Assessment of environmental performance combining life cycle assessment, multi-criteria analysis, and environmental performance indicators from a case study on the post-production of 3D-printed face masks

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Abstract. The paper proposes an assessment of the environmental impact of 3D-printed face mask production during the COVID-19 pandemic, integrating three quality management tools: Life Cycle Assessment (LCA), Multi-Criteria Analysis (MCA), and Environmental Performance Indicators (EPIs). The approach, named COMPLIMENT, emphasizes the importance of considering factors such as CO_2 emissions and regional/local impacts. The results reveal a significant environmental impact regarding CO_2 emissions, underscoring the need for mitigation strategies, such as efficient energy source management. Multi-criteria analysis allowed the assignment of weights to different criteria, considering diverse geographic scales. Beyond production, the article addresses product disposal management, and adopting Design for the Environment (DfE) principles. Practical recommendations include selecting sustainable materials, promoting reusable masks, and implementing collection and recycling programs. Despite positive results, the study acknowledges challenges in data collection for Life Cycle Assessment and emphasizes the need for future comparative research and long-term studies on the environmental impact of design practices and end-of-life considerations. The paper highlights the importance of an integrated approach to environmental assessment and product management, promoting sustainable practices from production to disposal. It contributes to a more informed understanding of environmental impacts, guiding decisions towards a more sustainable future.

Keywords: Sustainable Practices, Integrated Environmental Assessment, Sustainability.

1. Introduction

The World Health Organization (WHO) confirmed the occurrence of a new coronavirus infection in Wuhan, China, in January 2020. In the two subsequent years, the world experienced a pandemic comparable to the Spanish flu of 1918 as SARS-CoV-2 spread globally (PITLIK, 2020). The use of masks by at least 60% of the population was a crucial control strategy during the reopening of the economy, especially as it was easier to achieve mask usage than social distancing (AJAJ *et al*. 2023).

An impending crisis post-pandemic will be the management and safe disposal of used protective masks. While countries have regulations and guidelines for the management of plastic waste, most lack centralized regulations for the management and disposal of used masks (SELVARANJAN *et al*. 2021). The primary concerns regarding end-of-life mask selection are (i) ecotoxicological aspects, where inappropriate masks or micro/nanoplastics produced due to degradation can disrupt the daily lives of humans, animals, and aquatic life. (ii) Processes that consume a lot of energy and emit greenhouse gases during mask manufacturing, as well as the additional energy used for collecting, sorting, processing, and disposing of used masks. (iii) From a socioeconomic perspective, more money and resources are spent on PPE waste disposal (RAHMAN *et al*. 2022).

Aldama *et al*. (2023) affirm that Life Cycle Assessment (LCA) is a well-developed and standardized tool for evaluating the potential environmental impacts of a product system throughout the supply chain. The results of DfEstudies can identify "critical points" in the process that cause significant impacts, which can then be optimized as needed or help policymakers make sustainable decisions (AJAJ *et al*. 2023).

Multi-criteria analysis (MCA) can provide a clear and well-organized approach to better inform decision-making. It can encompass many different aspects simultaneously, covering all the various issues at play and addressing priorities set by stakeholders to evaluate plastic waste management solutions (BACHÉR *et al*. 2018; CUNHA *et al*. 2019).

Environmental performance indicators (EPIs) can compile complex information from various sources and use different measurement methods, transforming them into a communicable framework, such as a global index. Continuous measurement and communication of environmental performance have the potential to disseminate knowledge and promote policies aimed at preventing environmental issues (HAMMOND et al. 1995).

Based on Hermann *et al*. (2007) study, the combination of these three tools is referred to as COMPLIMENT. This acronym stands for the integration of Environmental Performance Indicators, Life Cycle Assessment, and Multi-Criteria Analysis for the assessment of global environmental impacts.

In Brazil, the public universities carried out activities during the pandemic, making a significant contribution to society by producing Face-Shield type face masks on a large scale, which were donated to municipalities to assist in people's protection.

