Advances in Reliability, Safety and Security, Part 10 – Kołowrocki, Kosmowski (eds.)
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Advances in Reliability, Safety and Security

ESREL 2024
Monograph Book Series

Sustainability In Safety: Evaluating Passive Safety Components Through Life Cycle Assessment

Francesco Di Paco[a], Marcello Braglia[a], Marco Frosolini[a], Roberto Gabbrielli[a], Luca Landi[b], Leonardo Marrazzini[a], Mauro Zampilli[b]

[a]*Department of Civil and Industrial Engineering, University of Pisa, Pisa, Italy*
[b]*Department of Engineering,University of the Studies of Perugia, Perugia, Italy*

Abstract

In recent years, growing concerns for environmental sustainability and workplace health and safety, as emphasized in the Sustainable Development Goals of the United Nations, have become increasingly prominent. This paper delves into the environmental impact assessment of passive safety devices for machine tools, aligning with international standards. Through a detailed Life Cycle Assessment, we analyse two distinct passive protective devices: a fixed fairing tailored for parallel CNC lathes and a perimeter fairing for large-size milling machines. The findings highlight steel as the predominant contributor to various environmental impact categories, showing its significant role in environmental damage. Consequently, the main way for enhancing the environmental sustainability of machine tool passive protective devices lies in minimizing and substituting, whenever feasible, the use of steel with less environmentally harmful materials.

Keywords: life cycle assessment, safety, sustainability, machine tool, guard, sustainable development goals

1. Introduction

In recent years, the imperative for a secure and integrated management of production systems has become undeniable. In accordance with the international standard UNI EN ISO 12100, the risk reduction process follows a three-step procedure. The first step involves the application of integrated protective measures during the design phase. The second step encompasses the adoption of complementary protections and additional protective measures. The final step concentrates on providing information for use, aiming to minimize residual risks that cannot be further reduced through other means. Specifically in the second step, the designer is tasked with selecting the most suitable protective devices to effectively mitigate the identified risks. Among these devices, fixed and movable guards, along with associated interlocking devices, play a crucial role in enhancing safety. In accordance with the international standard ISO 14120, a guard is specifically defined as a physical barrier integrated into the machine with the purpose of safeguarding operators. This standard categorizes guards into various groups, and the selection of the most appropriate type is determined by criteria including the probability and severity of injury, foreseeable misuse, machine hazards, frequency of access, and other relevant factors.

Concurrently with the growing awareness of safety considerations, there is a notable surge in concern for environmental conservation and other sustainability aspects. This trend is unmistakably articulated by the increasing integration of the Sustainable Development Goals (SDGs) into both public and private development plans. Forming the core of The 2030 Agenda for Sustainable Development, unanimously adopted by all United Nations Member States in 2015, these 17 goals represent a pressing call to action for all countries. They encompass and advance all three pillars of sustainability: economic, social, and environmental.

Specifically, SDG 8 is dedicated to promoting sustained, inclusive, and sustainable economic growth, along with ensuring full and productive employment and decent work for all. Among its targets, Target 8.8 is specifically centred on protecting labour and advocating for a safe and secure working environment for all workers. This underscores the integral role of workplace safety within the broader framework of sustainable economic development. From the environmental standpoint, Goals 13, 14, and 15 concentrate on tackling Climate Change, as well as the preservation and conservation of oceans and terrestrial ecosystems. These goals underscore the global commitment to address environmental challenges, including climate-related issues and the imperative to safeguard the health and vitality of both marine and terrestrial ecosystems.

In this paper, aligning with the United Nations guidelines, we try to harmonize the dimensions of a safe and secure workplace with environmental protection. This is achieved through a comprehensive assessment of the environmental footprint associated with the fairings of machine tools. More precisely, we have embraced the widely recognized Life Cycle Assessment (LCA) methodology to explore the environmental impact incurred in respecting the necessary safety standards. This integrated approach aims to shed light on the intersection of safety considerations and environmental sustainability in the context of machine tool fairings. To the best of our knowledge, there is currently no existing literature analysing the environmental costs associated with the necessary safety devices for machine tools. Therefore, conducting a LCA on safety and protective components represents a little step towards achieving true sustainable development. The rest of the paper is organized as follows: Section 2 provides an overview of the literature related to LCA and environmental assessment of machine tools, while Section 3 outlines the methodology, including the machine tool fairings under study and the conduct of the LCA. In Section 4, we present and discuss the results derived from the analysis. Finally, Section 5 concludes the paper and suggests potential opportunities for related future research.

