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Engineering Design Process of Face Masks Based on Circularity and Life Cycle Assessment in the Constraint of the COVID-19 Pandemic

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Abstract: Face masks are currently considered key equipment to protect people against the COVID-19 pandemic. The demand for such devices is considerable, as is the amount of plastic waste generated after their use (approximately 1.6 million tons/day since the outbreak). Even if the sanitary emergency must have the maximum priority, environmental concerns require investigation to find possible mitigation solutions. The aim of this work is to develop an eco-design actions guide that supports the design of dedicated masks, in a manner to reduce the negative impacts of these devices on the environment during the pandemic period. Toward this aim, an environmental assessment based on life cycle assessment and circularity assessment (material circularity indicator) of different types of masks have been carried out on (i) a 3D-printed mask with changeable filters, (ii) a surgical mask, (iii) an FFP2 mask with valve, (iv) an FFP2 mask without valve, and (v) a washable mask. Results highlight how reusable masks (i.e., 3D-printed masks and washable masks) are the most sustainable from a life cycle perspective, drastically reducing the environmental impacts in all categories. The outcomes of the analysis provide a framework to derive a set of eco-design guidelines which have been used to design a new device that couples protection requirements against the virus and environmental sustainability.

Keywords: face masks; life cycle assessment; LCA; environmental analysis; eco-design; product development process; circularity; engineering design; COVID-19

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1. Introduction

It is almost a year since the World Health Organization (WHO) classified the COVID-19 disease caused by the new SARS-CoV-2 virus as a pandemic [1], and by March 2021, more than 100 million people had been infected [2] around the world, causing a global emergency that will continue until effective health care, prevention and/or medical treatment solutions (e.g., vaccines) are widely implemented.

During this period, the world has seen how human interaction, work and personal hygiene habits, as well as daily routines, have changed. The most common method of disease diffusion is through respiratory droplets, meaning that the virus can be transmitted while people are breathing or speaking [3,4]. There are various methods of spreading the virus: by direct contact with surfaces/people on which these droplets have been deposited (large droplets > 20 μm) and airborne transmission, during which infection occurs when people inhale the droplets in the air (small droplets < 5–10 μm) [5–7]. Given this context, the importance of using devices that can reduce the spread of these particles has become more evident, facial masks being the most recommended and effective device to reduce contagion, along with the limitation of contact between people (such as lockdowns carried out in various countries) [8–10]. That is why WHO guidelines and several research studies recommend the use of masks both in closed and open spaces [8,11–13]. These devices act as a physical barrier to prevent particle dispersion, thus filtering the exhalation of infected individuals [14]. For this reason, masks should be worn during daily activities (work, public transport, etc.) by a large part of the population during 2021, especially in places where ventilation is not good [7,13–15].

The WHO has estimated that 89 million medical masks are needed per month [16], a huge quantity that caused limited stocks in many countries during the initial period of the pandemic [17–19]. Moreover, their production entails a large consumption of fossil-based materials and the generation of large amounts of waste (difficult to manage), which can cause an environmental issue. This problem should not be forgotten although, at this time, efforts should be focused on solving the current health emergency. These sustainability issues are due to the fact that masks (surgical and PPE, or personal protective equipment) are usually disposable devices, generally produced by using different layers of nonwoven fibers made of thermoplastic polymers [20] and sometimes functionalized to improve their filtering properties [21,22]. This type of devices is very difficult to recycle, which makes the end of life (EoL) of the product another critical and impactful aspect to manage since most of the masks end up being discarded in municipal/sanitary landfills or incinerated [23], with considerable emissions of greenhouse gases (GHGs) [24]. Furthermore, masks potentially represent a source of microplastics, which are very dangerous for microorganisms living in water and can reenter the human food chain, causing severe health problems [25,26]. This is the reason why studies are being promoted to obtain masks with biodegradable materials [27], which should facilitate their end-of-life disposal.

With the aim of improving the sustainability of the health sector, the focus is being placed on increasing the lifespan of these devices, mainly through their reuse [28]. In this way, some governments (i.e., Spain) [29] are taking measures that promote the manufacture and use of reusable hygienic masks (specified in UNE 0065 standard). Additionally, various investigations have focused on giving biocidal properties to masks to increase their useful life and reduce bio-infectious waste [30,31]. Studies such as those by McGain et al. [32] and Ertz and Patrick [28] have exposed the economic and environmental benefits of reusing medical devices. Klemeš et al. [33] have conducted research focused on the energy and carbon footprint associated with masks and PPE during the COVID-19 pandemic period. The result of this study shows that if a proper selection of materials is made, a suitable design is used, and user guides are drawn up, reusable PPE leads to a reduction in energy consumption and environmental footprint. Kumar et al. [34] have carried out an environmental analysis and sustainable waste management study of PPE kits (surgical mask, gloves, goggles, suit), considering different scenarios such as end-of-life landfill disposal or incineration (centralized and decentralized), finding, as a result, that the most unfavorable situation is landfill disposal. Allison et al. [35] carried out an investigation comparing single-use masks with reusable ones, considering various scenarios, finding that the use of reusable masks reduces the amount of waste entering general waste streams. Results obtained by Schmutz et al. [36] and Boix et al. [37] comparing surgical and reusable masks instead highlight the great dependence that the impact calculations have on the use phase (personal behavior) and materials used. However, these studies do not offer a global comparison of the different models of masks available on the market, a clear vision when comparing the different impacts (environmental, circularity, etc.), or facilitate decision making from the eco-design perspective.

Only a few and preliminary life cycle assessment (LCA) studies and eco-design analyses have been carried out on this topic (the environmental impact of face masks) [38,39]. The main goal of this research paper is to develop an eco-design actions guide that helps engineers and designers during the process of product development of new masks, with the objective to reduce the negative impacts of these devices on the environment during this pandemic period. To achieve this objective, an LCA analysis on different types of masks was carried out: (i) M1—3D-printed mask with changeable filters, (ii) M2—surgical mask, (iii) M3—FFP2 mask with valve, (iv) M4—FFP2 mask without valve, and (v) M5—

washable mask. The study was performed considering the Italian scenario; Italy was one of the first EU countries to face the pandemic emergency, therefore having the necessary data available for the analysis. However, the study can be transferred and replicated to other countries. This paper has the ambition to provide a scientific basis to reduce the waste produced during this pandemic, increase the circularity of these devices (through the study of the material circularity indicator (MCI)), and increase the overall sustainability of face masks. All analyses enable the definition of a framework for the development of an eco-sustainable mask, which undoubtedly can be of great relevance during the current serious health situation in the world. The novelty of the paper is to overtake the main limitations of general studies regarding the environmental performance of face masks, providing a study that allows having a global vision of the impacts of the masks currently on the market and facilitating eco-design decision making.

The rest of the article is organized as follows: Section 2 describes the methodology followed to develop the LCA analysis, the calculation of the circularity index, as well as the eco-design guidelines and mask development process; Section 3 presents the results obtained for the different masks, their most critical aspects and also develops an eco-design guide, in addition to proposing a framework for the development of a sustainable mask; Section 4 discusses the main outcomes of the research. Finally, Section 5 summarizes the conclusions and possible future developments.

2. Materials and Methods

The following study has been carried out using a methodology composed of three easily identifiable phases: (i) assessment of environmental and circularity key performance indicators (KPIs), (ii) a knowledge-based system for eco-design, and (iii) ask development process. The workflow and the main activities of each phase are reported in Figure 1 and detailed in the following subsections.

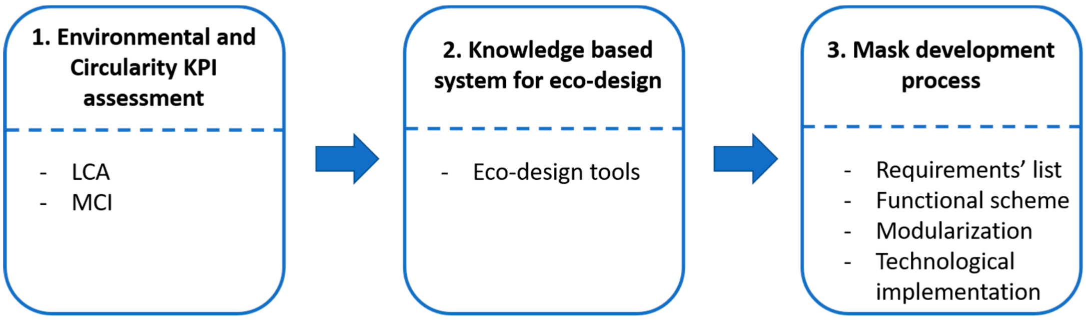

Figure 1. Methodology.

