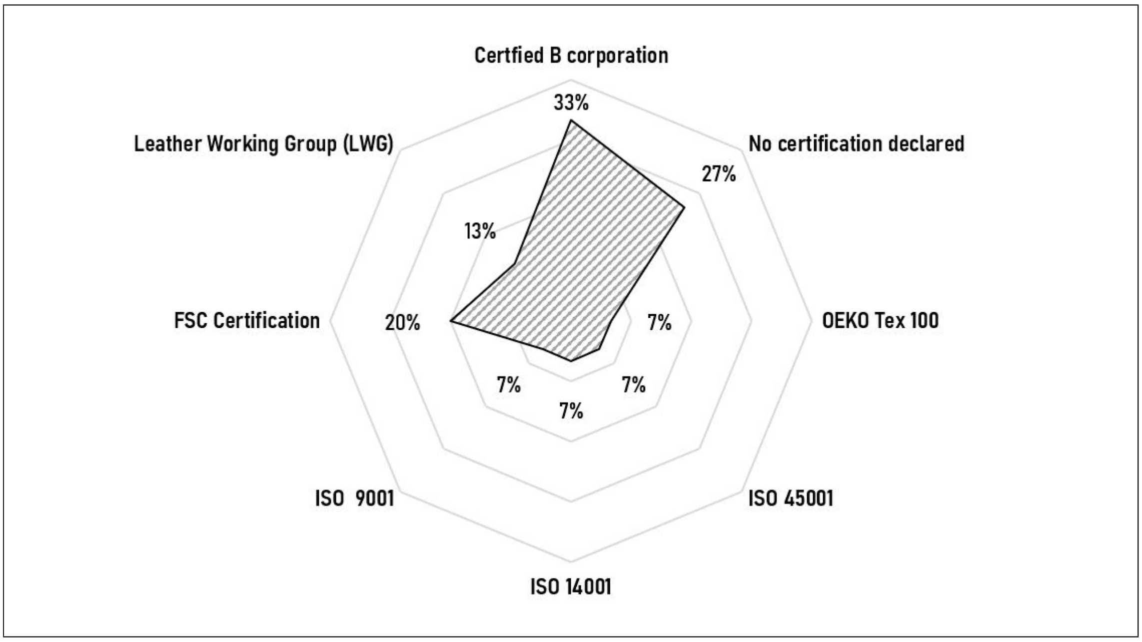


Figure 4.5: Analysis of statements in 2021 on certification and raw material management for companies in the Green Fashion category

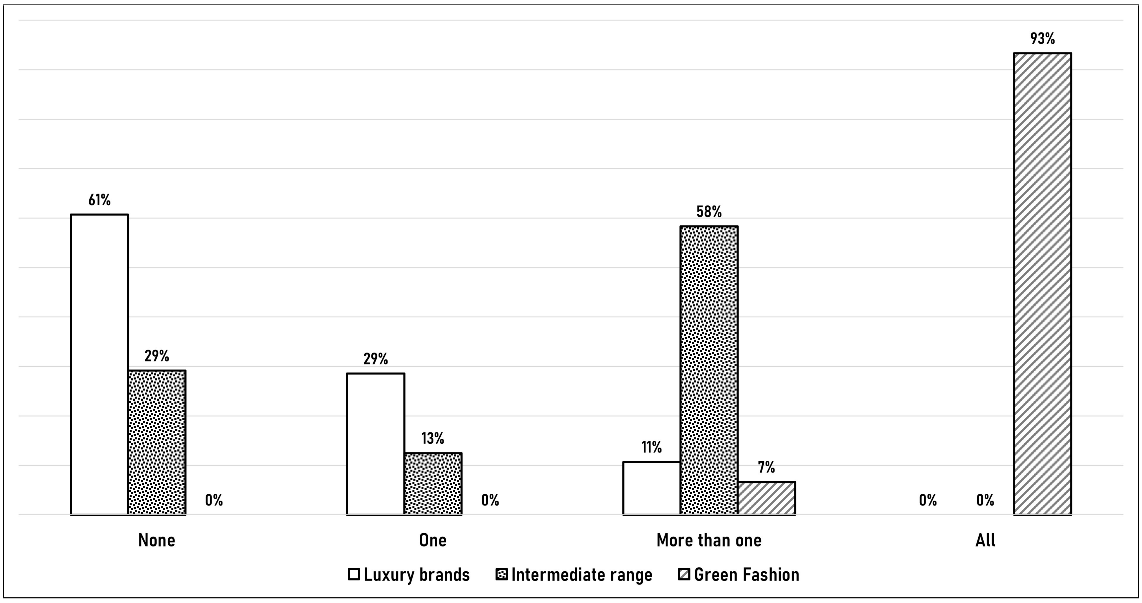


Figure 4.6: Footwear Analysis. Analysis of footwear models traceable to sustainability practices

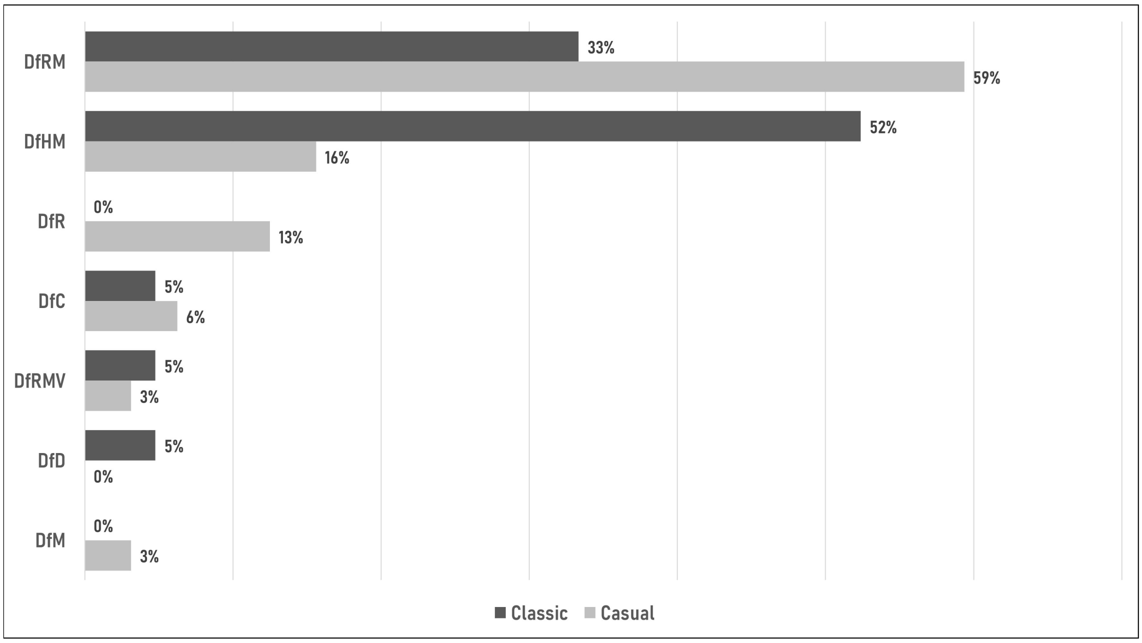


Figure 4.7: Declared Ecodesign for footwear, distributed according two type: casual or classic.

4.1.5 Supply chain analysis

This paragraph describes the results of the preliminary analysis of the supply chain, obtained through the codes of conduct of companies that can be found on their websites. In order to delve further into the supply chain management aspect and the raw materials used, we analysed the requirements of each company to their suppliers.

Figure 4.8 shows that 89% of Luxury companies and 84% of Intermediate range companies have a code of conduct available on their website that suppliers must sign.

Only 33% of companies belonging to green fashion declare a code of conduct: this may be due to the fact that most of them are small and production takes place entirely within the same location.

Figure 4.9a and *Figure 4.9b* show the requirements for suppliers on worker conditions and environmental aspects, respectively. From the analysis it emerges a greater focus on the social aspects regarding the environmental ones, in particular the safety of the conditions of job of the dependent and the decent treatment, comprising wages and suitable hours of job, are present in every code. Other aspects instead, like the equality of treatment and the freedom of association are present only in little more than half of the examined codes. Finally, environmental aspects are present in small numbers, with only 14 codes (38%) containing references to responsible water and waste management. It is worth mentioning the good practice of the Kering group, which requires standards to be met for raw materials, indicating guidelines that suppliers must follow.

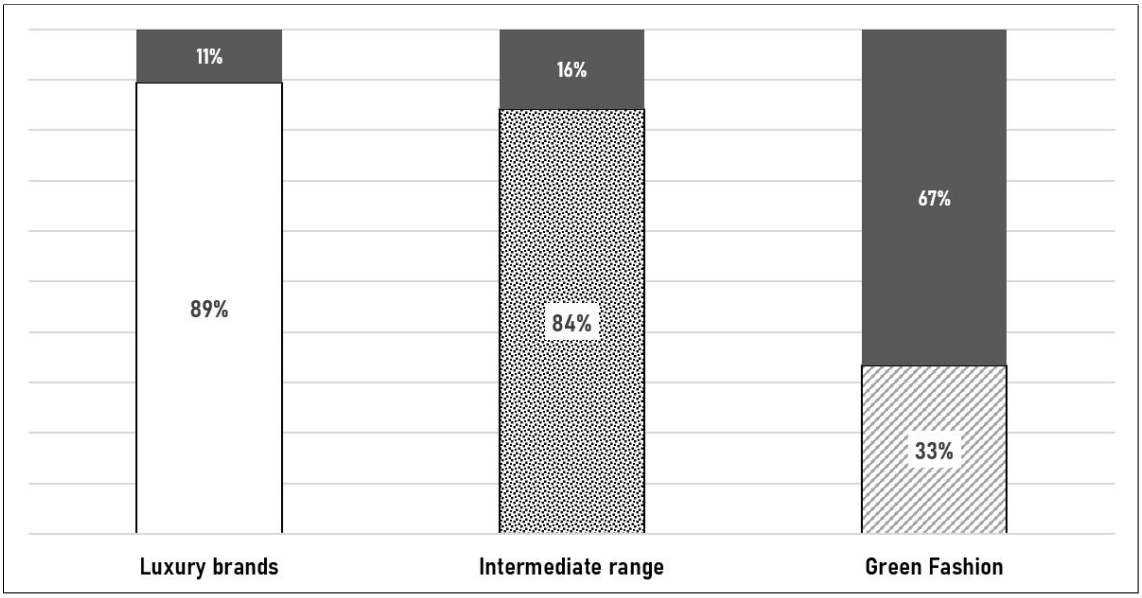


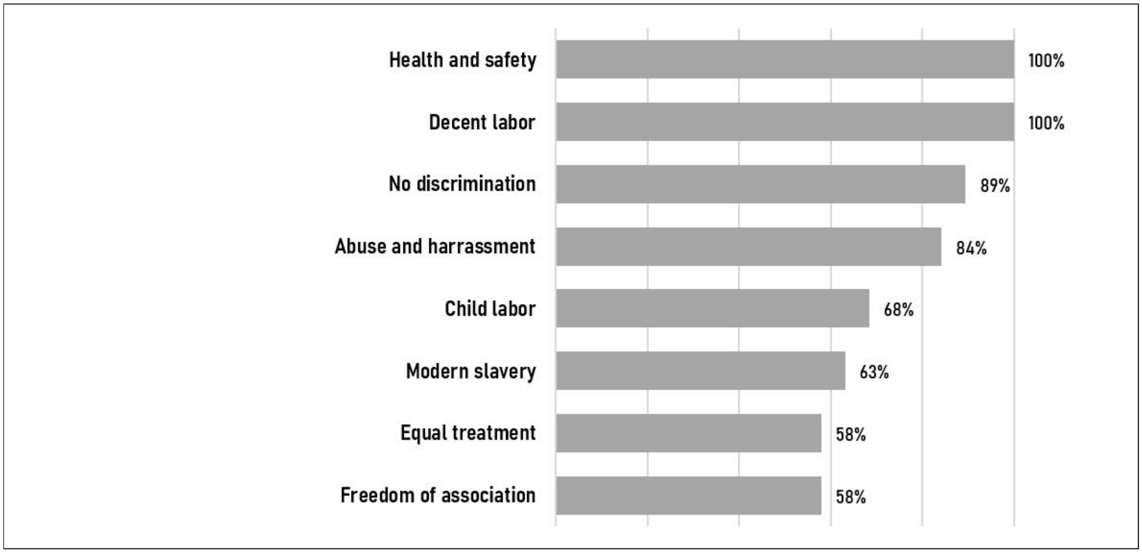
Figure 4.8: Companies requiring a code of conduct compared to the total number of companies in the individual category examined.

4.1.6 Brand comparison

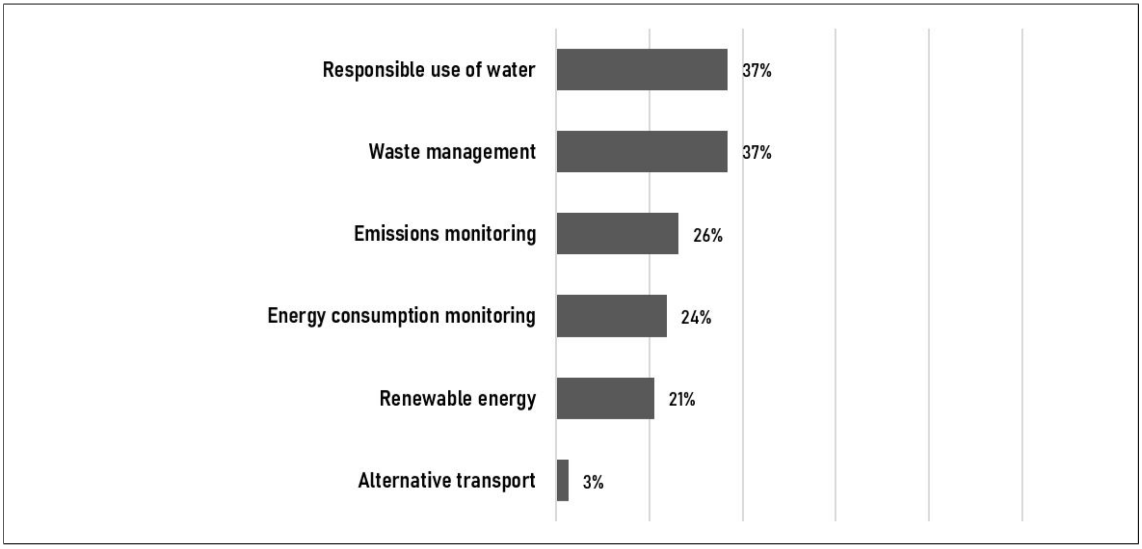
Following the analysis carried out individually for each of the 71 companies across the 4 evaluation criteria, a methodology was introduced through which a score could be assigned to each of them and comparisons could be made at a macro level (*Table 3.7*).

Figure 4.10 shows the distribution of the scores in terms of percentages for each of the three categories of the footwear sector. The final score shown in the figure is the sum of the individual scores assigned to each evaluation criterion and therefore ranges from 0 (worst) to 16 (best). Companies with a score between 0 and 3 are those that do not currently provide information on sustainability aspects. Companies scoring between 4 and 7 are those that communicate some sustainability actions at the governance or supply chain level but are not detailed. Companies scoring between 8 and 10 represent those companies that communicate some sustainability actions on one or a few sufficiently satisfactory evaluation criteria. Companies scoring between 11 and 13 are companies that communicate sustainability actions on most of the 4 evaluation criteria in an average satisfactory way. Finally, scores between 14 and 16 are assigned to those companies that have strong cross-communication on all 4 evaluation criteria.

From *Figure 4.10* it is possible to observe that:



(a) Worker



(b) Environment

Figure 4.9: Presence of aspects related to the treatment of workers (a) and to the environment (b) compared to the total number of codes of conduct considered.

- Luxury companies appear to have a generally lower rating than the other two types, as the majority of them turn out to have a rating of less than 7, reaching a maximum rating of 10. In particular, it was noted that the information regarding sustainability provided by these companies is generally less complete or more difficult to find.
- 8% of the companies in the Intermediate range have a rating between 0 and 3, while the majority have a rating above 7, including 9 of these (38%) with a rating between 11 and 13.
- 60% of Green fashion companies scored between 11 and 13, and there is one company, Vivobarefoot, with a rating of 15/16, placing it in the best class.

