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RESEARCH ARTICLE

Life Cycle Assessment and Circularity Assessment as Complementary Methods for the Circular and Sustainable Redesign of Multi-Material Products: A Case Study on Safety Industrial Footwear

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Abstract

The transition toward circular and sustainable products is critical for addressing environmental and resource concerns. Complex, multi-material products pose challenges due to their diverse material compositions, lifetimes, and end-of-life pathways. This study integrates Life Cycle Assessment (LCA) and the Material Circularity Indicator (MCI) to assess the sustainable and circular redesign of complex products using safety industrial footwear as a case of a multi-component product with strict safety standards. Results indicate that redesign improves both circularity and environmental performance. The circular model achieves a 51% reduction in environmental impact (normalized through environmental prices) versus the linear model, mainly through material substitution, design for recyclability, and reduced complexity. While circularity and sustainability align at the product level, they do not at the component level, making LCA and MCI complementary. Two decision-support tools were developed: (1) a product-level transition ladder and (2) a prioritization matrix for component-level redesign. This research contributes to the development of integrated assessments and informs policy discussions and design practice related to circular and sustainable products.

Keywords Circular Product Redesign · Circular Economy · Circularity Assessment · Sustainability Assessment · Industrial Footwear · Complex products

Introduction

The urgency to transition toward sustainable production and consumption systems has never been more critical (Guterres, 2018). Emerging environmental and regulatory demands (European Commission, 2015), challenge businesses with complex, multi-component, and multi-material products, as their sustainability and circularity assessments are not straightforward (Lifset & Eckelman, 2013; Reuter, 2011).

Complex products consist of multiple interconnected components that require additional disassembly processes (Stavropoulos et al., 2019); their diverse materials need to be separated and sorted (Cimpan et al., 2015), and often components have different lifetimes and recycling feasibilities, which hinder traceability and recovery (Jacobs et al., 2022). At scale, these processes depend on advanced material recovery technologies

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and are often feasible only when modularity and disassembly have been incorporated at the design stage (Machado & Morioka, 2021). As a result, (European Commission, 2015), their effectiveness in reducing environmental impact remains uncertain (Garcia-Saravia Ortiz-De-Montellano et al., 2023; Samani, 2023).

This study seeks to deepen the understanding of the relationship between circularity and environmental impact in complex products by exploring how product redesign, lifetime extension, and end-of-life (EoL) strategies influence both circularity and sustainability scores. To achieve so, this study uses safety industrial footwear (SIF) as a case study (ISO 20345, 2021).

Industrial Footwear as an Example of a Complex Product

Industrial footwear exemplifies the sustainability and circularity challenges of multi-material, multi-component products. Due to its strict safety and quality standards (ISO 20345, 2021), it remains highly reliant on leather, plastics, and textiles, the last two being a priority material in Europe's Circular Economy Action Plan (European Commission, 2015).

Existing LCA studies on footwear have primarily focused on running shoes (Cheah et al., 2013), casual leather footwear (Milà et al., 1998), toe-cap manufacturing (Bianchi et al., 2022), and leather shoe recycling (Luca et al., 2018). Only one paper reports on the environmental impacts of industrial footwear (Bodoga et al., 2024). However, like the work of Serweta et al. (2019), it reports only on global warming potential (GWP), limiting insights into other environmental impacts that might be of interest. None of these studies reports on the circularity score or potential of footwear.

The following section presents a literature review in the context of using LCA and MCI to evaluate (complex) products and the research gap this work addresses. The Methods section introduces the research design, including its scope, system boundaries, scenarios, and data and modeling choices. The Results and discussion chapter elaborates on the findings from the LCA and MCI and how they correlate at product and component levels, and advances these insights by proposing two ways of using and understanding the insights obtained: A transition ladder and a redesign support matrix, as well as the limitations of this study. Finally, the Conclusions section briefly summarizes these results and presents the concluding remarks.

Literature Review

Recent research on the complementary use of Life Cycle Assessment (LCA) and circularity metrics to quantify trade-offs and guide product redesign has emphasized that while circularity indicators provide valuable insights, they should not replace LCA in eco-design processes (Saadé et al., 2022). Table 1 presents a summary of existing literature on the application of LCA and MCI in products. The number of components and materials within the case studies is used as a proxy for a product's complexity level.

These studies demonstrate the potential benefits, challenges, and industry-specific conditions when integrating LCA and circularity assessments. Nevertheless, they largely focus on products with few components and straightforward EoL options. The work from Rufí-Salis and his team (2021) stands out both in depth and breadth of coverage on the assessment of a rooftop greenhouse and recommends further investigating complex systems and products to identify the benefits and trade-offs of applying circular economy principles (Rufí-Salís et al., 2021).

These studies highlight potential misalignments between LCA and MCI (Lonca et al., 2020; Samani, 2023; Vadoudi et al., 2022), particularly in energy-intensive scenarios (Brändström & Saidani, 2022). In their research, Glogic et al. (2021) found that improving circularity through recycling can reduce environmental impacts, but the extent of this reduction depends on scenario parameters, suggesting that MCI should use LCA as a guiding tool for selecting optimal circular strategies. Samani (2023) concluded that circularity assessment has the potential to identify hotspots and inform LCA models. Most recently, theoretical research has been published on the potential of harmonizing LCA with circularity metrics (Weiher et al., 2025) and integrating circularity indicators, the Sustainable Development Goals, and ecosystem services into the LCA framework (Koundouri et al., 2025). However, these proposals have yet to be validated by case study applications.

Table 1 A literature review on the application of LCA and Circularity Assessment for the redesign of products

Sector	Reference	Product/Material	Focus	Total components	Total materials
Construction Materials and Buildings	(Antwi-Afari et al., 2023)	Steel slabs for residential buildings	Recyclability of modular building components made from steel at EoL	1	1
	(Luthin et al., 2023)	Concrete industrial floor	Influence of using recycled carbon reinforcements in various EoL strategies	1	1
	(Kayaçetin et al., 2023)	Terraced-house building	Reuse and recycling potential of building modules	6	9
	(Kadawo et al., 2023)	Recycled Aggregate Concrete	Production and transport of recycled concrete with different proportions of replacement aggregates	1	2
	(Khadim et al., 2025)	Dutch terraced-house building	Environmental impact of various interventions to increase the circularity of existing terraced houses	4	10
	(Rufí-Salís et al., 2021)	Rooftop Greenhouse	Production, transport, installation, use, and waste management of rooftop greenhouse	>10	>50
Consumer products	(Saidani et al., 2021)	Lawn mowers	Report on students' findings after CE course comparing manual, electric, and autonomous scenarios	7-8	10-12
	(Luthin et al., 2024)	Carpet tiles	Six scenarios that consider the Reduce and Recycle strategies at production and EoL	1	15
	(Ancelina et al., 2022)	Silicone food containers	Transport and EoL alternatives for multi-use packaging versus single-use	2	4
	(Wiedemann et al., 2022)	Sweaters	Comparative assessment of fossil-based and bio-based PET for the manufacturing of Sweaters	1	2
Specialized equipment and industrial applications	(Schulte et al., 2021)	Electrophysiology catheters	Comparing the environmental impacts of virgin versus reused catheters.	1	13
	(Lonca et al., 2018)	Haulage truck tires	Effects of re-grooving versus re-threading as end-of-life strategies of used truck tires	N.D.	N.D.
	(Saidani et al., 2023)	Electric outboard motors	Reporting results from a workshop aimed at teaching the complementarity of LCA and MCI in product design processes	N.D.	N.D.
	(Walker et al., 2018)	Tidal energy installations	Evaluates the carbon footprint of six scenarios that use refurbish and recycle strategies at different points in the product's lifetime.	3	6
	(Glogic et al., 2021)	Alkaline batteries	Comparison of using open and closed loop recycling of zinc and steel, increased battery capacity, and a baseline scenario	N.D.	6
Packaging and materials	(Niero et al., 2016)	Aluminum beverage cans	Comparison of twenty scenarios with varying percentages of renewable energy and recycled content, following the C2C approach.	1	1
	(de Souza Junior et al., 2020)	Recycled polystyrene baseboards	Compares linear and recycled polystyrene systems by using Emergy and LCA	1	1

N.D. = Not disclosed

Preliminary findings of this research (Garcia-Saravia Ortiz-de-Montellano et al., 2023, 2024) provided initial insights into the integration of LCA and MCI, on which we built to develop the comprehensive and structured analysis presented in this paper. Overall, this upcoming body of literature recognizes that LCA and circularity assessment can improve the evaluation of circular economy initiatives (Rigamonti & Mancini, 2021) but also that the relationship between circularity and sustainability is not linear (Saidani & Kim, 2022), reinforcing the need for integrated approaches and tools for practitioners.

