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Functional Unit definition in a circular economy perspective: implication for LCA normalisation for a footwear outsole

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Abstract

It is a significant challenge to address the complex issue of comparing multiple products with the same function but distinct characteristics in the circular economy framework and its implications for Life Cycle Assessment (LCA) in the footwear sector. Our strategy involved developing a specific methodology for determining the durability characteristic of physical products, which was accomplished by combining the results of various physical tests. In particular, a set of urban soles was examined for the case study. The environmental footprints of the footwear were then normalised using this durability metric, aligning them with the number of units required to reach practical quality levels. Using this method, we achieved substantial changes in the results of the LCA analysis, particularly in the context of products whose design prioritised particular qualities like durability. As a result, this research emphasises the necessity of redefining the functional unit, particularly from the circular economy perspective, and illustrates how it may positively impact company eco-design policies.

Keywords: LCA; Durability; Footwear; Circular economy;

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1. Introduction

1.1. General framework

In the last decades, the world growing awareness of environmental themes has rapidly spread the use of life cycle assessment (LCA) studies, both at the research and policy levels. This increase in the number of studies involving different assumptions has generated the sometimes problematic situation of a lack of solid standardisation in the LCA community [1]. While several systems have been proposed and implemented to standardise modelling approaches in LCA and ensure comparability in results, from Product Category Rules (PCR) [2] to Product Environmental Footprint Category Rules (PEFCR) [3], the complexity of the task makes the comparison of multiple products a relevant challenge. According to the ISO standard [4], LCA has been defined as the inventory and assessment of a product system's inputs, outputs, and potential environmental impacts throughout its life cycle. ISO standards claim that a system may have a number of possible functions intended as services towards users or society and that the ones selected for a specific study depend on the goal and scope of the LCA study itself. The functional unit (FU) aims to fix a specific function for a product or service, quantify related flows and assess produced environmental profile [5]. The primary purpose of a FU is to provide a reference framework for modelling and to relate both inputs and outputs. When required, comparisons between systems should be made only based on the same function, quantified by the same FU in the form of their reference flows [5]. As stated before, several functions can be identified for a specific product or service, but only a specific FU can be defined to perform an LCA in an attributional or consequential approach. Such function overlap can generate multiple results, leading to remarkable differences in conclusions and outcomes in the evaluations and comparison of products. FU identification represents a key issue in performing LCA in several fields, from food [6; 7], and the fashion industry [8] to building development [9; 10], and mining [11], and should be one of the most researched topics tied to the advancing of LCA practices. The development of products designed to have a longer Life

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Span (LS) and higher durability, referred to as ”designed for durability”, can represent a serious modelling issue. Since the same FU requires to be defined for a fixed time span, high performance can be referred to multiple attributes within the same product under different use conditions and for different periods [1]. However, solutions considering the length of use should be analysed differently than those not considering product obsolescence [12].

1.2. Issue and case study

The present paper examines the application of obsolescence rules in FU for a footwear product. Nowadays, the fashion industry is one of the most relevant sectors of the world manufacturing industry, with 2.7 kg of footwear consumed per person every year in Europe [13]. This consumption has a significant environmental impact, caused mainly by the materials used during the production phase of all its components. In fact, shoes, at the end of their functional life, are often disposed of in landfills, and this is a consistent waste stream related to the footwear industry. At the design stage, some aspects can be considered to allow these products' potential reuse or recycling: the type of materials they are made of, their diversity, and the possibility of separating components [14]. Another critical aspect to consider related to footwear is safety: shoes are expected to protect feet, provide comfort, and enhance performance during various activities. As reported in Inail book about the fall risk assessment, in Italy falls on the floor represent the third leading cause of accidents in all industries, with total costs (direct and indirect) of injuries amounting to approximately 370 million euros per year; thus, sufficient friction force provided by footwear is necessary to promote walking safety [15]; moreover, shoes should deliver effectual slip resistance against any situation. Shoe tread and its changes over the life of the shoe have an impact on the tribology interaction at the shoe-floor-contaminant interface, and accordingly, micro- and macro-tread patterns of the shoe surface can be significantly modified and adapted to the necessities [16; 17]. Several LCA studies have been realised on the footwear sector, defining both the final product and its components, but they were developed based on an attributional approach that commonly does not take into account the LS of the footwear itself. As shoe obsolescence can vary significantly, in this work, we focused on this aspect and how this difference in LS can change the results of a product LCA analysis. Starting to develop a method to define footwear LS, it was clear the complexity of this paper goal, as obsolescence can be caused by several drivers, from physical (e.g. tears or other damages) to social (e.g. loss of appeal)[13]. In particular, in this work, we focused only on physical obsolescence by omitting perceived obsolescence, including cultural-based drivers such as social recognition and acceptance. It was decided to summarise the research question (**RQ**) as follows: How are environmental profiles affected by adopting a durability-dependent functional unit in the footwear sector?

