The potential environmental benefit of the ecodesign approach: a case study in the footwear industry

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Abstract: The goal of this work is to couple the ecodesign approach with the Life Cycle Assessment (LCA) methodology to understand how different ecodesign principles affect the environmental impacts supporting the selection of the materials employed in the manufacturing of the final product. Specifically, we focused on the footwear sector, by firstly, modelling 21 different materials, secondly selecting two ecodesign principles, and ultimately comparing a traditional footwear with the two alternative compositions representative of the ecodesign principles. The results indicate that, for most impact categories considered, the designs employing traditional materials have the highest average impact.

1. Introduction

According to the definition provided by the European Commission, Ecodesign refers to the integration of environmental aspects into the product design with the aim of improving the environmental performance of the product throughout its whole life cycle (Directive 2009/125/EC, 2009). It involves the estimation of the environmental impact of the product at every stage of its development, from the selection of raw materials to the disposal of the product at the end of its useful life (Herva et al., 2011). The approach also considers the social and economic impacts of the product, ensuring that it is not only environmentally sustainable but also socially responsible and economically viable (Borchardt et al., 2011). In recent years, the ecodesign approach has gained importance due to the increasing awareness of the impacts of human activities on the environment. Consumers are becoming more environmentally conscious and are demanding products that have a lower impact on the environment (Liu et al., 2012). Ecodesign can bring many benefits to businesses, including cost savings through material efficiency, reduced waste and energy use, improved brand image, and increased market share. It can also provide a competitive advantage, as consumers are increasingly choosing environmentally responsible products (Borchardt et al., 2011; García-Sánchez et al., 2020).

In this work, we focused on the quantification of environmental effects due to ecodesign approach in the footwear industry. Being part of the fashion industry, which is one of the most polluting sectors (Boström & Micheletti, 2016), the footwear industry contributes significantly to the environmental impact (Luximon & Jiang, 2016). From 2010 to 2018, the footwear production increased by 20.5% (Muthu & Li, 2021), with 24.2 billion pairs of footwear manufactured in 2018 (APICCAPS, 2019). The increased production is directly related to the excessive consumption of

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shoes, associated with the progressive reduction in the useful life of footwear (Van Rensburg et al., 2020). These trends lead to environmental impacts along the entire life cycle of footwear. The high production causes the exploitation of more resources and the use of more energy, while the increased consumption leads to a larger amount of waste that needs to be disposed of (Van Rensburg et al., 2020). Furthermore, for the manufacturing of a footwear 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 (Caniato et al., 2012; Van Rensburg et al., 2020). For this reason, there is a growing trend to replace traditional materials either with biogenic and fully biodegradable materials, animal-free or without the use of any harmful substances. Designers and producers are trying to develop these innovative materials from domestic waste, sawdust, or organic garbage (Meyer et al., 2021).

In the latest 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 policy-makers (Cheah et al., 2013). 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 (Quantis, 2018). Companies in the footwear industry can reduce their environmental impact by following the ecodesign principles when developing new products (Cimatti et al., 2017). Ecodesign can be implemented according to differen actions on the Footwear Life Cycle to reduce its environmental impact, such as choosing materials that have a longer lifespan or creating a product that is easy to be disposed of or recycled (Borchardt et al., 2011). The ecodesign principles need to be combined with Life Cycle Assessment (LCA) in order to estimate the environmental impacts of the product, identify hot spots, and further improve the designed product (Muñoz, 2013). 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. The ecodesign principles, coupled with the LCA, constitute a promising strategy to reduce the environmental impact by guiding the innovation process of new products (Borchardt et al., 2011). However, an ecodesign tool is not currently available, which implies that each company integrates independently the ecodesign principles and the LCA in their innovation process. This is not always straightforward since it requires implementation costs, dedicated resources, and data management.

The objective of this study is to integrate the ecodesign principles within the LCA to support industrial innovation by including the analysis of environmental sustainability aspects in the traditional innovation process of new products. To achieve this purpose, we attempt to answer the following research question (RQ):

> **RQ.** How the environmental impacts may vary by changing the materials for the components of a shoe according to the proposed ecodesigns?