Research Gap and Contribution of this Study While the existing body of literature provides valuable methodological lessons and sectoral applications, several limitations remain. Many studies are constrained by their focus on relatively simple products, limiting the generalizability of findings to more complex, multi-material systems. Additionally, although recent theoretical frameworks propose the integration of circularity metrics with LCA and broader sustainability goals, their practical validation is still missing. The limited scope and granularity of some studies, particularly in terms of real-world redesign constraints, reduce their utility for practitioners seeking actionable guidance. These gaps underscore the need for applied, case-based research that examines the complementarity and limitations of LCA and circularity indicators in the context of complex product redesign.

Furthermore, although LCA and circularity indicators are increasingly viewed as complementary, there is still no structured framework for their application in complex product redesign at product or component levels. This study addresses this gap by proposing a two-level LCA-MCI integration approach, using SIF as a case study to explore the synergies and trade-offs between material selection, modularity, product longevity, and recyclability. Within this context, the study addressed the following research questions:

1. How does product redesign affect circularity scores and environmental impacts?
2. How do MCI and LCA results compare at the product level vs. the component level?
3. What are the possibilities and limitations of using MCI and LCA as complementary tools for redesigning complex products?

Methods

This research was divided into four segments, delineated in the flow diagram of Figure 1 and explained below. This paper's methods section describes steps one and two, while the results section elaborates on steps three and four.

Selection of Case Study and Definition of Scenarios

This research focuses on a SIF model developed by a Dutch manufacturer. The original "business-as-usual" product was designed for a linear system and was later redesigned to align with circular economy and Cradle to Cradle (C2C) principles. This allowed access to data for both the original and the redesigned versions of the shoe.

The redesigned "circular shoe" incorporates several changes in materials and design. These include a simplification of components and a shift toward monomateriality, intended to facilitate end-of-life (EoL) separation and recycling. Solvent-based adhesives were replaced with water-based alternatives to reduce toxicity and improve disassembly. Using C2C material selection tools, the manufacturer substituted unrecyclable materials such as polyvinyl chloride (PVC) and ethyl vinyl acetate (EVA) with thermoplastic recyclable counterparts. The toe cap was also replaced with steel to improve material durability and recyclability. To increase durability, the remaining leather elements were thickened from 2 mm to 3 mm, and the tanning process was changed from chromium-based to a chromium-free technique. In addition, to support extended product life, the manufacturer began offering replacement laces and soles, as well as maintenance wax. It is important to note that all these changes were implemented by the manufacturer prior to this study, and the authors had no influence on the redesign process.

Although the circular redesign was tested for a guaranteed lifespan of sixteen months, compared to the conventional twelve-month use period, current industry practice still follows a standard twelve-month replacement cycle. This limits the practical realization of the product's extended durability. Moreover, recycling at EoL cannot always be guaranteed due to potentially inadequate infrastructure and insufficient material volumes, leading to products being potentially incinerated instead of recycled, as confirmed in a personal communication with the company (2022).

To account for these variables, six scenarios were defined that combine three key aspects: (a) product redesign (linear vs. circular), (b) EoL treatment (incineration with energy recovery vs. recycling), and (c) product lifetime extension (twelve vs. sixteen months for the circular model). Each scenario was assigned a code for clarity, as summarized in Table 2.

Table 2 Summary of selected scenarios and their names and codes

Scenario	Design	Lifetime	End of Life	Code
1	Linear	12 months	Incineration	L12i
2	Linear	12 months	Recycling	L12r
3	Circular	12 months	Incineration	C12i
4	Circular	12 months	Recycling	C12r
5	Circular	16 months	Incineration	C16i
6	Circular	16 months	Recycling	C16r

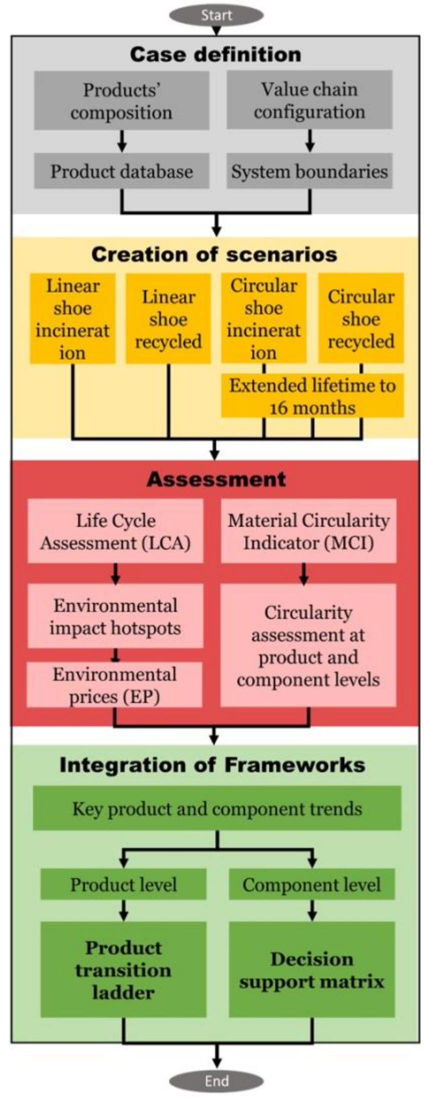

Figure 1 Process flow description for the research design.

Sustainability Assessment: LCA

The LCA was performed for each scenario according to the standard ISO 14044:2006, which specifies four stages: i) goal and scope definition, ii) life cycle inventory analysis, iii) life cycle impact assessment, and iv) life cycle interpretation (International Organization for Standardization, 2006).

Goal and Scope Definition The goal of this LCA is to evaluate the environmental impacts associated with the production and EoL treatment of linear and circular SIF models, as well as to assess the influence of product lifetime extension. The functional unit (FU) is defined as the protection of a worker's feet for a period of twelve months, in accordance with ISO 20345: 2011- safety and quality standards. The reference flow is one pair of shoes, size 42 (the most marketed shoe size in Europe), including packaging and labeling. This flow is applied to scenarios 1-4. For scenarios 5 and 6, a reference flow of 0.75 pairs is used to account for product life extension.

The system boundaries cover the extraction of raw materials up to and including delivery at the warehouse gate in Kerkrade, the Netherlands. EoL routes differ by scenario: Scenarios 1, 3, and 5 assume incineration with energy recovery through the Dutch waste management system. Scenarios 2, 4, and 6 consider the recycling of recyclable components and incineration of residuals. Materials representing less than 1% of the total weight of the FU and that lacked primary data, process database, or scientific literature were excluded, resulting in a total coverage of materials of 95.6%. System boundaries are illustrated in Figure 2.