2.1. Environmental and Circularity KPI Assessment

In order to meet the objectives of this study and identify critical points of these products, LCA methodology has been used, following the ISO 14040, ISO 14044 and ILCD Handbook, which identifies the following four phases [40]:

1. Goal and scope definition;
2. Life cycle inventory (LCI);
3. Life cycle impact assessment (LCIA);
4. Interpretation.

This type of analysis makes it possible to establish the environmental impacts and the resources used during the life cycle of the product, including some categories that may not be taken into account when a simpler study is conducted.

The functional unit chosen to carry out the comparison is *"The use of a face mask that complies with UNI EN 149:2009 or UNI EN 14683:2019 standards and is able to prevent the emission of respiratory droplets, in a pandemic situation for Italian citizen during a month."* It was decided to take the time reference of 1 month to facilitate the calculation of the impact during the entire pandemic due to the uncertainty that exists regarding the end of this period, making it possible to obtain the total impact by multiplying the results obtained by the total months. Italy has been used as the reference country due to the available data necessary for the analysis; however, the obtained results can be transferred to other EU countries and geographical areas.

To facilitate comparative analysis, it was established that the reference flow is a face mask that complies with UNI EN 149:2009 or UNI EN 14683:2019 in order to consider masks that assure a certain degree of safety for final users. The UNI EN 149:2009 is the reference standard for PPEs that foresees a series of testing and marking requirements (e.g., visual inspection, leakage, compatibility with skin, flammability of material, breathing resistance) for this kind of protective equipment dedicated to the protection of nose and mouth. Among the required performance tests, the penetration of filter material is the test related to droplet emission (and inhalation). The penetration of filter material is quantified through the particle filtration efficiency (PFE) parameter by following the test procedure in accordance with the UNI EN 13274-7:2019. According to this test, masks can be classified into three categories: FFP1 (PFE $\geq$ 80% of PFE), FFP2 (PFE $\geq$ 94%), and FFP3 (PFE $\geq$ 99%). The UNI EN 14683:2019 is the reference standard for surgical masks that foresees requirements and test methods for such equipment, generally dedicated to medical environments. The standard includes requirements about material breathability, splash resistance, microbial cleanliness (bioburden), biocompatibility, and bacteria filtration efficiency (BFE). The latter is the key parameter that allows the verification of whether the material used to manufacture the mask is able to filtrate a reference pathogen, the *Staphylococcus aureus*, with a certain efficiency: BFE $\geq$ 95% for Type I masks and BFE $\geq$ 98% for Type II or IIR masks (which are also resistant to splashes).

The system boundaries considered in the LCA study include (Figure 2) (i) mask production (material extraction and, for the M1 mask, the manufacturing process (additive manufacturing)); (ii) transportation (distribution center and final user); (iii) usage phase; (iv) maintenance (disinfection with ethanol or wash); and (v) end of life.

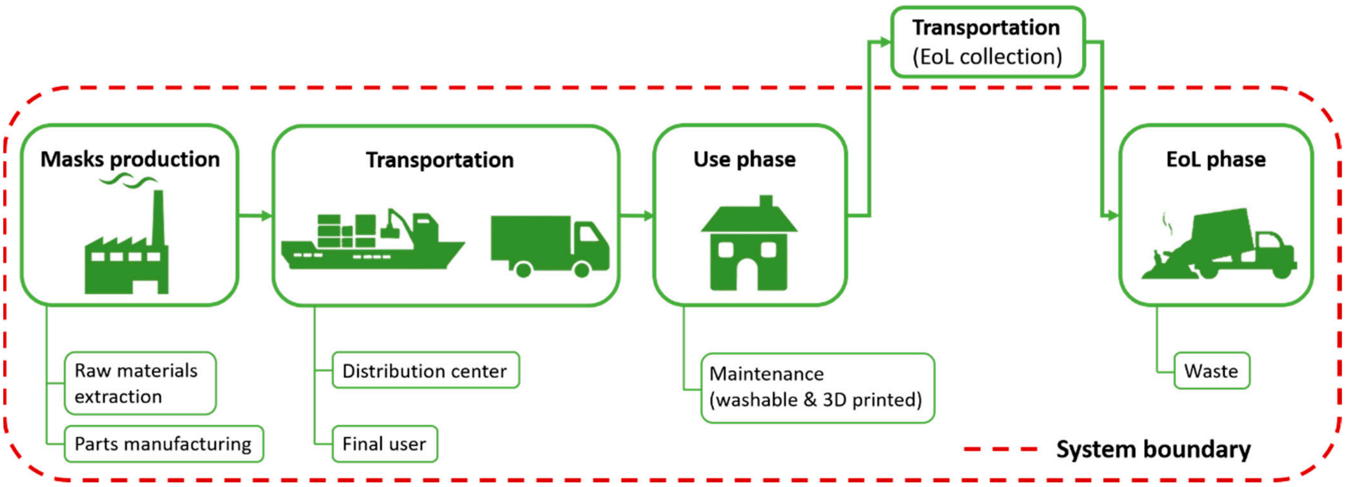

Figure 2. System boundary.

Five different types of masks available on the market have been selected as follows:

- M1—3D-printed model. This commercial mask uses disposable FFP2 filters. This technology is very widespread on the market for masks with a reusable structure. The 3D-printed part has to be disinfected to ensure that it is safe to use. FFP2 filters guarantee a filtration efficiency of at least 94% and must be changed every 8 h of use [41].

- M2—surgical mask. This type of device is for single use only and acts as a barrier to prevent droplets from being transmitted during breathing or speaking. They mainly protect other people, not the wearer, although they can help to prevent the user from coming into contact with a stream of liquid. They must be discarded every 4 h of use [41].
- M3—FFP2 with exhalation valve. This mask is for single use and is designed to facilitate breathing through its valve. It protects the user from possible external contamination, but it does not protect others. They must be discarded every 8 h of use [41].
- M4—FFP2 without an exhalation valve. As in the previous case, it is for single use but, since it does not have an exhalation valve, it protects both the user and others. It needs to be discarded every 8 h of use [41].
- M5—washable mask. Mask can be reused several times, maintaining its filtering efficiency for at least 50 washes. In this case, maintenance consists of washing the product in a washing machine at a recommended temperature between 40 °C and 75 °C [42].

The life cycle inventory (LCI) must consider all materials and energy flows (inputs and outputs) related to the functional unit so that they are quantified. The full description of the LCI (both foreground and background data) is reported as Supplementary Materials to make the study fully reproducible. In this manuscript, the LCI has been mainly divided into two parts: the first one is related to the materials used and manufacturing phase, and the second one is related to the use phase. The LCI for the materials and manufacturing phase seeks to know exactly the components and materials that make up these products. For this purpose, the five types of masks studied were manually disassembled, and each component was weighed using the appropriate equipment for it. Table 1 shows the results of the LCI manufacturing phase for each type of mask.

Table 1. Life cycle inventory (LCI) of the mask production phase.

Type	Image	Component	Weight [g]	Material	Manufacturing Process
M1		Filter	0.50	PP—Polypropylene	N.A.
			0.50	PE—Polyester	
		Structure	30.00	PLA	3D printing
		Bands	3.00	Synthetic rubber	N.A.
M2		Filter	1.28	PP—Polypropylene	N.A.
			1.28	PE—Polyester	
		Nose adapter	0.44	Aluminum	Wire drawing
		Bands	0.02	Cotton	N.A.
M3		Filter	5.00	PP—Polypropylene	N.A.
		Valve	5.00	PP—Polypropylene	Injection molding
		Nose adapter	0.95	Aluminum	Wire drawing
		Nose protection	0.05	PU—Polyurethane foam	N.A.
		Bands	3.00	Synthetic rubber	N.A.
M4		Filter	5.00	PP—Polypropylene	N.A.
		Nose adapter	0.95	Aluminum	Wire drawing
		Bands	3.00	Synthetic rubber	N.A.
M5		Filter	2.70	PP—Polypropylene	N.A.
			2.70	PE—Polyester	
		Bands	1.00	Cotton	N.A.

To define the inventory of the use phase, it must be taken into account that the study scenario is Italy where it is estimated that there is a daily need for masks of 40 million [43]. The daily mask estimation, together with the useful life of each type, allows us to know the total masks needed during the established period of time (one month), as can be seen in Table 2.

Table 2. Life cycle inventory (LCI) of the use phase.

Type		Lifespan	Units [million]
M1	Mask	-	40
	Filter	8 h	600
M2		4 h	1200
M3		8 h	600
M4		8 h	600
M5		50 washes	40

Considering the use phase, M1 and M5 models require some type of "maintenance." In the case of M1, the ethanol used to disinfect the 3D-printed mask was considered in the inventory. On the other hand, for the M5 model, the water, electricity, and soap that are consumed in a standard washing cycle performed with a washing machine were quantified. Concerning the end-of-life assessment, the hypothesis that all masks are disposed of in municipal landfills was established. For secondary data, datasets from Ecoinvent 3.5 were used.