The objective of the study is to apply three different environmental assessment methods to analyze the environmental impact of the production phase of 3D-printed face masks during the pandemic. These were manufactured by a Brazilian university. The integration of three methods will allow for a comprehensive environmental assessment, despite requiring data, time, and specialized knowledge. However, this thorough analysis will enable the creation of a Design for the Environment (DfE) project, with recommendations for the disposal phase.

The paper is divided into specific sections to guide readers through the study. Following the introduction, Section 2 offers a Literature Review contextualizing the importance of LCA and DfE related to a product. Section 3 describes the Research Methodology, integrating LCA, MCA, and EPIs into the COMPLIMENT framework. Section 4 presents the case study on producing 3D-printed masks, while Section 5 delves into environmental impact calculations. Section 6 analyzes Results and Discussions, and finally, Section 7 concludes by addressing the adoption of Design for the Environment (DfE) principles to mitigate environmental impacts related to the production and disposal of masks.

2. Literature review

In agreement with Apip *et al*. (2020), environmental performance encompasses a range of actions, policies, and strategies that aim to minimize negative environmental impacts, conserve resources, and promote sustainability. To promote this, management regulations must be implemented, the costs of proper management must be internalized, and a complete recycling industry must be established in the country (MANGMEECHAI, 2022). For Teow *et al*. (2021) LCA is a viable tool for understanding how the selected system can impact the environment.

Meex *et al*. (2018) noted that LCA helps predict the environmental impact of buildings over their entire lifespan and aids in making sustainable decisions. Per Ibbotson (2014), "Cradle-to-Gate" is a term commonly used in the context of LCA and environmental impact analysis, particularly in the field of sustainability and product design. They refer to different stages of a product's life cycle and are used to assess and quantify the environmental impacts associated with that product.

According to Fiksel (2009) DfE, often referred to as eco-design or sustainable design, is an approach that places environmental considerations at the forefront of the design process. DfE is considered the manufacturing phase and aspects like material selection, energy consumption, waste reduction, and end-of-life management.

Furthermore, Shaked and Reich (2021) affirm that DfE emphasizes the importance of designing products for longevity, ease of repair, and end-of-life recycling or disposal.

Cai *et al*. (2022) say that in today's rapidly changing world, where environmental concerns are paramount, DfE plays a pivotal role in addressing the global challenges of climate change, resource depletion, and pollution. It embodies the idea that design can be a force for positive change, promoting sustainability and responsible resource management.

3. Research Method

The synergy obtained through the combination of quality management tools goes beyond the individual analysis of each tool in terms of effectiveness and impact. To establish a comprehensive understanding of Quality Management tools, this study undertakes a rigorous examination of the existing literature and will critically review and analyze the application of an integrated tool that has been selected based on its relevance and significance to the subject matter. Figure 1 shows a flowchart about the steps and boundaries of the methodology.

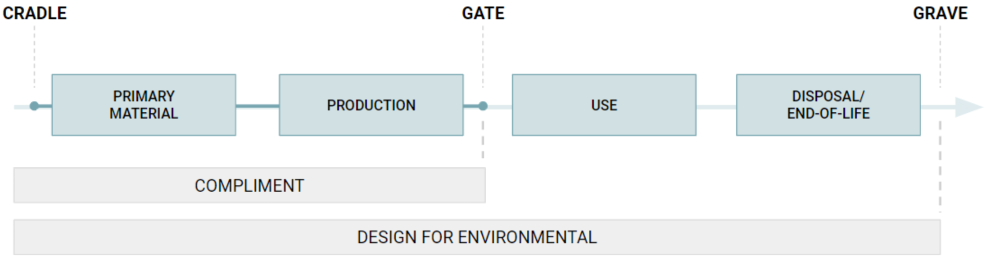


Fig. 1. Simplified steps and boundaries of this methodology.

This integration of three tools allows for a more comprehensive cradle-to-gate assessment when compared to LCA alone, for example, which takes us a step further in assessing the complexities associated with assessing the environmental impact of the production process.