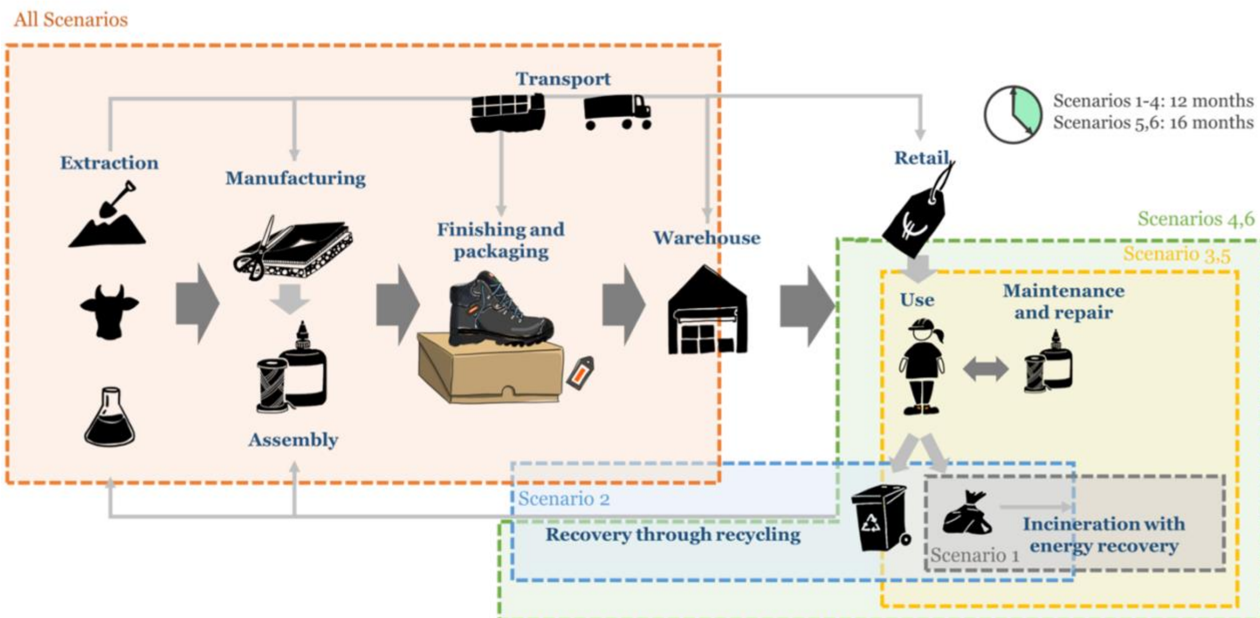

Figure 2 System boundaries for LCA of Safety Industrial Footwear for each of the six scenarios.

Life Cycle Inventory Two production datasets were developed: One for the linear SIF (L12 scenarios) and one for the circular SIF (C12 and C16 scenarios). The material inventory for each database was built by disaggregating the FU into components, sub-components, and materials. Figure 3 shows a condensed overview of the analysis for the circular model.

The main modeling choices across scenarios are summarized below. Detailed LCI tables are provided in the Supplementary Information (SI). Materials data include extraction, transformation, and transport to manufacturers. For the product assembly, manufacturing, and transport (local and inter-oceanic) were included. For leather manufacturing, a 3.5% economic allocation was applied according to the Product Environmental Footprint Category Rules for leather (De Rosa-Giglio et al., 2018). Conventional leather tanning processes were modeled using data from Joseph & Nithya (2008), and internal company data was used for the chrome-free and salt-free tanning process. Recycled materials were modeled using the avoided burden allocation method (Curran, 2015). All scenarios were modeled in Excel, combining primary data with secondary sources, including Ecoinvent 3.10 (Ecoinvent v3.10 - Ecoinvent, n.d.), technical reports, and scientific literature.

The product life extension of C16 scenarios considers the use of a maintenance kit in the inventory, which includes (1) a second pair of shoelaces made from recycled PET, (2) a second pair of inner soles, and (3) the addition of 0.05 kg of leather wax two times in twelve months.

In the recycling scenarios, materials were sorted into four categories: (1) packaging, (2) plastics, (3) metals, and (4) other materials. The first three categories are recycled, and the fourth one is incinerated with energy recovery. Because the L12r scenario is not designed for mono materiality or disassembly, the plastics are mechanically recycled into mixed plastic pellets (substitutability score 0.5). Conversely, for scenarios C12r and C16r, a higher quality of recyclate is assumed due to the mono-materiality of plastic components (substitutability score 1). All incineration scenarios assume energy recovery through the Dutch Waste Management System.

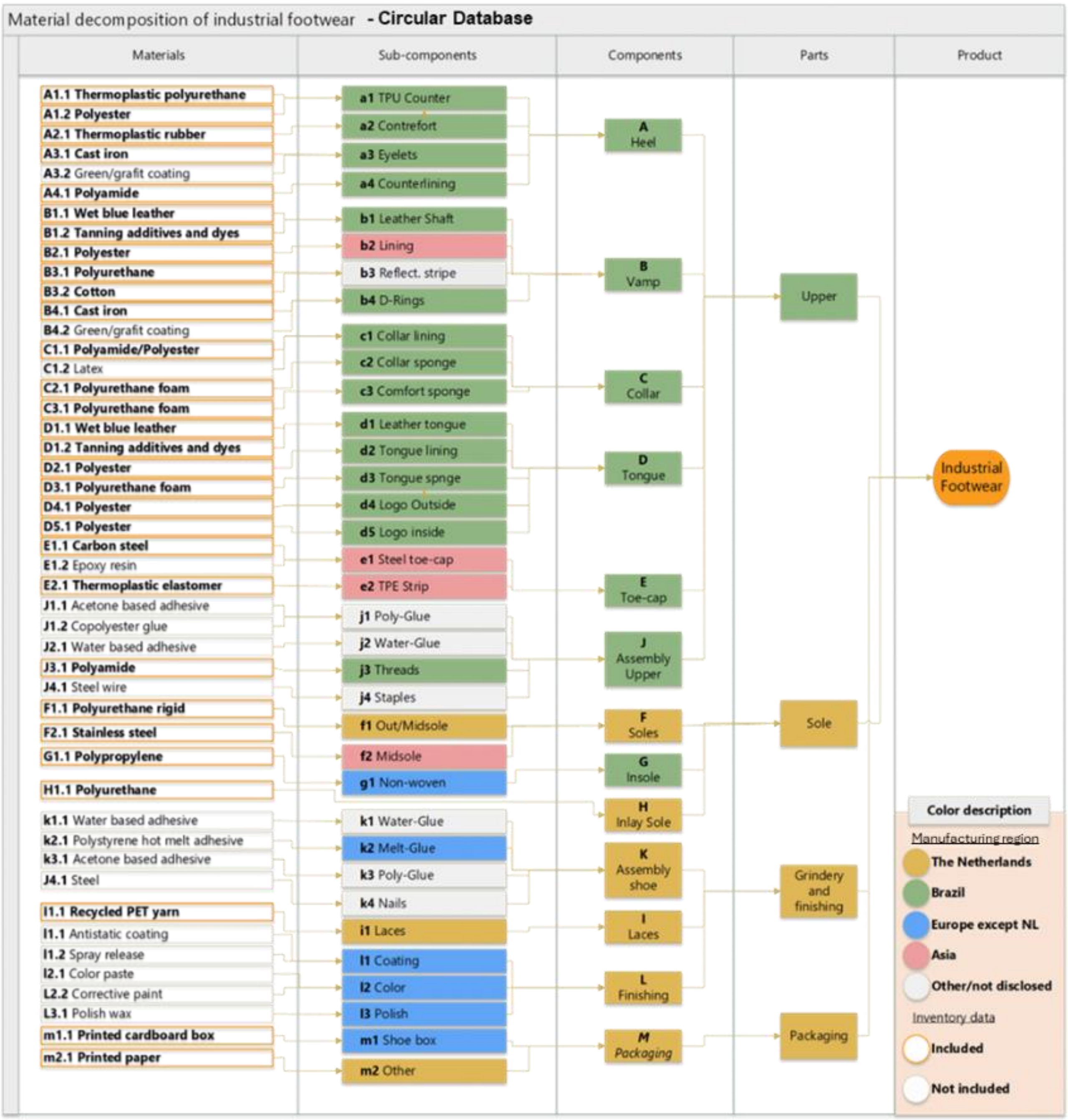

Figure 3 Material analysis of industrial footwear – circular database.

Life Cycle Impact Assessment The impact assessment followed the ReCiPe 2016 method (RIVM, 2017) from a hierarchist (H) perspective. Table 3 summarizes the impact categories with their units of assessment and abbreviations. Long-term emissions and infrastructure are excluded from the scope of this study. The environmental impacts were modeled through the open-source software Brightway 2, using Activity Browser as the interface (Steubing et al., 2020).