Life cycle impact assessment (LCIA) was carried out using a specific software tool (i.e., SimaPro 9.0.0.49). The selected impact indicators are the most suitable for the purpose of this article. Two different methods have been used: i) ReCiPe and ii) cumulative energy demand (CED). With the first method, it is possible to have an overview of the environmental loads using the midpoints (12 chosen categories, see Table 3) and endpoints (three categories, see Table 3), facilitating the interpretation of results [44]. On the other hand, the single-issue CED method was used to complement the information provided by ReCiPe concerning the LCIA of energy resources since CED allows us to take into account the energy consumption related to the product (directly or indirectly) during its life cycle [45].

Table 3. LCIA methods and indicators analyzed [44].

LCIA Method	Indicator	Acronym	Unit
ReCiPe Midpoints	Global warming potential	GWP	[Kg CO_2 eq]
	Ozone depletion potential	ODP	[kg CFC11 eq]
	Photochemical oxidant formation potential	OFP	[kg NOx eq]
	Particulate matter formation potential	PMFP	[kg PM2.5 eq]
	Terrestrial acidification potential	TAP	[kg SO_2 eq]
	Freshwater eutrophication potential	FEP	[kg P eq]
	Terrestrial ecotoxicity potential	TETP	[kg 1.4-DCB]
	Freshwater ecotoxicity potential	FETP	[kg 1.4-DCB]
	Marine ecotoxicity potential	METP	[kg 1.4-DCB]
	Human toxicity potential	HTP	[kg 1.4-DCB]
	Fossil fuel potential	FFP	[kg oil eq]
	Water consumption potential	WCP	[m3]
ReCiPe Endpoints	Human Health	HH	[-]
	Ecosystem	ED	[-]
	Resources	RA	[-]
Single Issue	Cumulative energy demand	CED	[MJ]

Finally, the research work includes the analysis of the product circularity, sharing the vision of the EU and its purpose of achieving a circular economy [46]. In order to evaluate this factor, the material circularity indicator (MCI) was used. MCI studies the flow of the product, indicating how restorative it is [47] and considering values in the range of

0 and 1 (0 being fully linear and 1 being fully circular). The MCI calculator tool [48] was used to obtain the value of this parameter (in this tool, the minimum value that can be reached is 0.1, considering this result fully linear). A key parameter for the calculation of the MCI is the "utility," which can be calculated using a simplified version of the method (Equation (1)) proposed by [47] as follows:

$$X = \left(\frac{L}{Lav}\right) \tag{1}$$

where

- L represents the useful life of the product;
- Lav refers to the average useful life of the industry.

2.2. *Knowledge-Based System for Eco-Design*

In order to minimize the consumption of resources and the impact on the planet, eco-design has to be adopted as a design method, using a life cycle thinking (LCT) approach in which the entire life cycle of the product is taken into account. Approximately 70% of a product's cost, environmental impact, and functional requirements can be determined during the design phase, thus demonstrating the importance of eco-design in those stages of the project [49]. The application of scientific and technological principles to design and carrying out engineering activities in a sustainable way, together with the LCT approach to optimize the life cycle of a product in order to protect the environment and improve economic progress, are defined as life cycle engineering (LCE). There are different design support tools that have been in use for years, with a broad spectrum ranging from extremely easy to use (i.e., recommendations) to some with a very complex structure [50].

To carry out the knowledge-based system step, methodologies that have already been shown to be effective in literature were followed. An example is the "Ten Golden Rules" explained in the study by Luttropp and Lagerstedt, which presented a qualitative approach to the application and creation of an eco-design guide [50]. On the other hand, the guidelines of the international ISO 14006:2011 [51] (updated in 2020) standard were used, establishing a methodology and a flowchart that must be followed to incorporate eco-design during the development of a product. This methodology is based on the following six phases:

- Define product functions;
- Environmental analysis;
- Environmental improvement strategies;
- Develop environmental objectives;
- Environmental product specification;
- Develop technical solutions.

During the environmental assessment phase, LCA analysis was used and integrated into the eco-design application. Articles that work with both methods (LCA and eco-design) were a source of inspiration [52,53], together with the detailed explanation and application of the methodology set out in the ISO 14006:2011, presented in the article by Navajas et al. [54]. Therefore, as reported in many of the reviewed existing success experiences, after an LCA analysis, the most impactful components are usually identified to create a database that has a key role in establishing which aspects should be the focus of attention for achieving a significant environmental improvement while maintaining the functionality of the product. In the present paper, to carry out this analysis and obtain an eco-design actions guide, the same methodology was followed by first establishing criticalities of each phase of the device's life cycle (once the LCA and MCI analyses have been performed) and then developing specific measures to improve these aspects. Figure 3 shows how this methodology has been customized for an application to the specific case study.

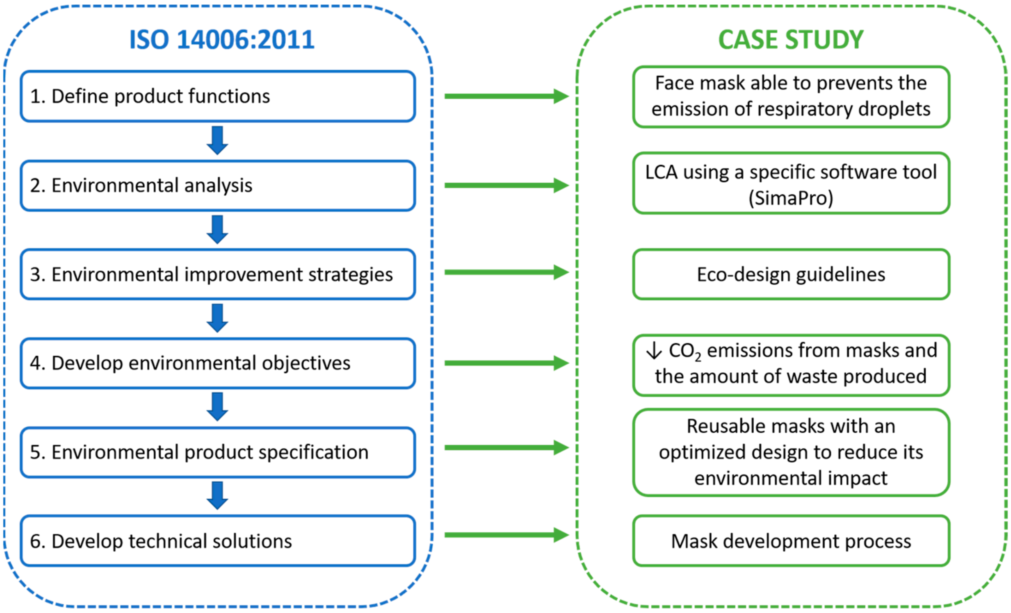

Figure 3. Eco-design methodology applied to this study.

2.3. Mask Development process

The process workflow followed to carry out the development of a new device is depicted in Figure 4.

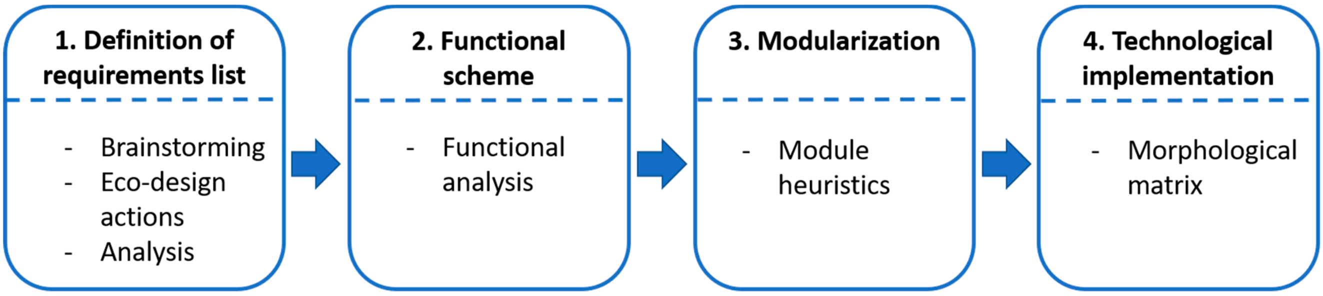

Figure 4. Process workflow.

First of all, eco-design measures should be included in the list of product requirements developed by the same authors of this paper and discussed in depth in [55], along with the specific regulations and standards for these devices. A list of requirements is the collection of customer's needs that must be satisfied by the creation of a physical product or system. In it, together with environmental aspects, other factors such as safety and ergonomic design were also covered. Table 4 shows an example of some sustainability requirements.

Table 4. Excerpt of the list of sustainable requirements [55].

Type	Requirement
Wish	Might be made of sustainable materials
Demand	Might be reusable
Demand	Might be durable
Wish	Might provide filtering status information
Wish	Might be recyclable
Demand	Need to allow to see the face
Wish	Might be personalized
Wish	Need to be cheap for daily use
Demand	Need to be available for each person in very constrained time

It is interesting to notice that pillars of sustainability other than environmental factors have been considered. For example, the "*Need to allow to see the face*" has an important role in the social aspect of sustainability (facilitating comprehension during a conversation and improving safety in certain environments). This requirement is highly debated in the social context; indeed, face masks decrease speech intelligibility and make communication more difficult, especially for people with hearing loss, and few works have been developed to tackle this issue [56–58].