2. Literature review

In this section, we provide an overview of the applications of LCA for the environmental assessment of machine tools. LCA is a systematic approach used to evaluate the environmental impacts of a product, process, or activity throughout its entire life cycle, from raw material extraction to disposal. It considers various stages such as production, use, and end-of-life treatment, aiming to identify the environmental burdens. The decision to utilize the LCA was straightforward, as it has been previously adopted and integrated into the design phase to evaluate the efficient way of managing the machine tools throughout its lifecycle (Daniyan et al., 2021). This choice ensures the incorporation of sustainability considerations from the early stages of a product's life, underscoring a proactive approach to addressing environmental and safety aspects throughout its entire lifecycle. From a safety perspective, LCA has been extensively utilized to identify and evaluate potential impacts (Breedved, 2013; Simoes et al., 2011). For example, Breedveld (2013) integrated LCA with Risk Assessment to analyse the potential adverse effects of emerging technologies on health, safety, and the environment. LCA has also evolved to include a focus on social aspects, leading to the emergence of Social Life Cycle Assessment (S-LCA) (UNEP/SETAC, 2009). S-LCA examines impacts on human capital, well-being, cultural heritage, and social behaviour. It has found application across diverse sectors such as food, biofuels, materials, technology, and services (Sala et al., 2015).

In the existing literature, several examples highlight the utility of LCA in examining the environmental impact of machine tools (Hirogaki et al., 2011; Ma et al., 2021; Yu et al., 2013). Hirogaki et al. (2011) utilized LCA to showcase that employing smaller-size machine tools is an effective approach for enhancing the environmental footprint in small parts manufacturing. Yu et la. (2013) performed a LCA to compare two different types of presses in order to understand quantitatively the environmental emissions during their life cycles. Ma et al. (2021) conducted an LCA to compare the environmental implications of using cast iron versus resin mineral composite for machine tool beds, specifically focusing on carbon emissions. These studies underscore the versatility of LCA in evaluating and optimizing the environmental performance of various aspects within the realm of machine tool manufacturing.

Upon examination of the existing literature, a gap emerges concerning analyses aimed at investigating the environmental impact of passive safety devices for machine tools. Consequently, this paper seeks to address this gap by conducting a LCA on two distinct types of machine tool fairings. The objective is to comprehend the environmental costs associated with ensuring protective devices that meet the required safety standards.

3. Methods

The Life Cycle Assessment (LCA), as outlined in the international standards ISO 14040:2006 and ISO 14044:2018, facilitates the evaluation of the environmental impact of the product under analysis through four key steps:

- Goal and Scope definition. This initial phase outlines the objectives, intended application, motivations driving the analysis, and the target audience. This crucial step establishes the framework by specifying system boundaries, defining functional units, addressing data quality parameters, and acknowledging any adopted hypotheses. It serves as the foundational phase, ensuring clarity and alignment with the overarching goals and context of the assessment.

- Inventory Analysis. This phase is dedicated to gathering data on input flows, including materials and energy, as well as output flows, encompassing waste, emissions, and other relevant environmental aspects.
- Impact Assessment. In this phase the environmental impacts are systematically evaluated across various impact categories, utilizing the data collected during the Inventory Analysis.
- Interpretation. This step is conducted in parallel with the others to provide a comprehensive understanding of all the information.

For the analysis, we employed the SimaPro software, a widely recognized tool for conducting assessments of this nature. SimaPro stands out for its extensive database, enabling the calculation of impact indicators associated with both input and output flows. This choice ensures a robust and comprehensive evaluation of the environmental impact of the product or process under consideration. In the sequent subsections, we provide detailed descriptions of the protective devices under examination, outlining the defined system boundaries, and presenting the collected data. This comprehensive approach aims to offer a thorough understanding of the protective measures considered and the parameters guiding our analysis.

3.1. CNC machine tools

The passive protection components considered in this study are fairings produced at a machine tool manufacturer in central Italy.