Table 3 Impact categories included in the ReCiPe 2016 method and their abbreviations for this paper

Impact category	Abbreviation	Units
Terrestrial Acidification Potential	TAP	kg SO2-eq
Global Warming Potential	GWP100	kg CO2eq
Freshwater Ecotoxicity Potential	FETP	1,4-DCB eq. emitted to freshwater
Marine Ecotoxicity Potential	METP	1,4-DCB eq. emitted to seawater
Terrestrial Ecotoxicity Potential	TETP	1,4-DCB eq. emitted to soil
Fossil-Fuel Resource Scarcity Potential	FFP	kg oil-eq
Freshwater Eutrophication Potential	FEP	kg P-eq. to freshwater
Marine Eutrophication Potential	MEP	kg N-eq to marine water
Human Carcinogenic Toxicity Potential	HTPc	1,4-DCB eq. emitted to urban air
Human Noncarcinogenic Toxicity Potential	HTPnc	1,4-DCB eq. emitted to urban air
Ionizing Radiation Potential	IRP	kBq Co-60 to air eq
Land Occupation Potential	LOP	m2*a
Mineral Resource Scarcity Potential	SOP	kg Cu-eq
Stratospheric Ozone Depletion Potential	ODP	kg CFC11-eq
Particulate Matter Formation Potential	PMFP	kg PM2.5-eq
Human Damage Ozone Formation Potential	HOFP	kg NOx-eq
Ecosystem Damage Ozone Formation Potential	EOFP	kg NOx-eq
Water Consumption Potential	WCP	m3

To enable a comparative assessment, the results were normalized following the latest Environmental Prices (EP) method (De Vries et al., 2024). Environmental Prices represent the estimated societal cost of emissions or resource use, expressed in euros per unit (e.g., €/kg), based on central economic valuations of environmental damage. For each impact category, midpoint characterization results were multiplied by their corresponding EP coefficients to yield a monetized environmental burden. All coefficients were sourced directly from the Environmental Prices Handbook 2024 list (De Vries et al., 2024), and the central value scenario was used for consistency across categories. This approach allows aggregation of different impact categories into a single comparable unit (euro-equivalent), facilitating interpretation and trade-off analysis.

As required by ISO 14006, the individual impact category results are fully disclosed in the supplementary tables, with EP values used solely to support the comparative discussion. No regional weighting or discounting factors were applied beyond those embedded in the EP method itself.

Circularity Assessment

The circularity assessment was performed using the Material Circularity Indicator (MCI), a standardized metric developed by the Ellen MacArthur Foundation (2015) (Ellen MacArthur Foundation, 2015) to quantify how restorative the material flows of a product are. The MCI score ranges from 0.1 (completely linear) to 1 (fully circular), based on the proportion of virgin or recycled input, unrecoverable waste, and the product's utility (i.e., its relative lifetime and intensity of use). In this study, the MCI was calculated at both product and component levels, following the methodology outlined by the Foundation.

The MCI is a combination of three product characteristics: the mass V of virgin material, the mass W of unrecoverable waste (and consequently the mass of recovered or circular materials), and a utility factor F(x) that accounts for the length and intensity of the product's use. These are integrated in formula (1):

$$MCI = 1 - \frac{V+W}{2M+(\frac{W_F - W_C}{2})} * F(x) \qquad (1)$$

Where M is the total mass of the product; V is the total virgin material used as input for a product; W is the total mass of unrecoverable waste; WF is the mass of unrecoverable waste generated when producing recycled feedstock; WC is the mass of unrecoverable waste generated in the process of recycling parts of a product, and F(x) is the utility factor built as a function of the utility X of a product.

Formula (2) presents the expanded version that accounts for recycling efficiencies and relative utility. All variables used are defined in Table 4. For a step-by-step example of applying the MCI, we refer readers to (Ellen MacArthur Foundation, 2015), where clear guidance on the methodology is provided.

$$MCI = 1 - \frac{4-2(F_R+F_U+F_S+C_R+C_U+C_C+\left(\frac{E_R}{HHV*M_B}\right)B_C)}{4+\frac{(1-E_F)F_R}{E_F}+(1-E_C)C_R} * \frac{L}{L_{av}} * \frac{U}{U_{av}} \qquad (2)$$

All variables from formulas (1) and (2) are described in Table 4 below:

Table 4 Variables for calculating the Material Circularity Indicator

Symbol	Definition
M	Mass of a product
F_R	Fraction of mass of a product's feedstock from recycled sources
F_U	Fraction of mass of a product's feedstock from reused sources
F_s	Fraction of a product's biological feedstock from Sustained Production.
V	Material that is not from reuse, recycling, or biological materials from Sustained Production.
Cc	Fraction of mass of a product being collected to go into a composting process
C_E	Fraction of mass of a product being collected for energy recovery where the material satisfies the requirements for inclusion.
C_R	Fraction of mass of a product being collected to go into a recycling process
C_U	Fraction of mass of a product going into component reuse
E_C	Efficiency of the recycling process used for the portion of a product collected for recycling
E_E	Efficiency of the energy recovery process for biological materials satisfying the requirements for inclusion.
E_F	Efficiency of the recycling process used to produce recycled feedstock for a product
B_C	The carbon content of a biological material, by default, a value of 45% is used unless supported by evidence to the contrary.
W	Mass of unrecoverable waste associated with a product
W_0	Mass of unrecoverable waste through a product's material going into landfill, waste-to-energy, and any other type of process where the materials are no longer recoverable

Exploratory Integration of Assessment Methods: LCA and MCI

The objective of integrating LCA and MCI as complementary tools was to determine whether shared hotspots and trends could be identified across both methodologies and to explore whether design choices that enhance circularity, such as modularity, extended product lifetimes, and recyclability, also lead to environmental impact reductions. This was done as a Type II integration: an independent LCA and MCI analysis with the aim of providing an overarching framework of results (Miah et al., 2017).

Results and Discussion

The results are structured into three sections: The first section presents the LCA results. The second section elaborates on the MCI results, and the third section discusses the integration of LCA and MCI as decision-making tools.

LCA Results

In the LCA results, C16 consistently scored at circa 75% of the value of C12, directly proportional to its life extension from 12 to 16 months, suggesting that the use of a second pair of laces, soles, and leather wax for maintenance does not have a significant environmental impact relative to the overall SIF impact. For this reason and the sake of brevity, this section only discusses C12 scenarios. However, all results are provided in the SI. For the following segments, please refer to Table 3 in the methods section for the abbreviation of each environmental impact.

The existing literature on the environmental impacts of SIF does not present the full range of impact categories; rather, it focuses solely on GWP100. Nevertheless, the findings of this study are in the same order of magnitude as those reported by Bodoga et al. (2024) and Serweta et al. (2019), who used a similar FU and system boundaries, as shown in Figure 4.

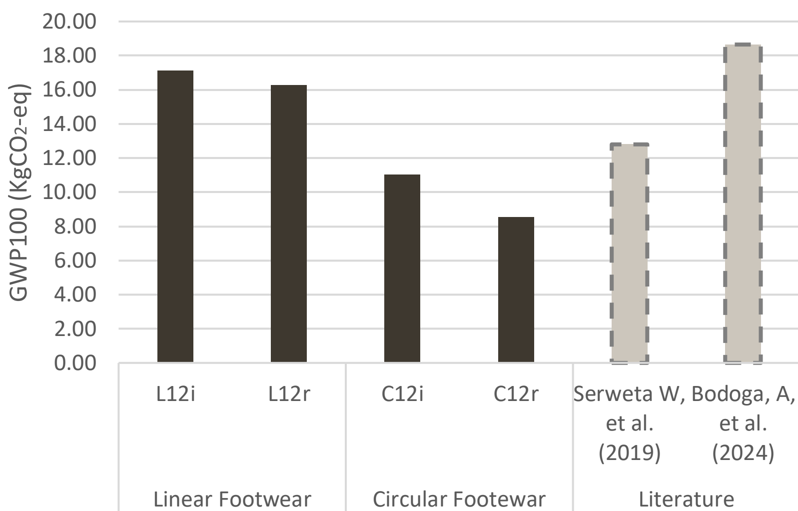

Figure 4 Global Warming Potential of Linear and Circular SIF, compared to available literature.