To answer this question, it was decided to focus the work on the physical durability of the good. In particular, this study focuses on footwear sole (intended as the sum of midsole and outsole), as it is one of the two main components (sole and upper) and the only one with wear that is time-dependent and not directly tied to one-off events. This study focuses on four types of soles that should be fitted on shoes for urban use. This choice influences the FU definition, as the characteristics that were considered in this study, and their relative weight in the normalisation process, depend on the function that the sole would end up fulfilling.

2. Materials and Methods

Durability is intended as the ability of a physical product to remain functional without requiring excessive maintenance or repair when operating in its use phase [18]. Durability also identifies how long a product can be used before it needs to be replaced or repaired [19]. It can be determined by measuring the product's expected lifetime, the number of repairs or replacements it shall require over time, and its expected performance. In this case, performance is intended as how a product works, measures up and meets customer expectations as a physical feature along a specific LS. It must be noted that ISO 590220 while defining the durability concept do not provide specific guidance on the measurement and calculation of said parameter[18]. Durability is also considered a key concept in LCA since FU is referred to a specific LS. Proper attribution of such LS can be complex since a different set of service levels and threshold values can be identified for each product family. Firstly, a specific Use Pattern (UP) must be defined, representing how a physical product is used. Then the decaying of each functionality under a specific threshold value requires ending the LS and the substitution of the product.

In general, four possible approaches to determining the LS can be identified (Fig.1):

1. **Avoiding LS attribution.** A pure accounting perspective is applied, and the reference flow corresponds to a physical reference element (e.g. 1sq.m. of a fabric) independently of its actual use. The products' use conditions under this approach cannot be determined a priori due to their wide variety of uses and possible applications in other downstream life cycles.
2. **LS attribution by a standardised test.** The product life is matched to a specific threshold value under a specific UP, reached after a certain number of uses, through a standardised method referring to a single attribute (e.g. colour tone over time) or a set of them. In this case, the LS is determined by a single test and a single value following sectoral agreements.
3. **Multiple LS attribution.** There are different ways to assess product durability and related LS. The functional unit is matched to a vector of functional attributes. The strategies for identifying the LS within this performance space may differ. For example, LS can be identified as the lowest one attributable to a product characteristic (e.g. durability of the least resistant component), or a single physical ref-

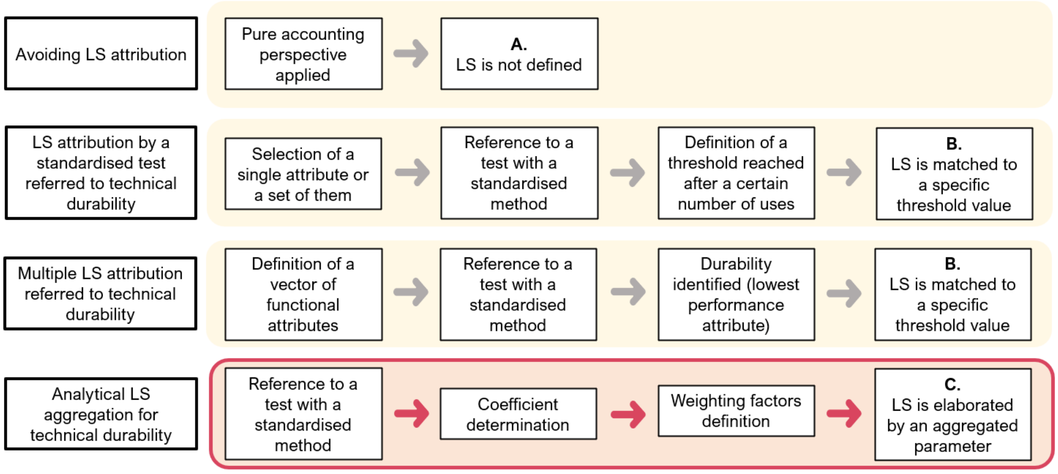


Fig. 1. Graphical representation of possible approaches for Life Span identification.

