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Environmental Impact of Footwear Using Life Cycle Assessment—Case Study of Professional Footwear

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Abstract: Life cycle assessment (LCA) is a method for assessing the environmental impact of a product, activity, or system across all the stages of its life cycle. LCA can identify the activities with a major impact on the environment throughout the life cycle of a product. To analyze the environmental implications of footwear, the LCA was applied to a pair of shoes designed for professional use. In this paper, the impact of a single pair of shoes was studied. Every year, footwear production worldwide is over 22 billion pairs, which has a significant impact on the environment. In this case study, the "cradle-to-grave" approach was used, which refers to all the activities involved in the life cycle of a footwear product, starting from raw material extraction, manufacturing, use, maintenance, and, in the end, disposal. The LCA was conducted using the SimaPro software. The environmental impact assessment of the analyzed shoe needed the acquisition of two crucial datasets. Background inventory data were sourced from the Ecoinvent database (version 3.3). The impact was quantified using the Global Warming Potential (GWP) metric, which calculates the contribution of emissions to global warming over a 100-year time limit according to the established values provided by the Intergovernmental Panel on Climate Change (IPCC). The impact of greenhouse gas (GHG) emissions was measured in relative carbon dioxide equivalents (kg CO_2eq) to facilitate a standardized comparison. The results show that the total carbon footprint for a pair of safety boots is 18.65 kg of CO_2eq with the "component manufacture" stage as a major contributor accumulating almost 80%.

Keywords: environmental management; cradle-to-grave approach; sustainability; carbon footprint

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Citation: Bodoga, A.; Nistorac, A.; Loghin, M.C.; Isopescu, D.N. Environmental Impact of Footwear Using Life Cycle Assessment—Case Study of Professional Footwear. *Sustainability* **2024**, *16*, 6094. https://doi.org/10.3390/su16146094

Academic Editors: Md Mazedul Islam, Pammi Sinha, Abu Sadat Muhammad Sayem, Abhijit Majumdar and Antonio Boggia

Received: 17 April 2024
Revised: 12 July 2024
Accepted: 15 July 2024
Published: 17 July 2024

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1. Introduction

In recent years, climate change has been integrated into decision making at the level of individuals, companies, public administrations, or policymakers [1]. Another concerning aspect is the worldwide energy consumption which is rapidly growing and generates huge quantities of emissions and waste to the environment. To determine the environmental impacts of various products/systems tools and instruments such as life cycle assessment (LCA), ecological footprint, Environmental Risk Assessment (ERA), Strategic Environmental Assessment (SEA), and environmental impact assessment (EIA) have been developed. This paper presents the LCA applied to a pair of shoes designed for professional use.

The environmental impact of footwear has been a subject of increasing scholarly interest, particularly through the application of LCA methodologies. Previous studies have extensively examined various categories of footwear, including casual, athletic, and fashion shoes, assessing their environmental footprints across different life cycle stages. For instance, the environmental impacts of leather shoes [2] emphasizing the supply chain have been discussed. Similarly, casual footwear has been investigated, identifying key areas for environmental improvement in materials and end-of-life management [3] or the environmental ramifications of fashion footwear, underscoring the substantial impact

of the manufacturing process on overall sustainability [4]. The specialized literature [5] synthesizes findings from multiple LCA studies on footwear, highlighting common hotspots such as material production, manufacturing, and end-of-life disposal.

Despite the approaches of the existing research, a critical gap persists in the literature regarding the environmental impacts of professional footwear. Occupational footwear, designed for work-related settings with specific functional, safety, and durability features, has not been sufficiently explored in terms of its environmental implications. This omission is significant, as professional footwear often involves specialized materials and manufacturing techniques that could have distinct environmental impacts compared to other types of footwear.

By employing LCA methodologies to analyze professional footwear, this paper aims to provide a comprehensive assessment of the environmental impacts associated with this specific category of shoes. The findings will contribute to a more nuanced understanding of the sustainability challenges and opportunities within the professional footwear sector, thereby informing both industry practices and policymaking aimed at reducing the environmental footprint of occupational footwear.

LCA is a powerful instrument which helps to evaluate the environmental impact of a product, an activity, or system over its life cycle. LCA is a tool that studies the environmental aspects and the potential impact that a product has through its life cycle and focuses only on the impact of the product on the environment, without taking into consideration political, social, or financial factors [6]. Evaluation includes the extraction of raw materials, production, use, disposal, and even the reintroduction of components into the system.

LCA can be defined as an objective process of environmental impact assessment associated with a product or activity that identifies and quantifies energy and material consumption [7].