2. Materials and methods

To answer our RQ, the study was conducted following the procedure reported in **Error! Reference source not found.**. To understand the most common ecodesign principles and the materials used in each ecodesign principle, we conducted a benchmark analysis of companies in the footwear industry. The companies were selected based on their presence in terms of product campaigns on major sectoral websites. The sample considered comprises a total of 71 companies. We examined the shoes created by the chosen companies and, if present, the shoes made with alternative materials such as natural or recycled materials. Among the sample considered, 45

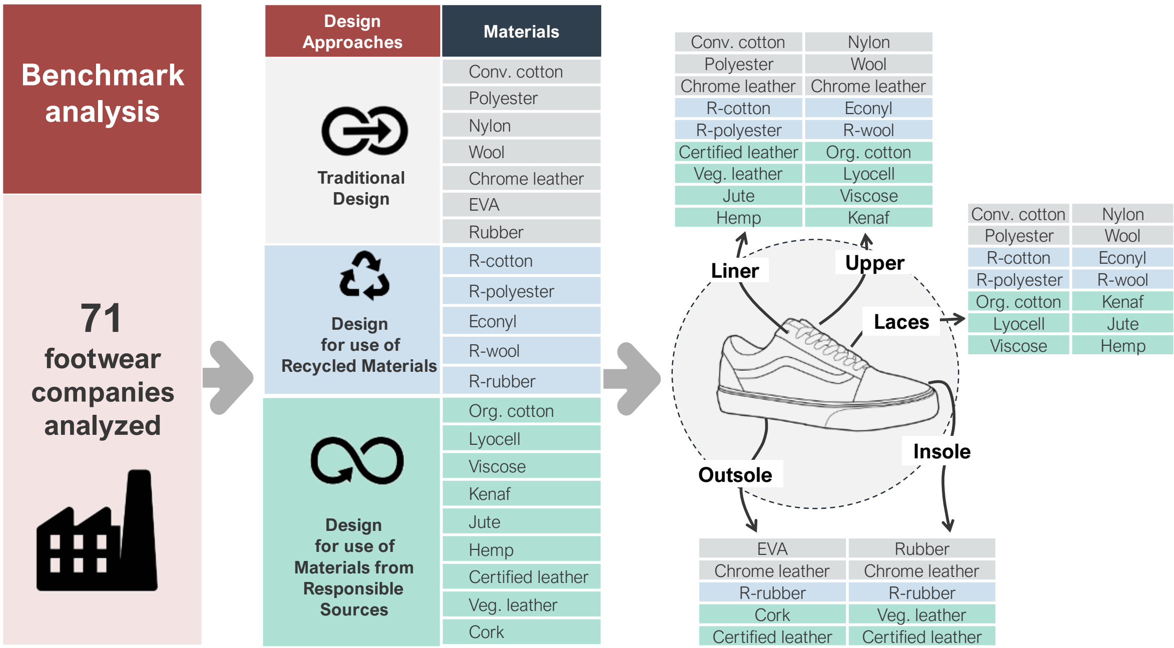

Figure 1. Methodologic framework followed in the study. The materials were classified according to the following definition of the ecodesigns considered: Design for Use of Recycled Materials: the shoe is made from recycled or reused materials ; Design for use of Materials from Responsible Sources: the shoe is made with materials from responsible sources, materials safe for human health, or use of natural materials.

companies realize at least one model with an ecodesign approach. The ecodesigns that were found to be most prevalent were those related to the use of recycled or reused materials, named Design for use of Recycled Materials (DfRM), and to the use of materials from responsible sources, such as certified suppliers, materials safe for human health, or use of natural materials, such as hemp and organic cotton, referred to as Design for use of Materials from Responsible Sources (DfMRS). In order to compare these two ecodesign solutions and to understand their potential, we consider also traditional materials.

Shoes usually are made from different materials and many parts (Weib, 1999). In this study, we considered the main footwear component, such as the upper, liners, laces, insole, and outsole. No other components were considered, such as glue, metal parts, and reinforcements, since it was decided it was best to consider the most characteristics of a shoe and those that are most relevant in its composition, in terms of overall weight (Gottfridsson & Zhang, 2015). The shoe composition considered in our study relates to the Bellamont Plus model of the Italian footwear company Aku (Aku, 2018). The weights of the shoe components are given in Table 1 and refer to the amount of material actually used in the component without taking waste into account. The total amount of components considered covers 62% of the shoe's overall weight. We considered a total of 21 materials that can be employed in the various parts of the footwear, classified according to the ecodesign considered (**Error! Reference source not found.**). For each material, the system boundaries comprehend all production processes of the component, from the raw material extraction to the manufacturing of the component ready to be used by the footwear manufacturers (i.e. gradle-to-gate, where the gate is the component manufacturer). The analysis did not consider the transport from the component manufacturer to the footwear manufacturer as well as the assembly of the footwear assuming that those steps of the life cycle reasonably do not significantly change by changing the component used. Furthermore, the use phase was not included in the system boundaries. Regarding the modelization of the recycled materials, the recycling process were included in the system boundaries. The functional unit (FU) considered is the shoe considering the composition reported in Table 1. The physical properties and durability of materials were not considered since at the moment there is not a framework that allows to integrate the performances of the materials into a product. Life Cycle Inventories (LCIs) were constructed using data available in the Ecoinvent 3.6 database with the cut-off system model or, as a second choice, from LCA studies in the literature. Europe was chosen as the location of the processes taken from the database, and 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. Since many of the materials were modelled using secondary data available in the Ecoinvent 3.6 cut-off, no allocation were performed, while for the leather an economic allocation was applied to the cattle breeding stage, according to Milà et al., 1998.