The first, a device named K8_21X_XXBXXX_01, corresponds to a complete fairing of a lathe with a pallet length of about 1 meter. The other apparatus, named DC_0510_18, consists of a series of identical modules and serves as a perimeter enclosure for a milling machine with a large tilting table (approx. 10 m) with transparent Lexan merguard panels, i.e. solid sheets of glass and polycarbonate with a 6 mm thick scratch-resistant protective coating. By selecting these specific machine tools and their corresponding fairings, we can explore two distinct yet representative scenarios within the tooling ecosystem. The former scenario depicts a smaller-scale case where the fairing is fixed to the machines, restricting the ingress and egress of objects from the tooling area. This setup is typical for lathes designed for single-part production or small to medium-sized series. Conversely, the latter scenario involves perimeter fairings designed to prohibit access to the working area on a much larger scale. Such large machines are typically utilized in high-volume production contexts. By analysing these differing situations, we can consider factors such as productivity capacity and the size requirements of the fairings.

The machine with integrated protective device K8_21X_XXBXXX_01 is a CNC parallel lathe. The head on which the spindle is housed is cast in one piece and is very rigid. The spindle is case-hardened, quenched and ground. It is lubricated with a special grease that simplifies maintenance. The enclosure is fully enclosed to ensure the confinement of the swarf. The hardened safety glasses allow proper visibility of the working area (Figure 1).

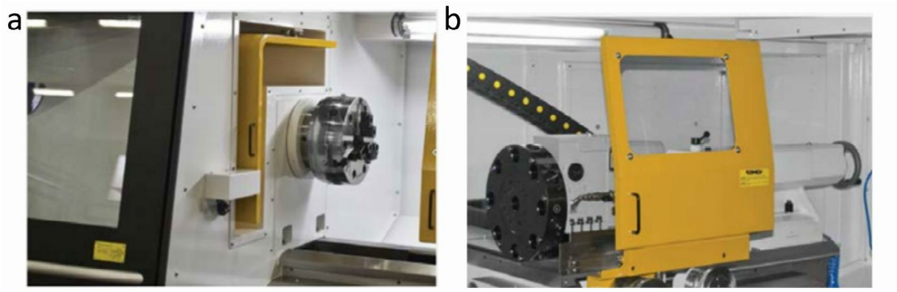

Fig. 1. (a) Head of the lathe; (b) Fairing of the lathe.

The second machine is a large five-axis milling machine (Fig.2). The bulkhead under study surrounds the machine perimeter.

Fig. 2. Five-axis milling machine.

Both the machine tools fairings are designed according to the requirements of ISO 14119, ISO 14120, ISO 23125 and Machinery Directive 2006/42 CE.

3.2. System boundaries

The LCA has been conducted considering the PCR MACHINE-TOOLS FOR DRILLING, BORING OR MILLING METAL PRODUCT GROUP: UN CPC, version 3.02. These rules define the parameters and criteria for conducting life cycle assessments and environmental impact assessments within this specific category. The system boundaries for this PCR encompass the entire life cycle of machine tools designed for drilling, boring, or milling metal. This includes the upstream process, the core process and the downstream process. Specifically, in the upstream process the raw material extraction and production play a major role. The core process focuses on the electricity and natural gas consumption, while the downstream process is centred around the End-Of-Life aspects. Processes not directly related to the life cycle of the machine tools, such as unrelated ancillary equipment or non-metal machining tools, fall outside the scope of this PCR.

For the case at hand, we adopted a cradle-to-gate approach evaluating the environmental impact of the fairings from the extraction of the raw materials to the gate of the company (Figure 3).

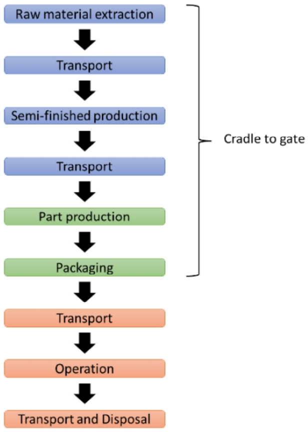

Fig 3. Cradle to gate adopted approach.

3.3. Fairing analysis of K8_21X_XXBXXX_01

We selected the entire fairing, as depicted in Fig. 4, as the functional unit. Following this selection, we proceeded to compile essential data, specifically assessing the material, volume, and weight for each component of the fairing. The findings from this evaluation are documented in Table 1.