The first step of development was followed by the functional analysis of the product, applying the methodology proposed by Pahl and Beitz [59]. The Pahl and Beitz theory uses a black box to represent the main product function, while the flows of material, energy, and signal are transformed by the function itself passing through the black box. The main function is then divided into subfunctions with a hierarchical structure. and a complex tree structure is created. In order to carry out this analysis, the main function (characterized by a black box) must be defined (*"Filter air from viruses and pollutants to protect a person")*, which is also composed of various subfunctions related to each other through different fluxes (i.e., mass, signal, and energy fluxes).

The result of the functional analysis represents the starting point for the modularization phase, following the heuristics method for product modularization proposed by Stone and Wood [60]. The lowest hierarchical level of the functional analysis is used to identify modules. This step consists of grouping functions by using three separate strategies (heuristics): (i) dominant flow (DF), (ii) branching flows (BF), and (iii) conversion–transmission modules (CTM). The main objective of the identification of the modules is to group the functions of the previous phase into categories that facilitate the identification of the technological implementation.

To carry out the last product development phase, a morphological matrix [61] can be used, which allows us to analyze and compare the different possible solutions for a given problem. The morphological matrix allows generating an exhaustive set of solutions for a given problem (in this case, each product "module"), organizing them into a matrix in which rows identify modules and columns identify possible solutions (i.e., design options). The morphological matrix enables the analysis of all the engineering solutions that may occur during the development of the facial mask. It concerns the analysis and permutations of any possible solutions generated to fulfill each module identified within the previous step. Thus, the various solutions obtained in the morphological matrix can be combined to obtain the final product that meets all the requirements.

3. Results

3.1. Environmental and Circularity KPI Assessment

This section presents the results obtained during the environmental and circularity investigations. Table 5 shows the values of the LCA midpoints studied, considering the use phase of the product and its end of life. These results show that the highest values in all categories analyzed have been obtained for M3 (FFP2 mask with valve), then M4 (FFP2 mask without valve), followed by M2 (surgical mask), and with a large difference of up to an order of magnitude in some categories (i.e., GWP), M1 (3D-printed mask) and M5 (washable mask). Figure 5 shows the percentage distribution for the GWP indicator; the rest of the ReCiPe midpoints are reported in Table 5, and the percentage distribution is analogous.

Table 5. ReCiPe midpoints (H).

Impact Category	Unit	M1	M2	M3	M4	M5
GWP	[Kg CO_2 eq]	3.9×10^6	2.7×10^7	5.6×10^7	3.8×10^7	1.5×10^6
ODP	[kg CFC11 eq]	1.8	6.1	1.0×10	8.3	2.3
OFP	[kg NOx eq]	1.3×10^4	1.0×10^5	1.9×10^5	1.4×10^5	5.7×10^3
PMFP	[kg PM2.5 eq]	3.7×10^3	3.4×10^4	5.7×10^4	4.5×10^4	2.1×10^3
TAP	[kg SO_2 eq]	9.9×10^3	8.0×10^4	1.5×10^5	1.1×10^5	4.5×10^3
FEP	[kg P eq]	5.9×10^2	5.3×10^3	1.0×10^4	7.7×10^3	4.2×10^2
TETP	[kg 1.4-DCB]	4.9×10^6	2.9×10^7	4.8×10^7	4.3×10^7	1.9×10^6
FETP	[kg 1.4-DCB]	1.2×10^5	1.0×10^6	3.4×10^6	3.1×10^6	4.5×10^4
METP	[kg 1.4-DCB]	1.7×10^5	1.3×10^6	4.7×10^6	4.3×10^6	5.8×10^4
HTP	[kg 1.4-DCB]	2.4×10^6	1.4×10^7	9.6×10^7	9.2×10^7	7.5×10^5
FFP	[kg oil eq]	1.2×10^6	7.3×10^6	1.7×10^7	1.1×10^7	4.1×10^5
WCP	[m3]	5.4×10^4	2.0×10^5	3.9×10^5	2.9×10^5	7.0×10^4

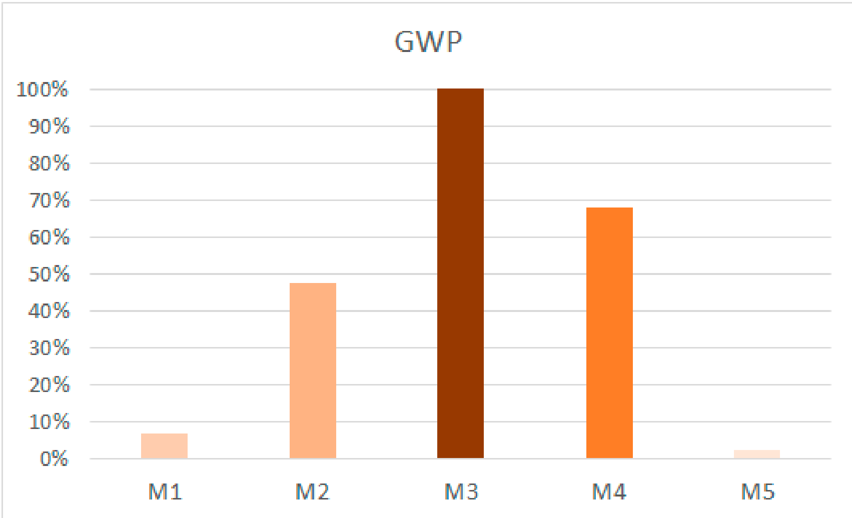

Figure 5. Percentage distribution of the GWP indicator.

In order to make the interpretation of results easier, disposable masks and other ones that allow total or partial reuse of the device were analyzed separately. The first group refers to M2, M3, and M4; it should be kept in mind that the useful life of M2 is half of M3 and M4 but entails fewer environmental impacts for its manufacturing. M3 greatly differs from M4 in the FFP, GWP, and OFP categories (about 36%, 32%, and 27%, respectively), with the average difference of 20%. The variations within these two models, which have the same lifespan, are due to, among other factors, the fact that the M3 is composed of five different components, and the amount of plastic (PP) used is double that in the M4 case. On the other hand, when comparing M4 and M2, it is observed that the highest differences occur in the HTP, METP, and FETP categories (about 85%, 68%, and 67%, respectively), with an average difference of 40%. The fact that the average difference is notably greater in this second case is due to the completely different manufacturing and use phases of M2 with respect to M4. In addition, the amount of material necessary to fulfill the overall demand of face masks is significantly different for M4 and M2; thus the mask production for M2 has a greater impact.

As regards reusable solutions, after comparing M1, which allows the reuse of the mask structure since the filters are disposable, with M5, which can be reused up to 50 washes without losing the filtration performance, it is observed that the greatest difference occurs in HTP, FFP, and METP (about 69%, 66%, and 66%, respectively). By contrast, the impact of ODP and WCP categories of M5 are higher than those of M1 (about 33% and 30%, respectively). The fact that WCP is higher in the case of M5 is due to the cotton used during the mask production phase (a critical material for this indicator) and the maintenance (i.e., washing) required by this mask during its useful life for the purpose of disinfection.

Subsequently, a more in-depth analysis of the midpoints for each mask was carried out. Figure 6 shows the results for M3, which exhibits the highest levels of impact.

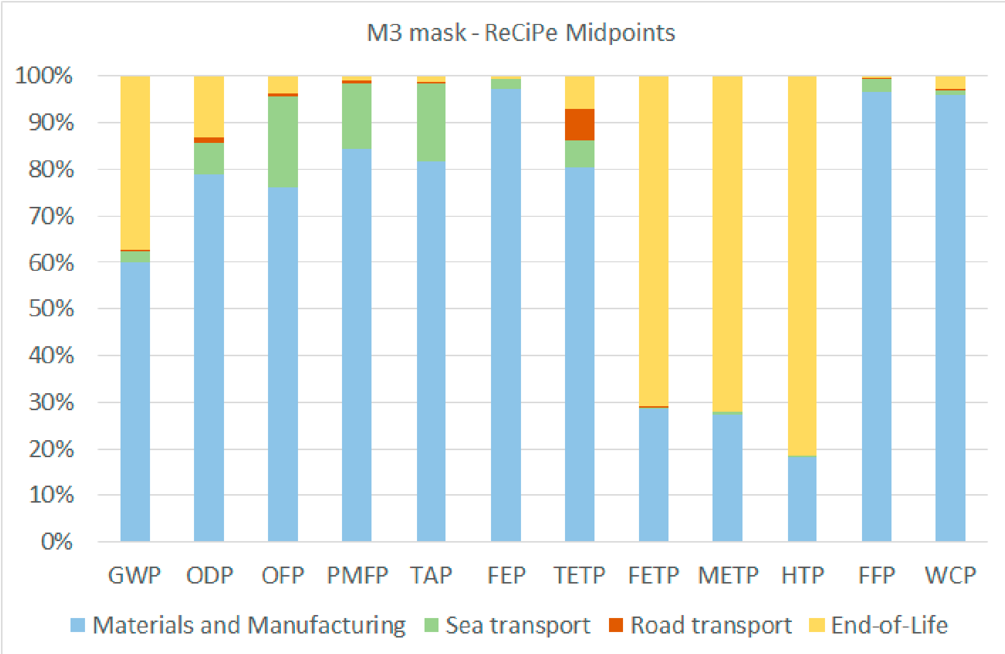

Figure 6. Midpoints (H) for M3 mask (percentage distribution).