Shoe component	**Weight [g]**
Upper	169.6
Liner	74.8
Laces	26.8
Insole	114.8
Outsole	206.8

Table 1. Weights of the shoe components considered, adapted from the Bellamont Plus model of the Italian footwear company Aku (Aku, 2018).

The Life Cycle Impact Assessment (LCIA) is computed with the use of Brightway2. The environmental impacts were computed considering ReCiPe as the impact assessment method, choosing the Midpoint (H) V1.13 no LT version. The impact categories were selected in accordance with the product categories rules (PCR) for leather footwear (Synesis Consortium & ITIA-CNR, 2019), Bovine Leather (Aequilibria S.r.l. 2011) and textiles materials (Aquafil, 2022) and from the general guidelines for the EPD (Environdec, 2023).

In order to answer the RQ, we computed the potential overall impact of the shoe for the traditional and the 2 ecodesign scenarios considered. This was achieved by computing the average environmental impacts and, to evaluate the worst and best-case for each of them, we considered the maximum and minimum potential impacts. Hence, the average environmental impacts $\bar{I}_{i,e}$ of the entire shoe were computed according to the following equation:

$$\bar{I}_{i,e} = \sum_{c_e} \left(\frac{1}{M_{c_e}} \sum_{m_{c_e}} \mathcal{I}_{i,m_{c_e}} \right) * w_c \tag{1}$$

Where:

- M_{c_e} is the number of materials employed in the component *c* associated with the ecodesign *e*.
- $\mathcal{I}_{i,m_{c_e}}$ is the impact of the material m, employed in the component *c*, associated to the ecodesign *e* for the impact category i, according to the functional unit (1 kg).
- w_c is the weight of the shoe component *c* according to the shoe composition considered (Table 1).

Similarly, we computed the impacts associated with the worst and best-case scenarios for every ecodesigns, with the following two equations:

$$I_{min_{i,e}} = \sum_{c} \left(\min_{m_{ce}} (\mathcal{I}_{i,m_{ce}}) \right) * w_c \tag{2}$$

$$I_{max_{i,e}} = \sum_{c} \left(\max_{m_{ce}} (\mathcal{I}_{i,m_{ce}}) \right) * w_c \tag{3}$$

We made these calculations by assuming a perfect substitution between alternative materials, meaning that the weight of the component is assumed to be independent with respect to the material used and that the materials have the same lifespan. These assumptions were made to facilitate the calculation process and enable a straightforward comparison between different materials. However, it is crucial to acknowledge that these assumptions may not always be valid in practical scenarios and can potentially affect the accuracy of the results. For example, leather and cotton have distinct physical characteristics, such as different densities and durability.

3. Results and Discussions

In this section, we report the main findings of our research study, starting by showing the LCIA results for each material considered. **Error! Reference source not found.** reports the comparison of the environmental impacts of the materials considered in the analysis. Each subplot shows the results for every impact category considered. The results are presented in relative terms, meaning that the impact of the materials is compared to the material with the highest impact for each impact category. The LCIA results show that the traditional materials have higher environmental impacts, across many of the impact categories, compared to the alternative ones. For some of the impact categories, some materials have far greater impacts than others. For instance, wool has the greatest impact on agricultural land use, global warming, photochemical oxidant formation and terrestrial acidification, while conventional cotton has the most significant impact on water depletion. Interestingly, some responsible and recycled materials have