In the analysis, the consumption of raw materials, energy factors, emissions (air, water, and soil), and waste resulting from the entire value chain are identified and quantified to establish the potential impact on the environment. This approach shows that all the elements from the value chain participate in the impact on the environment [8]. To achieve the goal, the key factor is the configuration of the supply chain. The companies should set their own supply chain to create value for both shareholders and customers. The scientific literature shows that companies who introduce environmental aspects in their supply chain have benefits [9], and they are also responsible for the environmental performance of their partners and suppliers [10,11]. At the same time, it allows the easy identification of processes with a significant impact on the environment, thus offering the possibility to improve them.

LCA is one of the most widely used tools for assessing the environmental performance of alternative systems considering the entire life cycle (cradle to grave) or only some components (cradle to gate or gate to grave) and can be performed by choosing one of the three boundaries of the system presented in Figure 1.

In the realm of LCA, a comprehensive understanding of a product's environmental footprint is essential for sustainable decision making. Among the various methodologies employed, four prominent approaches delineate different scopes and depths of analysis: cradle to gate, cradle to grave, gate to gate, and cradle to cradle [13].

Cradle-to-gate analysis gives essential information on the environmental impacts regarding production, without considering the product use and disposal. This method provides insight into the impact of the product from raw material extraction up to the factory gate before the product is purchased by the consumer [13,14].

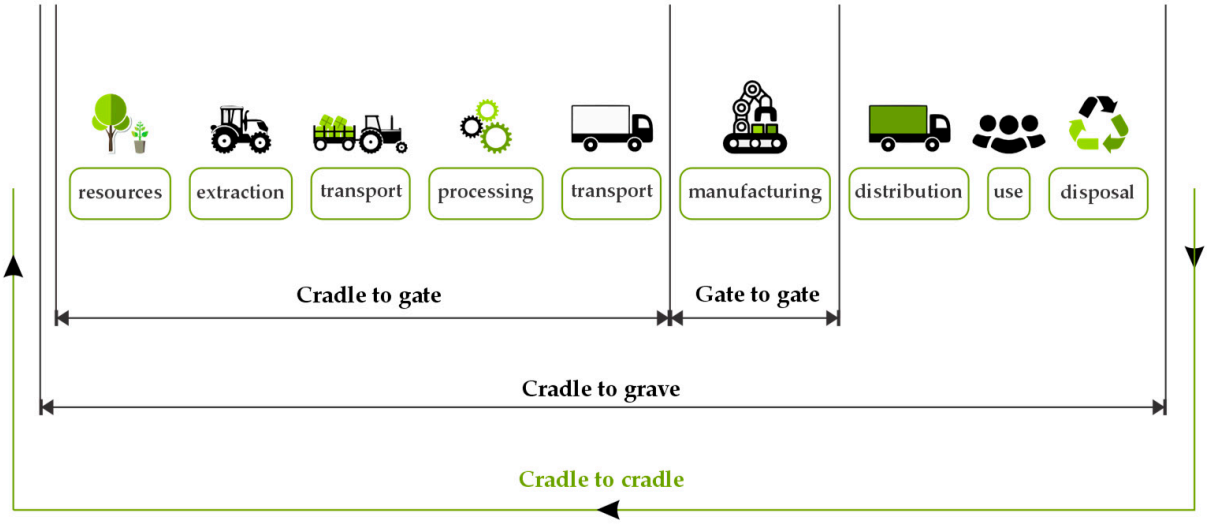

Figure 1. LCA boundaries. Adapted from [12].

In contrast, cradle-to-grave analysis represents a more exhaustive endeavor, encompassing the product's entire life cycle [15]. Beginning with the extraction of raw materials, traversing through manufacturing, distribution, consumption, and concluding with disposal or recycling, this approach offers a holistic perspective on environmental implications across all the stages of a product's existence. Its comprehensive nature renders it indispensable for evaluating sustainability extensively.

Gate-to-gate analysis, meanwhile, offers a narrower focus, examining specific processes within the production chain rather than the entire life cycle [16]. This approach is particularly useful for pinpointing environmental hotspots and optimizing the individual stages of production to enhance overall sustainability.

Lastly, cradle to cradle shows an aspirational paradigm wherein products are meticulously designed to circulate within closed-loop systems, thereby fostering perpetual utility without generating waste or depleting resources [13]. This approach seeks to transcend the conventional linear model of production and consumption by creating products that not only minimize environmental harm but actively contribute to human well-being and ecological balance.

In the context of the present study, a cradle-to-grave approach was adopted, acknowledging the intricate interplay of environmental factors throughout the product life cycle, from inception to eventual disposal. This methodology was deemed most appropriate for comprehensively assessing the environmental impacts associated with the product and pinpointing sustainable product development and management.