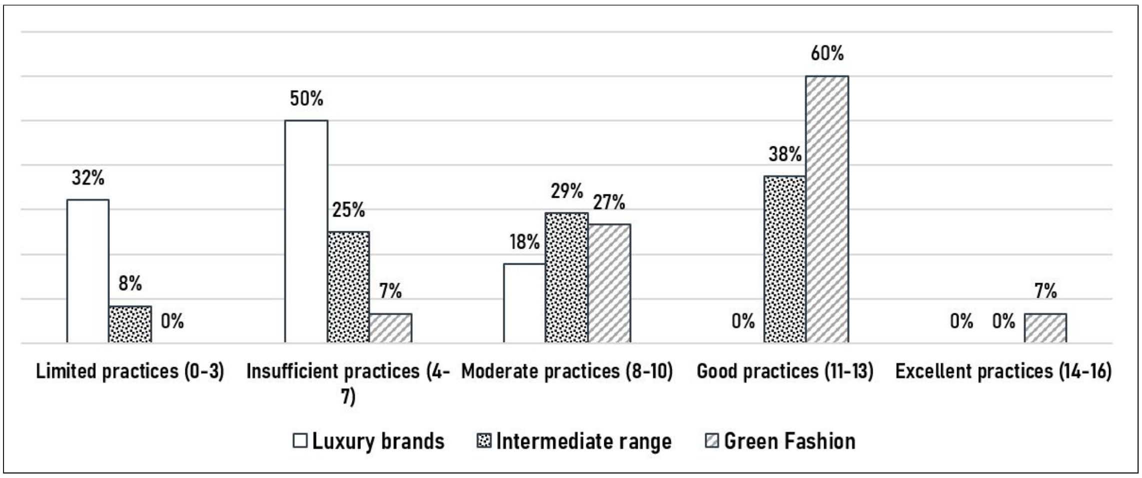


Figure 4.10: Breakdown of companies compared to the overall assessment

4.2 LCIA materials results

This section shows an overview of the LCIA results of the considered materials. The results are reported for each of the impact categories considered, comparing all the included materials according to the usual classification (leather, textiles, and soles materials). The section is structured following the same ordering of *section 3.2.4*. Firstly, the results of the leather materials are presented in *paragraph 4.2.1*, including a sensitivity analysis on the chosen allocation factor for the cattle breeding stage. Secondly, *paragraph 4.2.2* report the results of the textiles materials, and finally, *paragraph 4.2.3* shows the main outcomes for the soles materials.
All the results for each material are reported in *appendix B*, in terms of absolute value.

4.2.1 Leather

The results obtained for the leather materials are reported in *Figure 4.12*. The figure compares the three types of leather material considered, i.e., conventional chrome tanned leather, LWG certified leather, and vegetable tanned leather. At first glance, it can be seen that the total impacts for all materials are mainly due to the LCA stages of cattle breeding and tanning, while the impacts related to the slaughter and storage stage are almost negligible compared to the others.
The tanning stage of chrome leather and certified leather shared the same input of raw hides, hence the impacts of the cattle breeding stage are equivalent. The environmental performances of vegetable tanned leather are better than the other alternatives in all of the eight impact categories examined. It can be seen that the main differences are due to the impacts related to the cattle breeding stage.
Focusing on the tanning stage, *Table 4.1* report the differences, in percentage terms, between chrome leather and the other two tanning options, showing that the alternatives have better performances than the conventional one, except for the ALOP category for vegetable tanning, which is higher.
The chosen economic allocation factor for the cattle breeding stage represented a critical aspect of the modeling. The importance of this parameter was evaluated in a sensitivity analysis, assessing how the overall impacts of cattle breeding change with a variation of +- 5% from the chosen one. *Figure 4.11* shows that a variation of 5% of the parameter results in a variation of 65% of the impacts of the cattle breeding.

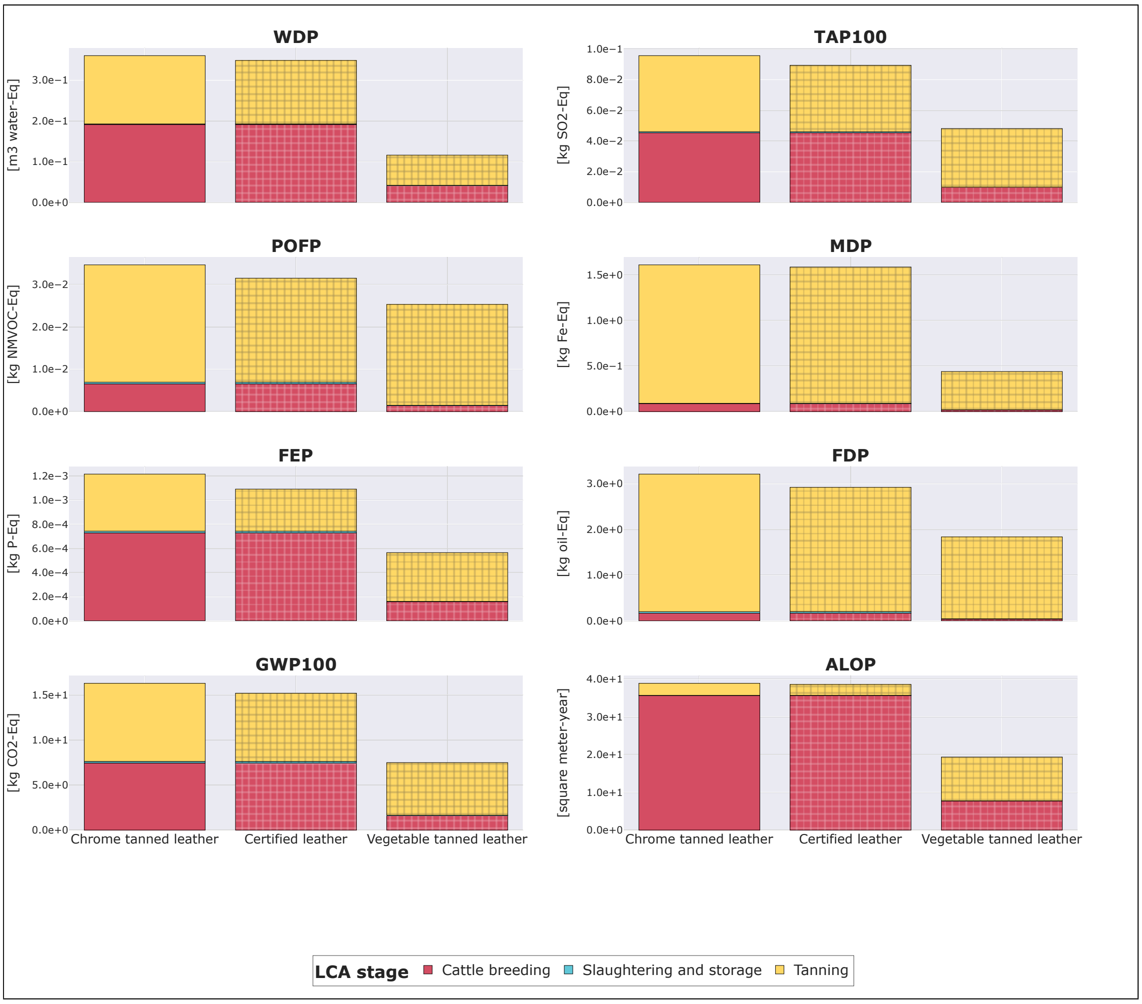


Figure 4.11: LCIA results of the leather materials subdivided between the impact categories. The different patterns are related to the specific ecodesign of the materials: - None: conventional materials; - Squared grid: healthy materials.

Table 4.1: LCIA results for the tanning stage for certified and vegetable tanning processes, reported as variation compared to the conventional chrome tanning.

Impact category	Certified leather	Vegetable leather
ALOP	-9%	265%
FDP	-10%	-40%
FEP	-26%	-14%
GWP100	-13%	-33%
MDP	-2%	-72%
POFP	-11%	-14%
TAP100	-13%	-23%
WDP	-7%	-56%

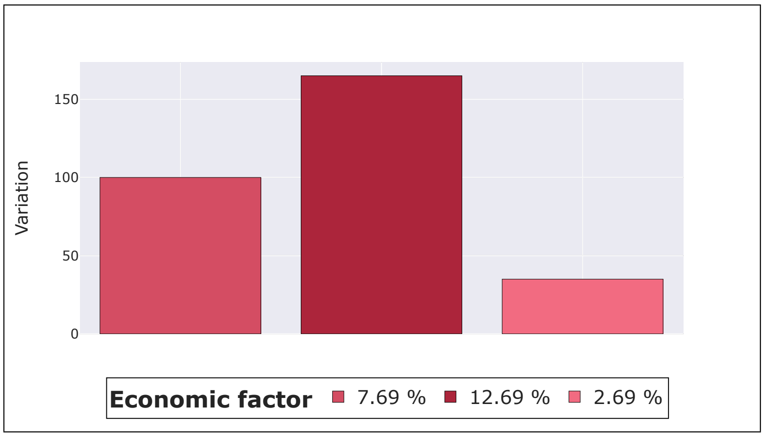


Figure 4.12: Sensitivity analysis on the economic allocation factor chosen in the cattle breeding stage. The economic factor used to model the cattle breeding stage constitute the base case from where the variations of the other factors were computed..

4.2.2 Textiles

In *Figure 4.13* are reported the LCIA results of the textile materials considered. It can be seen how some materials stand out for their high impacts across the different categories. In particular, wool presents the biggest impacts in the categories: ALOP, GWP, MDP, POFC, and TAP. Looking at how the impacts are distributed across the LCA stages, the most critical is constituted by the fiber production, i.e. the sheep farming and scouring of greasy wool. The material that presents the greater water consumption (WDP) is conventional cotton, mainly due to the huge amount of water needed in the cultivation stage. Looking at the FDP category, the results show that all the materials and every LCA stages have a consistent contribution, which could mainly be due to the amount of energy consumption. The textiles that have the lower contribution to climate change are jute and kenaf. Comparing the results of the recycled materials with the correspondent conventional one, the reduction of the impacts results to be substantial. Indeed, the recycling of fabrics and clothes allows avoiding the majority of the impacts related to the fiber production stage, particularly relevant for the case of wool. Furthermore, the use of recycled raw materials in the production of recycled polyester allows to halves the GWP contribution compared to the polyester made from virgin PET. While the contribution to climate change of econyl fiber production is 10 times lower than the one of nylon.

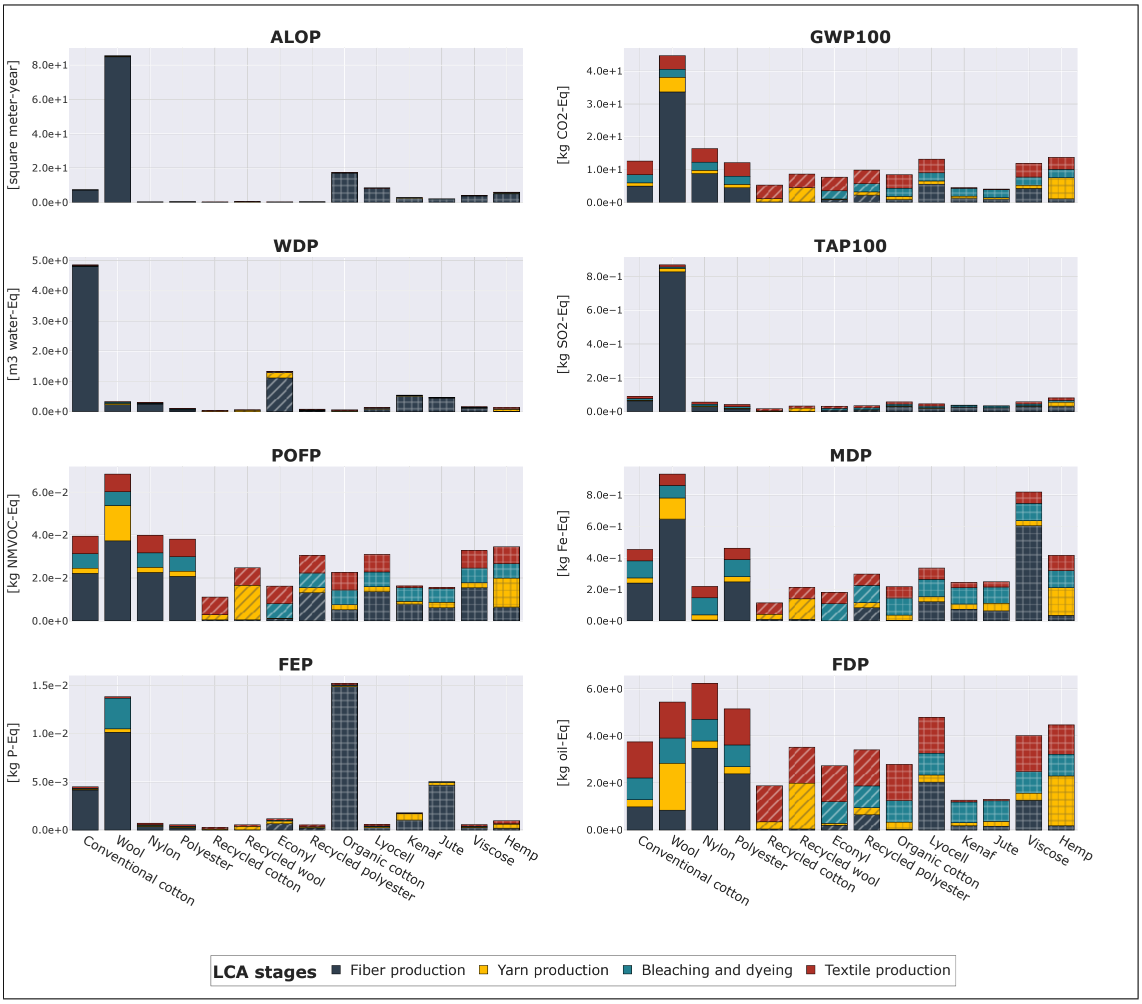


Figure 4.13: LCIA results of the textile materials subdivided between the impact categories. The different patterns are related to the specific ecodesign of the materials: - none: conventional materials; - Diagonal line: recycled materials; - Squared grid: healthy materials.

4.2.3 INSOLES AND OUTSOLES MATERIALS

The LCIA results for the soles materials are reported in *Figure 4.14*. Here the four materials considered for the soles component are compared, i.e. rubber, EVA, recycled rubber, and cork. Obviously, in the ALOP category, the material with the highest impact is cork. While for the other impact categories cork has the lowest impacts, mostly due to the processing of raw cork in the soles production stage. The water consumption and the exploitation of fossil resources are high for both rubber and EVA. As for the other categories rubber has the greatest impact.