Soles	Abbreviation	Description	Sole weight [g]
Recycled 1	**R1**	first recycled product, recycled content 15% w/w	508.85
Recycled 2	**R2**	second recycled product, recycled content 20% w/w	517.70
High performance	**HP**	product designed for increased durability	500.00
Traditional	**T**	traditional product, not eco-designed	517.70

Fig. 2. Different typologies of analyzed soles, with relative description and weight. (w/w= weight on weight)

erence feature can account for all features (e.g. abrasion test as proxy for product duration).

4. **Analytical LS aggregation.** In this case, the LS is represented by an indicator obtained by aggregating several physical performances into a single indicator. This study focused on the fourth method, starting with an attributional approach and implementing consequential elements considering the number of items needed to comply with a reference FU.

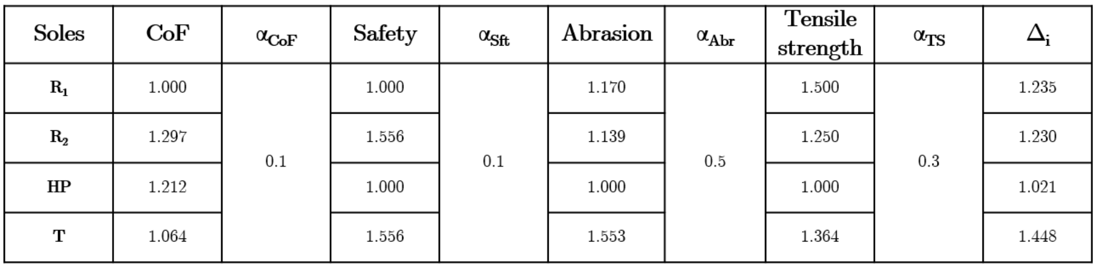
In particular, we decided to select four soles to be used as reference products, using them as references to define the variability that adopting a normalised method should generate. The four products studied are described in Fig. 2.

In the last decades, several methods have been developed to test the physical characteristic of footwear, from abrasion tests to SATRA's Pedatron [20] , but defining the effective LS of a shoe is difficult, as it cannot be directly tested. As several factors can influence the shoe LS, we combined four parameters, Coefficient of Friction (CoF), Safety, Abrasion and Tensile Strength (TS). The testing of the four parameters was conducted based on ISO standards (Coefficient of friction [21; 22], Abrasion [23] and Tensile strength [24]) and the experience of a quality laboratory (Safety). Then the results were normalised on the maximum value for each tested parameter. The resulting values can be seen in Fig. 3. To calculate a unique parameter that would represent the sole's durability, each parameter would be weighted using the factor αp and then used to multiply the environmental burdens tied to the sole production in order to normalise the effect of the durability on the sole LS and consequently on the sole's burden. αp has been defined as an arbitrary factor for each parameter to weigh its relevance in determining a single durability parameter Δ_i, that would represent each product's LS. The use case of the soles under study drove the decision of different αp values. In the context of the analysis, consisting of urban soles, αp factors were assumed, as reported in Fig. 3. Equation 1 describes the calculation process of the Δ_i parameter.

$$\Delta_i = \frac{CoF_{max}}{CoF_i} * \alpha_{Cof} + \frac{Sft_{max}}{Sft_i} * \alpha_{Sft} + \frac{Abr_{max}}{Abr_i} * \alpha_{Abr} + \frac{TS_{max}}{TS_i} * \alpha_{TS} \quad (1)$$

Where:

Δ_i is the durability parameter of soles (R_1, R_2, HP, T);
CoF_{max} is the maximum value of the Coefficient of Friction



Soles	CoF	α_{CoF}	Safety	α_{Sft}	Abrasion	α_{Abr}	Tensile strength	α_{TS}	Δ_i
R_1	1.000	0.1	1.000	0.1	1.170	0.5	1.500	0.3	1.235
R_2	1.297		1.556		1.139		1.250		1.230
HP	1.212		1.000		1.000		1.000		1.021
T	1.064		1.556		1.553		1.364		1.448

Fig. 3. Coefficient results of different tests and relative weight.

between all four of the soles;
CoF_i is the value of the Coefficient of Friction of a specific sole (R_1, R_2, HP, T);
Sft_{max} is the maximum value of the Safety parameter between all four of the soles;
Sft_i is the value of the Safety parameter of a specific sole (R_1, R_2, HP, T);
Abr_{max} is the maximum value of the Abrasion parameter between all four of the soles;
Abr_i is the value of the Abrasion parameter of a specific sole (R_1, R_2, HP, T);
TS_{max} is the maximum value of the Tensile strength parameter between all four of the soles;
TS_i is the value of the Tensile strength parameter of a specific sole (R_1, R_2, HP, T);
α_p is an arbitrary weighting factor that represents the relevance of each tested parameter in evaluating a single durability parameter.