In addition to examining the environmental impacts of 3D mask production, this article endeavors to propose an effective approach for managing product disposal. It adopts the design for environment methodology to provide a more comprehensive analysis, encompassing the product's end-of-life stage.

3.1 Life Cycle Analysis

The method begins with a cradle-to-gate Life Cycle Assessment (LCA) of facial masks, tracing material and energy flows throughout the product's lifecycle boundaries, as outlined by Chehebe *et al.* (2002). The Life Cycle Inventory Analysis (LCI) quantifies system inputs and outputs, including energy, raw materials, products, emissions, and other environmental aspects, following guidelines from Ribeiro *et al.* (2009) and ISO 14044 standards.

Data collection took place at the Maker Laboratory, Federal University of Paraná (UFPR), Jandaia do Sul, during COVID-19 combat efforts. Primary data came from questionnaires and lab documents, supplemented by secondary data from the Ecoinvent database via SimaPro 9 software. Inventories of inputs to produce Facial Masks were inserted and adapted to the Brazilian reality and the IPCC method was used to quantify and evaluate environmental impacts. The study adheres to ISO 14044:2006 requirements, which recommend four phases for an LCA, depicted in Figure 2.

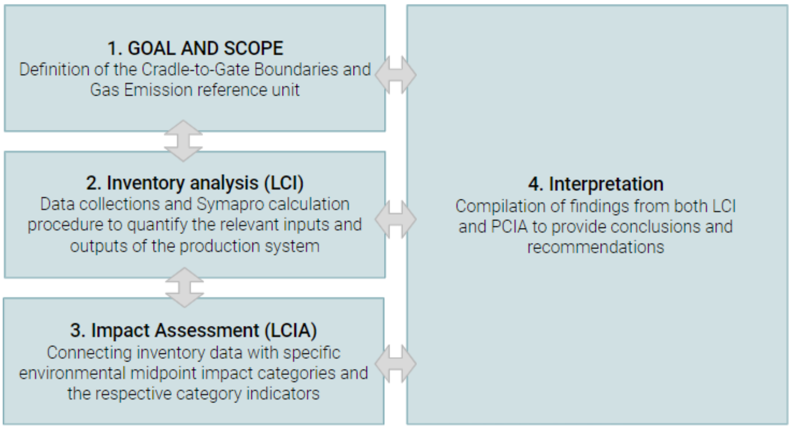
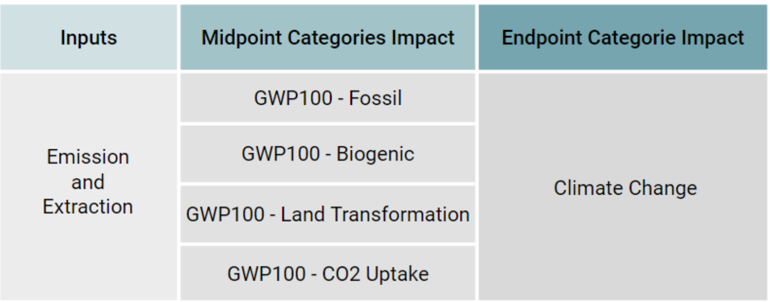


Fig. 2. Methodology and steps for LCA studies according to ISO 14044:2006.

3.2 Environmental Indicators

To relate the data and results obtained in the Inventory Analysis step it is essential to employ an appropriate methodology for carrying out Life Cycle Impact Assessment (LCIA). The chosen one is the IPCC 2021 Methodology, which is used to estimate the emissions of carbon dioxide gas (CO_2) associated with the mask's production, allowing users to calculate the Global Warming Potential (GWP) of these emissions which is a measure of their impact on climate change within the time frame of 100 years. The characterization factors are based on Forster et al. (2021).