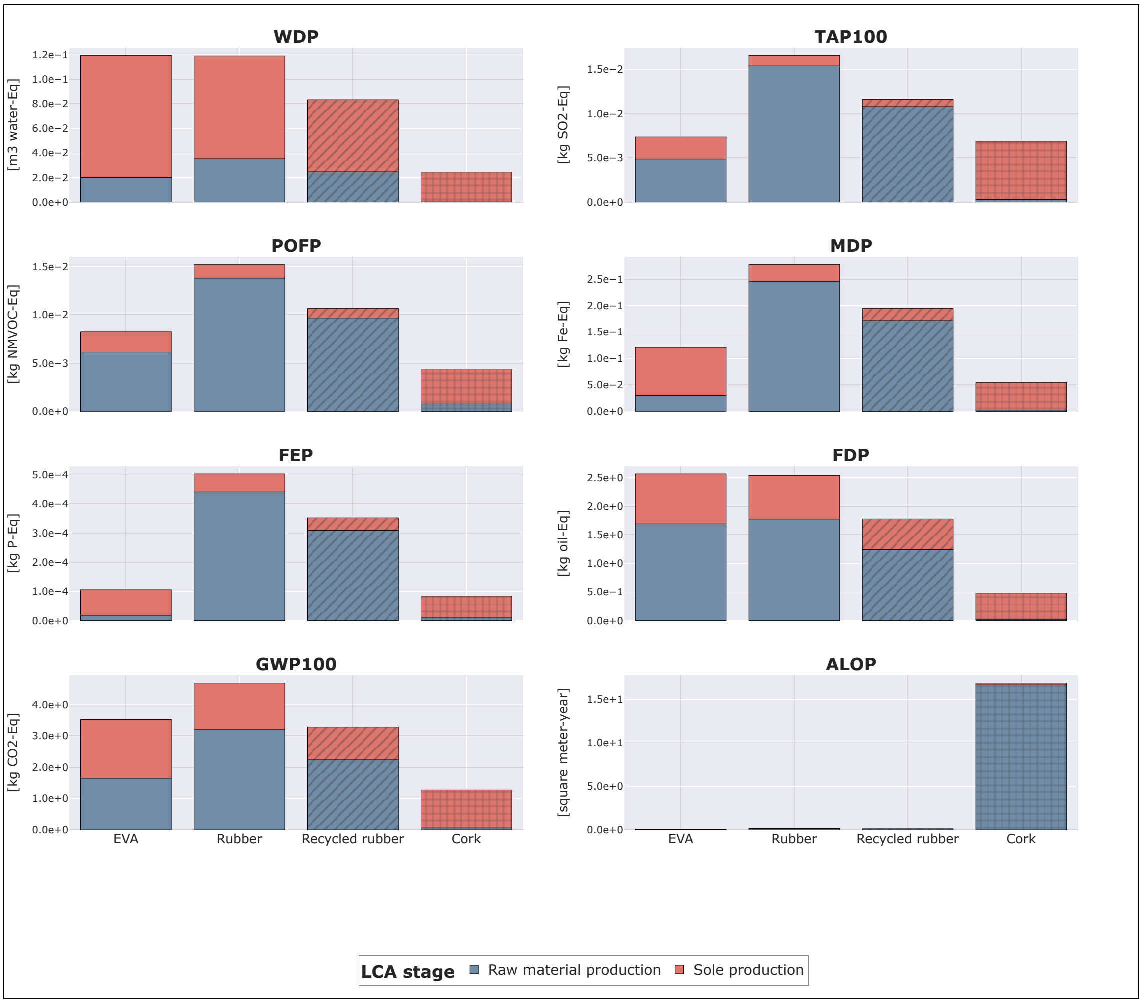
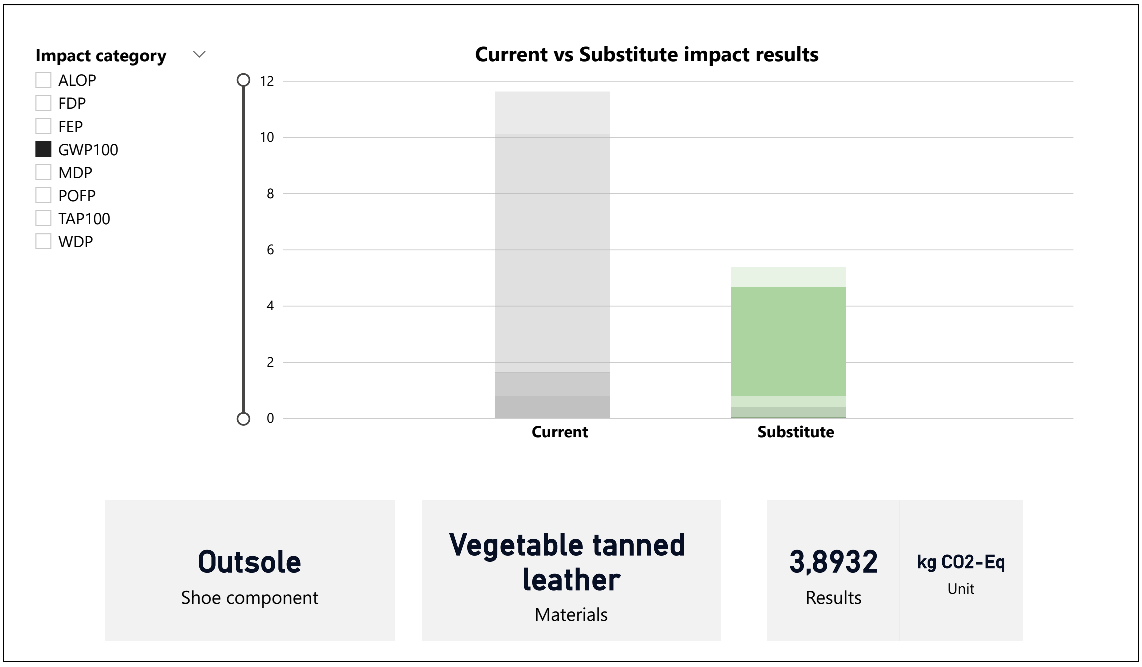


Figure 4.14: LCIA results of the sole materials subdivided between the impact categories. The different patterns are related to the specific ecodesign of the materials: - none: conventional materials; - Diagonal line: recycled materials; - Squared grid: healthy materials.

4.3 Ecoshoe tool results

The LCIA results presented in the previous section are the building blocks upon which the Ecoshoe tool is built. In this section are reported the outcomes of the scenarios as they should be provided from the tool. Firstly, *paragraph 4.3.1* provides the scenario results for the classic shoe model, while *paragraph 4.3.2* reports the results comparing the scenarios considered of the casual model. *Figure 4.15* reported an example of interactive visualization of the results: the user first chooses the impact category to evaluate, then by selecting one of the shoe components, highlighted with the different colors of the bar, can directly read the component material and the relative contribution to the impact category. In the example in *Figure 4.15* is highlighted the contribution to GWP of the outsole made of vegetable leather in the substitute scenario.
Since the visualization is interactive, to report the results of the scenarios and to understand the impact of the different components, in the following paragraphs, for practical reasons, the results are reported with a different layout. The results are reported for the GWP impact category, the results for all of the other categories considered are reported in *appendix C*.



Impact category
☐ ALOP
☐ FDP
☐ FEP
☒ GWP100
☐ MDP
☐ POFP
☐ TAP100
☐ WDP

Outsole
Shoe component

Vegetable tanned leather
Materials

3,8932
Results

kg CO2-Eq
Unit

Figure 4.15: Interactive visualization of the results on Microsoft Power BI.

4.3.1 Classic shoe

The user once inserted all the information about the current shoe and the alternative one, according to the scenarios composition reported in *Table 3.24*, can visualize the results comparing the two shoes. In *Figure 4.16* is reported a screenshot of the visualization interface implemented in Microsoft Power BI. The user can evaluate the impact of the two scenarios considered, for the desired impact category, and the contribution of each component. The results reported for the GWP category show how the impacts of the traditional scenario are halved (-54%) in the substitute case. Comparing each shoe component, the impacts related to the ones of the substitute scenario are lower with respect to the ones of the traditional. The component that contributes the most to the overall impact is, in both cases, the outsole. This is mainly due to its heavyweight, constituting 72% of the total weight of the shoe.
Since for the classic model chrome leather is replaced with vegetable leather in every component except for the laces, the outcomes reflects the results shown in *paragraph 4.2.1*. This is also true for the laces where conventional cotton is replaced by organic cotton (*paragraph 4.2.2*).
Furthermore, the substitute scenario performed better in all of the other impact categories (*appendix C.1*).

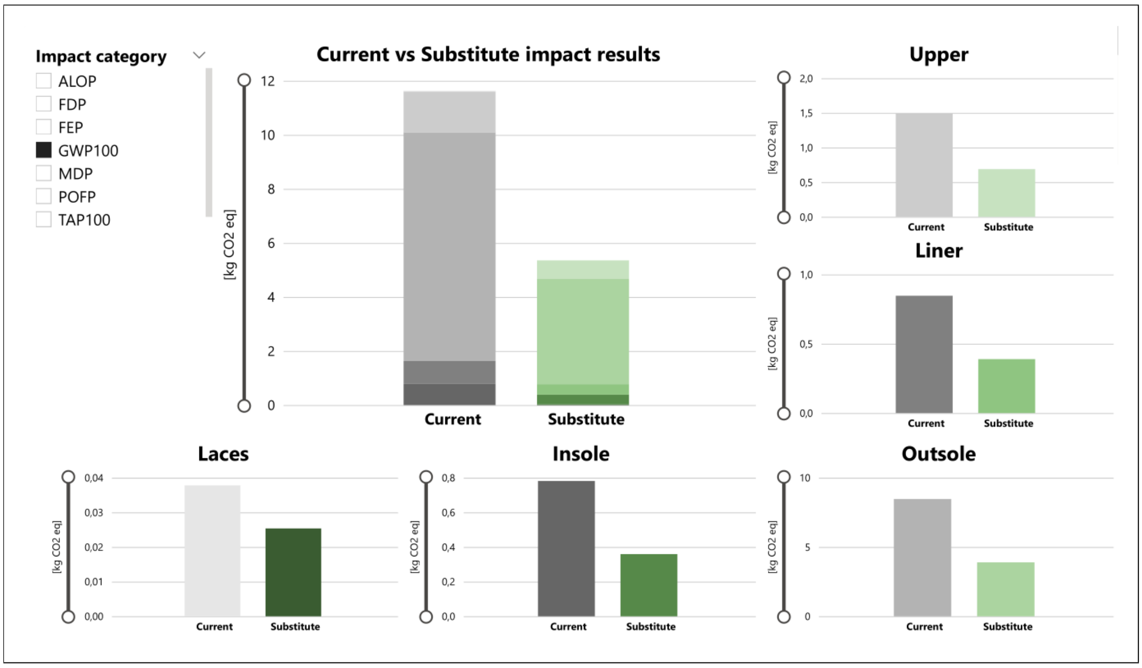


Figure 4.16: GWP results visualization on Microsoft Power BI for the scenarios of the classic model.

4.3.2 Casual

The substitution scenarios of the casual model are compared, one at a time, with the identified current scenario following the usual procedure of the Ecoshoe tool.

4.3.2.1 DfHM scenario

The current scenario is compared with a substitute one where the materials selected in the shoe composition were chosen according to the ecodesign DfHM. *Figure 4.17* shows the comparison between the two scenarios. Looking at the overall results, the impact related to the substitute scenario results to be a third of the impact of the current one. Every shoe component of the substitute scenario has a lower impact compared to the component of the current scenario, for the GWP impact category. The higher contribution to the total impact of the shoe is related, in both scenarios, to the upper, made of polyester and kenaf in the current and substitute scenario, respectively.
However, for some of the other impact categories, the substitute scenario results to be worse than the traditional one (*appendix C.2*)..

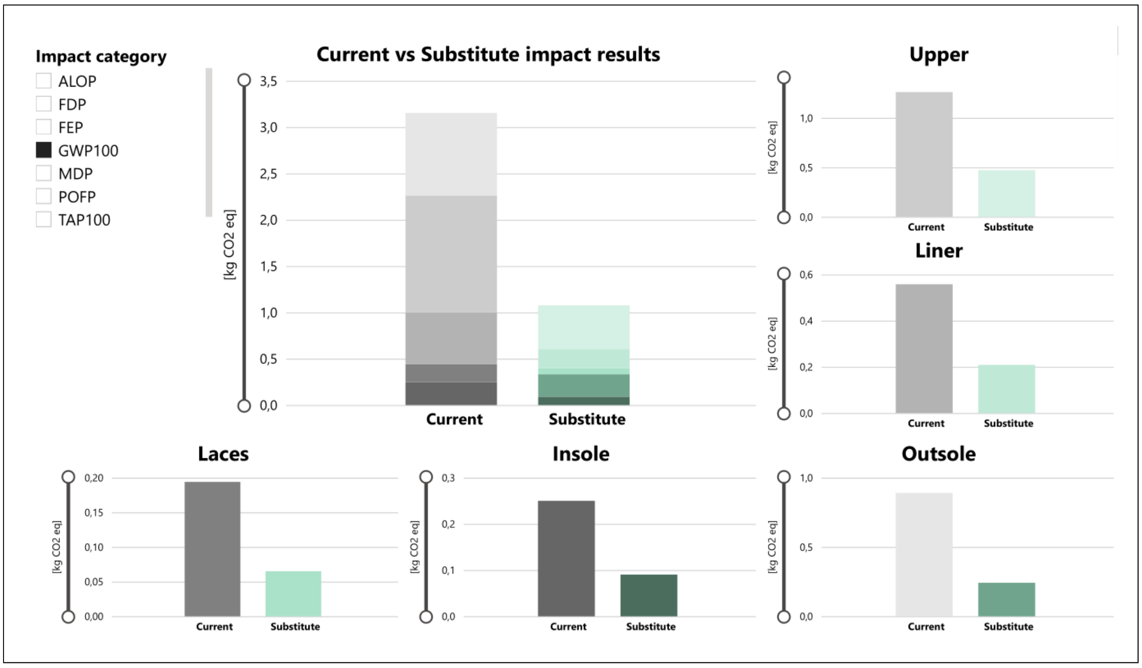


Figure 4.17: GWP results visualization on Microsoft Power BI for the traditional and the healthy materials scenarios of the casual model

4.3.2.2 DfRM scenario

The selected materials for the substitute scenario were chosen among the ones that fall into the ecodesign class DfRM, coming from recycling process. *Figure 4.18* report the comparison of the impact caused by this scenario with the traditional one. The DfRM scenario results in a 30% potential reduction in the GWP category. This reduction is distributed along every material used in the shoe components. Like the previous scenario, also for DfRM the higher contributor is represented by the upper, made of econyl.

As for the other impact categories, the substitute scenario presents a potential reduction in each of them, except for the water consumption. This is due to the higher amount of water needed in the production of econyl (*appendix C.2*).

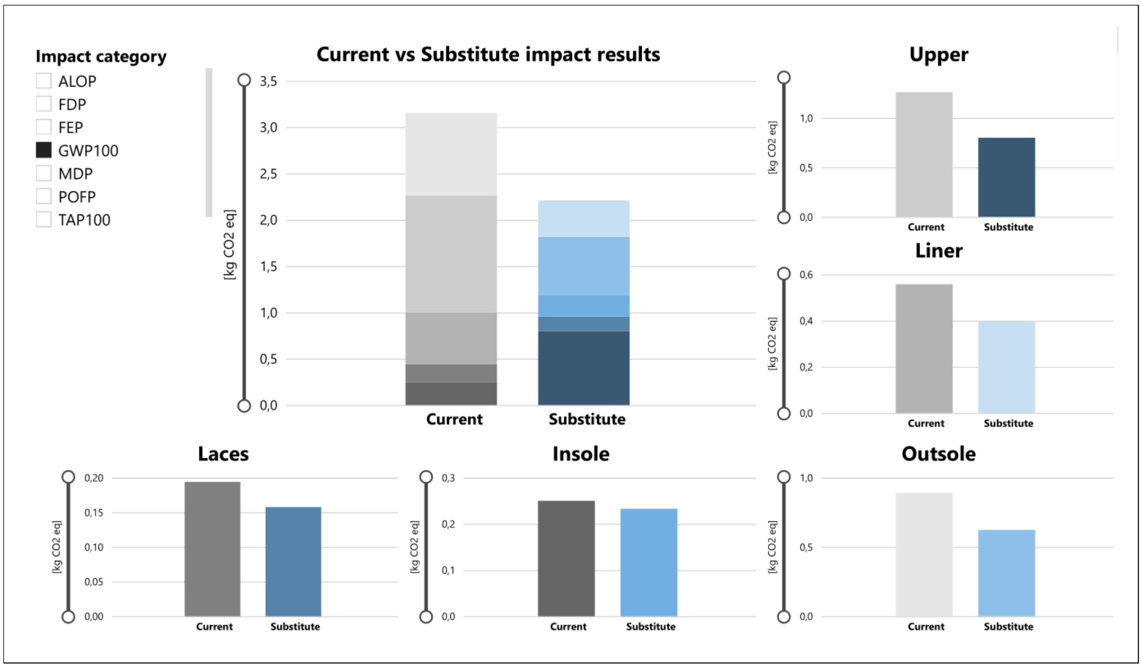


Figure 4.18: GWP results visualization on Microsoft Power BI for the traditional and the recycled materials scenarios of the casual model

DISCUSSION

5

The results presented in *chapter 4* need to be contextualized according to the scientific literature, highlighting the role of the analysis conducted and the main limitations of the approach used. This chapter is subdivided according to the same order followed in presenting the results. Firstly, *section 5.1* reports the main outcomes of the benchmark analysis, followed by stating the limits of the approach used. *Section 5.2* stated first the general assumptions made in modeling the LCA stages of the materials, followed by the contextualization of the results with the relative LCA studies. Finally, *section 5.3* first highlights some considerations on the application of the tool, and then reports its main limitations, at the current stage of development.