The LCA was conducted utilizing the SimaPro software. Essential datasets were required to evaluate the environmental impacts of the analyzed footwear. Background inventory data were sourced from the Ecoinvent database, version 3.3. The environmental impact was quantified using the Global Warming Potential (GWP) indicator, which calculates the contribution of emissions to global warming over one hundred years according to the values established by the Intergovernmental Panel on Climate Change (IPCC 2007). The impact of greenhouse gas (GHG) emissions was measured in terms of relative carbon dioxide and expressed as an equivalent mass of carbon dioxide (kg CO_2eq).

2. Materials and Methods

2.1. Entry Data and Materials

A deliberate selection process focused on a specific product category: professional footwear tailored for men. Professional footwear denotes shoes specifically engineered and used for professional or occupational contexts. These shoes are meticulously designed to address the diverse demands of various work environments, ensuring an optimal combination of functionality, safety, comfort, and style suitable for work settings. The distinct features and conditions of occupational footwear exhibit considerable variation, contingent upon the specific nature of the job and the industry, and are subject to specific standards. This selection was also made due to footwear's critical role in ensuring foot protection during various work activities. As per industry standards and regulations, specialized footwear is mandated to adhere to rigid national and international guidelines concerning protective measures.

Adherence to the current standards ISO 20345, 20346, 17249, and 20347 [17–20] is imperative, as these standards outline the essential requirements that professional footwear must meet. These requirements encompass a spectrum of factors ranging from durability and slip resistance to protection against specific hazards prevalent in various occupational settings.

The analyzed model conforms to the European Standard ISO 20347:2012 O2 FO SRC, falling under "category 0" for work shoes. This categorization denotes that the footwear is designed for environments without mechanical risks, such as impact or compression hazards. The European Standard ISO 20347:2012 delineates both basic and optional specifications for work shoes like the one under evaluation [20]. These specifications aim to ensure adequate protection for individuals working in environments where foot injuries pose potential risks. Notably, this type of footwear, as stipulated by the standard, does not mandate a metal toe cap.

The studied sample falls in the category of work shoes made from hydrophobized cowhide, toe caps without protection, and double-density polyurethane-injected soles. Further technical characteristics state that one pair weighs 1160 g for size 42 (European size). This standardization allows for consistent and comparable assessments across different footwear products and facilitates meaningful comparisons within the industry.

A general definition of the component materials of a footwear product is outlined in ISO/TR 16178:2021 [21]. According to this standard, the materials commonly employed in professional products encompass leather, thermoplastic polyurethane, rubber, textiles, and PVC.

The materials from which the benchmarks of the analyzed product are made were identified using Fourier-Transform Infrared Spectrometers (FTIR). This spectroscopic technique enables the clarification of the molecular structures and chemical compositions present within a given sample through the measurement of infrared radiation absorption and transmission properties [22]. The spectroscopic study was conducted using the diamond crystal reflection technique.

To embark on the LCA analysis of the targeted footwear product, a systematic approach was adopted. The component benchmarks, essential for understanding the product's environmental footprint, were organized in alignment with the categorization provided in Table 1. This categorization serves as a framework for dissecting and evaluating the various stages and components within the lifecycle of the footwear product.

Table 1. Highlights of analyzed product components.

Footwear Ensemble	Component Highlights	Material	No. of Paired Benchmarks	Benchmark Mass (g)	Paired Mass (g)
Superior ensemble					
Outer subassembly	vamp	chrome-tanned cowhide, finished with a polyurethane coating film	2	55.3	110.6
	counter		2	36.1	72.2
	upper staple reinforcement		2	2.1	4.2
	lower staple reinforcement		2	0.7	1.4
	backstay		4	4.2	16.8
	shoelace port		4	7.1	28.4
	upper quarter	textile material—polyester	4	2.4	9.6
	lower quarter		4	9.3	37.2
	collar	leather substitute—polyurethane	2	4.2	8.4
	tongue		2	3.2	6.4
	bellows tongue		2	11.4	22.8
Intermediate subassembly	rigid counter	polyester and PVC	2	7.9	15.8
	toecap	polyester and plastic	2	8.6	17.2
	collar reinforcements	cotton	2	2.1	4.2
	vamp reinforcements	polyester	2	5.4	10.8
	tongue filling	polyurethane	2	5.1	10.2
	collar filling	polyurethane	2	5.1	10.2
Inner subassembly	quarter inner lining	textile material—polyester	2	7.1	14.2
	quarter outer lining		2	7.1	14.2
	vamp lining		2	6.1	12.2
	tongue lining		2	3.7	7.4
	staple reinforcement lining		4	1.8	7.2
			Total superior ensemble		441.6
Inferior ensemble					
Inner subassembly	insole cover	textile material—polyester	2	11.6	23.2
Intermediate subassembly	insole	anti-puncture composite material	2	81	162
Outer subassembly	sole	double density polyurethane	2	243.4	486.8
			Total inferior ensemble		672
Auxiliary materials					
thread		polyester	-	-	3.5
adhesives		natural rubber solution	-	-	15
finishing products		wax and solvents	-	-	10
laces		polyester	2	4.8	9.6
eyelets		metal	28	0.3	8.4
insider packaging		wrapping paper	1	26	26
outer packaging		cardboard box	1	188	188
			Total auxiliary materials including packaging		260.5
			Entire packed product		1374.1