In SimaPro, the results can be presented in a few impact categories. These impact categories can be aggregated into a single impact assessment result by selecting Damage Assessment in SimaPro. In LCIA, the IPCC 2021 method converts emissions of hazardous substances and extraction of natural resources into midpoint environmental impact categories. These impact categories can be aggregated into a single impact assessment result by selecting Damage Assessment in SimaPro. The Inputs of the mask’s production result in four midpoint categories that result in climate change endpoint. (See Fig. 3)



Inputs	Midpoint Categories Impact	Endpoint Categorie Impact
Emission and Extraction	GWP100 - Fossil	Climate Change
	GWP100 - Biogenic	
	GWP100 - Land Transformation	
	GWP100 - CO2 Uptake	

Fig. 3. Impact Categories Indicator of Life Cycle Inventory Analysis.

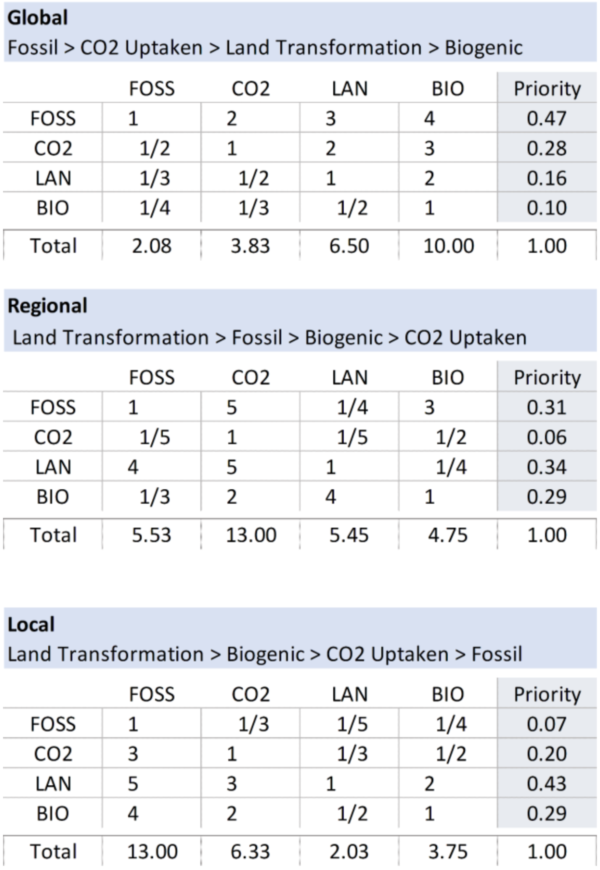
3.3 Multicriteria Analysis

The multi-criteria decision-making process allows you to assign weights to criteria through similar comparisons. In the context of LCA and EPIs, this methodology is used to combine impact categories into a single index, considering the geographic scale: Local, Regional, and Global, reflecting the relative importance of environmental impacts at different scales.

The influence and impact of the GWP100 - Fossil, GWP100 - Biogenic, GWP100 - Land Transformation, and GWP100 - CO_2 Uptake indicators can vary significantly depending on the location, region, and scale considered.

In summary, the global impact is most related to fossil fuel emissions, while biogenic ecosystems, land use changes, and carbon sequestration processes have significant impacts at local, regional, and global scales. This study considered the indicator's impact based on the scale classification according to:

1. Global Scale: Fossil > CO_2 Uptaken > Land Transformation > Biogenic
2. Regional Scale: Land Transformation > Fossil > Biogenic > CO_2 Uptaken
3. Local Scale: Land Transformation > Biogenic > CO_2 Uptaken > Fossil



Global
Fossil > CO2 Uptaken > Land Transformation > Biogenic

	FOSS	CO2	LAN	BIO	Priority
FOSS	1	2	3	4	0.47
CO2	1/2	1	2	3	0.28
LAN	1/3	1/2	1	2	0.16
BIO	1/4	1/3	1/2	1	0.10
Total	2.08	3.83	6.50	10.00	1.00