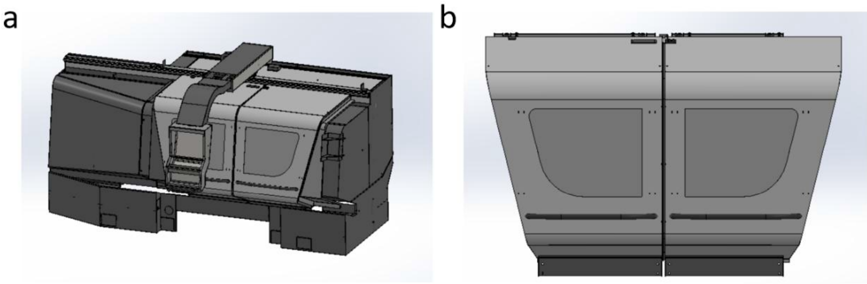

Fig. 4. (a) 3D rendering of the lathe; (b) Functional unit of the LCA

Table 1. Data collected for K8_21X_XXBXXX_01.

N°	Part	Component	Volume [cm^3]	Material	Weight [kg]
1	Left Door	K84720_1	6462	Steel	6.47
		K84720_2	489.9	Steel	0.50
		K84720_3	140.0	Steel	0.15
		K84720_4	494.9	Steel	0.50
		K84720_5	735.7	Steel	0.74
		K84720_6	1.4	Steel	0.01
		K84720_7	12.1	Steel	0.02
		K84720_9	214.7	Steel	0.22
		K84720_10	409.6	Steel	0.42
		K84720_11	491.9	Steel	0.50
		K84720_12	29.2	Steel	0.04
		K84720_13	19.8	Steel	0.03
		K84720_14	67.6	Steel	0.08
		K84720_15A	21.3	Steel	0.03
		K84720_15B	529.2	Steel	0.54
		K84720_15C	7.7	Steel	0.02
		K84720_15D	359.8	Steel	0.37
		K84810	902.0	Steel	0.91
		K82070	3287	Lexan	3.29
		K82040	4382	Glass	4.39
		K84170_3	690.5	Steel	0.70
		K84170_4	2.4	Steel	0.01
		Assembled wheels	51.8	Steel	0.06
		RHBG	576.9	Steel	0.58
2	Right Door	K84720_1	6462	Steel	6.47
		K84720_2	489.9	Steel	0.50
		K84720_3	140.0	Steel	0.15
		K84720_4	494.9	Steel	0.50
		K84720_5	735.7	Steel	0.74
		K84720_6	1.4	Steel	0.01
		K84720_7	12.1	Steel	0.02
		K84720_9	214.7	Steel	0.22
		K84720_10	409.6	Steel	0.42
		K84720_11	491.9	Steel	0.50
		K84720_12	29.2	Steel	0.04
		K84720_13	19.8	Steel	0.03
		K84720_14	67.6	Steel	0.08
		K84720_15A	21.3	Steel	0.03
		K84720_15B	529.2	Steel	0.54
		K84720_15C	7.7	Steel	0.02
		K84720_15D	359.8	Steel	0.37
		K84810	902.0	Steel	0.91
		K82070	3287	Lexan	3.29
		K82040	4382	Glass	4.39
		K84170_3	690.5	Steel	0.70
		K84170_4	2.4	Steel	0.01
		Assembled wheels	51.8	Steel	0.06
		RHBG	576.9	Steel	0.58

3.4. Fairing analysis of DC_0510_18

The perimeter fairing under examination serves the purpose of enveloping a large-sized machine or delineating distinct machines. We designated the whole fairing, as illustrated in Figure 5, as the functional unit. Subsequently, we systematically gathered data, meticulously evaluating the material, volume, and weight for each individual component of the fairing. The outcomes of this evaluation are detailed in Table 2.

Table 2. Data collected for DC_0510_18.