2.2. Methods and Necessary Steps

The International Standard 14040 [23], a cornerstone in the realm of LCA, delineates a structured methodology crucial for comprehensive environmental analysis. This methodology unfolds across four key stages:

- Goal and scope definition—defining a clear goal and scope of the study (a successful result depends on this phase) and selecting a functional unit;
- Inventory Analysis—an inventory of data inputs and environmental releases (life cycle inventory analysis LCI);
- Impact Assessment—evaluating the potential environmental impact based on the identified inputs and releases (life cycle impact assessment LCIA);
- Interpretation—interpreting the results.

2.3. Goal and Scope Definition

2.3.1. Scope

The scope of this research encompasses a comprehensive assessment of the environmental implications associated with a pair of shoes employing the LCA methodology. The evaluation of environmental performance is conducted based on a clearly defined functional unit. The LCA utilizes data sourced from industry, the scientific literature, and the Ecoinvent database, processed through the SimaPro software. The study aims to identify processes within the product's life cycle that have significant environmental impacts and to propose improvement solutions. This scope is aligned with the overarching goal of enhancing the environmental sustainability of the company or product by minimizing its ecological footprint.

2.3.2. Functional Unit

All the data encompassing inputs and outputs in and out of the system, including the results obtained, are intrinsically linked to the defined functional unit.

In the context of this study, the functional unit is defined as "one pair of safety boots, for men, size EU 42 with its primary packaging".

This rigorous delineation of the functional unit serves as the basis of the study's framework, ensuring precision and comparability in the assessment of environmental impacts across the various stages of the product life cycle.

2.4. Inventory Analysis (LCIA)

2.4.1. Reference Flow

The amount of the material used to fulfill the functional unit (analyzed shoe = 1160 g). Shoe materials are classified into three main components: upper, sole, and packaging. In the upper, bovine leather, polyurethane, and textile were used. The sole is separated into the outsole and midsole, both made of polyurethane. The manufacturing and assembling of the shoe model under study includes many processes such as cutting and stitching the parts for the upper and injection for the outsole and midsole. The manufacturing process takes place in Romania.

2.4.2. System Boundaries

For this study, a "cradle-to-grave" approach was employed, encompassing all the activities pertinent to the lifecycle of the product, as depicted in Figure 2. This approach entails tracing the journey of the product from raw material extraction through manufacturing, utilization, maintenance, and disposal.

Specifically, the shoe assembly process included solely energy information, focusing on the energy inputs involved at each stage of assembly. This approach facilitates the understanding of the environmental impacts associated with the lifecycle of the product, aiding in informed decision making and the implementation of sustainable practices.

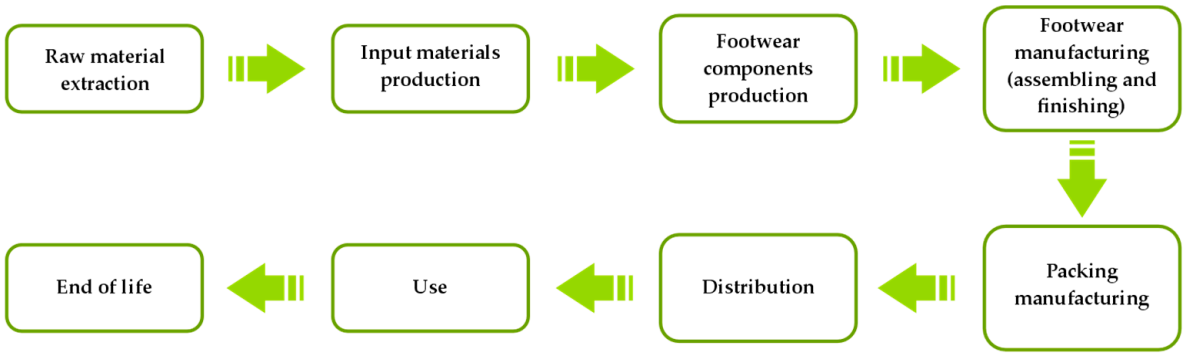

Figure 2. Footwear lifecycle phases. Adapted from [24].