We defined the FU that uses the maximum durability value that can be achieved with this product mix ($\Delta = 1$). By assigning an α_p to each tested parameter, we calculated the durability parameter Δ_i for each sole, assigning them a theoretical LS. Then we calculated the number of items needed to cover the maximum expected lifetime for each sole, N_i, normalising the environmental burdens of the production of each sole with its durability parameter. The data used to calculate the Δ_i are reported in Fig. 3, while N_i was calculated using Equation 2.

$$N_i = \frac{\Delta_i}{\Delta} \qquad (2)$$

A cradle-to-gate LCA analysis has been implemented for each sole using a pair of soles as the FU (the weights are reported in Fig. 2), obtaining the baseline data. From there, the results of each product were multiplied with its specific N_i to obtain the normalised data. We modelled each product using Ecoinvent 3.8 as the database and OpenLCA as the software while selecting the EPD (2018) as the method to calculate the impacts.

3. Results and Discussion

Having completed the LCA study of the products, we determined their environmental impacts for the baseline scenario. By adopting this approach, they were determined the normalised impacts of the soles after considering the number of items tied to obtaining the desired durability value. Fig. 4 represents this study's results in the categories considered most relevant. Looking at the baseline data, it was clear that, while none of the soles has a higher impact than the others on all categories, the virgin-based soles tend to have higher impacts than the two containing secondary material. This comes out by examining the results on the traditional sole, implying the highest impacts, being the most impacting in four of the six exterminated categories and the second one in the remaining two. Similarly, although with less intensity, it was clear that the HP sole has a higher impact than the two recycled ones. On the other hand, observing the normalised data leads to a different picture, with the HP sole being the overall less impacting one. This change in relative positioning is due to the higher performances that reduce the number of needed items N_i for this specific sole. The increase in impacts is directly connected to the number of needed items N_i; thus, this rise is spread across all categories. At the same time, this leads to different relative changes, as categories with significant differences like Abiotic Depletion Potential, element (ADP, elements), and Water Depletion Potential (WDP) were impacted less than the others, showing fewer changes in the impacts ranking. It can be interesting to notice the increased impacts of R_1 and R_2 soles after normalisation, highlighting how products containing recycled material, usually carrying less environmental burdens, may not always be the less impacting solution. The increased impacts are due to the relatively lower durability and performance of R_1 and R_2, making them a less desirable option in multiple categories.

Nonetheless, the durability parameter of soles R_1 and R_2 results superior to that of the traditional sole, which ranks last. This is because of secondary material presence, obtained via mechanical recycling, in both R_1 and R_2 soles that, according to literature, can be used as a reinforcing element without additional treatment, increasing the sole performance [25]. The reinforcing material presence explains the lower number of needed items N_i for both the R_1 and R_2 soles compared to the Traditional soles that lack the increase in performance tied to the presence of these elements. On the other hand, we can observe how a more dedicated sole, eco-designed for high performances and increased durability, can sustain a much more prolonged use, reducing its relative impact compared with the others. These results can be interpreted as a validation of the design for durability approach, as a more durable virgin-based sole can reach lower levels of impact than soles that contain a