As can be inferred, in almost all categories, the upstream production of the mask is the phase causing the most impact during its life cycle. Only in FETP, METP, and HTP, the end of life causes the highest impacts. This distribution of the impacts of contributions is quite similar to that of M1 and M4 masks (the other devices studied with FFP2 filters). However, considering the given functional unit, which recalls the time frame of a month for the M2 and M5, the influence of volume of masks required is higher in all categories without any exception.

Given its great relevance, the results of the mask production phase were studied in detail. Due to the fact that GWP is the most relevant indicator for polymers [62–64], Figure 7 shows the comparison of the different models studied in terms of GWP. As expected, M1 has the greatest value due to the amount of plastic required to produce its structure, but this initial impact will be offset during the use phase (due to the reuse of this part of the mask).

Endpoints (HH, ED, RA) were also analyzed, allowing a global overview of how each component affects each area of protection and thus facilitating decision making for eco-design. As can be inferred in Figure 8, in the case of the M1 mask, the 3D-printed structure, which is also the reusable part of this device, is the part with the greatest impact during its production. This fact shows the importance of the material selection, seeking durable and easy-to-disinfect solutions.

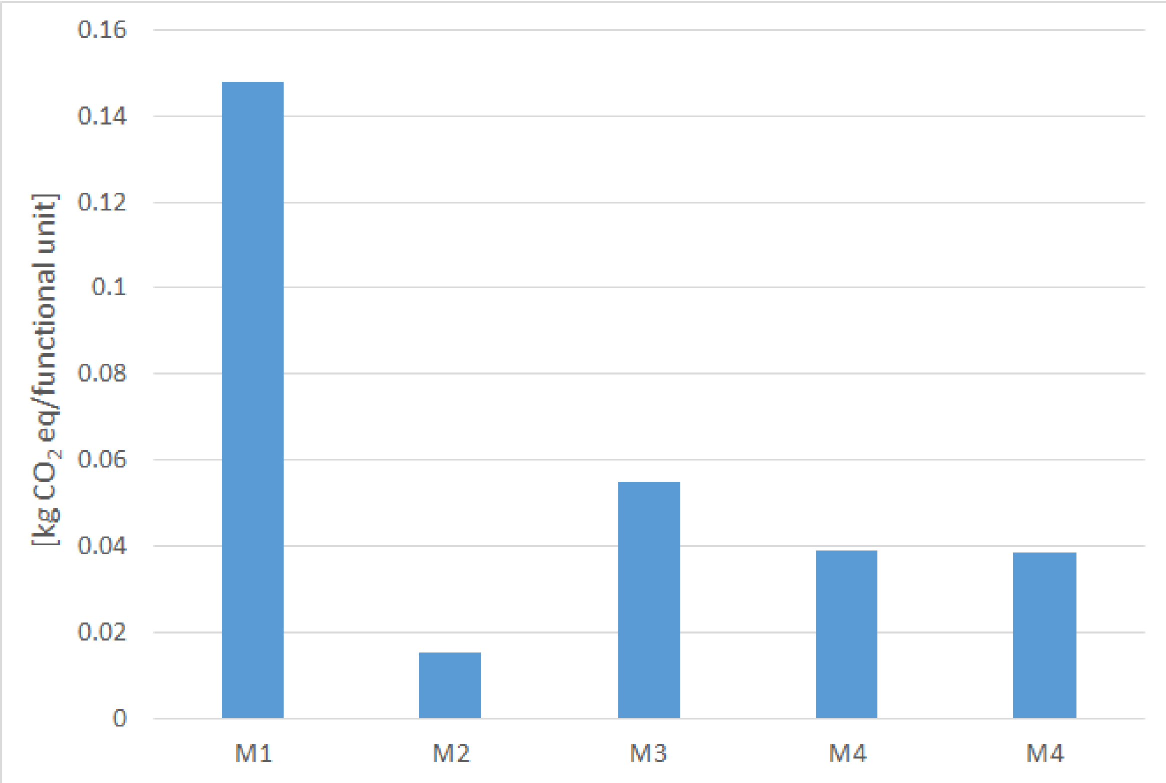

Figure 7. GWP [kg CO_2-eq/functional unit] of the manufacturing phase.

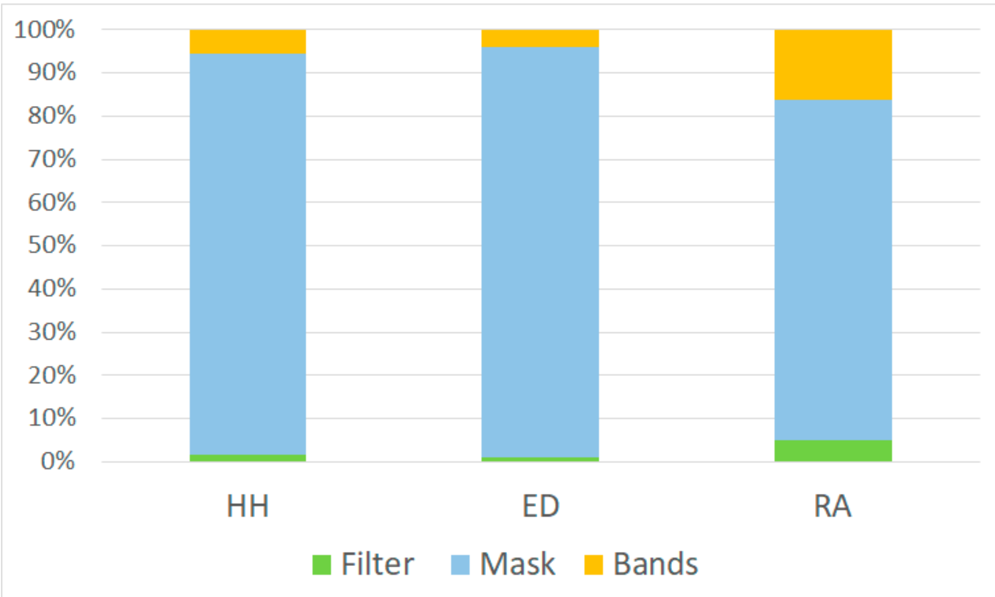

Figure 8. Endpoints (H) for M1 (percentage distribution).

For M2 (see Figure 9), the nose adapter (made of aluminum) is the component that has the greatest impact on HH and ED, while in the case of RA, the material needed to make the mask (PP and PE) represents the most critical flow.

M3 is composed of five elements, with nose protection practically negligible. Once again, the nose adapter is the most relevant on HH and ED, while for the RA endpoint, the valve is the component that has the greatest impact, as can be seen in Figure 10.

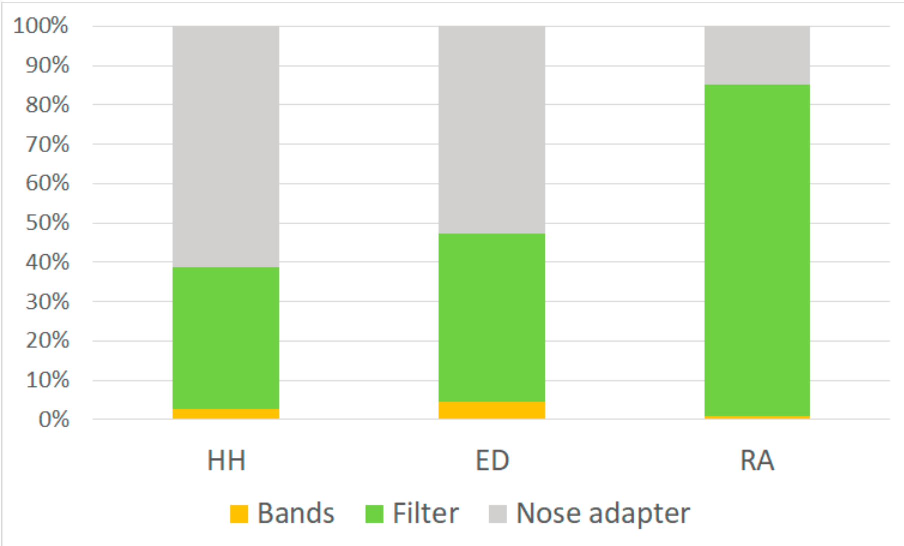

Figure 9. Endpoints (H) for M2 (percentage distribution).