5.1 MAIN OUTCOMES OF THE BENCHMARK ANALYSIS

The benchmark analysis conducted aimed at assessing the most widespread best practices adopted by footwear brands on sustainability. From the results reported in *section 4.1*, some behaviors can be recognized across the three categories of companies considered. In general, luxury companies provided less information about their sustainability practices across all four evaluation criteria than the other two categories. Intermediate range companies fared better, but there is still a substantial share of companies that provide insufficient information. Green fashion companies perform better, as these companies were chosen from those who claim to implement sustainable practices, like selecting alternative materials, having a short supply chain, or reducing resources consumption.
Indeed, the average overall evaluation of the three categories reflects their general behavior, at least based on the declarations publicly available *Figure 4.10*. Luxury companies obtained an average score of 4.7, Intermediate range companies a score of 8.8, and companies of the green fashion category a score of 11.
Focusing on the most common ecodesign, it was found that for the classic shoe, the use of non-harmful and sustainably-sourced materials is the most common, while for the casual model the most frequent is the use of recycled materials.

Limits of the benchmark analysis

The conducted benchmark analysis presents some limitations that need to be clarified:

- The analysis was based only on data sources made available directly by companies through sustainability reports, information contained on official websites, industry articles or blogs, and online sales platforms;
- The information on practices that are not made public by individual companies means, for the purposes of our analysis, that these actions were not being taken by the company. However, an action that was not publicly reported does not imply that it was not performed by the company itself;
- Each statement provided by a company was assumed to be true, and it has not been verified.
- The supply chain analysis was limited to assessing the requirements for a supplier to work with a brand, through the code of conduct;
- Companies belonging to the luxury and intermediate range category were not directly comparable with companies belonging to the green fashion category due to their differences in terms of structure and organization and to the different evaluation criteria defined.
- The analysis was conducted during the period from September - November 2021.

5.2 Materials LCIA results contextualization

The LCIA results reported in *section 4.2* showed that the traditional materials have higher environmental impacts, across many of the impact categories, compared to the alternative ones.
The hypothesis made in modeling the LCA of the materials could strongly affect the results. The selection of the provider location for the ecoinvent process is particularly relevant. This is especially true for the energy flows since each country has a different energy mix, which leads to different environmental impacts. In this thesis were selected providers from the European region, considering other locations could lead to very different results.
Furthermore, some of the materials were modeled based on data provided by literature LCA studies, while others were based on processes available in the ecoinvent database, usually related to the European average flows. When comparing the materials, this fact should be kept in mind.

5.2.1 LEATHER

Figure 4.12 shows that the alternatives to the conventional chrome tanning process allows to reduce the environmental impacts across every impact category. The best alternative seems to be vegetable tanned leather, having better performances across all of the eight impact categories. This may be due to the higher efficiency of the vegetable tanning: from the data of the tanning process emerged that a lower amount of raw hides is needed compared to the case of chrome tanning (*Table 3.10 and 3.14*). The *Table 4.1* show that both certified leather and vegetable leather have generally lower impacts with respect to chrome leather, except for the ALOP category, where the contribution of vegetable tanning is 2.65 times higher than the conventional one. This may be due to the greater amount of vegetable tannins needed in the vegetable tanning process, being the tannins considered produced from spruce barks.

Concerning how the leather was modeled, the main limitations are due to some of the assumptions made in modeling the LCA stages. The selected economic allocation is the one used by *Mila et al., (1998)* [63], they reported that this LCA stage contributes to 35-45% of the total GWP impacts. In the chrome case, it was obtained a contribution by the cattle breeding stage of 49%. The choice of the economical factor for allocating the impact of the cattle breeding stage to leather production is particularly critical. In *subsection 4.2.1* the sensitivity analysis showed the importance of this parameter, where a variation of 1 percentage point caused a 13% variation of the impacts of the cattle breeding stage. Furthermore, it is important to point out that the chosen allocation factor was taken from a paper from 1998 and related to a specific production system, hence this value may be outdated.

In the tanning stage were considered three different types of process. In order to contextualize the obtained results, a comparison with the relative literature was needed. Regarding the conventional chrome tanning process, the results were compared to the one from *Notarnicola et al., (2011)* [1], resulting in slightly higher values for the GWP category: 8.7 $\mathrm{kg}_{\mathrm{CO}_{2\mathrm{eq}}}$ obtained against the 6 $\mathrm{kg}_{\mathrm{CO}_{2\mathrm{eq}}}$ from *Notarnicola et al., (2011)* [1]. The differences could be due to the different datasets used, and to the fact that this study was from 2011. For the other impact categories, the results are in line with the outcomes from this study.

Considering how the LWG certified tanning was modeled, and so by changing only the energy and water consumption flows of the chrome tanning process, and without considering every aspect of the LWG requirements [2], the actual environmental performances could be better than the ones obtained. This can be further assessed through a targeted study of a real certified tannery. However,

the obtained results of this process were compared to a study from *Laurenti et al., (2017)* [116] in order to verify the consistency of the results. In this study, different tanneries which use different tanning technologies were compared. The functional unit was measured in m^2, so in order to compare the results, a conversion is needed. The weight of leather depends on the thickness, the study referred to a thickness of 1.2-1.4 mm, the correspondent weight was retrieved from the densities presented by *Buljan et al., (2000)* [135]. *Laurenti et al., (2017)* obtained a range of GWP impact for the LWG certified chrome tanneries between 2.4 to 11.5 $kg_{CO_{2eq}}$, the value obtained in this thesis was 7.5 $kg_{CO_{2eq}}$.
For vegetable tanning, *Baquero et al., (2021)* [4] did not report any absolute value for the impacts, hence the obtained results were compared to other literatures. In particular, comparing the GWP impact obtained with the ones of *Laurenti et al., (2017)* [116], the value results to be slightly higher (5.8 vs 4.8 $kg_{CO_{2eq}}$ of the paper)
.

5.2.2 Textiles

The textile with the higher environmental impacts, across most of the impact categories, is wool, with the higher contribution related to sheep farming. For most of the materials, and across many of the impact categories, the LCA stage identified the fiber production as responsible for the greatest contributor to the overall impacts. The tables in *appendix B* show that focusing on the fiber production stage, the alternative materials can reduce the impacts, across most of the categories, compared to the traditional ones.

In modeling most of the textiles materials it was assumed that the stages of yarn production, bleaching and dyeing, and textile production were similar among the different materials, considering the same ecoinvent processes referred to cotton. These assumptions are not necessarily true since some of the materials could require different processes. Moreover, the impacts of yarn production and textile production may vary considering the different thicknesses.
By comparing the outcomes obtained with the respective literature studies, it was found that they are mainly consistent with the results in the reference LCA studies, showing slight variations due to the same reasons made for the leather materials.
However, from *Figure 4.13* emerged that the higher impact on the eutrophication potential category is represented by organic cotton, and mainly to the cultivation stage. Instead, literature data suggest that organic cotton should have a lower impact compared to conventional one [67, 136]. However, since the process was taken directly from ecoinvent, this could be due to how it was implemented

into the database. For the other categories, the results are in line with the literature, with general lower impacts of organic cotton compared to conventional [67, 136, 69], except for the ALOP category.

The results obtained for hemp are lower than the ones of *Van Eynde, H. (2015)* [5]. This could reflect the different energy mix considered, indeed the production system considered by *Van Eynde, H. (2015)* was based on the Chinese textile manufacturing, where China had a much greater share of coal in its energy mix compared to Europe [137, 138].

These differences were also found in the case of lyocell, where the LCA study conducted by *Guo et al., (2021)* [8] was as well related to a Chinese production system.

The modeling of Kenaf and jute were entirely based on the ecoinvent database. The yarn and textile production stages were modeled without considering the yarn thickness, this is reflected in the lower impacts of these stages compared to the same ones of the other materials. Given that the characteristic of hemp are similar to the ones of jute and kenaf, the impacts should be similar, too [69]. The differences are mainly due to the fact that hemp was modeled from a literature study that referred to a specific production system [5].

Among the materials considered, wool is the one with the greatest environmental impacts across the majority of the category considered. The largest contribution to the impacts is associated with sheep farming. The values obtained for this LCA phase are at an intermediate level of the range retrieved from literature studies, suggesting that the impacts could be even greater [6]. As for the stage of yarn production and bleaching and dyeing, the outcomes are coherent to the ones from *Cardoso A., (2013)* [6].

In modeling the recycling post-consumption waste clothes it was made the assumption of considering the same process for recycled wool and cotton, according to the data from *Liu et al., (2020)* specific for cotton [7]. For recycled wool, this may be considered as an approximation and should be verified with further study.

In the case of nylon an ecoinvent process was considered, for the fiber production stage, where it was not clear if the output considered was in the fiber form. Furthermore, for the yarn production stage, the same fraction of fiber loss of polyester was assumed.

The impact of econyl was simply taken an EPD specific of the production process of Aquafil. This should be considered when econyl is compared to materials based on more generic data.

5.2.3 Outsoles and Insoles materials

The results reported in *Figure 4.14* show that cork has the lowest environmental impacts in every impact category, except for ALOP: this is mainly due to the fact that cork, for this component, is the only material being cultivated. The highest impacts are related to rubber and EVA. Recycled rubber is produced with the same processes as conventional rubber, but with a fraction of recycled production scrap of 30%, therefore the impacts are reduced by the same percentage.

The sole production of EVA was quite critical since in ecoinvent was present the production of the copolymer Ethylene Vinyl Acetate, so for the manufacturing of the sole was assumed the core stage of the EPD from Vibram.
The impacts of rubber are related to a specific outsole, taking the output of the EPD as they are. As for the case of econyl, this must be considered when comparing the other sole materials. The sole production stage of cork was modeled considering the ecoinvent process related to the production of cork slab. hence the process is not specific to the production of cork soles for footwear, which may require different operations. For this reason, the impacts of this material could be underestimated.

5.3 Ecoshoe tool

The results provided by the tool for the scenarios considered can be seen as examples of the tool's functioning, showing that the current scenario and an alternative one can be easily compared. From the classic model scenarios, it can be seen that substituting the conventional chrome leather with vegetable leather can bring a reduction of the environmental impacts across every impact category, estimated between 27% and 73%. However, this result must be contextualized following the reasoning made in the previous section on the materials LCA. This stands also for the casual shoe case, where the results report that, for the selected shoe composition, the alternatives have better performances across most of the impact categories. However, the natural origin of the materials used in the DfHM scenario of the casual model, is responsible for the higher impacts for the ALOP, FEP, and WDP categories, compared to the traditional case constituted by synthetic materials. As for the other impact categories, the DfHM scenario of the casual model can bring a reduction of up to 78%.
The scenario DfRM also has higher contributes to the water consumption respect to the traditional case; this is mainly due to the high amount of water needed in the production of econyl, which is the main contributor to the overall impact. In the other categories, the DfRM scenario can lead to a reduction of the impact between 21% and 39% (*appendix C.2*).

LIMITATIONS OF THE ECOSHOE TOOL

The Ecoshoe tool can be used in order to estimate the potential impacts generated by a certain shoe composition, considering the materials and weights. At the current stage of development the Ecoshoe tool has some limitations:

- The modeling of the materials represents the main limitations of the tool. As it was already mentioned, the impacts caused by a material can vary greatly according to the location of the process considered and to which production stages are taken into consideration.
- From the tool, the modeling of the shoe accessories was excluded. Furthermore, the shoe components included in the analysis covered 89% and 69% of the whole weight of the considered classic and casual models, respectively. Moreover, the composition of the sneaker model was retrieved by adapting the weights reported in Aku's EPD [10] according to the overall weight of a usual sneaker. This constitutes an approximation of a sneaker composition, since it is not based on a real case.
- The shoe assembly stage was not included in the tool. However, this stage has a lower contribution compared to the early LCA stages of footwear, i.e. raw material extraction and processing [24].
- The tool was conceptualized assuming the same weight of the materials. Hence, the substitution did not include the weight of the substituted material. Further development of the tool can integrate the right weight of the substituted material.

CONCLUSIONS AND FUTURE WORKS

6

The main goal of the thesis was to create the Ecoshoe tool, with the purpose to support the footwear brands and manufacturers to design a more sustainable product. To achieve this goal, firstly a benchmark analysis of the major brands of the footwear sector was conducted, in order to understand which are the most common best practices implemented. From this analysis, the most used materials were then identified, both the traditional and the more sustainable alternative ones. These materials have been evaluated, so as to understand the relative environmental impact through LCA studies.
The key findings of the work are reported in the next paragraphs, following the usual scheme. At the end of the chapter are reported some of the potential future developments of the tool.

6.1 BENCHMARK

From the overall evaluation, it was found that Luxury companies generally report less information than the other two categories. This fact is reflected in each of the aspects analyzed. In fact, considering the supply chain, the majority (64%) report only the countries or geographical areas in which production takes place in percentage terms, and only 6 of them (21%) provide a detailed list of producers. Looking at Intermediate Range companies instead, the performance is on average better: 54% of them, in fact, provide information regarding both Tier-1 and Tier-2 suppliers, and some of them even go up to Tier-4.
In the case of governance, 61% of Luxury companies do not prepare a sustainability report, while for those belonging to the Intermediate Range the ones without sustainability report constitute a quarter of the total. 42% of the companies in the latter category refer their practices directly to the SDGs with quantitative evaluation and targets.
The most widespread certifications for the Luxury and Intermediate Range categories are LEED certification for the energy efficiency of buildings, considering the company level, present in 29% and 49% of the cases respectively, while at the supplier level the most widespread is Leather Working Group certification. In the case of Green Fashion, the most common certification is the B-corporation

certification, present in 5 of the 15 companies considered.
The most widespread sustainable footwear for sports shoes are those made with recycled materials, present in 59% of cases, very often represented by synthetic materials, such as econyl. For elegant footwear, the most widespread ecodesign is represented by the use of responsible materials or not harmful to human health, such as leather from certified tanneries, and textiles from natural fibers, such as certified cotton and wool or hemp. As highlighted in *paragraph 4.1.5*, almost all of the big companies (89% for Luxury and 84% for Intermediate Range) require to their suppliers to comply with a code of conduct. A future development of this analysis is to investigate the actual practices implemented by suppliers operating in the sector, through interviews and field research.
In addition, it might be interesting to repeat the analysis conducted over the next few years to track how footwear brands' behavior is changing, and how quickly it is changing, with regard to sustainability.

6.2 Materials key findings

From the LCIA results reported in *section 4.2* can be summarized some of the main outcomes.
The alternatives to the conventional tanning process present better performances in almost every impact category considered.
The best alternatives to the traditional textiles used in footwear are sustainably sourced natural materials (DfHM), such as kenaf, jute, hemp, organic cotton, lyocell, and viscose, but also recycled materials (DfRM), such as recycled cotton and wool, econyl, and recycled polyester.
The recycling of fabrics and clothes allows to avoid the majority of the impacts related to the fiber production stage, particularly relevant i Furthermore, the use of recycled raw materials in the production of recycled polyester allows to halve the GWP contribution compared to the polyester made from virgin PET, while the contribution to climate change of econyl fiber production is 10 times lower than the one of nylon.
Cork could represent a sustainable renewable source material for the outsole and insole components, allowing to strongly reduce the environmental impact with respect to the traditional materials.
In future studies it could be further considered the evaluation of other types of recycled sources, like lyocell made from paper waste. The LCA evaluation could be expanded to consider the innovative materials as well.

6.3 FUTURE DEVELOPMENT OF THE ECOSHOE TOOL

The tool has the purpose of supporting the companies of the footwear sector in designing a more sustainable product, allowing to assess the potential reduction of environmental burdens by substituting a traditional material used for a shoe component with a more sustainable one. At the current stage of development, the Ecoshoe tool can be further improved in the future across different aspects.
Firstly, more materials can be considered in order to expand the choice for each component of the shoe. In this way also other ecodesigns can be implemented, e.g. introducing bio-degradable materials. Instead of just two options available for the model of shoes, others can be included, like high heels, boots, etc. Hence, the stage of the actual assembly of the shoe can be included, in order to count the impact related to this stage as well.
The Ecoshoe tool could be upgraded by considering every component of the shoe, thus including the reinforcements, the midsoles, the glue and adhesives, the eyelets, but also the packaging.
An important improvement is constituted by the implementation of the substitution factors between the materials considering the different weight densities. This is done in such a way that when the user inserts the current materials for the shoe components, the relative weights, and the chosen substitute materials, the weights of the latter are automatically updated. In the choice of substitution materials, it must also be considered the aspect related to their different durability.
In an real application, the tool could be personalized according to the specific model of shoe produced, and the production processes involved in the supply chain of a company. Hence, the input flows of raw materials, energy, and resources, the definition of the production location for a material, and the shoe final production site all change.