The entire production process of the examined model takes place in Romania. Most of the raw materials and auxiliary materials are sourced from Europe, specifically Italy. To conduct the life cycle analysis, the processes involved in product production were divided into three different processes:

- Processes for obtaining raw materials and auxiliary materials;
- Production/manufacturing processes;
- Processes regarding the use and disposal of the product.

The processes for obtaining raw materials and materials include all the phases from raw material extraction to their transformation into finished materials necessary for footwear production, namely the extraction of raw materials and the production of materials, other than leather; leather production; the production and transport of technical materials for the footwear sector (from RER and market Ecoinvent database); energy generation for material production; the production of auxiliary products necessary for production processes; and the production of packaging materials.

Manufacturing processes represent all the operations necessary to obtain a product. This category includes the specific elements of the footwear manufacturing process (electric and thermal energy): the transportation of raw materials (from Italy to Romania); the preparation of materials; the processing of parts; the assembly of the footwear product; the internal and external transport of raw materials and semi-finished products; the supply of water necessary for the production process; emissions into the air and wastewater; and production waste, if applicable, recovery/recycling.

Processes regarding the use and disposal of the product include information related to the distribution chain, product usage duration, and waste resulting from packaging. The transport of the product to the consumer is determined by considering an average distance. The average distance is calculated as the number of kilometers traveled from the factory's warehouse (Romania, Bacau City) to distributors (Romania, all cities).

System boundaries encompass all inputs and outputs and the stages of the footwear life cycle. Figure 3 shows the flow diagram of the system under analysis.

2.4.3. Inventory Data

Several sets of data were required to assess the environmental implications of the shoe analyzed for this study. The background inventory data were obtained from the Ecoinvent database, version 3.3. [25]. The Ecoinvent database contains LCI data from different fields such as energy production, building materials, transport, the production of chemicals, and metal production. The database includes over 10,000 interlinked datasets, each of which describes a life cycle inventory on a process level. The data processes used were selected from the Ecoinvent database available in the SimaPro 8.5.2.0. software. Depending on the process, the country of origin associated with that process has been chosen as RER (Europe).

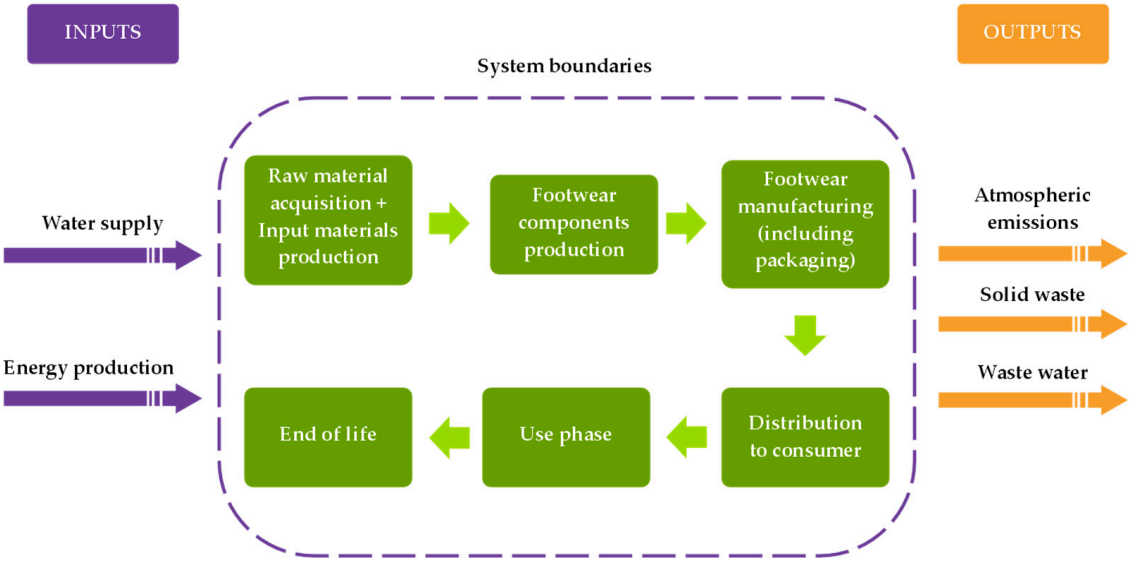

Figure 3. Flow chart of the analyzed system. Adapted from [3].

2.5. Impact Assessment

2.5.1. Environmental Impact Categories

The determination of impact utilized the Global Warming Potential (GWP), which quantifies the contribution of emissions to global warming over a 100-year period based on the values established by the Intergovernmental Panel on Climate Change [26]. The emissions of greenhouse gasses resulting from human activities are classified into impact categories. According to the scientific literature [27–29], the most significant greenhouse gasses include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halocarbons.