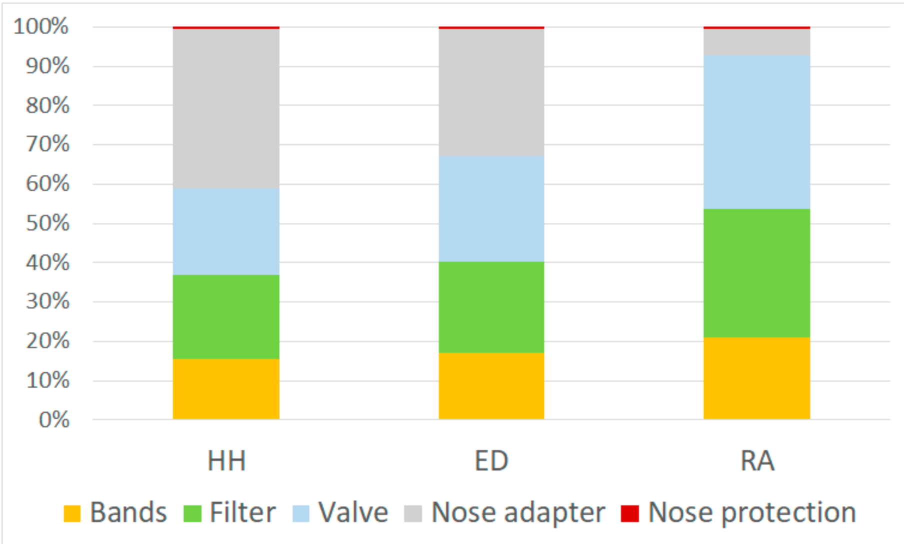

Figure 10. Endpoints (H) for M3 (percentage distribution).

The results of M4 are shown in Figure 11 and are analogous to the previous ones but without the valve and the nose protection.

Lastly, for the M5 mask, the bands (made of cotton) have the greatest impact on HH and ED, while for the RA endpoint, the material used as a filter causes the highest level of impact (see Figure 12).

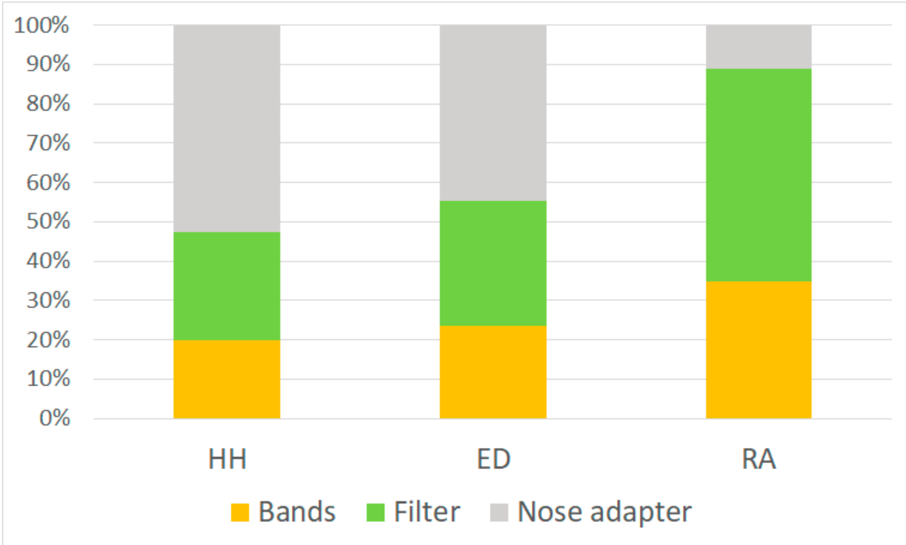

Figure 11. Endpoints (H) for M4 (percentage distribution).

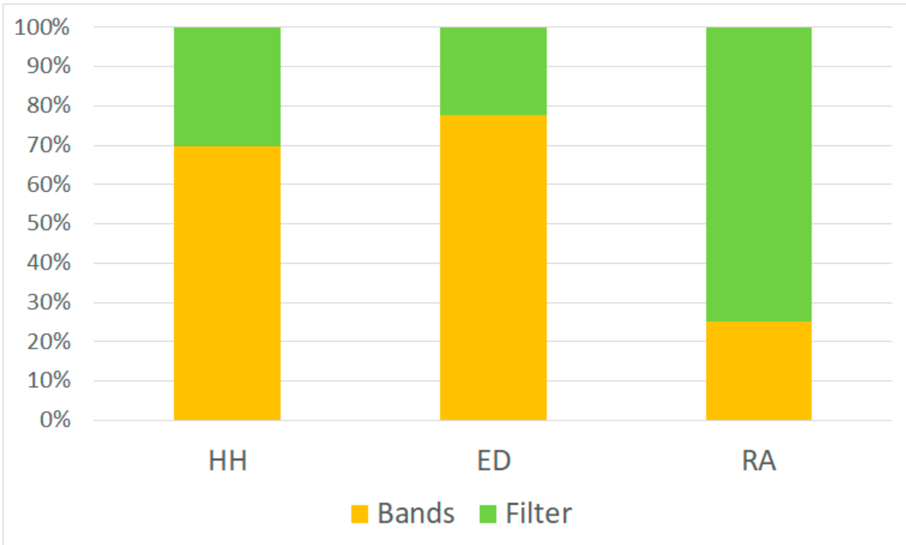

Figure 12. Endpoints (H) for M5 (percentage distribution).

Finally, in order to understand in more detail the energy resources used during the life cycle of these devices, the results of the CED are shown (Table 6).

Table 6. Cumulative energy demand for the use phase.

Impact Category		Unit	M1	M2	M3	M4	M5
Non renewable	Fossil	MJ	5.4×10^7	3.3×10^8	7.6×10^8	4.8×10^8	1.9×10^7
	Nuclear	MJ	3.7×10^6	1.9×10^7	7.3×10^7	3.9×10^7	2.0×10^6
	Biomass	MJ	4.2×10^3	5.5×10^3	1.2×10^4	1.1×10^4	6.2×10^3
Renewable	Biomass	MJ	3.5×10^6	3.7×10^6	1.3×10^7	7.6×10^6	1.6×10^6
	Wind, solar, geothermal	MJ	3.0×10^5	7.4×10^5	3.6×10^6	2.0×10^6	1.7×10^5
	Water	MJ	1.1×10^6	1.4×10^7	2.3×10^7	1.8×10^7	6.4×10^5
Total		MJ	6.3×10^7	3.7×10^8	8.7×10^8	5.5×10^8	2.3×10^7

As in the previous cases, M3 has the highest values, followed by M4, M2, and with a large difference (of an order of magnitude), M1 and M5. The fact that M1 and M5 are not disposable masks makes their demand during the whole life cycle much lower. This result explains why their values of CED are lower, as in the other impact categories. From these results, it can be inferred that to reduce the impacts related to resources and energy (RA and CED), action must be taken on the filters. If the objective is the ecosystem and human health, the nose adapter is more relevant.

After the LCA analysis, a study of the circularity of these devices was also carried out through the MCI (Table 7). The first analyzed mask was the 3D-printed (M1) mask, for which the utility parameter was based on lifespan. M1 is composed of the mask structure and filter, which have a very different useful life, thus MCI was calculated separately. For the 3D-printed structure, it is assumed that the durability is 300 times higher than an FFP2 mask, which is 8 h (X = 300). On the other hand, filters have a lifespan equal to the average of the FFP2 devices (X = 1). In all cases, it was considered that the source of input materials is "virgin" and that 100% of output materials have a landfill destination.

Table 7. Utility and MCI for different masks.

Type	Utility	MCI
M1 filter	1	0.1
M1 structure	300	1.0
M2	1	0.1
M3	1	0.1
M4	1	0.1
M5	50	0.9

As can be seen in Figure 13, the M1 structure is a completely circular product (because of high utility), while the M1 filter (along with other disposable devices) is considered fully linear. In order to increase the circularity of this mask, recycled or reused sources for materials should be used, together with actions aimed at increasing utility. In general, eco-design actions should be mainly focused on masks considered fully linear since these devices have the worst circularity performance.