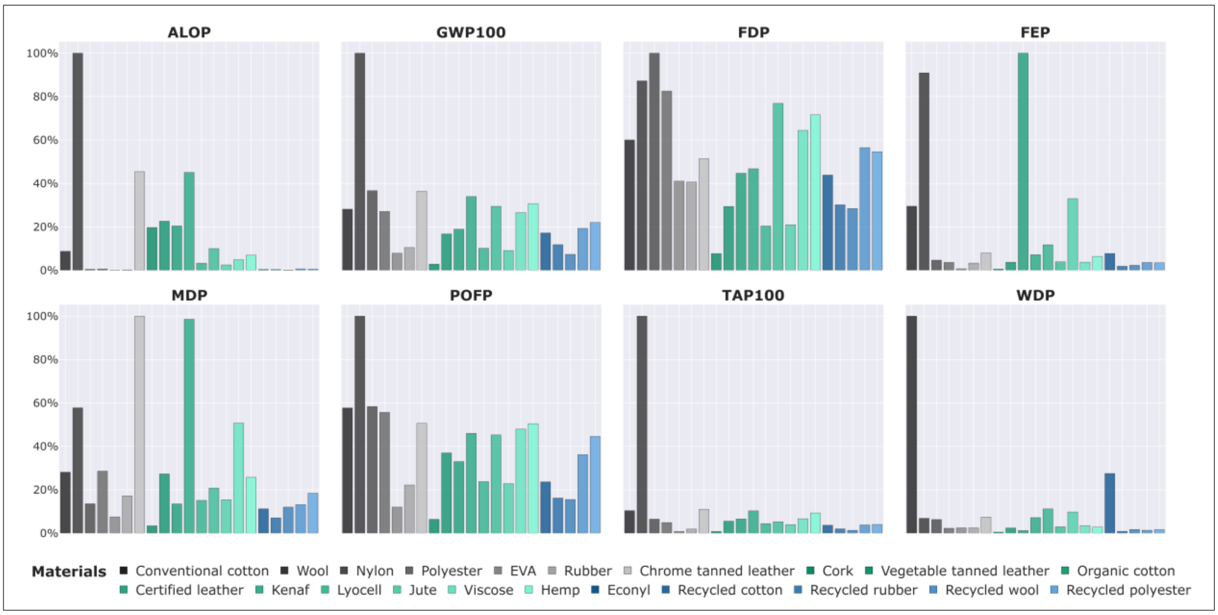

Figure 2. LCIA results for materials considered in the study, referred to the FU. The different shades of the bar color identify the ecodesigns, traditional materials are indicated with shades of gray, materials associated to ecodesign DfRM with shades of blue, while responsible materials (DfMRS) with shades of green. Impact categories: ALOP=Agricultural Land Occupation Potential; GWP=Global Warming Potential; FDP=Fossil Depletion Potential; FEP=Freshwater Eutrophication Potential; MDP=Metal Depletion Potential; POFC=Photochemical Oxidant Formation Potential; TAP=Terrestrial Acidification Potential; WDP=Water Depletion Potential.