The impact of greenhouse gas emissions is assessed in terms of relative carbon dioxide and expressed as an equivalent mass of carbon dioxide (kg CO_2eq). The rationale for selecting this impact category stems from the acknowledgment of climate change as a substantive concern within the textile and footwear industry. Climate change assumes prominence due to its extensive impacts on the operational dynamics and environmental footprint of these industries [30]. Therefore, a deliberate emphasis on this aspect is warranted, considering its potential implications across the various dimensions of industry operations, and not all the relevant impact categories and indicators pertinent to the footwear industry were subject to analysis. The impact categories considered were derived from characterization models. Among the various methods available in the SimaPro software, the IPCC GWP method [31] was employed for this investigation.

2.5.2. Assumptions

In undertaking an analysis of a complex system, such as the procurement of a pair of shoes, it becomes imperative to establish certain foundational hypotheses to facilitate the investigation process [32]. Within the framework of this study, these hypotheses are categorized into several key domains:

General Assumption: This assumption dictates a decision-making approach in situations of uncertainty, advocating for the selection of the less favorable option. In contexts where materials or processes present ambiguities or lack definitive information, this principle guides the selection process towards options that are presumed to have higher environmental impact or lesser sustainability credentials. For caution, this assumption ensures that the analysis maintains a conservative stance, guarding against the underestimation of environmental implications.

Transport Assumption: Central to this assumption is the consideration of greenhouse gas (GHG) emissions from transportation activities integral to the supply chain of shoes, specifically focusing on the movement of goods from the shoe manufacturing facility to the

end consumer, specifically the transit route between Romania and Italy facilitated primarily by trucking operations. Recognizing the significant role of transportation emissions in the overall environmental footprint of products, this assumption emphasizes the importance of analyzing and quantifying emissions associated with logistical operations, thereby contributing to a more comprehensive understanding of the product's lifecycle impact.

Material Assumption: This assumption portrays the scope of analysis concerning emissions from the manufacturing processes of shoe components, encompassing both the extraction of raw materials and the production of packaging materials. Notably, the focus remains on energy consumption within the footwear manufacturing facility, reflecting a pragmatic approach aimed at capturing the primary energy-intensive activities of the shoe production process. By defining the boundaries of material-related emissions, this assumption enables a focused examination of key production stages, facilitating targeted interventions to mitigate environmental impacts.

End-of-Life Assumption: In describing the end-of-life state, this assumption specifies the disposal method selected for the study, opting for a landfill scenario as the designated endpoint for the shoes' lifecycle. By adopting this disposal pathway, the analysis acknowledges the frequent practice of landfilling as a common fate for end-of-life products and highlights the need to assess the environmental consequences associated with such disposal practices. Moreover, this choice enables the evaluation of potential emissions and impacts occurring from landfilling activities, contributing to a comprehensive evaluation of the product's lifecycle sustainability performance.

2.5.3. Limitations

In the investigation of certain parameters, such as water consumption, wastewater generation, and solid waste production, precise quantification poses a notable challenge within the confines of the model under study. In addressing this methodological obstacle, an approach was devised wherein the cumulative value for the designated calculation period was assessed. Subsequently, this total value was partitioned by the entire number of pairs generated, thereby affording a nuanced understanding of the interplay between the inputs and outputs within the study. This technique not only facilitated a more granular examination of resource use but also gave invaluable insights into the dynamics governing the production process. Moreover, by leveraging this methodological approach, research was able to capture the robustness and comprehensiveness of the analytical framework.

Therefore, some inputs and outputs such as water consumption, wastewater generated, and solid waste were difficult to quantify concerning the specific amount related to the model under study. For this, the total value for the calculation period was considered and divided into the total number of pairs produced.

3. Results and Interpretation

The carbon footprint obtained for each stage of the life cycle is presented in Table 2. The impact was determined using the IPCC 2007 GWP 100y indicator [33] which is based on climate change over a period of one hundred years and was conducted using the SimaPro software.

Table 2. Product carbon footprint per stage.

Stage	Kg CO_2eq
Component manufacture	79.8
Footwear manufacturing (assembling and finishing)	7.03
Primary packaging manufacture	2.37
Distribution to consumer	2.78
End of life (landfill)	8.02

The results show that the total carbon footprint for the functional unit defined in this study (a pair of safety boots, for men, 42 EU size, and its primary packaging) is

18.65 kg of CO_2eq. This value also includes two components: the packaged product and the disposal phase. The packaged product contains the product itself, the wrapping paper, and the cardboard box for which the carbon footprint obtained is 17.91 kg CO_2eq. For this analysis, the disposal scenario was the landfill, and the environmental impact equivalent was obtained as being 0.74 kg CO_2.