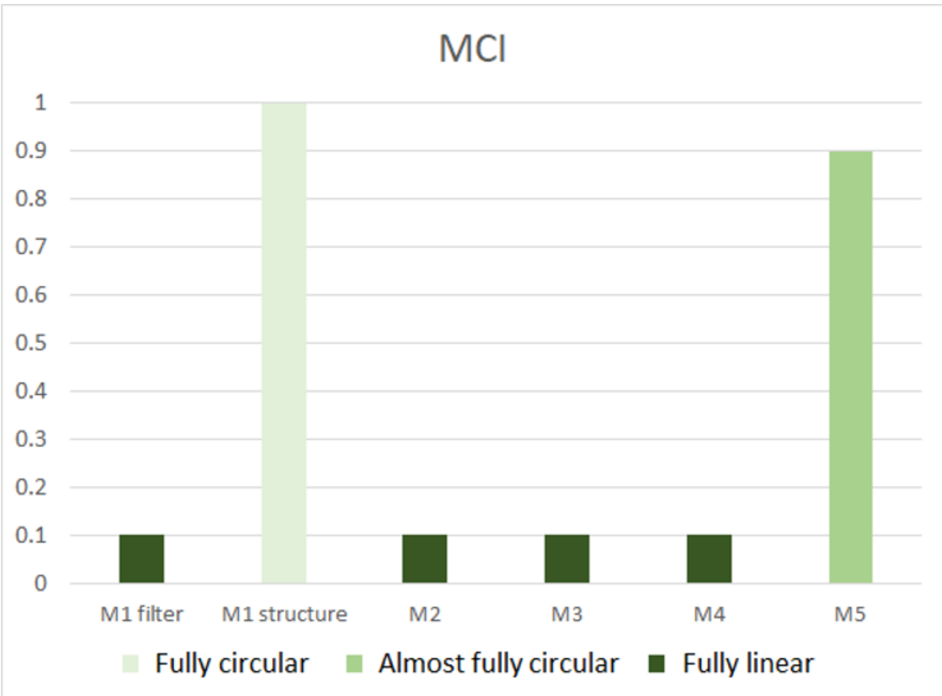

Figure 13. MCI chart.

3.2. Knowledge-Based System for Eco-Design

Through the results of various indicators revealed in the previous section and taking into account the objectives of this study, which seeks to create a guide of eco-design actions that allows reducing the negative impact on the environment due to the design and production of face masks, it can be established that the best alternative studied is M5, followed by M1. This demonstrates that totally or partially reusable products favor the reduction of negative impacts. By following the methodology described in Section 2.2, Table 8 reports a list of eco-design actions to make face masks a more circular and sustainable product. To improve the usefulness of the identified guidelines, they have been divided according to the main phases of the mask life cycle: material and manufacturing, use, and end of life.

Table 8. Eco-design guidelines.

Lifecycle Phases	Criticalities	Related Eco-Design Guidelines
Material and manufacturing	High impacts related to manufacturing process (3D printing) (M1)	• To choose the most sustainable and low energy-intensive 3D printing processes • To evaluate if it is a large production volume and change the manufacturing process to a more sustainable one (i.e., injection molding)
	High impacts due to complex structure (M3)	• To reduce the number of components (integrate parts with same material) • To use as few diverse materials as possible • To avoid outlet valve
	High impacts and low circularity due to the use of virgin materials (M1, M2, M3, M4, M5)	• To choose more sustainable materials (i.e., PP instead of PE) • To avoid coupling PP and PE for the manufacturing of filters (nonwoven fabric) • To use a mix of virgin and recycled input materials (or if possible, only recycled plastics) • To avoid the use of Aluminum as nose adapter
Use	Disposable products (M2, M3, M4)	• To prefer washable and reusable (fully or partially) products
	Low duration of filters (M1)	• To increase useful life of the filters by modifying the material's properties (i.e., surface activated filters) [65–67] • To optimize weight and surface of filters • To use washable and interchangeable filters
End of life	Multimaterial for filters that reduces circularity (M1, M2)	• To use single materials
	Difficulties in separating components and materials (M2, M3, M4)	• To develop products according to the design for disassembly rules • To reduce the number of components • To use easy to disassemble joints (i.e., snap-fit and press-fit)
	Open loop EoL (M1, M2, M3, M4, M5)	• To develop dedicated EoL processes for material recycling • To organize dedicated collection systems

3.3. Mask Development Process

As can be seen, LCA and MCI help to identify the critical factors of the product (face mask) and successively define eco-design actions that can be taken into account during the design of new masks, thus creating a framework for the development of these products in a sustainable manner. In this way, following the methodology proposed by Pahl and Beitz [59], a new product can be developed in a very short time, concentrating efforts on critical aspects and making the reaction to this health emergency swift and efficient. Applying the process workflow explained in Section 2.3, it is possible to obtain a mask prototype adapted to the needs expressed in the list of requirements. The main level of functional analysis is shown in Figure 14.

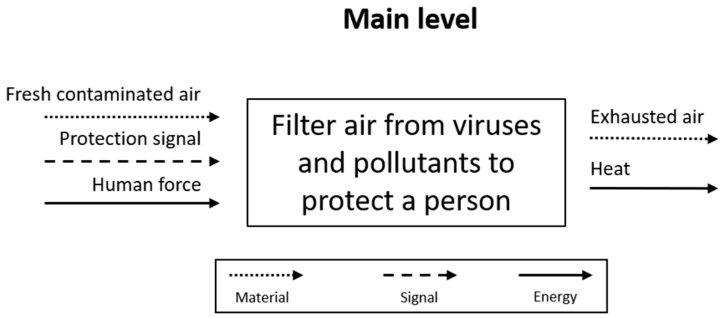

Figure 14. Functional analysis (main level).

The input flows identified in terms of material, signal, and energy can be defined as follows:

- Fresh contaminated air: the material needed for breathing;
- Protection signal: the signal to activate the protection;
- Human force: the force required to apply the protection.

On the other hand, two outputs have been considered:

- Exhausted air: represents the result of the breathing process (contaminated air);
- Heat: generated by the breathing process.

After having defined a detailed functional structure, results of the modularization phase that takes only the dominant flow into account can be seen in Figure 15, identifying five modules and two auxiliaries: (i) import and regulate air, (ii) allow safely breathing; (iii) protect and cover exposed body parts; (iv) guarantee filter efficiency; (v) guarantee filter change; (Auxiliary 1) display filtering status; and (Auxiliary 2) personalize.

The full set of modules identified by the use of the three heuristic methods are reported in the following Table 9.

Table 9. Modules retrieved by the use of the three heuristic methods.

ID	Module	Type	DF	CTM	BF
A	Import and regulate air	Main	X		
B	Allow safely breathing	Main	X		
C	Protect and cover exposed body parts	Main	X		
D	Guarantee filter efficiency	Main	X		
E	Guarantee filter change	Main	X		
F	Personalize	Auxiliary	X		
G	Display filtering status	Auxiliary	X		
H	Display protection sterilization	Auxiliary		X	
I	Extract water after virus separation	Auxiliary		X	X
L	Monitor protection efficiency	Auxiliary		X	
M	Convert air	Main		X	X
N	Dissipate exhaust air	Main		X	X
O	Block water droplets after breathing	Main		X	X
P	Ergonomic for fixation and adaptation	Main		X	
Q	Dissipate heat	Auxiliary			X

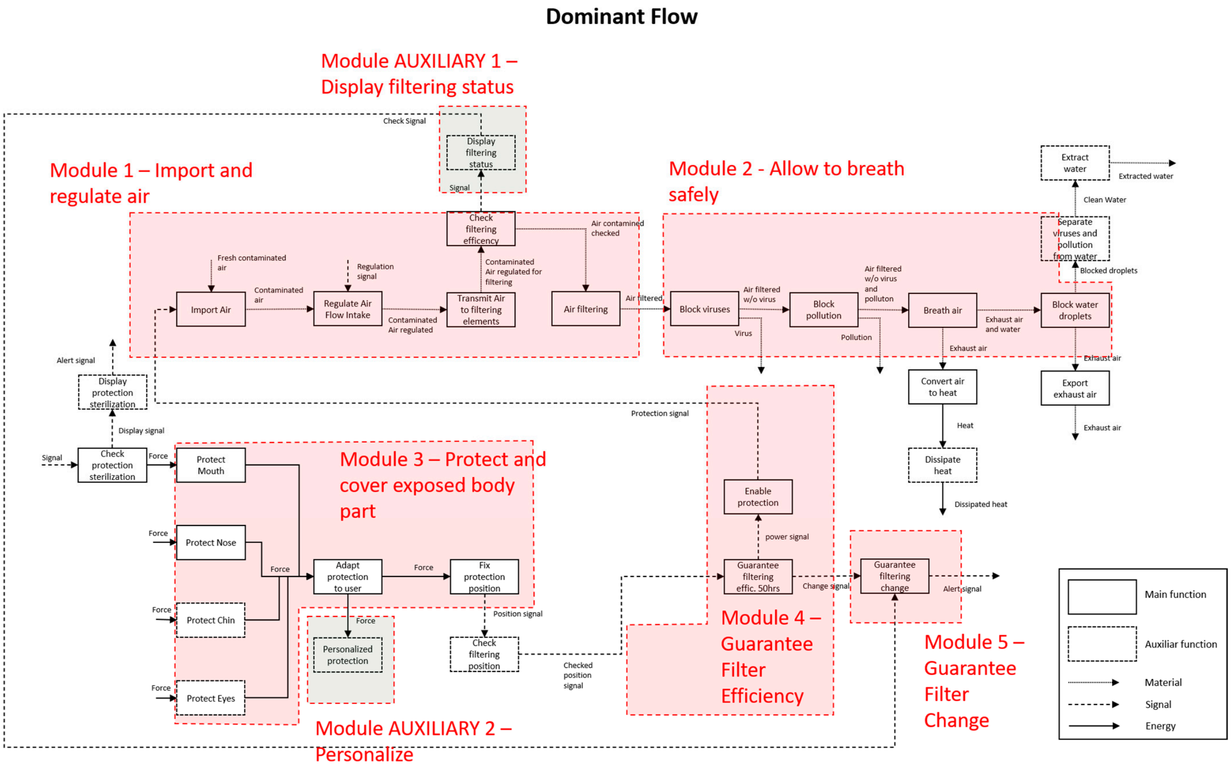

Figure 15. Functional analysis including dominant flow heuristic method for module identification.