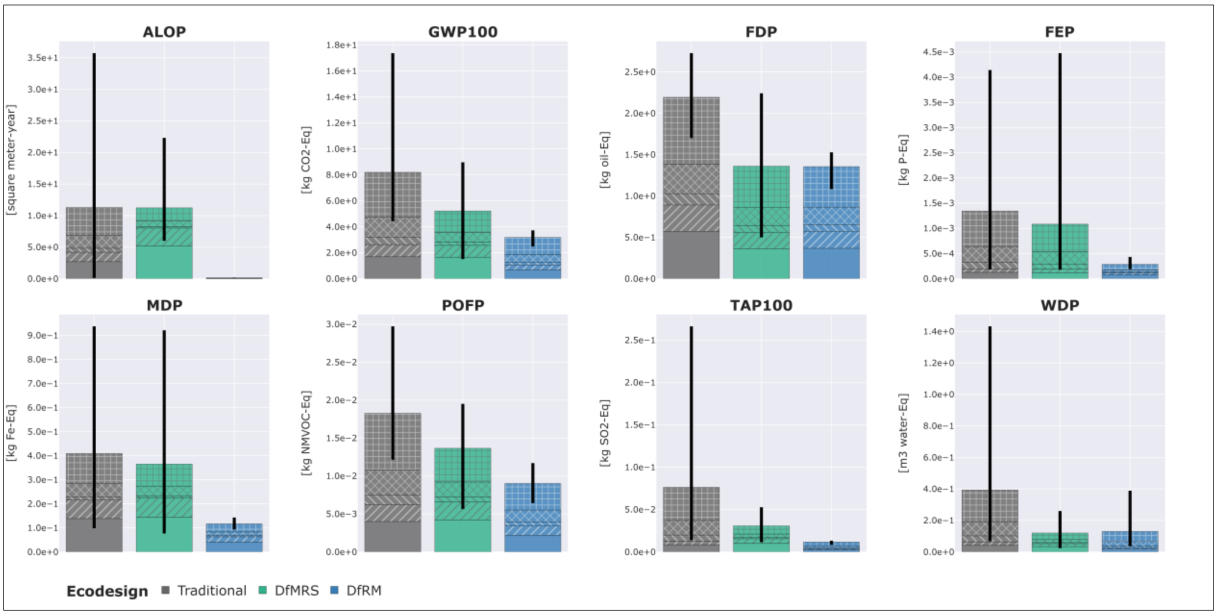

Figure 3. Results obtained for the traditional and the 2 ecodesign considered, subdivided between the impact categories. The bars shows the average impact of the shoe, while the impact range due to the possibles shoe compositions are highlighted with the black line . Finally, the different patterns indicate the contribute of each shoe components: None=outsole; "//"=insole; "\\"=laces; "x"=liner; "+"=upper. Impact categories: ALOP=Agricultural Land Occupation Potential; GWP=Global Warming Potential; FDP=Fossil Depletion Potential; FEP=Freshwater Eutrophication Potential; MDP=Metal Depletion Potential; POFC=Photochemical Oxidant Formation Potential; TAP=Terrestrial Acidification Potential; WDP=Water Depletion Potential.

comparable impacts to conventional materials, while others actually have the potential to mitigate environmental impacts. The hypothesis made in modelling the LCA of the materials could strongly affect the results. Furthermore, some of the materials were modelled 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. The results for the entire shoe, according to the shoe composition considered in Table 1, and to the ecodesigns are reported in **Error! Reference source not found.**. The bars of the plot in the figure correspond to the average impact for each design scenario, computed according to equation (1), while the black line indicates the range of potential impacts from the minimum to the maximum value, computed with equations (2) and (3), respectively. From the results, it can be seen that the traditional design has the highest impact across almost every impact category. Comparing the average impacts achievable with the 3 designs considered, i.e. the bar in the graphs, the design that seems to have the lowest impact for most of the categories is the ecodesign DfRM. However, if we focused on the minimum impacts achievable and for some categories, such as global warming, fossil depletion and photochemical oxidant formation, the lowest impacts are associated with the ecodesign DfMRS. This demonstrates that a careful design, substituting traditional materials with alternative ones, is paramount to reducing the potential environmental burdens.

4. Conclusions and future works

The objective of this study was to evaluate the potential environmental impacts through the integration of the ecodesign approach with the LCA methodology in the innovation process of a footwear, resulting from a careful selection of materials to be used in its manufacturing. We considered a total of 21 materials, identified by a benchmark analysis of the footwear industry among the most commonly used materials. Then, we linked these materials to a design principle, i.e. traditional design, and the ecodesigns DfRM and DfMRS. The study focused on the impacts related to the production of the materials, excluding from the analysis the footwear assembly, and the end of life. The results showed that a shoe made with traditional materials has a higher impact across most of the impact categories. For the global warming impact category, employing responsible and recycled materials can reduce the average potential impact by 36% and 61%, respectively. While the minimal potential impact for this category is achieved through a specific shoe composition made of responsible materials. Finally, DfRM resulted to be the ecodesign principle with the lowest average impact, across the majority of the impact categories.

As a research study, this work has limitations. Firstly, the results obtained were computed considering a perfect substitution between the materials, also in terms of reference flow, and secondly assuming the same durability for all the materials. An important improvement in future studies is the introduction of the variability of these two aspects in the analysis to enhance reliable comparisons. An additional limitation of the case studies developed is the exclusion of the technical design in the choice of the footwear composition. This means that the ecodesign analysis should be performed together with a design team that evaluates the performances and compatibility of materials in the footwear products.

A second limitation was related to the fact authors considered data based on avaliable disclosed LCA profiles for footwear materials (research paper and registerd studies). A further refinement should imply also a homogeinization of LCA Materials category rules among different components also under accounting perspective and perfect substitution hypotesis.

Additionally, the work can be improved by considering other components of the shoe (reinforcements, midsoles, glue and adhesives, eyelets, and the packaging), additional available materials, and other design principles (e.g. biodegradable materials, low variety of materials, etc.). Including the aforementioned improvements may lead to a more comprehensive analysis of the potential reduction of environmental burdens resulting from this approach. This study represents the first step in the application of ecodesign principles, demonstrating the potential benefit of this approach in the innovation process of products in the footwear industry. In particular, the study poses a basis for a quantitative-conscious ecodesign of footwear aiming at concurrently considering both ecodesign strategies together with environmental hotspots related to specific footwear materials. Similarly, this approach could be beneficial for the sectors employing a high variety of materials, for instance automotive, cosmetics, etc.

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