Figure 4 presents the percentage of emissions per stage. The results show that the "component manufacture" stage contributes the most to the total carbon footprint of the analyzed product (79.81%). It should be noted that this stage also includes the impact resulting from the raw material extraction and the production of materials needed to manufacture components. At this stage, the components with a significant impact are the upper (39.94%) and the sole (30.10%). The next major contribution is the end-of-life phase, which represents 8.02% of the total carbon footprint (6.99% footwear and 1.02% packaging). The stage "footwear assembling and finishing" has a contribution of 7.03%. The process with the largest contribution is energy consumption (6.39%) and chemicals used (1.9%). The "packaging manufacturing" stage represents 2.37% of the total carbon footprint. At this stage, the production of cardboard (2.1%) has a higher impact than the production of packaging paper (0.26%). It must be stated that, after purchasing the product, the assumption of recycling the box, respectively, and the wrapping paper by the consumer was considered, but the landfill end-of-life scenario was chosen to assess the maximum possible impact. Finally, distribution to customers has a contribution of 2.78%.

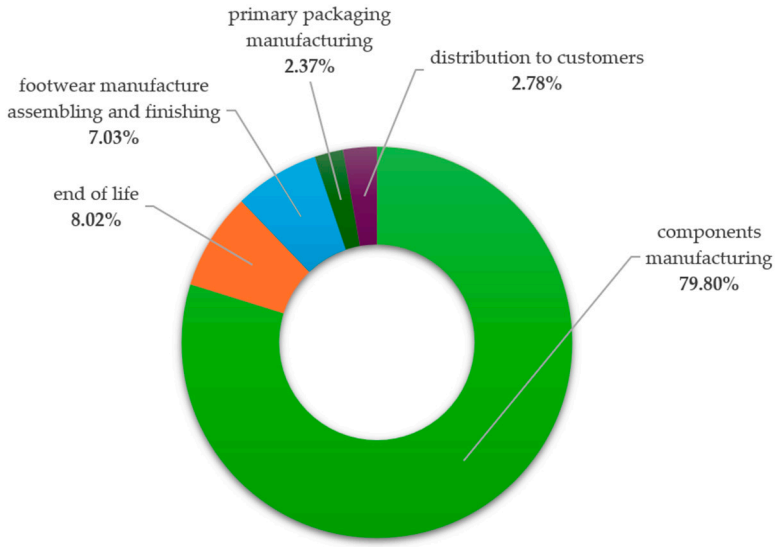

Figure 4. Percentage of emissions per stage.

4. Discussion

The LCA revealed significant hotspots in the environmental impact of the safety boots. The "component manufacture" stage emerged as the primary contributor, encompassing raw material extraction and component production. Specifically, the upper and sole components exhibited substantial impacts, indicating the need for targeted interventions to mitigate environmental burdens associated with their production [4,34].

Moreover, the end-of-life phase, particularly landfill disposal, represented a notable hotspot, highlighting the importance of addressing disposal practices to minimize environmental implications [35,36]. This underscores the necessity of implementing strategies such as material recycling or alternative disposal methods to mitigate the environmental impact of product disposal.

Addressing all the hotspots identified in the component manufacture stage is important for reducing the overall environmental impact of the safety boots by implementing measures to improve resource efficiency, minimize energy consumption, and adopt eco-friendly materials [37]. The packaging manufacturing stage exhibited a contribution to the

carbon footprint even if only consisting of cardboard. Strategies such as utilizing recycled and fewer materials can minimize packaging waste and significantly reduce the carbon footprint associated with product packaging.

In comparison, the GORE-TEX® LCA of a pair of hiking boots reveals a higher total carbon footprint of 27.1 kg CO_2eq per pair [38]. Both LCAs identify that the manufacturing and material production stages are the most significant contributors to the overall environmental impact. Additionally, both analyses highlight the importance of material choice and the environmental burden associated with the production of raw materials. For the hiking boots, the longevity of the boots is identified as the most influential factor in reducing annual environmental impacts and overall recommendations include using sustainable materials, sourcing responsibly, switching to renewable energy sources for energy-intensive raw materials, localizing manufacturing, adopting green standards for retail stores, and designing boots for longevity and easy repair.

In analyzing a leather shoe supply chain, the environmental burden of slaughtering and tanning processes due to long transport distances and the use of unsustainable chemicals are highlighted [2]. The use of cotton during upper manufacturing and shoe assembly is shown as another critical environmental hotspot, but both LCAs underscore the significant environmental impacts of material production and manufacturing in footwear.