Linear SIF Scenarios In the L12 scenarios, leather production stands out as the primary environmental hotspot, contributing significantly to MEP (7.34E-04 kg N-eq), LOP (4.50E-01 m2*a), and HTPnc (2.31E+01 1,4-DCB eq.), as shown in Figure 5 and detailed in the SI. These impacts are largely linked to upstream emissions from cattle farming in Brazil, including NH_3, NO_x, and SO_2.

The energy required for processing and manufacturing the different shoe components remained the driving source of impacts in GWP (16.9 kg CO_2-eq), TAP (6.45E-02 kg SO2-eq), FFP (5.7 kg oil-eq), and TETP (63.14 kg 1,4-DCB-eq), underlining the energy intensity of the manufacturing phase. Transport contributions to TETP and METP (8.36E-02 1,4-DCB-eq) reflect the impacts of global complexity and geographic dispersion of the supply chain.

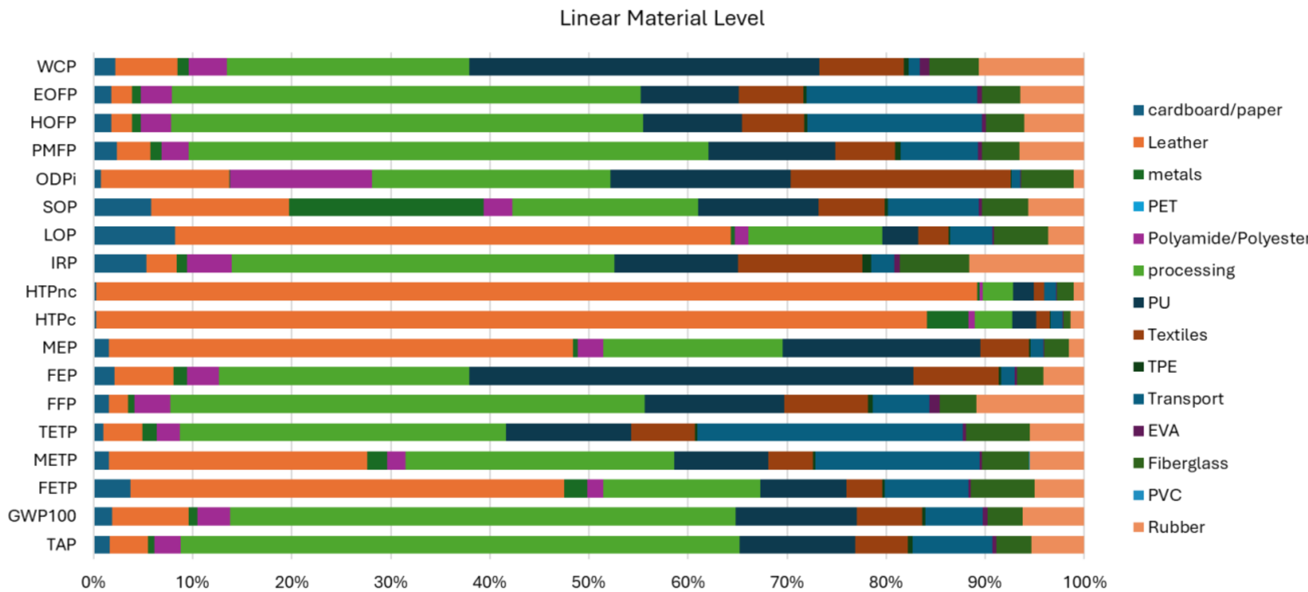

Figure 5 Relative material contribution of L12 scenario to different Environmental Impacts. Cradle-to-gate results.

Circular SIF Scenarios As depicted in Figure 6, leather remains a hotspot for C12 scenarios, but the use of chromium- and salt-free tanning results in reductions in TETP (−69%), FETP (−75%), METP (−85%), and HTPc (−99.7%) compared to L12. These improvements are aligned with findings from Xu et al. (2015) and Navarro et al. (2020). However, the larger mass of total leather utilized in C12 contributes to a minor increase in HTPnc (+2%) compared to L12. Processing energy remains a hotspot across environmental impacts. However, the simplification of components and reduction in material diversity, paired with a more centralized supply chain and the use of renewable energy in the Dutch assembly facilities, contribute to improvements in processing energy across all impact categories, from a 17% reduction in FEP to a 42% reduction in LOP. Overall, C12 scenarios show a 31–35% reduction in key impact categories such as GWP, FFP, and TETP.

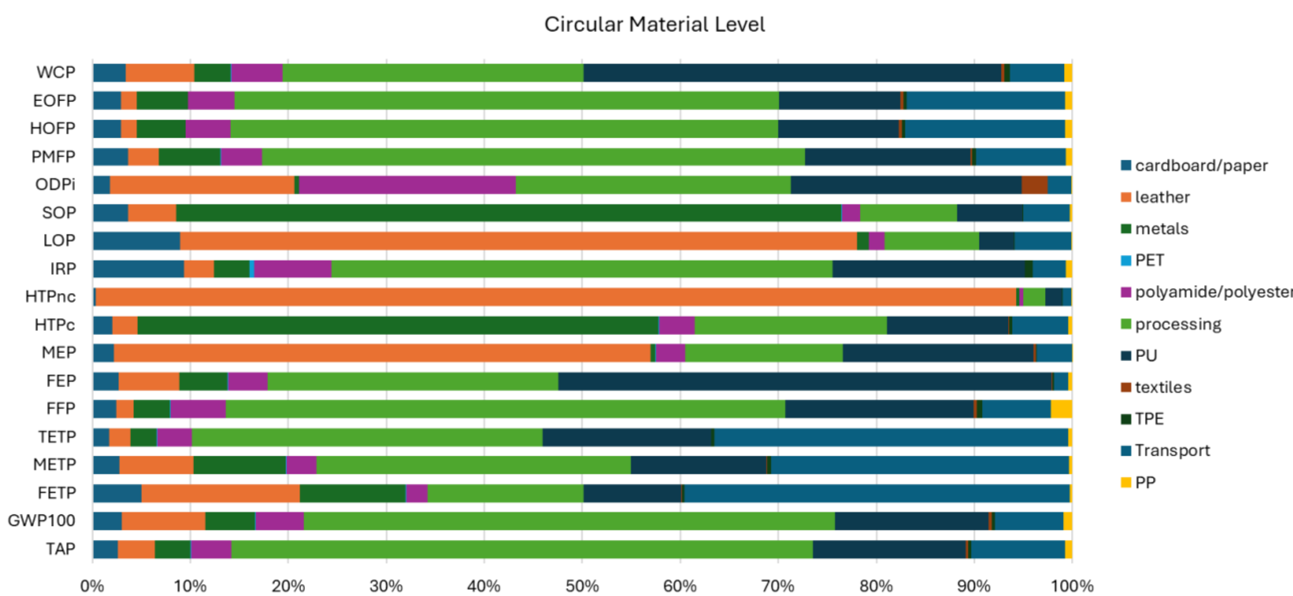

Figure 6 Relative material contribution of the C12 scenario to different Environmental Impacts. Cradle-to-gate results.

The plastic composition in the C12 scenario shifted compared to L12, incorporating recycled PET in the laces and PP in the insole (instead of Ethyl Vinyl Acetate). Additionally, TPU, both in foam and rigid forms, was introduced to increase mono materiality and remove the use of PVC, Rubber, and some TPE. Overall, C12 outperforms L12 across all impact categories except SOP due to the increased use of steel, which results in a 44% increase in SOP. The remaining impact categories show improvements ranging from 4% in HTPnc to 99.7% in HTPc and an average impact reduction of 66%.

End-of-life Scenarios Both L12 and C12 scenarios show reduced environmental impact when recycled rather than incinerated with energy recovery. Recycling improves all impact categories except TETP, IRP, and LOP for L12 and IRP for C12, as shown by the green cells in Table 5. Nonetheless, these results should be interpreted cautiously, as plastic mix estimates rely on generic PE, PP, and PET recycling inventories due to the lack of primary data.