Regional
Land Transformation > Fossil > Biogenic > CO2 Uptaken

	FOSS	CO2	LAN	BIO	Priority
FOSS	1	5	1/4	3	0.31
CO2	1/5	1	1/5	1/2	0.06
LAN	4	5	1	1/4	0.34
BIO	1/3	2	4	1	0.29
Total	5.53	13.00	5.45	4.75	1.00

Local
Land Transformation > Biogenic > CO2 Uptaken > Fossil

	FOSS	CO2	LAN	BIO	Priority
FOSS	1	1/3	1/5	1/4	0.07
CO2	3	1	1/3	1/2	0.20
LAN	5	3	1	2	0.43
BIO	4	2	1/2	1	0.29
Total	13.00	6.33	2.03	3.75	1.00

Fig. 4. HP matrices containing the relative degrees of importance and resulting valuation factors.

Weights are calculated based on the Analytical Hierarchy Process (AHP) methodology in comparison matrices (SAATY et al. 2006). Figure 4 presents the degrees of importance and the resulting weights for each impact category and perspective.

4. Case Study

Based on the production of facial masks produced by UFPR and used during the pandemic, this study aims to illustrate the combination of tools and analyze the results. While mask production contributes to CO_2 emissions wherever it occurs, more data is needed to understand this sector's specific impact and identify areas for mitigation.

The Jandaia Makers Extension Project at UFPR aimed to provide facial masks for healthcare professionals on the frontlines of COVID-19. Initially serving UFPR's Hospital das Clínicas, it expanded to four Brazilian states.

Research data was collected through observation of mask production and questionnaires at the UFPR Maker Laboratory. Secondary data for non-elementary processes was obtained from the Ecoinvent database.

LCA involves a thorough study and collection of data, which requires a lot of time and resources. Limitations may include the lack of primary data from phases before elementary processes and the use of secondary data from databases that do not completely reflect reality but have been adapted for this study.

5. Environmental Impact Calculations

The first step is taken from the LCA methodology. To obtain the potential impact, the total emissions of each production input and output flow are calculated as a kilogram of equivalent CO_2 (kg CO_2e) - considering the total production of 1000 masks. This unit of measurement expresses the global warming potential of greenhouse gas emissions. It represents the amount of CO_2 that would have the same global warming effect as one kilogram of a specific greenhouse gas over a specified time frame, in this case - 100 years. Figure 5 shows the total potential impacts calculated by obtaining the amount of kg CO_2q per impact category considering each process input.

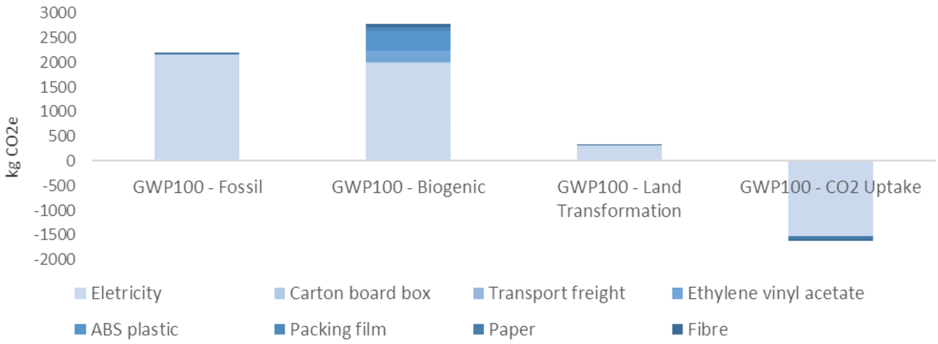


Fig. 5. Total potential impact amount of kg CO_2q per impact category.

Once the multi-criteria weights were defined, the scores of each category were multiplied by the corresponding criterion weight to obtain weighted scores for each one. Considering the data are on different scales, the results are normalized to a common scale of 1, as shown in Figure 6.