A Brands evaluation

A.1 Intermediate range

Table A.1: Evaluation of the brands belonging to the Intermediate range category.

Name	**Supply chain**	**Governance**	**Certifications and raw materials management**	**Shoe ecodesign**	**Total**
VF corporation	4	4	2	1	10
Timberland	4	4	2	3	13
Vans	4	4	2	2	12
North Face	4	4	2	2	12
Nike	3	4	2	3	12
Converse	3	4	2	3	12
Adidas	3	3	2	3	11
Reebok	3	3	2	3	11
Puma	1	4	2	3	10
New Balance	3	1	2	0	6
Skechers	1	1	1	2	5
Fila	2	2	1	1	6
Scarpa	2	1	2	3	8
Vagabond	1	4	2	3	10
Asics	3	4	2	3	12
Camper	2	2	2	3	9
Clarks	2	2	2	3	9
FRAU	3	0	1	1	5
Geox	1	4	2	3	10
NeroGiardini	1	0	0	1	2
ECCO	3	1	2	1	7
Saucony	0	1	1	3	5
Vibram	3	3	2	3	11
Levi's	2	4	2	1	9
Diesel	0	1	1	1	3

A.2 LUXURY BRANDS

Table A.2: Evaluation of the brands belonging to the Luxury category.

Name	**Supply chain**	**Governance**	**Certifications and raw materials management**	**Shoe ecodesign**	**Total**
Kering	1	2	2	1	5
Gucci	2	2	2	3	9
Bottega Veneta	1	0	2	2	4
Balenciaga	1	1	1	2	5
Yves Saint Laurent	1	1	1	1	4
Alexander McQueen	1	1	0	1	3
Capri Holdings	1	2	2	1	5
Gianni Versace	1	2	2	1	5
Jimmy Choo	1	0	1	1	3
OTB	0	1	0	0	1
Maison Margiela	0	1	1	2	4
Prada	1	3	2	3	9
Miu Miu	1	1	1	2	5
Church	2	1	1	1	5
Louis Vuitton	1	3	2	2	8
Christian Dior	1	1	0	0	2
Fendi	2	1	2	1	6
Givenchy	1	1	0	0	2
Marc Jacobs	1	1	0	0	2
Christian Louboutin	0	1	0	0	1
Chloé	0	2	2	2	6
Dolce & Gabbana	0	1	1	1	3
Armani	1	3	1	1	6
Salvatore Ferragamo	1	3	2	2	8
Valentino	1	1	1	0	3
Stella McCartney	1	2	2	3	8
Vivienne Westwood	1	1	2	1	5
Tods	2	1	0	1	4
Moreschi	1	1	0	1	3
Rossetti	2	0	1	2	5
Santoni	2	1	0	1	4

A.3 GREEN FASHION

Table A.3: Evaluation of the brands belonging to the Intermediate range category.

Name	**Supply chain**	**Governance**	**Certifications and raw materials management**	**Shoe ecodesign**	**Total**
Allbirds	2	4	2	4	12
Able	2	2	3	4	11
Baabuk	4	2	3	4	13
Christy Dawn	4	2	2	4	12
8000Kicks	3	2	0	4	9
NAE	2	2	2	4	10
Nisolo	1	4	3	4	12
Ragioniamo con i piedi	4	2	2	4	12
Darzah	4	2	1	4	11
SAYE	1	2	3	4	10
ACBC	0	2	0	4	6
Aku	3	2	2	3	10
Camminaleggero	4	2	2	4	12
Vivobarefoot	4	4	3	4	15
Thaely	4	2	2	4	12

B

LCIA results of the selected materials

B.1 Leather

Table B.1: LCIA results of chrome and LWG certified tanned leather

Impact category	Unit	Cattle breeding	Slaughtering and storage	Chrome tanning	LWG certified tanning
ALOP	square meter-year	3.57E+01	3.32E-02	3.18E+00	2.89E+00
FDP	kg oil-Eq	1.67E-01	3.49E-02	3.01E+00	2.72E+00
FEP	kg P-Eq	7.29E-04	1.47E-05	4.73E-04	3.48E-04
GWP100	kg CO2-Eq	7.44E+00	1.77E-01	8.67E+00	7.57E+00
MDP	kg Fe-Eq	8.83E-02	2.88E-03	1.52E+00	1.50E+00
POFP	kg NMVOC-Eq	6.55E-03	4.06E-04	2.77E-02	2.46E-02
TAP100	kg SO2-Eq	4.54E-02	7.40E-04	4.96E-02	4.33E-02
WDP	m3 water-Eq	1.91E-01	1.33E-03	1.68E-01	1.56E-01

Table B.2: LCIA results of vegetable tanned leather

Impact category	Unit	Cattle breeding	Slaughtering and storage	Vegetable tanning
ALOP	square meter-year	7.73E+00	7.19E-03	1.16E+01
FDP	kg oil-Eq	3.61E-02	7.56E-03	1.79E+00
FEP	kg P-Eq	1.58E-04	3.18E-06	4.04E-04
GWP100	kg CO2-Eq	1.61E+00	3.84E-02	5.84E+00
MDP	kg Fe-Eq	1.91E-02	6.24E-04	4.21E-01
POFP	kg NMVOC-Eq	1.42E-03	8.79E-05	2.38E-02
TAP100	kg SO2-Eq	9.84E-03	1.60E-04	3.82E-02
WDP	m3 water-Eq	4.15E-02	2.88E-04	7.44E-02

B.2 TEXTILES

LCIA RESULTS OF THE FIBER PRODUCTION STAGE

Table B.3: LCIA results of conventional, organic and recycled cotton.

Impact category	Unit	Conventional cotton	Organic cotton	Recycled cotton
ALOP	square meter-year	7.12E+00	1.71E+01	1.96E-01
FDP	kg oil-Eq	9.89E-01	3.00E-02	1.53E+00
FEP	kg P-Eq	4.16E-03	1.49E-02	1.66E-04
GWP100	kg CO2-Eq	4.97E+00	8.24E-01	4.15E+00
MDP	kg Fe-Eq	2.40E-01	4.02E-03	7.26E-02
POFP	kg NMVOC-Eq	2.21E-02	5.21E-03	8.22E-03
TAP100	kg SO2-Eq	6.36E-02	3.04E-02	1.28E-02
WDP	m3 water-Eq	4.79E+00	2.08E-04	2.46E-02

Table B.4: LCIA results of hemp, jute and kenaf

Impact category	Unit	Hemp	Jute	Kenaf
ALOP	square meter-year	4.98E+00	1.89E+00	2.54E+00
FDP	kg oil-Eq	1.83E-01	1.64E-01	1.84E-01
FEP	kg P-Eq	1.70E-04	4.65E-03	1.04E-03
GWP100	kg CO2-Eq	1.09E+00	1.00E+00	1.33E+00
MDP	kg Fe-Eq	3.45E-02	6.31E-02	7.37E-02
POFP	kg NMVOC-Eq	6.43E-03	6.16E-03	7.84E-03
TAP100	kg SO2-Eq	3.27E-02	2.20E-02	2.56E-02
WDP	m3 water-Eq	1.12E-02	4.48E-01	5.15E-01

Table B.5: LCIA results of wool and recycled wool.

Impact category	Unit	Wool	Recycled wool
ALOP	square meter-year	8.49E+01	1.96E-01
FDP	kg oil-Eq	8.46E-01	1.53E+00
FEP	kg P-Eq	1.01E-02	1.66E-04
GWP100	kg CO2-Eq	3.37E+01	4.15E+00
MDP	kg Fe-Eq	6.46E-01	7.26E-02
POFP	kg NMVOC-Eq	3.74E-02	8.22E-03
TAP100	kg SO2-Eq	8.27E-01	1.28E-02
WDP	m3 water-Eq	2.29E-01	2.46E-02

Table B.6: LCIA results of lyocell and viscose.

Impact category	Unit	Lyocell	Viscose
ALOP	square meter-year	8.17E+00	3.77E+00
FDP	kg oil-Eq	2.04E+00	1.26E+00
FEP	kg P-Eq	2.57E-04	2.34E-04
GWP100	kg CO2-Eq	5.54E+00	4.24E+00
MDP	kg Fe-Eq	1.22E-01	6.04E-01
POFP	kg NMVOC-Eq	1.36E-02	1.54E-02
TAP100	kg SO2-Eq	1.90E-02	3.13E-02
WDP	m3 water-Eq	8.40E-02	1.10E-01

Table B.7: LCIA results of synthetic textiles.

Impact category	Unit	Nylon	Econyl	Polyester	Recycled polyester
ALOP	square meter-year	1.20E-03	-	1.51E-01	1.03E-01
FDP	kg oil-Eq	3.49E+00	1.91E-01	2.39E+00	6.51E-01
FEP	kg P-Eq	3.76E-04	6.75E-04	2.18E-04	1.92E-04
GWP100	kg CO2-Eq	8.77E+00	8.19E-01	4.49E+00	2.22E+00
MDP	kg Fe-Eq	5.44E-03	9.03E-07	2.48E-01	8.35E-02
POFP	kg NMVOC-Eq	2.26E-02	1.02E-03	2.07E-02	1.32E-02
TAP100	kg SO2-Eq	2.98E-02	7.91E-03	1.58E-02	8.39E-03
WDP	m3 water-Eq	2.47E-01	1.11E+00	5.21E-02	2.18E-02

B.3 SOLES

Table B.8: LCIA results of the raw material production stage for the soles material category.

Impact category	**Unit**	**EVA**	**Rubber**	**Recycled rubber**	**Cork**
ALOP	square meter-year	1.95E-02	1.48E-01	1.03E-01	1.67E+01
FDP	kg oil-Eq	1.69E+00	1.77E+00	1.24E+00	2.18E-02
FEP	kg P-Eq	1.83E-05	4.41E-04	3.09E-04	1.14E-05
GWP100	kg CO2-Eq	1.65E+00	3.20E+00	2.24E+00	6.11E-02
MDP	kg Fe-Eq	2.99E-02	2.46E-01	1.72E-01	2.45E-03
POFP	kg NMVOC-Eq	6.15E-03	1.38E-02	9.66E-03	7.71E-04
TAP100	kg SO2-Eq	4.87E-03	1.54E-02	1.08E-02	2.94E-04
WDP	m3 water-Eq	2.01E-02	3.53E-02	2.47E-02	1.77E-04

Table B.9: LCIA results of the soles production stage for the soles material category.

Impact category	**Unit**	**EVA**	**Rubber**	**Recycled rubber**	**Cork**
ALOP	square meter-year	5.77E-02	1.48E-02	1.04E-02	2.01E-01
FDP	kg oil-Eq	8.75E-01	7.63E-01	5.34E-01	4.58E-01
FEP	kg P-Eq	8.74E-05	6.20E-05	4.34E-05	7.25E-05
GWP100	kg CO2-Eq	1.87E+00	1.49E+00	1.04E+00	1.21E+00
MDP	kg Fe-Eq	9.13E-02	3.14E-02	2.20E-02	5.24E-02
POFP	kg NMVOC-Eq	2.10E-03	1.40E-03	9.77E-04	3.61E-03
TAP100	kg SO2-Eq	2.50E-03	1.18E-03	8.28E-04	6.60E-03
WDP	m3 water-Eq	9.93E-02	8.36E-02	5.85E-02	2.43E-02

C

Ecoshoe tool visualization

C.1 Classic shoe

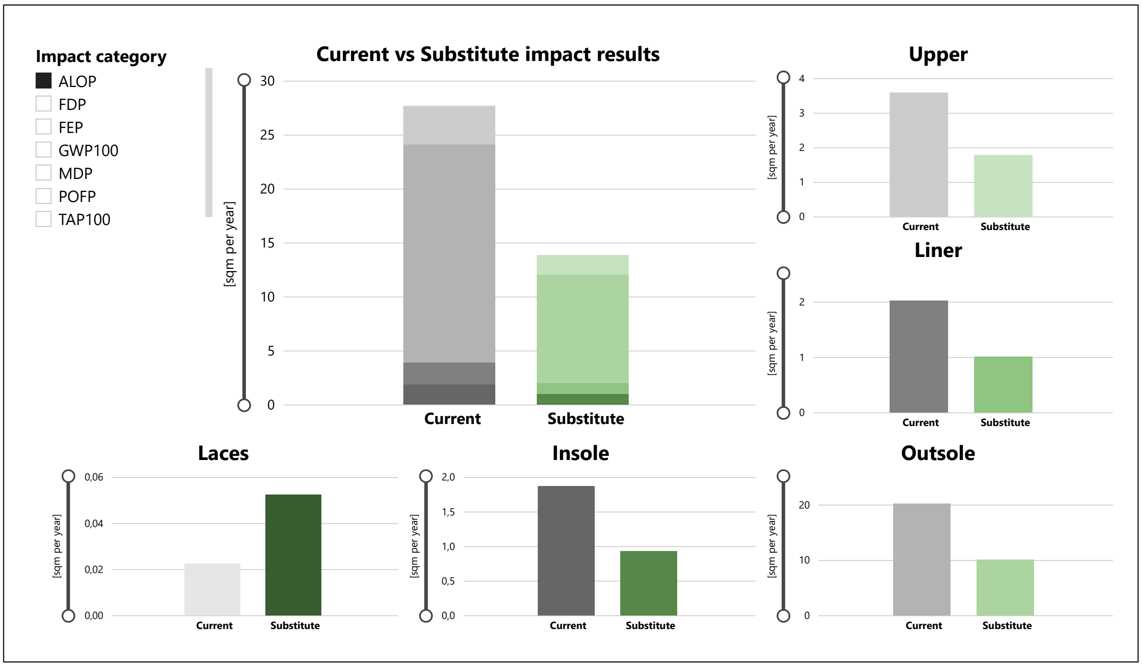
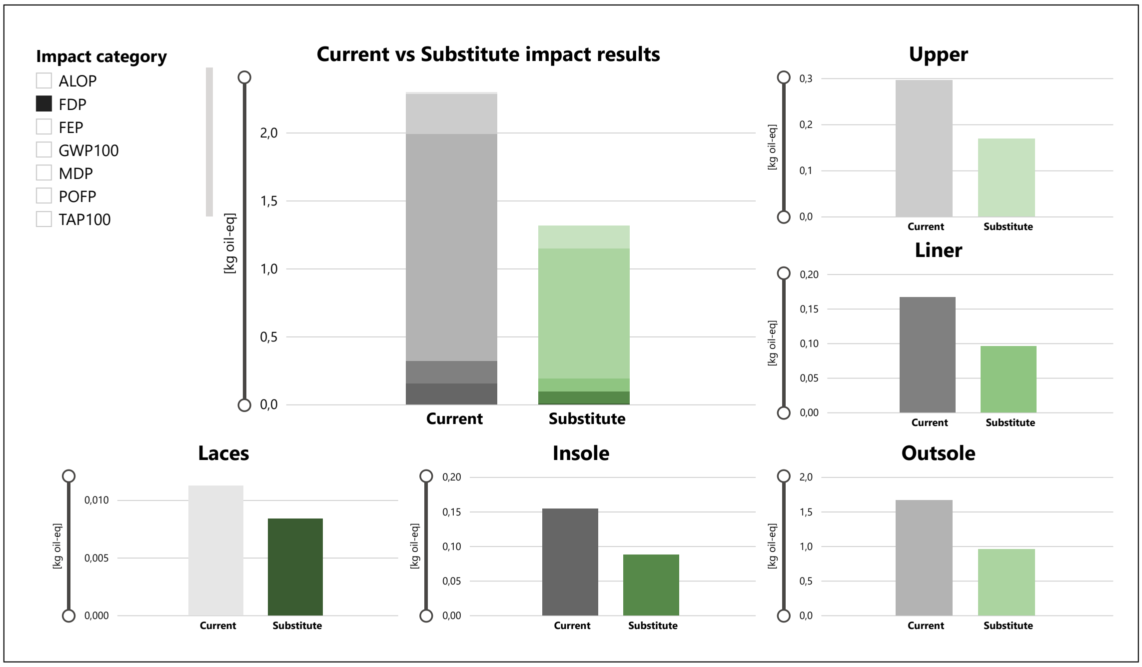
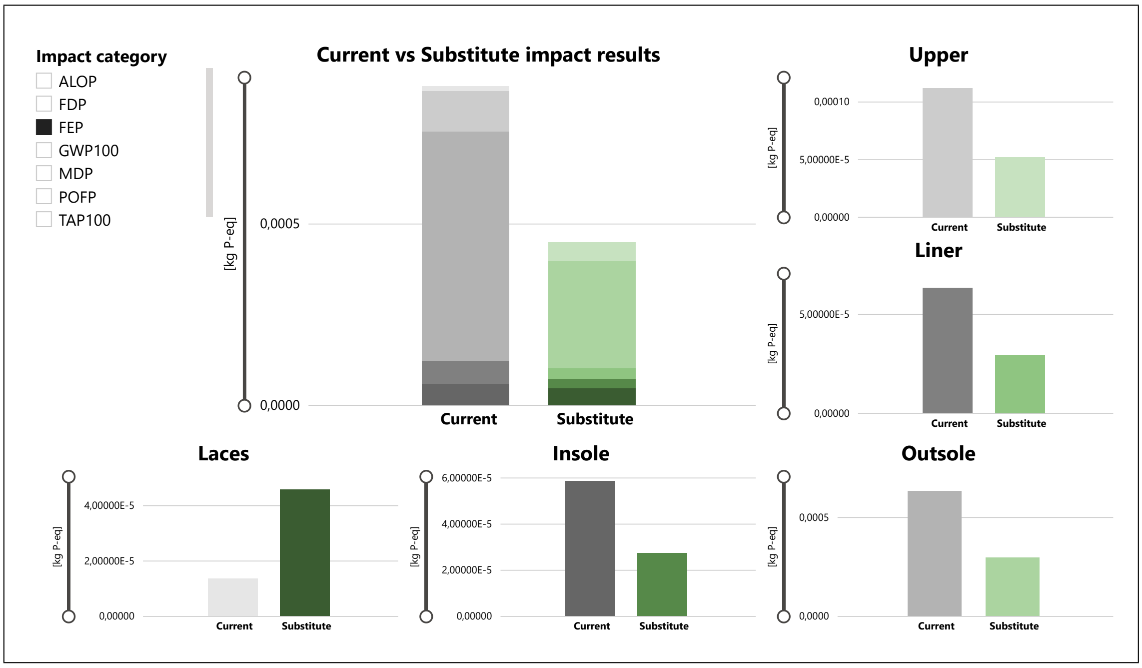