Table 5 Environmental impacts of two EoL options: Incineration and Recycling for L12 and C12

Impact category	Units	Linear (L12)		Circular (C12)	
		Incineration w/ER	Recycling	Incineration w/ER	Recycling
TAP	kg SO2-eq	-3.60E-04	-4.70E-03	-2.58E-04	-9.28E-03
GWP100	kg CO2eq	2.29E-01	-6.40E-01	1.76E-01	-2.31E+00
FETP	1,4-DCB eq. emitted to freshwater	6.78E-03	1.35E-03	5.09E-03	-3.54E-03
METP	1,4-DCB eq. emitted to seawater	9.82E-03	4.73E-03	7.37E-03	-5.83E-03
TETP	1,4-DCB eq. emitted to industrial soil	4.50E-01	3.77E+00	3.44E-01	-3.65E+00
FFP	kg oil-eq	-2.25E-01	-5.04E-01	-1.67E-01	-9.45E-01
FEP	kg P-eq. to freshwater	-1.21E-05	-2.77E-04	-8.70E-06	-4.01E-04
MEP	kg N-eq to marine water	-1.32E-04	-3.37E-04	-9.52E-05	-4.46E-04
HTPc	1,4-DCB eq. emitted to urban air	9.41E-03	-2.92E-02	7.07E-03	-2.28E-01
HTPnc	1,4-DCB eq. emitted to urban air	1.43E-01	-9.72E-02	1.07E-01	-5.72E-01
IRP	kBq Co-60 to air eq	-3.45E-04	1.41E-02	-2.47E-04	2.16E-03
LOP	m2*a	-1.47E-02	1.10E-02	-1.05E-02	-2.23E-02
SOP	kg Cu-eq	-4.41E-04	-2.99E-02	-2.94E-04	-2.04E-01
ODPi	kg CFC11-eq	7.03E-07	-3.62E-06	5.27E-07	-4.87E-06
PMFP	kg PM2.5-eq	-1.61E-04	-2.12E-03	-1.15E-04	-4.45E-03
HOFP	kg NOx-eq	-2.74E-04	-1.70E-03	-1.97E-04	-5.39E-03
EOFP	kg NOx-eq	-3.10E-04	-1.77E-03	-2.23E-04	-5.67E-03
WCP	m3	-3.88E-04	-4.22E-02	-2.26E-04	-6.31E-02

It is important to note that the choice of glues and attachment methods is critical to the manufacturing and end-of-life processing of complex products (Maciel et al., 2017; Orgilés-Calpena et al., 2019), as they significantly influence material separation, sorting, and recyclability beyond their individual environmental impacts. In L12, materials are assumed to be separated into mixed plastics, metals, and others. C12 replaces acetone-based adhesives with water-based alternatives, enabling cleaner plastic streams. This assumption and its related results align with the discussion by Parchomenko et al. (2023) and Thys et al. (2023) on the essential role that adhesives designed for controlled disassembly play in improving the circularity and recyclability of products.

Normalized Impact Assessment Using Environmental Prices (EP) The EP results for each scenario, based on the latest 2024 normalization factors (De Vries et al., 2024), are presented in Table 6. The L12 scenarios consistently exhibit higher EP across all shoe components (see Figure 4 for the component overview). The vamp (€3.53) and tongue (€1.96), made out primarily of leather and metals, have the highest values, followed by the heel (€1.87) and soles (€1.58), which are predominantly plastic. In contrast, the C12 scenarios show reductions in the vamp (€1.65), soles (€0.94), and tongue (€0.57), representing a reduction of 54.17%, 40.51%, and 71.50%, respectively.

Table 6 Environmental prices at the component level for each scenario, including EoL options

Components	L12	C12	C16
Heel	€ 1.87	€ 1.01	€ 0.76
Vamp	€ 3.53	€ 1.65	€ 1.24
Collar	€ 0.21	€ 0.21	€ 0.16
Tongue	€ 1.96	€ 0.57	€ 0.43
Toe Cap/Shank	€ 0.36	€ 0.40	€ 0.30
Soles	€ 1.58	€ 0.94	€ 0.70
Insole	€ 1.01	€ 0.21	€ 0.16
inlay sole	€ 0.55	€ 0.12	€ 0.09
Laces	€ 0.03	€ 0.01	€ 0.01
Assembly Brazil	€ 0.20	€ 0.20	€ 0.12
Assembly NL	€ 0.35	€ 0.32	€ 0.24
Finishing	€ 0.00	€ 0.00	€ 0.00
Packaging	€ 0.14	€ 0.12	€ 0.09
Distribution	€ 0.20	€ 0.11	€ 0.06
EoL Incineration	€ 0.05	€ 0.04	€ 0.03
EoL Recycling	€ -0.48	€ -1.82	€ -1.38
Total with Incineration	€ 12.04	€ 5.92	€ 4.38
Total with Recycling	€ 11.51	€ 4.06	€ 2.97

At the EoL stage, the C12r scenario achieves a net EP of -€1.82, while L12r (-€0.48) reaches only 26% of this benefit. This is largely due to the quality of the plastic recyclate and the percentage of unrecyclable materials that must go into energy recovery. Conversely, incineration scenarios L12i (€0.05) and C12i (€0.04) present nearly equal results. These findings highlight the importance of EoL strategies next to material selection: while C12 consistently outperforms L12 across impact categories, at EoL, recycling of L12 proves more beneficial than incineration of C12.

While environmental pricing is a useful normalization tool for decision-making (Pizzol et al., 2017), it should be interpreted with caution to avoid oversimplification of environmental trade-offs (De Laurentiis et al., 2023). Impact categories such as Land Occupation Potential, Mineral Resource Scarcity Potential, Fossil-Fuel Resource Scarcity Potential, and Water Consumption Potential have a higher degree of uncertainty (De Vries et al., 2024), and environmental costs tend to be underestimated (De Vries et al., 2024; Kim et al., 2013). Therefore, the primary LCA results of this study remain those presented under *Linear SIF Scenarios* and *Circular SIF Scenarios*. However, despite its limitations, environmental pricing provides insight into the scale of environmental costs associated with SIF production. In the baseline scenario (L12i, €12.04), EP represents roughly 10–15% of the retail price (€80–100 per pair). This suggests that the environmental burden of products like SIF represents a significant fraction of their market value. However, EP should not be misinterpreted as a direct financial offset to be compensated through price adjustments. Instead, these findings reinforce the need and urgency of proactive design choices, material circularity, sustainable production, and circular EoL strategies to address impacts at the source.

Material Circularity Indicator (MCI) Results

Product-level Circularity The MCI results indicate that short product use coupled with incineration at EoL results in the lowest circularity scores, with L12i being the lowest (0.14), followed by C12i (0.25). When recycling is considered at EoL, L12r (0.33) achieves a higher score than C12i, while C12r (0.46) surpasses C16i (0.44), demonstrating that a longer product lifespan alone does not guarantee higher circularity if the EoL treatment is incineration. The highest score is observed in C16r (0.59), which combines circular design, extended use, and recycling strategies. The distance between L12i (baseline scenario) and C16r (redesign, paired with longevity and recycling) is 0.59, indicating that incorporating multiple circularity strategies simultaneously has the potential to increase product circularity nearly fourfold.

Role of Product Life Extension As shown in Figure 7, for the circular scenarios, a 25% increase in product lifetime (from 12 to 16 months) results in an approximate 65% increase in MCI for the incineration scenario and 30% for recycling. These findings demonstrate that product lifetime extension is a highly effective strategy for increasing circularity (Bakker et al., 2021; Boyer et al., 2021; Figge et al., 2018) even if the EoL is incineration (Bakker et al., 2021; Boyer et al., 2021; Figge et al., 2018).