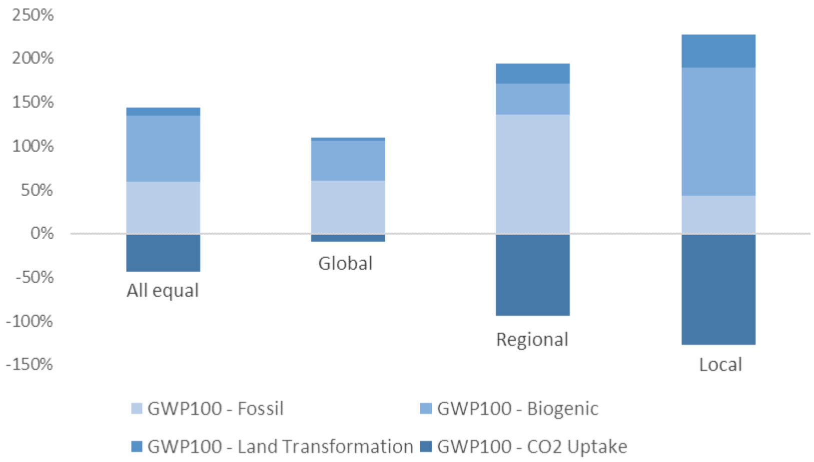


Fig. 6. Relative contribution of the impact categories to the total environmental impact, calculated for a global, regional, and local perspective as well as a reference perspective in which all impact categories are viewed as equally important.

The goal of the graphics of Figure 6 is to express the relative contribution of the different environmental indicators in different geographic scales, considering their respective criteria weights. The results are then visualized as the bar chart where each impact category is represented as a percentage of the reference value.

Stakeholders can interpret the normalized graphic to prioritize areas for environmental improvement. The categories with the highest percentage values represent the areas with the most significant environmental impact, and they are the focus of potential mitigation efforts.

6. Results and discussions

The integration of quality management tools into a single framework demonstrated synergy compared to individual analyses. The combined application of MCA, EPIs, and LCA allowed for a comprehensive assessment of the environmental impacts of 3D face mask production, from raw material to final disposal.

The LCA analysis revealed that the production of 3D face masks has a significant environmental impact, particularly in terms of CO_2 emissions. The predominance of fossil fuel emissions underscores the need for more effective energy management strategies and the use of cleaner energy sources to mitigate this impact.

The application of MCA methodology enabled the assignment of weights to different criteria, considering geographic scales. The results highlight the importance of adaptable management that takes into account local and regional contexts.

Recommendations for sustainable mask management include selecting eco-friendly materials, promoting reusable masks, implementing DfE principles in manufacturing, providing clear labeling and recycling instructions, establishing collection and recycling programs, promoting biodegradable masks, minimizing packaging, and launching public awareness campaigns.

The integration of DfE principles throughout the lifecycle requires collaboration among stakeholders. Reciprocity among actors facilitates the development of sustainable practices. Awareness and collaboration are essential for the sustainable management of masks during and after the pandemic.

7. Conclusion

This article demonstrates the integration of MCA, EPIs, and LCA to assess the environmental impact of 3D-printed face masks by a Brazilian university during the COVID-19 pandemic. The approach provided a comprehensive view of cradle-to-gate environmental impacts, emphasizing CO_2 emissions and various impact categories at different geographic scales.

Adopting DfE principles in mask production and disposal is crucial for mitigating environmental impact. Sustainable materials, reusable options, and eco-friendly manufacturing processes reduce the ecological footprint. Clear labeling, recycling programs, and awareness campaigns ensure responsible disposal.

Acknowledging research limitations, including data collection challenges and context specificity, future research should enhance data collection and analysis methods. Comparative studies on 3D-printed products and exploring manufacturing processes' impacts are needed. Investigations into long-term effects and end-of-life considerations are essential for product sustainability.

This study establishes an integrated approach to environmental assessment and product management. Incorporating quality management tools highlights the need for considering multiple aspects and geographic scales. Moving towards sustainability requires adaptable management approaches throughout the product life cycle, prioritizing eco-friendly practices.

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