Figure C.1: ALOP results visualization on Microsoft Power BI for the scenarios of the classic model



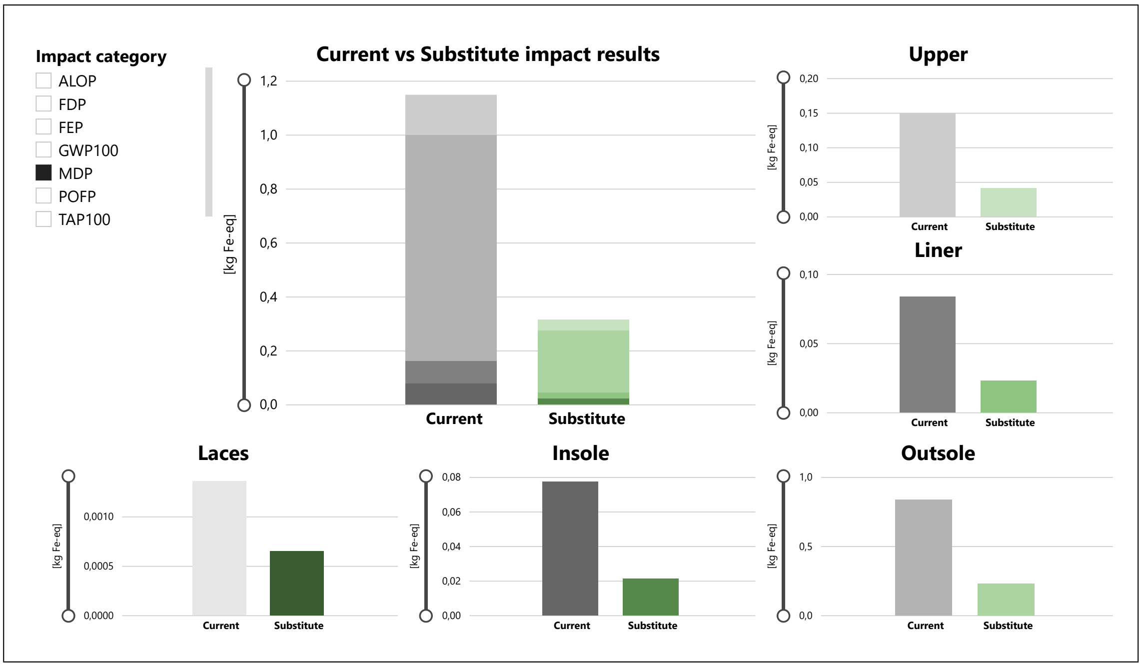
Impact category
☐ ALOP
■ FDP
☐ FEP
☐ GWP100
☐ MDP
☐ POFP
☐ TAP100

Figure C.2: FDP results visualization on Microsoft Power BI for the scenarios of the classic model



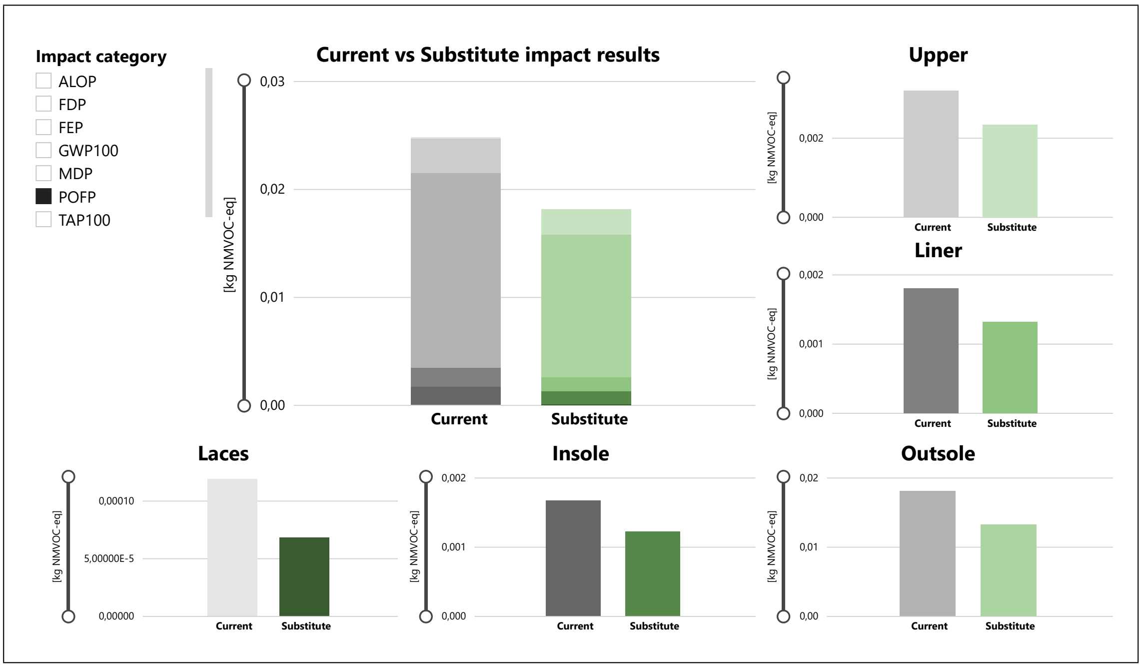
Impact category
☐ ALOP
☐ FDP
■ FEP
☐ GWP100
☐ MDP
☐ POFP
☐ TAP100

Figure C.3: FEP results visualization on Microsoft Power BI for the scenarios of the classic model



Impact category
- ☐ ALOP
- ☐ FDP
- ☐ FEP
- ☐ GWP100
- ■ MDP
- ☐ POFP
- ☐ TAP100

Figure C.4: MDP results visualization on Microsoft Power BI for the scenarios of the classic model



Impact category
- ☐ ALOP
- ☐ FDP
- ☐ FEP
- ☐ GWP100
- ☐ MDP
- ■ POFP
- ☐ TAP100

Figure C.5: POFP results visualization on Microsoft Power BI for the scenarios of the classic model

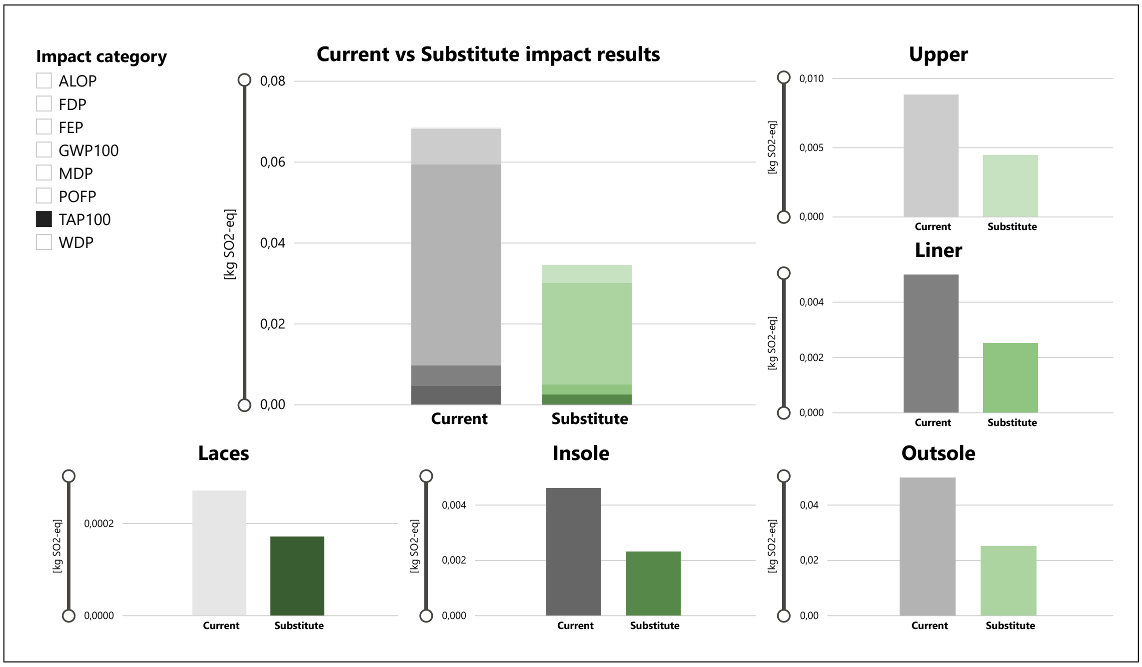


Figure C.6: TAP results visualization on Microsoft Power BI for the scenarios of the classic model

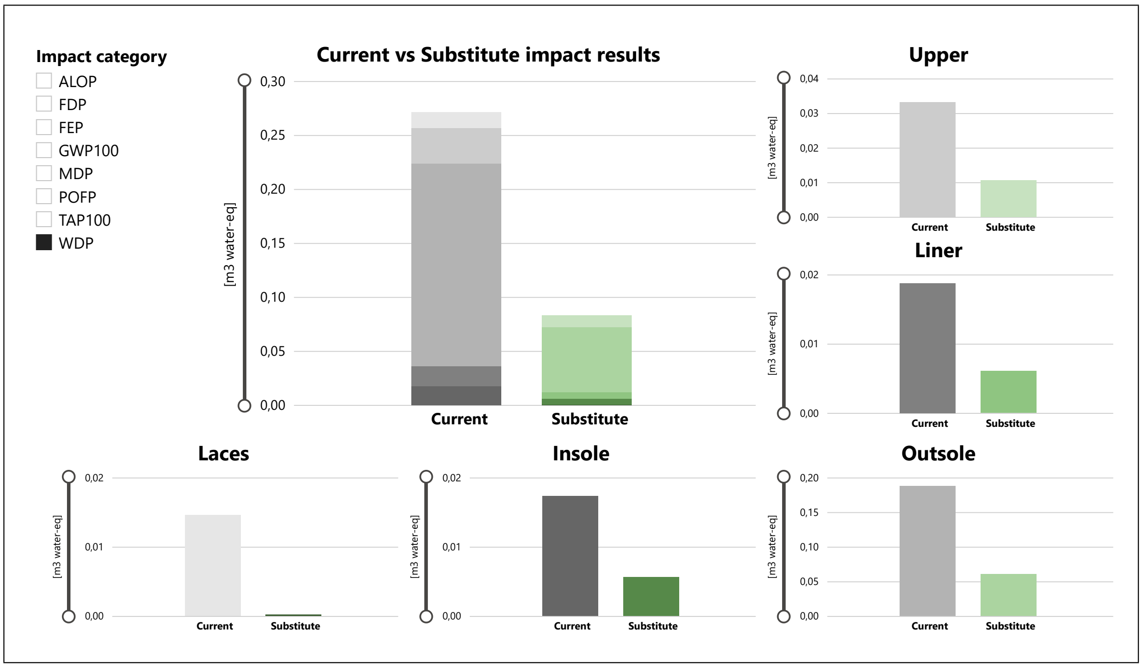


Figure C.7: WDP results visualization on Microsoft Power BI for the scenarios of the classic model

C.2 Casual shoe

Design for use of Healthy Materials

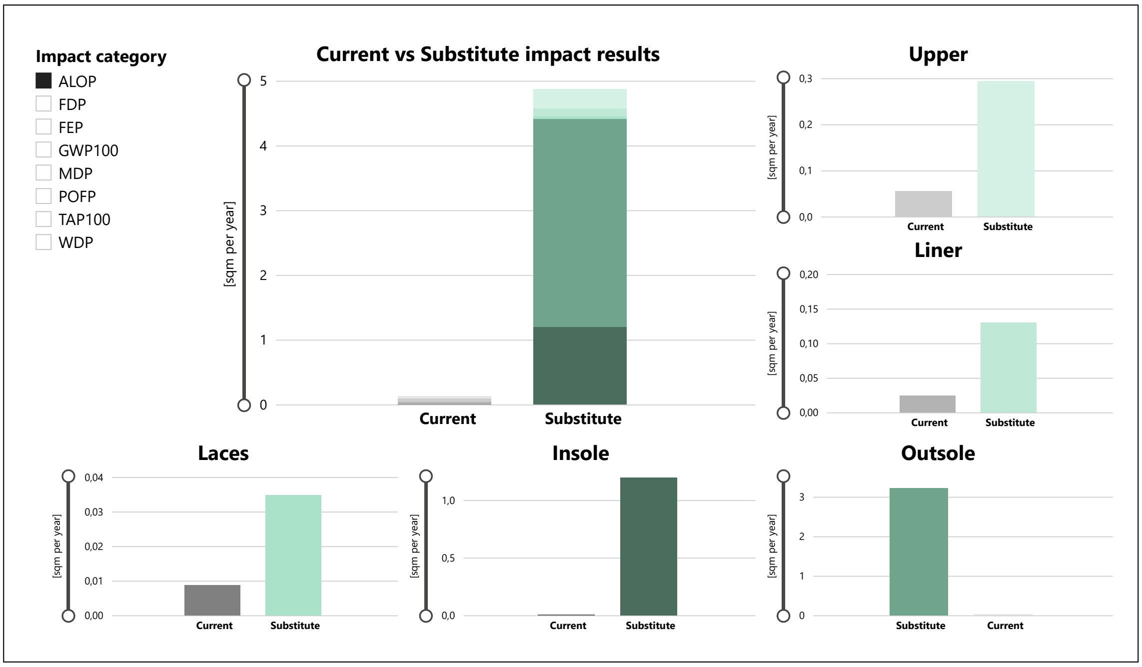


Figure C.8: ALOP results visualization on Microsoft Power BI for the traditional and DfHM scenarios for the casual shoe model