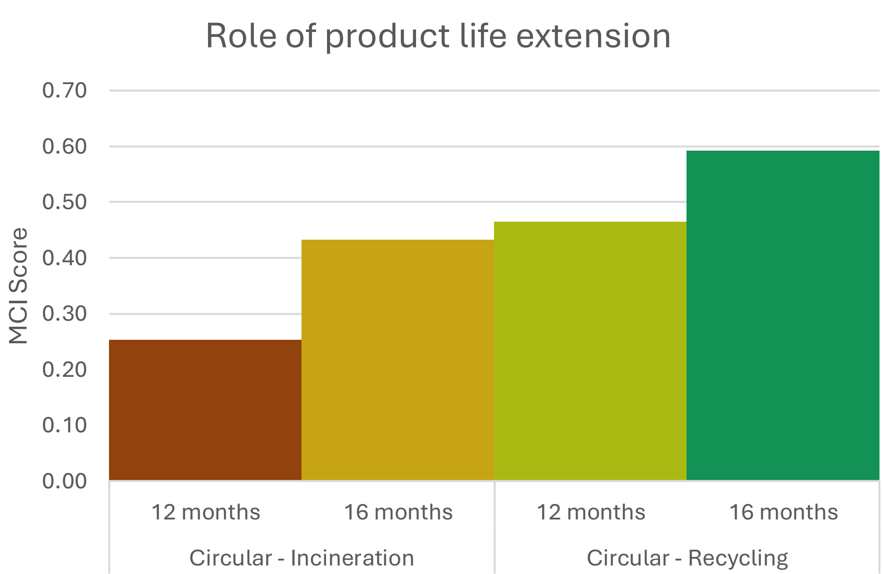

Figure 7 MCI score of circular SIF comparing product life extension and EoL alternatives.

Component-level Circularity Across all components, L12i scores the lowest on the MCI scale. C16r outperforms all other scenarios in every component except packaging (which is also recycled in all other scenarios and uses recycled materials in the C12 and C16 scenarios). Components that heavily rely on leather, such as the vamp and tongue, score low in the L12 and C12 scenarios and slightly higher in the C16 scenarios due to product lifetime extension. Conversely, polymer-reliant components, such as soles and laces, greatly benefit from recycling strategies for their circularity score. A summary of the MCI scores at component and product levels is shown in Figure 8.

These results highlight the importance of using durable and recyclable materials to achieve a higher circularity score at the component level. However, it is also important to acknowledge a key limitation of the MCI: it does not distinguish between renewable and non-renewable resources, nor does it fully account for improvements in material processing. Changes such as the removal of chromium in leather tanning or the use of renewable energy can significantly influence long-term circularity but are not adequately captured by the MCI (Leslie et al., 2016; Olabi, 2019; Wiedemann et al., 2022).

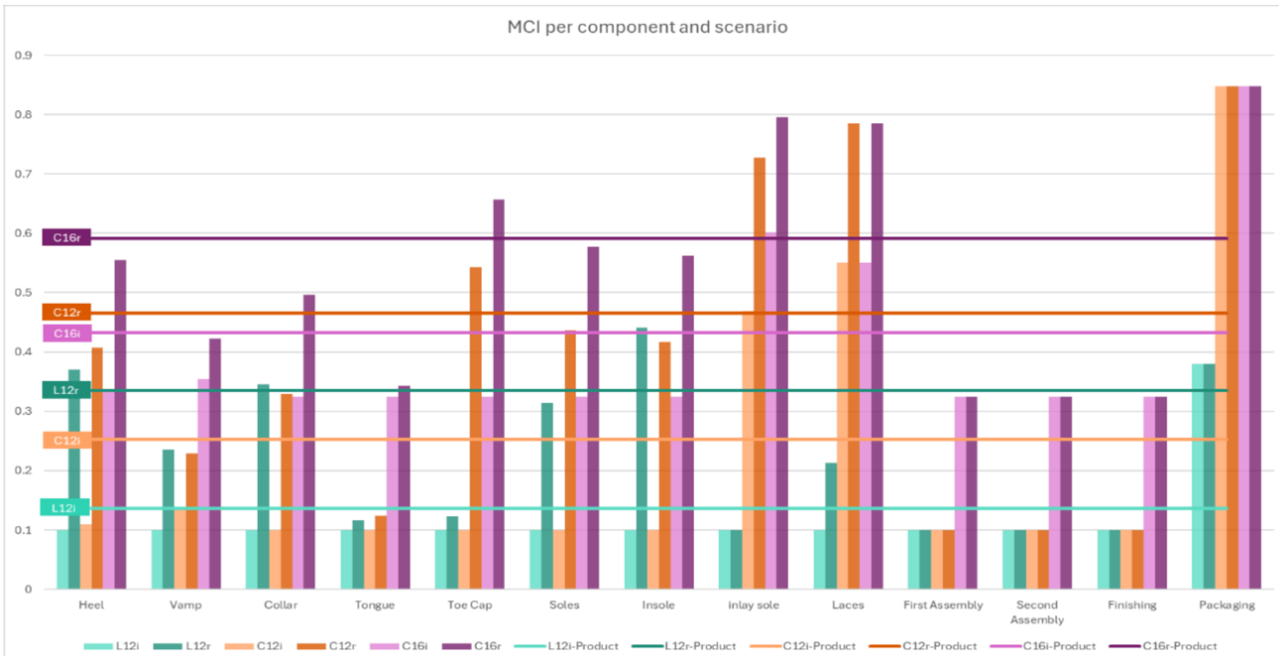

Figure 8 MCI scores for each scenario. Bars indicate the MCI score at the component level independent of their relative contribution to the weight of the functional unit, and horizontal lines indicate the MCI at the product level.

Integration of LCA and MCI

Product-level Integration At the product level, the relationship between MCI and LCA indicates that transitioning from a linear to a circular product (L12 to C12) results in a greater reduction in EP (51% decrease) than changing from incineration to recycling (-4% for L12r vs L12i; and -31% in C12r vs C12i). While recycling marginally improves EP, it significantly increases the MCI, suggesting that material retention and environmental impact reduction are not proportionally correlated (Brändström & Saidani, 2022; Glogic et al., 2021; Lonca et al., 2018).

A comparison between L12r and C12i illustrates this point. As shown in Figure 9, both achieve similar MCI values (0.33 and 0.25, respectively), but C12i has substantially lower EP (€ 5.92 for C12i versus € 11.54 for L12r). This indicates that while recycling contributes to value retention from a material circularity perspective, product redesign plays a more critical role in mitigating environmental impacts.

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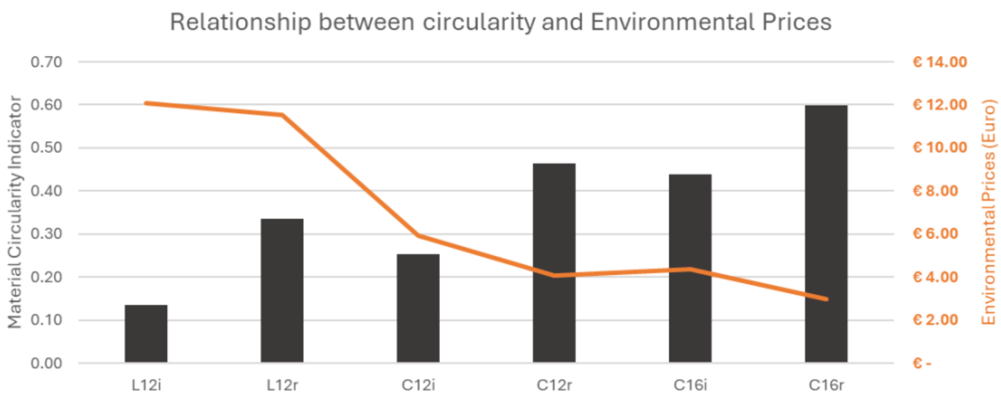

Figure 9 Relationship between MCI and EP at the product level for each of the six scenarios

When evaluating product lifetime extension (C16i and C16r), the results indicate that it is a viable strategy to increase both circularity and sustainability. However, without ensuring effective material recovery at EoL, this strategy (C16i) offers a comparable circularity benefit and slightly worse EP than recycling a circular product with an industry-average lifespan (C12r). These findings suggest that industries such as SIF can still make progress toward circularity, even if current industry practices favor shorter lifespans, allowing for gradual behavioral shifts and systemic adaptation over time.