N°	Part	Component	Volume [cm^3]	Material	Weight [kg]
1	Sliding Door	Frame door	8552	Steel	67.1
		Sheet metal	1352	Steel	10.6
		Sheet metal	2374	Steel	18.6
		Sheet metal	1352	Steel	10.6
2	Sliding Door	Frame door	8552	Steel	67.1
		Sheet metal	1352	Steel	10.6
		Sheet metal	2374	Steel	18.6
		Sheet metal	1352	Steel	10.6
3	Sliding Door	Frame door	8552	Steel	67.1
		Sheet metal	1352	Steel	10.6
		Sheet metal	2374	Steel	18.6
		Sheet metal	1352	Steel	10.6
4	Sliding Door	Frame door	8552	Steel	67.1
		Sheet metal	1352	Steel	10.6
		Sheet metal	2374	Steel	18.6
		Sheet metal	1352	Steel	10.6
5	Sliding Door	Frame door	8552	Steel	67.1
		Sheet metal	1352	Steel	10.6
		Sheet metal	2374	Steel	18.6
		Sheet metal	1352	Steel	10.6
6	Sliding Door	Frame door	8552	Steel	67.1
		Sheet metal	1352	Steel	10.6
		Sheet metal	2374	Steel	18.6
		Sheet metal	1352	Steel	10.6
7	Strut	Rod and foot	1018	Steel	8
8	Fixed Door	Sheet metal	2374	Steel	18.6
9	Strut	Rod and foot	1789	Steel	14.1
10	Strut	Rod and foot	1018	Steel	8
11	Fixed Door	Sheet metal	2374	Steel	18.6
12	Strut	Rod and foot	1789	Steel	14.1
13	Fixed Door	Sheet metal	2374	Steel	18.6
14	Strut	Rod and foot	1018	Steel	8
15	Fixed Door	Sheet metal	2374	Steel	18.6
16	Fixed Door	Sheet metal	2374	Steel	18.6
17	Strut	Rod and foot	1018	Steel	8
18	Strut	Rod and foot	1018	Steel	8
19	Fixed Door	Sheet metal	2374	Steel	18.6
20	Strut	Rod and foot	1018	Steel	8
21	Fixed Door	Sheet metal	2374	Steel	18.6
22	Strut	Rod and foot	1018	Steel	8
23	Fixed Door	Sheet metal	2374	Steel	18.6
24	Fixed Door	Sheet metal	2374	Steel	18.6
25	Strut	Rod and foot	1018	Steel	8
26	Strut	Rod and foot	1018	Steel	8
27	Door Support	Rod	22030	Steel	173
28	Fixed Door	Sheet metal	1845	Steel	14.5
29	Panel	Panel	770	Glass and Lexan	1.44
30	Panel	Panel	770	Glass and Lexan	1.44
31	Panel	Panel	770	Glass and Lexan	1.44
32	Panel	Panel	770	Glass and Lexan	1.44
33	Panel	Panel	770	Glass and Lexan	1.44
34	Panel	Panel	770	Glass and Lexan	1.44
35	Panel	Panel	770	Glass and Lexan	1.44
36	Panel	Panel	770	Glass and Lexan	1.44
37	Panel	Panel	770	Glass and Lexan	1.44
38	Panel	Panel	770	Glass and Lexan	1.44
39	Panel	Panel	770	Glass and Lexan	1.44
40	Panel	Panel	770	Glass and Lexan	1.44
41	Panel	Panel	770	Glass and Lexan	1.44
42	Panel	Panel	770	Glass and Lexan	1.44
43	Panel	Panel	770	Glass and Lexan	1.44
44	Panel	Panel	770	Glass and Lexan	1.44

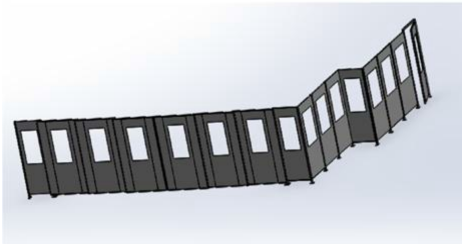

Fig. 5. 3D rendering of the perimeter fairing.

4. Results and discussion

In the forthcoming Section, we delve into the outcomes of our analysis, presenting key findings and insights derived from the comprehensive evaluation. The selection of environmental impact categories aligns with the criteria outlined in the international standard ISO 14042. To enhance clarity and facilitate a comprehensive understanding, the environmental impacts derived from the analysis are methodically presented in tabular format. Specifically, Table 3 reports the outcomes of the analysis conducted on the fairings K8_21X_XXBXXX_01 and DC_0510_18.

Table 3. Results of LCA.

Impact Category	Unit of Measure	DC_0510_18	K8_21X_XXBXXX_01
Global Warming	kg CO2eq	1575	21730
Stratospheric Ozone Depletion	kg CFC11eq	0.0005	0.0064
Ionizing radiation	kBq CO-60eq	58.1	803
Ozone formation (Human health)	kg NOxeq	4.62	63.26
Fine particulate matter formation	kg PM2.5eq	4.06	55.97
Ozone formation (Terrestrial ecosystems)	kg NOxeq	4.85	66.49
Terrestrial acidification	kg SO2eq	5.95	80.75
Freshwater eutrophication	kg Peq	1.55	21.59
Marine eutrophication	kg Neq	0.048	0.679
Terrestrial ecotoxicity	kg 1.4-DCB	11410	158700
Freshwater ecotoxicity	kg 1.4-DCB	213.5	2982
Marine ecotoxicity	kg 1.4-DCB	302	4216
Human carcinogenic toxicity	kg 1.4-DCB	1252	17520
Human non-carcinogenic toxicity	kg 1.4-DCB	6430	89760
Land use	m2 a crop eq	32.5	446
Mineral resource scarcity	kg Cueq	86.7	1212
Fossil resource scarcity	kg Oileq	380	5231
Water consumption	m3	11.3	156