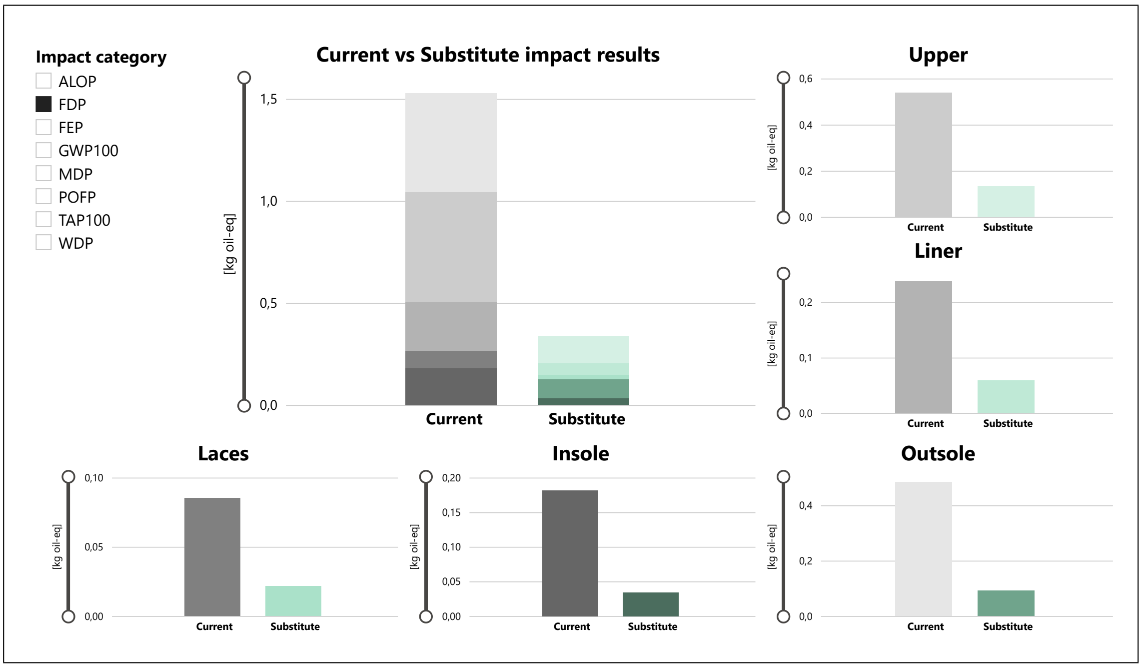
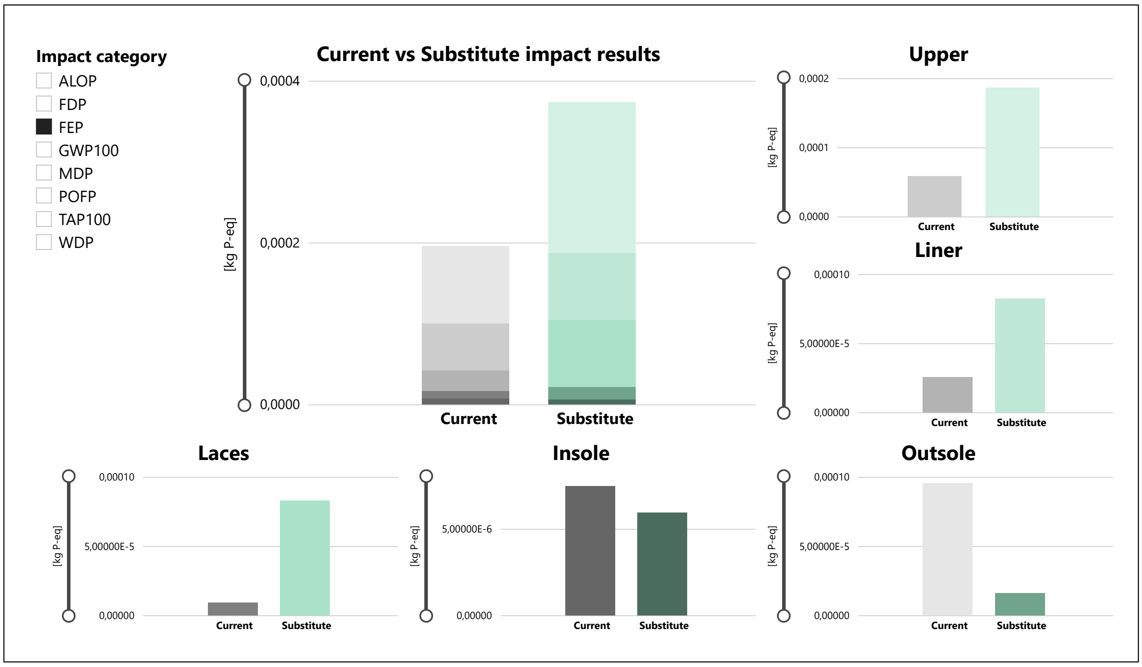


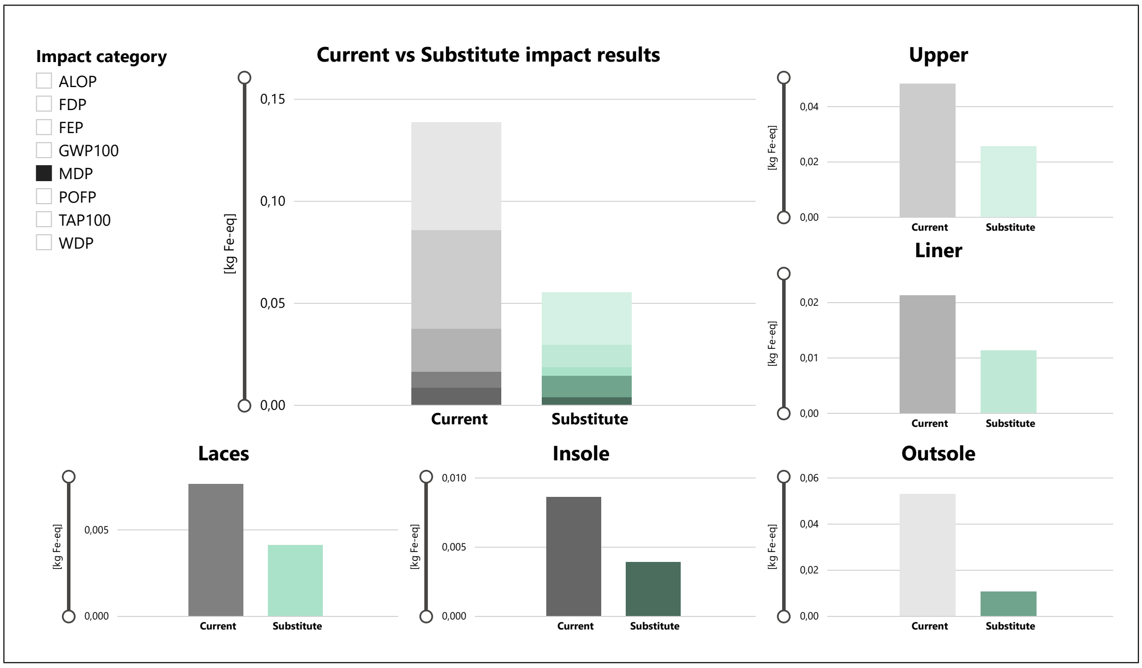
Figure C.9: FDP results visualization on Microsoft Power BI for the traditional and DfHM scenarios for the casual shoe model



Impact category

☐ ALOP
☐ FDP
☑ FEP
☐ GWP100
☐ MDP
☐ POFP
☐ TAP100
☐ WDP

Figure C.10: FEP results visualization on Microsoft Power BI for the traditional and DfHM scenarios for the casual shoe model



Impact category

☐ ALOP
☐ FDP
☐ FEP
☐ GWP100
☑ MDP
☐ POFP
☐ TAP100
☐ WDP

Figure C.11: MDP results visualization on Microsoft Power BI for the traditional and DfHM scenarios for the casual shoe model

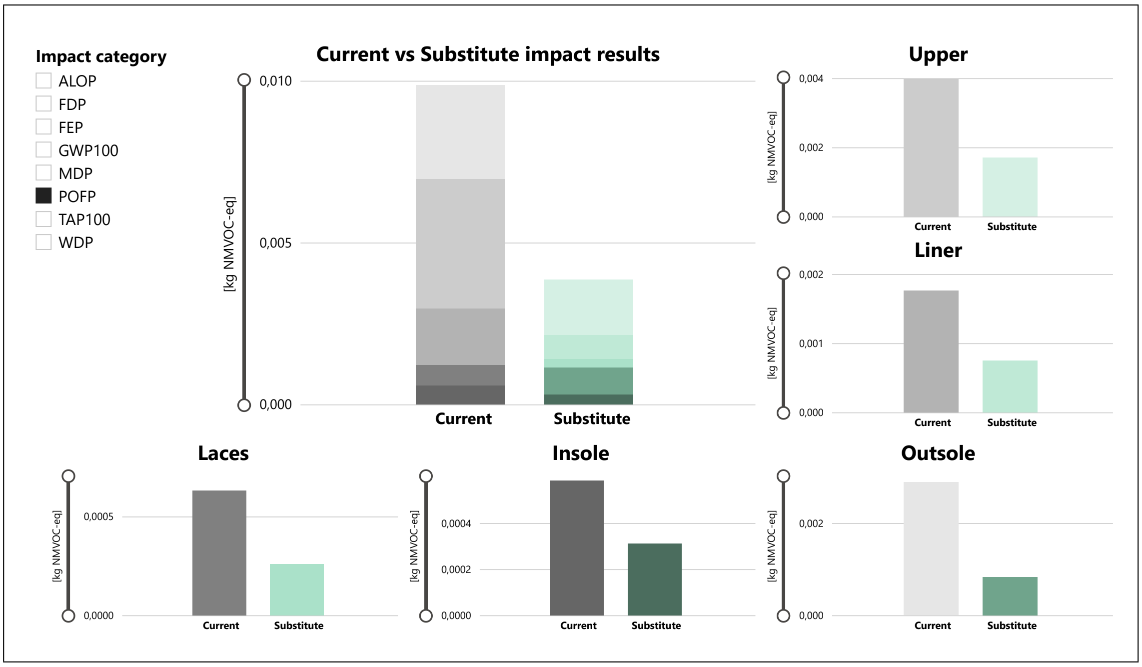


Figure C.12: POFP results visualization on Microsoft Power BI for the traditional and DfHM scenarios for the casual shoe model

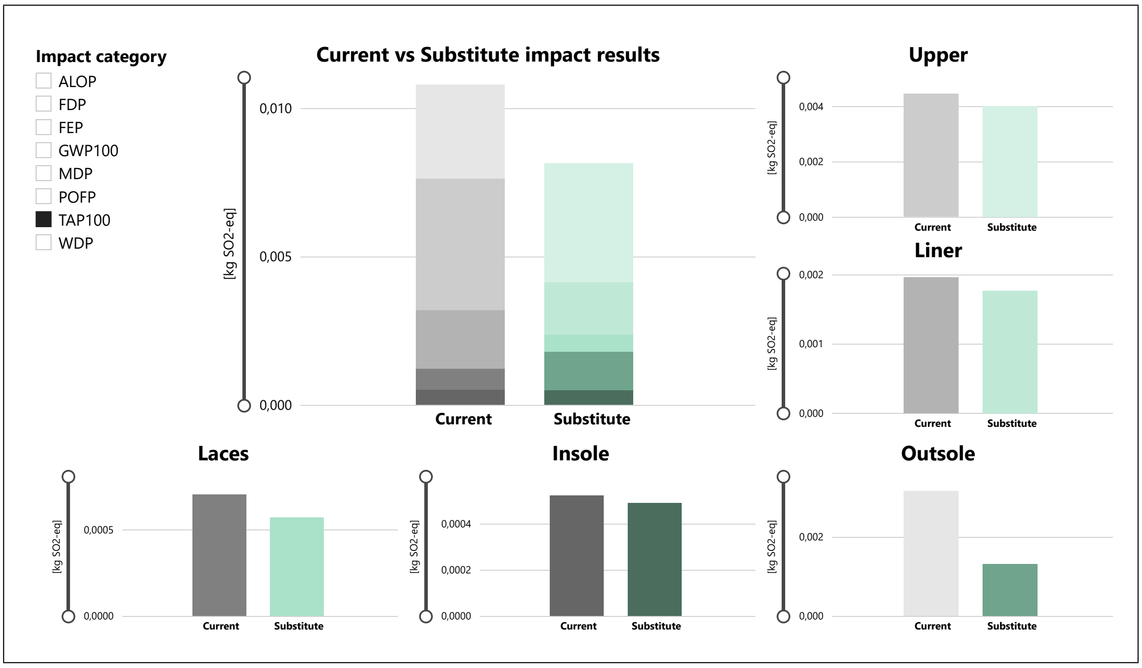


Figure C.13: TAP results visualization on Microsoft Power BI for the traditional and DfHM scenarios for the casual shoe model

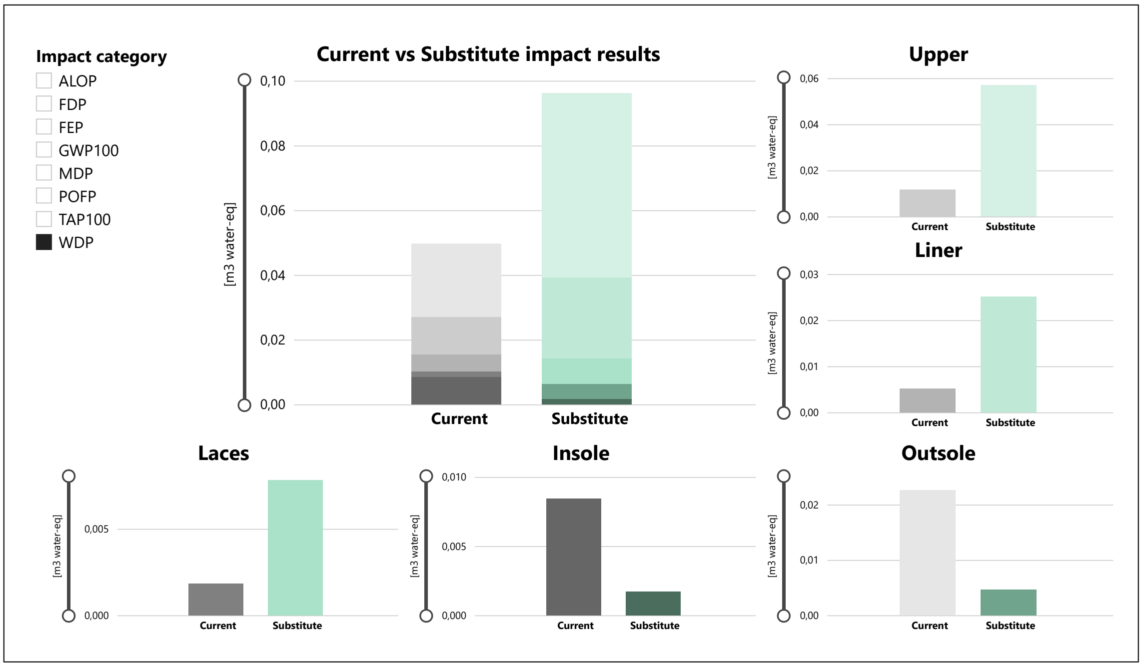


Figure C.14: WDP results visualization on Microsoft Power BI for the traditional and DfHM scenarios for the casual shoe model

Design for use of Recycled Materials

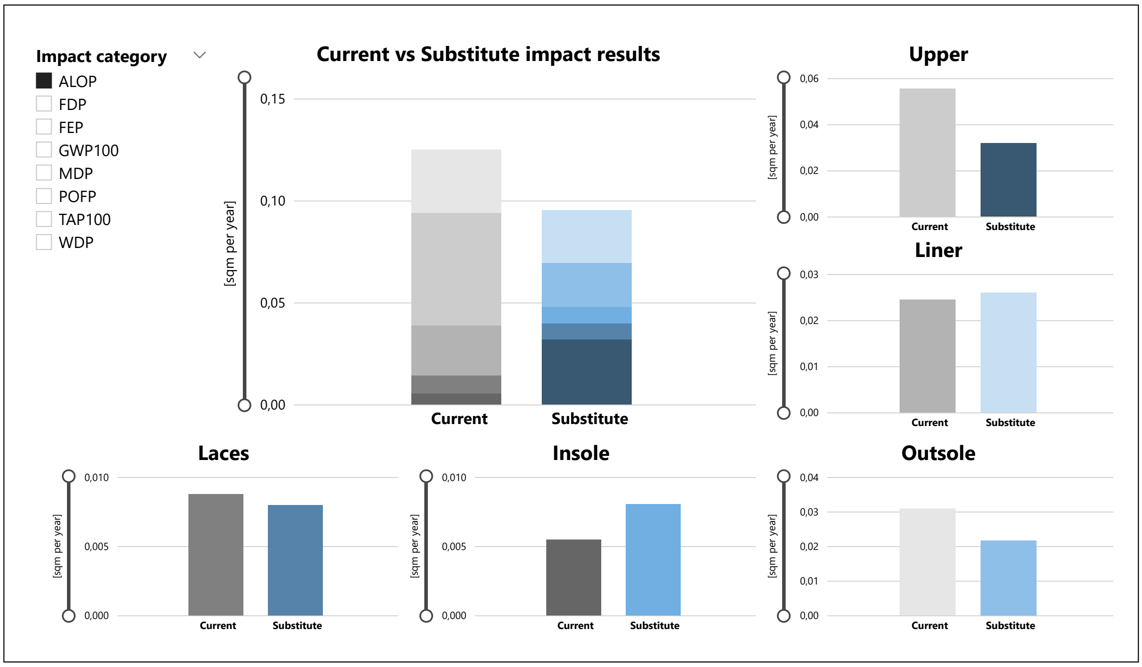


Figure C.15: ALOP results visualization on Microsoft Power BI for the traditional and DfRM scenarios for the casual shoe model