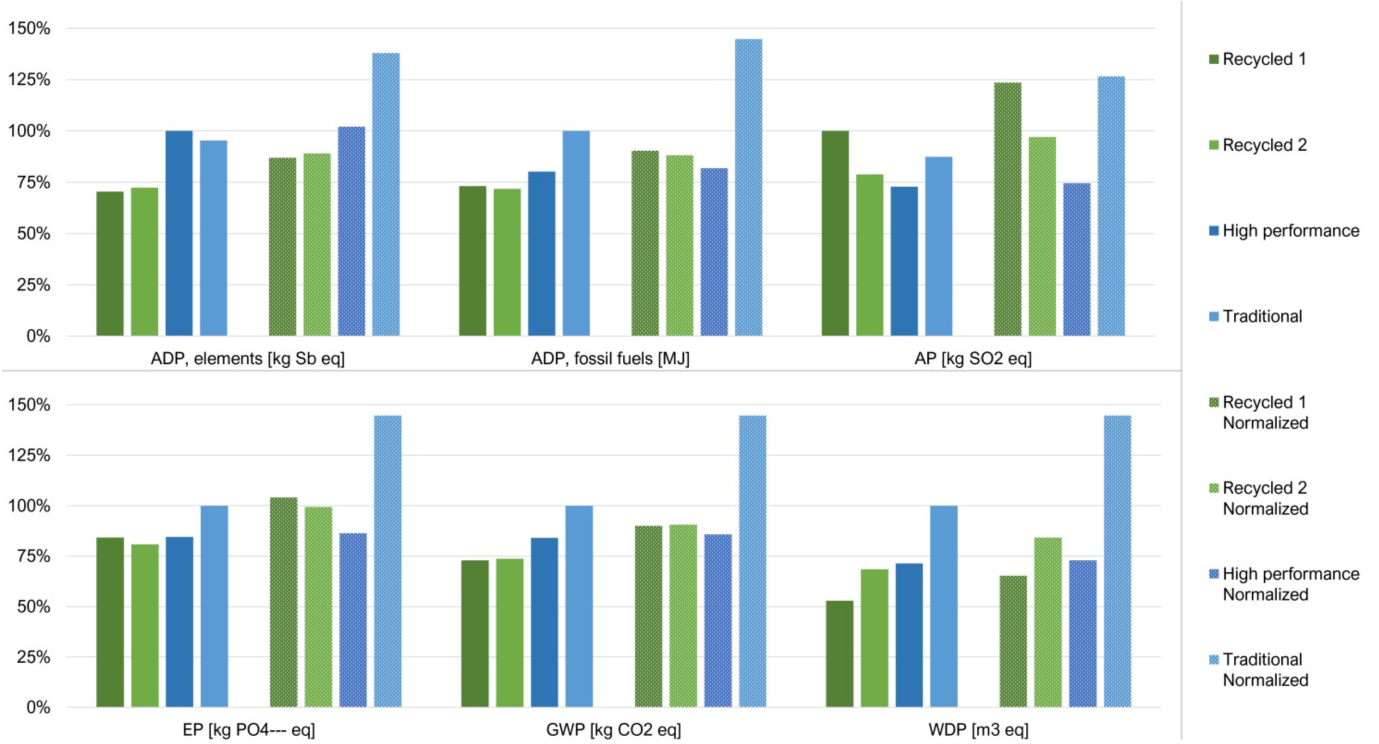


Fig. 4. The four products' environmental impacts are expressed as percentages: baseline on the left and normalised values on the right. (ADP, elements: Abiotic depletion potential, elements. ADP, fossil: Abiotic depletion potential, fossil fuels. AP: Acidification potential. EP: Eutrophication potential. GWP: Global warming potential. WDP: Water depletion potential). .

significant amount of secondary materials. It is interesting to notice that the values of Δ, Δ_i and α_p depend on both the performed tests and the soles considered. This specificity must be considered, as it causes the results to only apply to the study itself. As the quality reference defining the FU, Δ_i takes into account the highest properties achieved in each test, making it inextricable from the products used in the quality tests. A stringent and standardised methodology should be developed before extending this approach outside the boundaries of the design phase of a product. Until then, we recommend using this approach only internally, as its results could be easily misinterpreted if taken out of context.

4. Conclusions

During this study, it was observed how adopting a durability parameter Δ can significantly influence the environmental impacts of a product. This variation strictly depends on the parameter's value, the model used to calculate it, and relative comparison with other models, making the designing phase critical. Through this approach, we could implement a proxy representation of the product's durability as a quality function representing its LS, allowing us to normalise the LCA results on the Δ parameter. This approach led to a relative reduction in the environmental burdens tied to the product designed for durability, as its increased performances assure a longer LS and consequently distribute their impacts over a broader time period. At the same time, assumptions in the model could significantly affect the results. In this case, arbitrary assumptions have been based on the technical experience of the involved experts producing different weighting coefficients (α) in Δ assessment. The increased model complexity and the subjectivity derived from arbitrary weighting factors may reduce the methodology sharing in the industrial area of interest. In light of this, a stringent methodology should be agreed upon among industry players in order to develop a model that considers all the factors with their relative weights. Nonetheless, we think that this approach to defining quality-dependent functional units should be implemented. It allows us to analyse the product's life cycle more significantly, considering its length of use and contextualising produced environmental impacts in a quantitative framework mirroring their effective use.

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