The LCA findings underline the importance of holistic approaches to sustainable product development, encompassing the design, manufacturing, use, and end-of-life phases [39]. By addressing hotspots and implementing targeted interventions, companies can enhance the environmental performance of their products and contribute to a more sustainable future. Enhancing end-of-life management practices, such as promoting recycling and implementing circular economy principles [40,41], can mitigate the environmental impact of product disposal. Some sustainable approaches deal with improving footwear and clothing's carbon footprint from the designing phase [42]. By extending product lifespan and facilitating material recovery, a circular approach can contribute to conservation and environmental sustainability [43]. Even optimizing packaging design and material selection can significantly reduce the carbon footprint associated with product packaging. Embracing sustainable packaging solutions [44], such as biodegradable materials and minimalistic packaging designs, can minimize environmental impact while maintaining product integrity and consumer appeal.

Moreover, the transportation and distribution stages are also potential areas for further investigation. These stages can contribute significantly to the overall carbon footprint, especially in global supply chains [45]. Implementing more efficient planning, optimizing distribution routes, and exploring low-carbon transportation options are recommended areas for future research.

Innovation in materials and manufacturing techniques is essential for reducing environmental impact and enhancing sustainability performance [46]. Companies should explore alternative materials, eco-friendly production processes, and energy-efficient technologies [47] to minimize resource consumption and emissions throughout the product life cycle.

In addition, the application of circular economy principles is essential to encourage the efficient reuse of resources, to extend the life of products, and to encourage the recovery of materials [48–50]. In this context, practices such as the refurbishment, remanufacturing, and recycling of products can help reduce waste and promote a closed-loop system, thereby reducing environmental impact and conserving resources.

5. Conclusions

The primary objective of this study was to evaluate the environmental impact of footwear through the application of an LCA. A "cradle-to-grave" approach was employed, encompassing all the activities within the product life cycle of footwear. This approach includes raw material extraction, manufacturing, usage, and disposal. The assessment utilized the IPCC 2007 GWP 100y indicator (World Meteorological Organization, Geneva,

Switzerland), which evaluates climate change impacts over a 100-year period, facilitated by the SimaPro software.

The findings of the LCA indicate that the carbon footprint for the functional unit defined in this study—a pair of safety boots (size 42 EU) along with its primary packaging—is 18.65 kg of CO_2 equivalent (CO_2eq). The analysis identified significant environmental impacts throughout the safety boots' life cycle, with notable hotspots in the component manufacturing and end-of-life phases.

The manufacturing phase, particularly the production of the upper and sole components, emerged as the predominant contributor to carbon emissions. This phase accounted for approximately 80% of the total life cycle impact (GWP 100 years). The substantial emissions from this phase can be attributed to the inclusion of the raw material extraction processes in this study. The findings underscore the critical need to optimize manufacturing processes and select materials with lower environmental impacts. This optimization can potentially reduce the overall carbon footprint of safety boots, contributing to more sustainable footwear production practices.

The end-of-life phase, especially the disposal of safety boots in landfills, represented another significant hotspot. This phase highlights the urgent need for improved end-of-life management practices. Enhancing recycling programs, promoting circular economy principles, and developing biodegradable materials are essential strategies to mitigate the environmental repercussions associated with the disposal of professional footwear.

The study's results underscore the critical environmental impacts associated with the life cycle of safety boots, with significant emissions resulting from both the component manufacturing and end-of-life disposal phases. To enhance environmental sustainability in the footwear industry, it is imperative to address these hotspots through targeted interventions.

Optimizing manufacturing processes and material selection can reduce emissions in the production phase. In parallel, implementing effective end-of-life management strategies, such as improved recycling and waste reduction practices, is crucial. Moreover, the study suggests that future research should focus on comparing the impact of varied materials also, which are present in shoes, exploring alternative materials and innovative manufacturing technologies that minimize environmental impacts.

By adopting a comprehensive approach that considers the entire life cycle of footwear products, informed decisions to improve sustainability can be made. This study provides a foundational framework for future assessments and underscores the importance of continuous improvement in environmental practices within the industry.

Author Contributions: Conceptualization, A.B. and A.N.; methodology, A.B.; software, A.B.; validation, A.B.; formal analysis, A.B. and A.N.; investigation, A.N.; resources, A.B. and D.N.I.; data curation, A.B.; writing—original draft preparation, A.B. and A.N.; writing—review and editing, D.N.I. and M.C.L.; visualization, A.B. and A.N.; supervision, D.N.I. and M.C.L.; project administration, D.N.I. and M.C.L.; funding acquisition, D.N.I. All authors have read and agreed to the published version of the manuscript.

Funding: This paper was elaborated with the support of the "Eco-innovative Products and Technologies for Energy Efficiency in Constructions—EFECON" research grant, project ID P_40_295/105524, a program co-financed by the European Regional Development Fund through Operational Program Competitiveness 2014–2020.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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