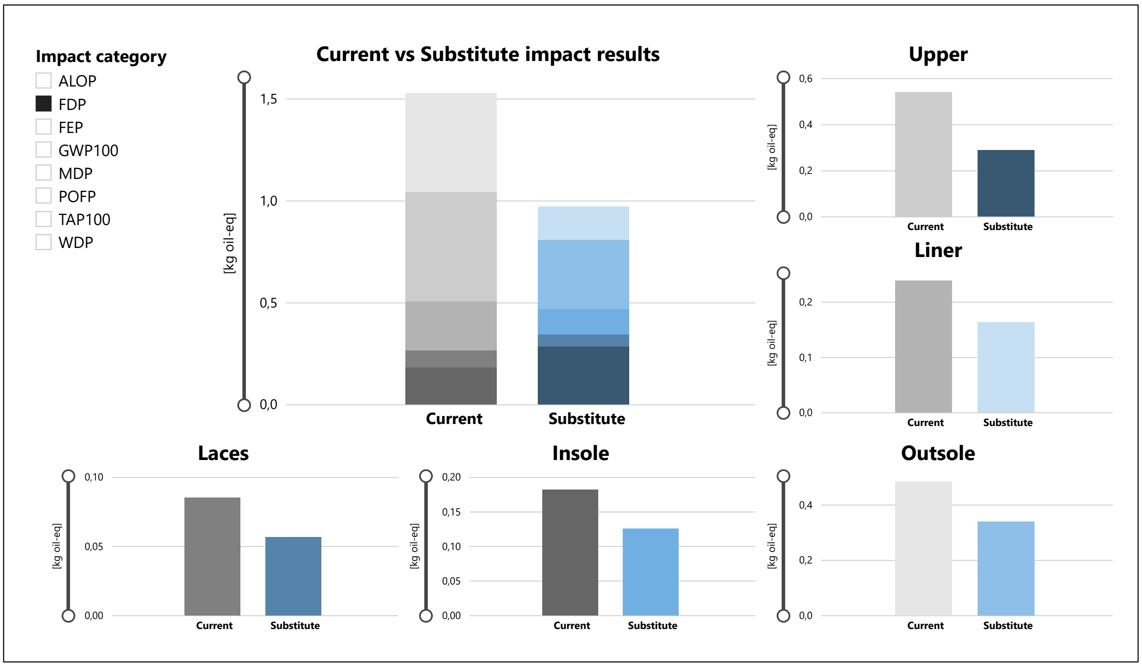


Figure C.16: FDP results visualization on Microsoft Power BI for the traditional and DfRM scenarios for the casual shoe model

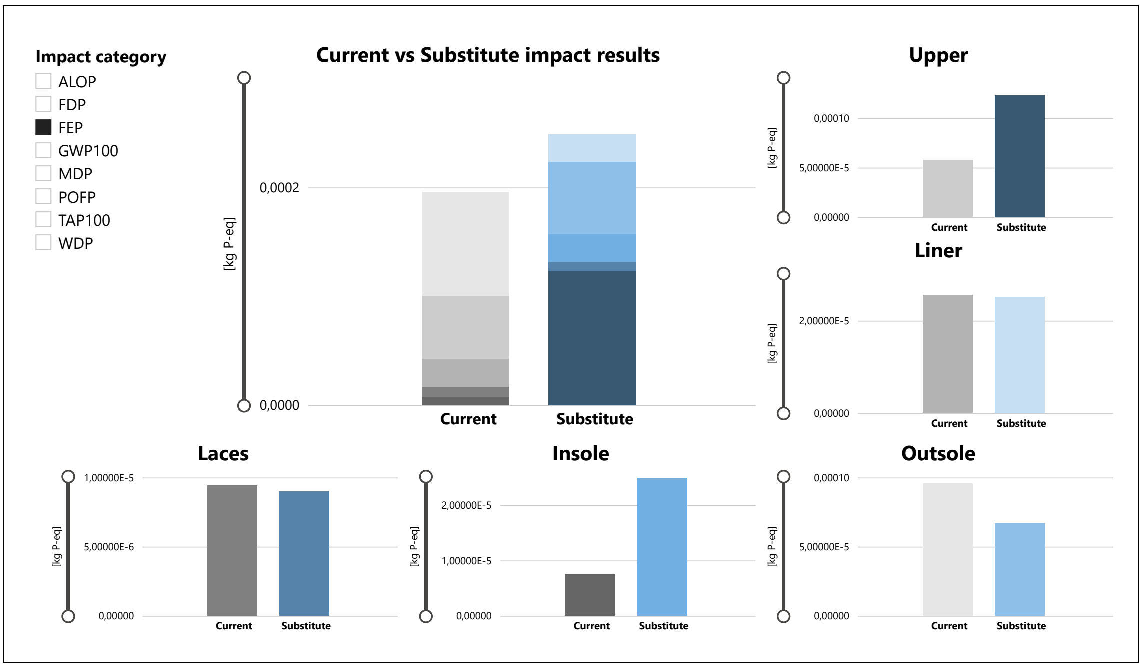


Figure C.17: FEP results visualization on Microsoft Power BI for the traditional and DfRM scenarios for the casual shoe model

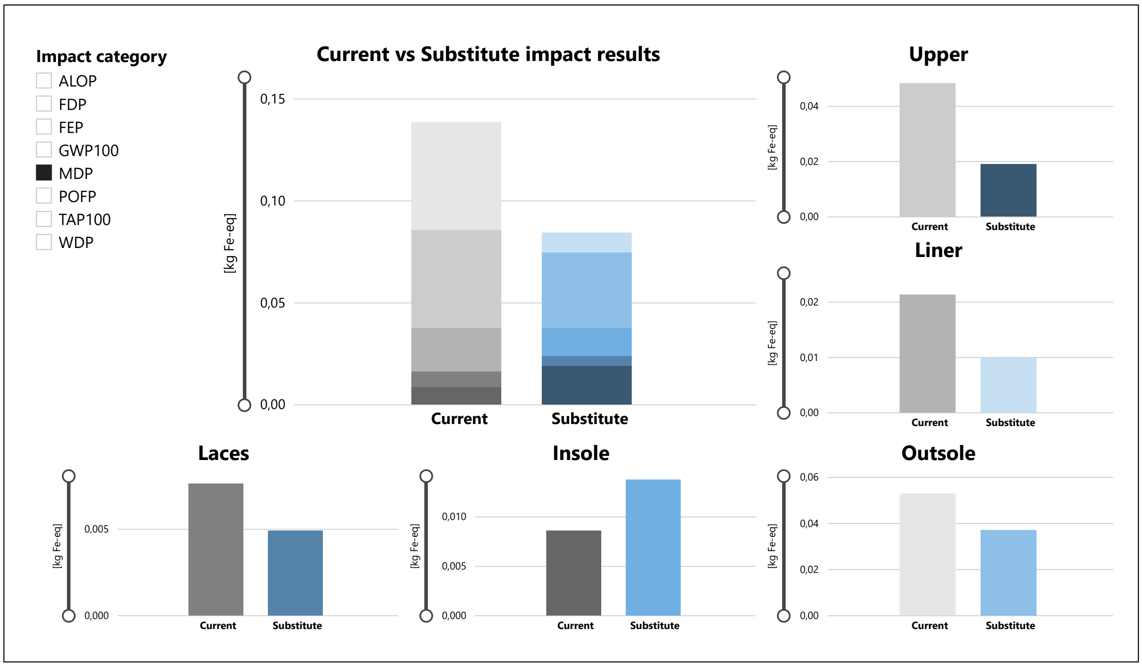


Figure C.18: MDP results visualization on Microsoft Power BI for the traditional and DfRM scenarios for the casual shoe model

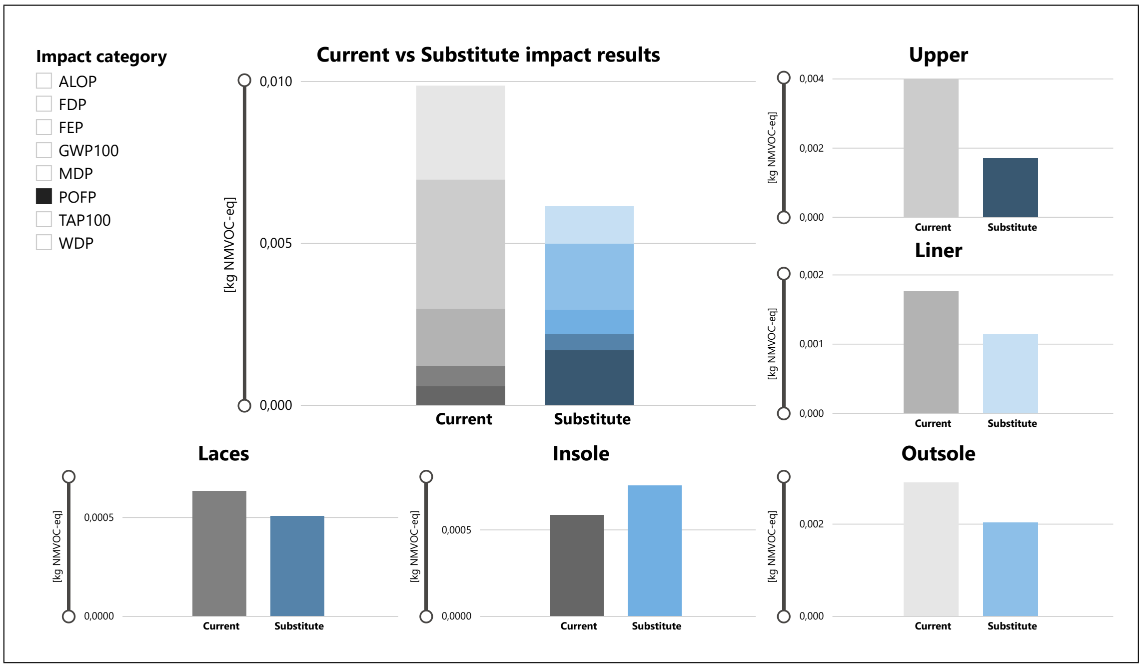


Figure C.19: POFP results visualization on Microsoft Power BI for the traditional and DfRM scenarios for the casual shoe model

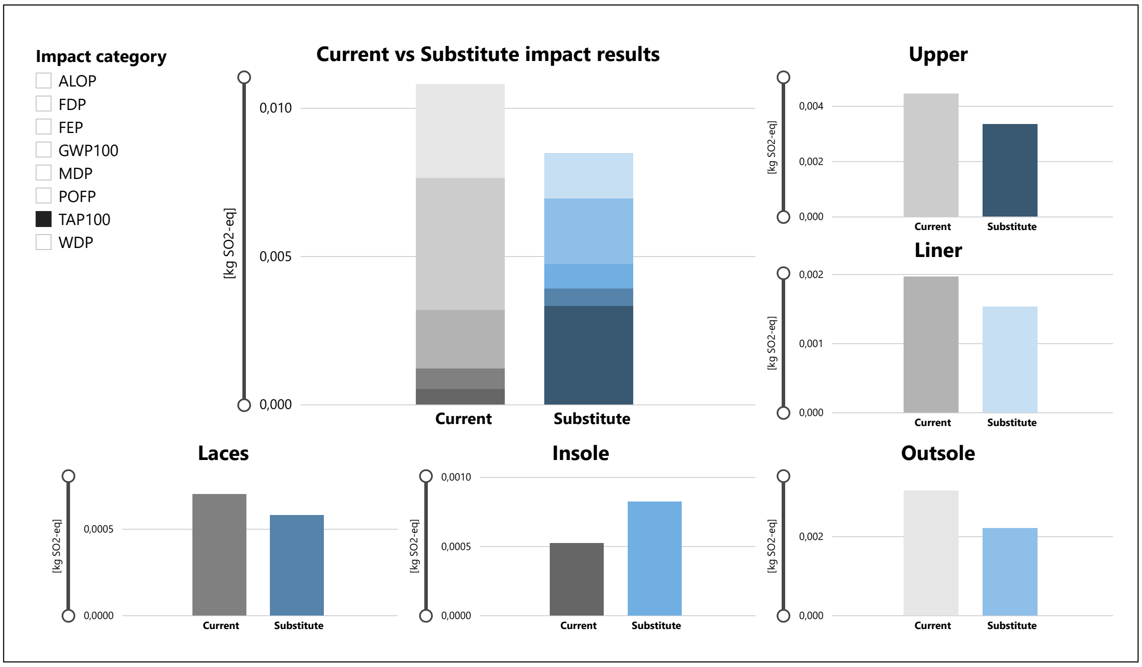


Figure C.20: TAP results visualization on Microsoft Power BI for the traditional and DfRM scenarios for the casual shoe model

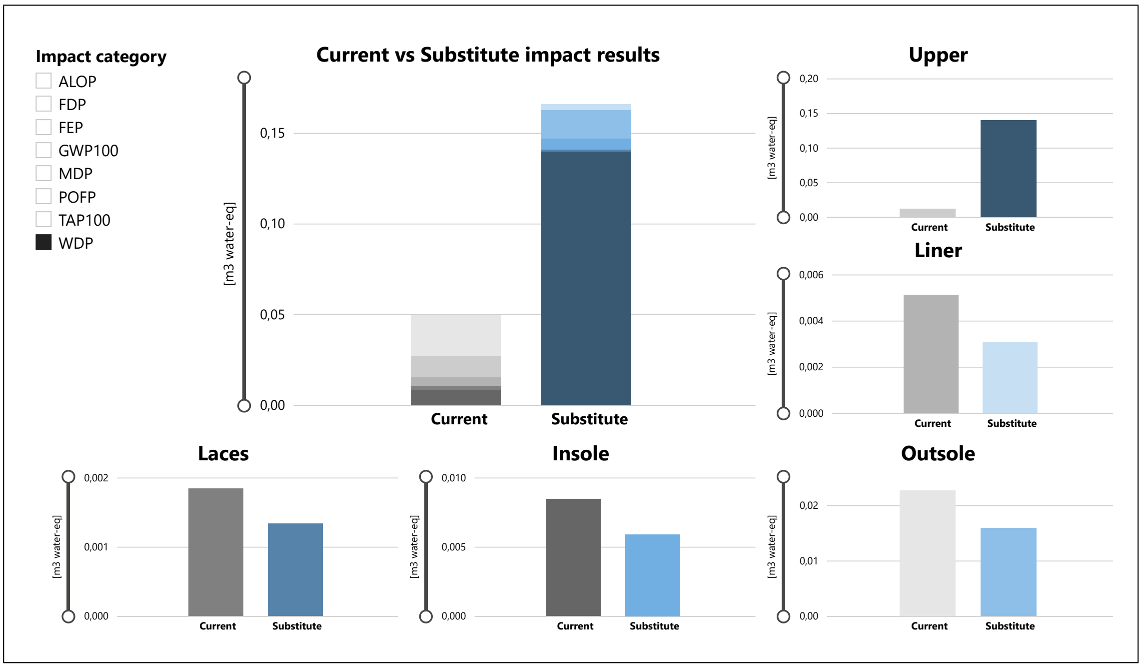


Figure C.21: WDP results visualization on Microsoft Power BI for the traditional and DfRM scenarios for the casual shoe model

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