The analysis reveals that the predominant use of steel emerges as the primary contributor to the environmental impacts associated with the fairings. Indeed, upon scrutinizing the individual contributions to diverse environmental impacts for both fairings, it becomes apparent that enhancing the sustainability of these safety devices necessitates the substitution of steel with a less environmentally impactful material. This proposition is exemplified, for instance, in the Global Warming and Water Consumption category as detailed in Table 4 and Table 5.

Table 4. Global Warming category.

Fairing	Material	Weight Percentage	Unit of Measure	Contribution	Percentage
DC_0510_18	Steel	63%	kg CO_2eq	21667	99.70%
	Polycarbonate	16%	kg CO_2eq	56.7	0.26%
	Glass	21%	kg CO_2eq	9.1	0.04%
K8_21X_XXBXXX_01	Steel	97.9%	kg CO_2eq	1548	98.24%
	Glass and Lexan	2.1%	kg CO_2eq	27.8	1.76%

Table 5. Water Consumption category.

Fairing	Material	Weight Percentage	Unit of Measure	Contribution	Percentage
DC_0510_18	Steel	63%	m^3	155	99.74%
	Polycarbonate	16%	m^3	0.35	0.23%
	Glass	21%	m^3	0.06	0.04%
K8_21X_XXBXXX_01	Steel	97.9%	m^3	11.1	98.40%
	Glass and Lexan	2.1%	m^3	0.18	1.60%

In the context of the Global Warming category, the contribution of steel in both fairing DC_0510_18 and fairing K8_21X_XXBXXX_01 is striking, representing over 99% and 98%, respectively. This underscores the almost negligible contributions of glass and polycarbonate to this environmental impact category. Notably, for DC_0510_18, where steel constitutes 63% of the total weight, its substantial contribution becomes even more pronounced, accounting for 99% of the Greenhouse Gas (GHG) Emissions. A parallel pattern emerges in the Water Consumption impact category, where, notably for fairing DC_0510_18, steel constitutes over 99.5%, rendering the contributions from polycarbonate and glass irrelevant. This is particularly noteworthy given that steel comprises approximately 63% of the total fairing weight, emphasizing the considerable water demands associated with the extraction, transportation, and production of steel components compared to other materials. Similar observations hold for fairing K8_21X_XXBXXX_01, where steel accounts for over 98% of the total water consumption. Overall, these findings underscore the pronounced impact of steel on GHG emissions production and water usage and emphasize the importance of considering alternative materials for improved environmental sustainability.

5. Conclusions

Considering the growing concern for environmental sustainability and workplace safety aspects, this paper aims to investigate how much cost to design passive safety devices in terms of environmental impact that align with the requirements of international standards. To a chieve this goal, we performed a LCA on two distinct passive protective devices: a fixed fairing designed for a parallel CNC lathe and a perimeter fairing intended for five-axis large-size milling machines. The analysis adhered to the international standards ISO 14040 and ISO 14044, guiding the comprehensive exploration of study objectives, system boundaries, functional units, data collection methodologies, and impact categories. This structured approach ensured a robust and standardized framework for the assessment, aligning with established protocols in LCA methodology.

Consistent findings are evident across various impact categories, leading to the conclusion that the extensive utilization of steel renders it the most environmentally impactful material. Consequently, the primary imperative is to minimize the use of steel whenever feasible. Promising directions for investigation involve exploring alternative materials that respect identical structural requirements with a reduced environmental impact, such as recyclable plastic materials. Additionally, optimizing steel thickness represents another option worthy of consideration.

Based on the findings, future research could pursue two distinct avenues. Firstly, exploration into alternative materials to replace steel while maintaining a life cycle perspective could be pursued. Secondly, conducting a thorough analysis to establish the relationship between the environmental costs incurred by the fairings and their economic costs could be beneficial. By doing so, it would be feasible to integrate all three dimensions of sustainability.

Acknowledgements

We extend our sincere gratitude to COMEV S.P.A. for their collaboration in conducting the LCA for this research. Their support and expertise significantly contributed to the successful completion of the study.

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