These results can be conceptualized in a "transition ladder" (Figure 10), a stepwise model toward achieving a circular and sustainable product. This ladder suggests that companies can progress gradually from linear to circular products while also aligning with sustainability goals. The transition ladder outlines an incremental approach, recognizing that an immediate shift to fully circular products and systems may not always be feasible.

The first step involves either redesigning the product for circularity, even if recycling infrastructure is not yet available, or identifying opportunities to recycle components and materials from the existing linear products as an intermediate measure. In the next stage, companies can either proceed with product redesign (if recycling was the first step) or, if redesign was the starting point, either establish a network to support disassembly and recycling or test the possibilities of product life extension. Finally, at the highest level of the ladder, both the product and its supporting infrastructure are optimized for circularity and sustainability, minimizing environmental impacts, increasing lifetime, and closing resource loops.

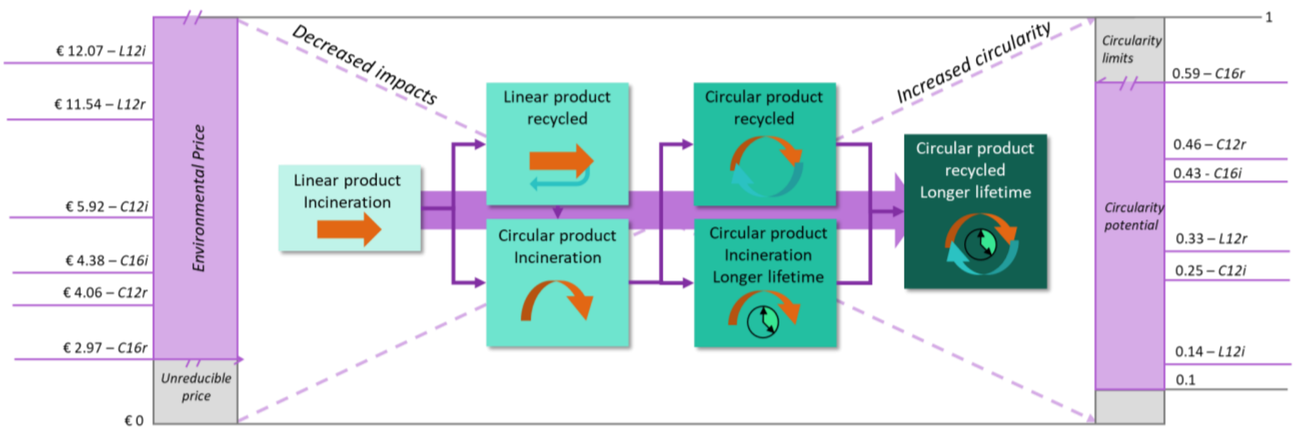

Figure 10 Product-level transition ladder for circularity transformations

For this purpose, LCA and MCI function as mutually informative tools, allowing flexibility in where companies begin their analysis. With MCI being less data-intensive, early circularity assessments could guide initial design decisions even when full LCA data are not available. Conversely, companies with prior LCA information can use environmental hotspots as guidelines for the redesign process at product and component levels.

Component-level Integration At the component level, the integration of LCA and MCI shows no consistent correlation, suggesting that materials can have conflicting scores across these two dimensions. Four distinct patterns emerge: (1) Components such as the vamp and insole, largely made out of leather, show high EP and low MCI, signaling a hotspot that requires urgent intervention. (2) Metal components show a substantial increase in circularity, but at the expense of worsening EP. Ensuring effective material recycling at EoL is critical for these materials in order to offset the EP. (3) Components made from virgin plastics, such as soles and insoles, have both low EP and low circularity, highlighting the potential to increase MCI through better EoL strategies and recycled content. Lastly, (4) components such as packaging and shoelaces, made from recycled cardboard and PET, already perform well in both MCI and EP, which might indicate low urgency for redesign.

To facilitate informed decision-making, Table 7 introduces a structured decision-support matrix to prioritize the redesign components of complex products by integrating their LCA and MCI results. The redesign priority in the last column (1–4) reflects the urgency of intervention, where 1 indicates immediate redesign and 4 suggests no action needed. The colour scale (red to green) visually reinforces this gradient from high to low priority.

Table 7 Decision-support matrix for the redesign of components in complex products

Environmental Price (EP) (low = good)	Material Circularity Indicator (MCI) (high = good)	Action	Redesign priority
High	Low	Redesign	1
High	High	Secure EoL	2
Low	Low	Explore recovery options	3
Low	High	Maintain	4

Limitations, Recommendations and Future Work

While this study demonstrates the complementary roles of LCA and MCI in circular product redesign, these results occur within a range of limitations. First, the LCA results rely on secondary data for some materials, particularly in the absence of specific inventories for glues, inks, color pastes, and releasing agents used in the assembly of the SIF. Additionally, the study assumes a uniform functional lifespan across scenarios, while in reality, user behavior and maintenance practices could introduce variability in product longevity and EoL product quality for recycling. Future research should explore consumer-driven factors influencing the use, maintenance, and disposal of such products to build an assessment model that is closer to real-life behavior. Furthermore, the route taken to model the EoL could be improved to incorporate different recyclate qualities, consider the role of impurities, and quantify the impact of collection, sorting, and separation.

In practical terms, this study provides decision-support tools for companies to prioritize circular redesign strategies. However, transitioning toward circular systems requires broader systemic changes, including supply chain adaptations, policy incentives, and infrastructure development for efficient end-of-life processing. Future research should explore how regulatory frameworks, extended producer responsibility (EPR) schemes, and financial mechanisms could accelerate the adoption of circular strategies, particularly for complex, multi-material products. Furthermore, these decision support tools should be broadly tested across a wider range of products and applications to refine and improve them.

Conclusion

The results of this study demonstrate that integrating LCA and MCI in the assessment of complex products such as SIF can function as a framework that captures both environmental and circularity dimensions, addressing the need for sustainable and circular product redesign. By combining LCA and MCI, it becomes possible to identify trade-offs between value retention and environmental impact reduction at product and component levels, preventing designers from shifting burdens from circularity to environmental sustainability or vice versa.

Overall, the best-performing scenario resulted from a redesigned product that incorporated simplified material composition, reduced overall weight, increased recycled content, enhanced disassembly through improved glues and threading techniques, extended durability, and improved mono materiality at the component level for better recycling. This combination of strategies, rather than any individual modification, yielded the highest MCI score and lowest EP value.

While insights from this study indicate that product lifetime extension improves circularity and sustainability, policy barriers restricting product lifetime flexibility, such as fixed 12-month replacement cycles, limit the potential that design for longevity can bring to the SIF industry. Furthermore, as economic pressures often prioritize affordability over sustainability, the EP results highlight that products perceived as inexpensive often carry significant ecological costs. This metric might support more informed policy regulations and potentially embed environmental considerations in production and consumption models and prices.

Two key findings emerged from this study: (1) at the product level, MCI and EP exhibit a general correlation, while (2) at the component level, these metrics do not align. To address this, two complementary decision support tools are introduced: First, at the product level, the transition ladder provides a stepwise model for companies to progress from linear to circular products through incremental improvements. Second, at the component level, a redesign prioritization matrix offers a structured approach to prioritizing component redesign based on environmental impact and circularity scores. Together, these findings offer companies and decision-makers practical entry points for approaching circularity and sustainability based on their unique needs and information availability. This research provides actionable decision-support tools applicable to other complex, multi-material products where circularity and sustainability priorities (and therefore transitions) remain fragmented.

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Data availability The authors declare that the data supporting the findings of this study are available within the paper and the Supplementary Information. Should any data be needed in another format, they are available from the corresponding author upon reasonable request.

Supplementary information (SI) The SI of this research paper is presented as an Excel file with five tabs:
1. Life Cycle inventory of L12 scenarios
2. Life Cycle inventory of C12 and C16 scenarios
3. Life Cycle Impact Assessment Results of All Scenarios
4. Material Circularity Indicator data and calculations
5. Material Circularity Indicator and Environmental Prices final results.

Declarations

Competing interests The authors declare no competing interests.

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