The technological implementation was carried out taking into account all the eco-design actions (i.e., type of filter material, ease of disassembly), creating a morphological matrix. An excerpt of the results is shown in Figures 16 and 17.

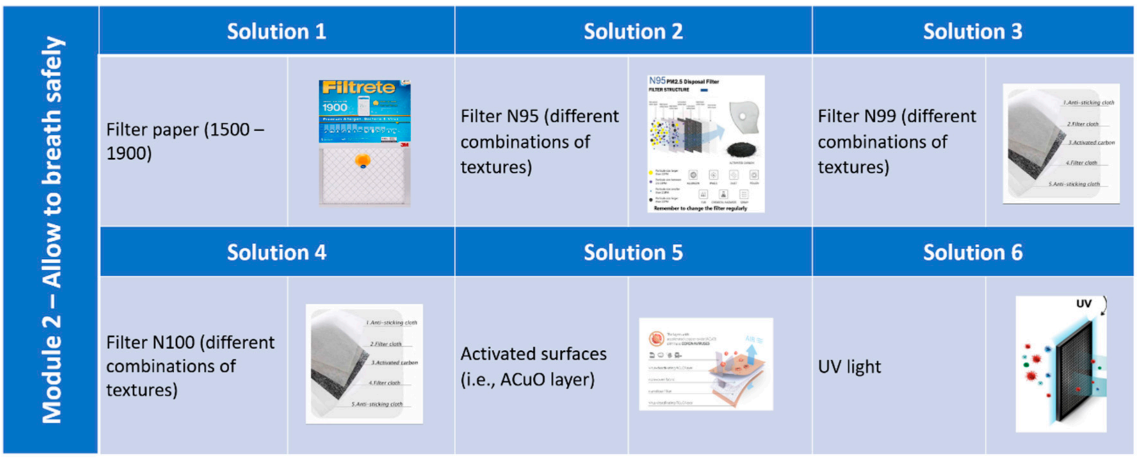

Figure 16. Morphological matrix for Module 2.

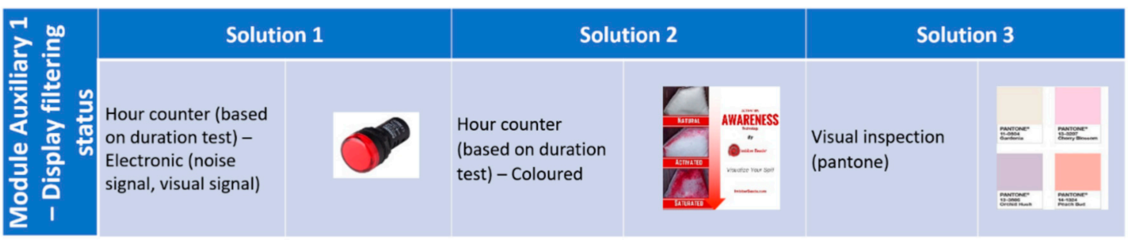

Figure 17. Morphological matrix for Module Auxiliary 1.

All the design steps previously described were carried out by the same authors of this work following the design process described by [59]. In particular, a systematic requirements analysis (also known as requirements engineering) was adopted, and several tools were used to define the list of requirements (i.e., market analysis, discussion forum, checklist) [68]. As previously mentioned, for the development of functional/modular decomposition, the approach proposed by Pahl and Beitz [59] was adopted for the functional analysis, while the heuristic method developed by Stone and Wood [60] was used for the module derivation. Finally, the last step dealt with the definition of the morphological matrix, which was carried out with brainstorming sessions between the authors of this work, other researchers, and students of the mechanical engineering course, including systematic analysis of the industrial patents.

After all analyses, it was possible to obtain a final mask result, combining the different solutions identified in the morphological matrix in order to fulfill the requirements previously established and taking into account the eco-design guidelines identified through the initial LCA and MCI analyses. The device proposed in Figure 18 is the simplest version, which only considers the main modules, and it was developed by the authors of this work, together with classroom work performed with the students of the mechanical engineering course.

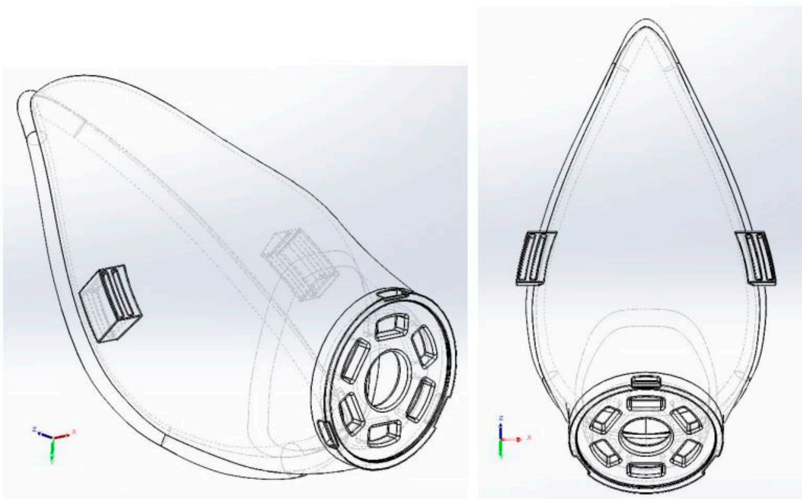

Figure 18. Face mask prototype developed by the authors of this work.

In this device, respiration (inhalation and exhalation) is carried out by natural depression (thus avoiding electronic devices, which increase the number of components with the corresponding economic and environmental impacts). For the filtering phase, a widely used N95 filter was chosen, minimizing the surface in order to reduce the amount of material used. In addition, it was decided to activate the filter surface with metallic oxide coating to guarantee its efficiency and antimicrobial properties [22,67]. In order to simplify the filter changing process, a snap-fit fixing system for the mask structure and the cover of the filter was chosen in order to have an economic and easy-to-use solution. Furthermore, to optimize shape and dimensions based on the anthropometric and ergonomic characteristics, the mask wearability was studied with a virtual human model (Figure 19). The ergonomic analysis was performed by the authors of this work using a virtual fit assessment method (by means of CAD environment) to design a facial mask that fits with people presenting different anthropometric features (e.g., the distance from the ear's tragus up to the top point in the bridge of the nose, the height of the tip of the nose, skull width, the distance between eyes, nose width, etc.) [69]. The study was developed using 3D face scan data of more than a hundred people to find the most proper shape of a facial mask. Since this phase is not the focus of this work, the ergonomic analysis is not discussed in detail.

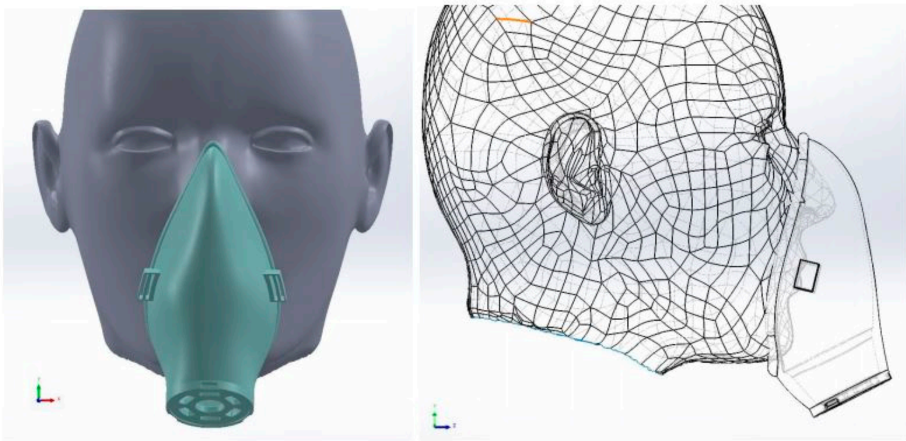

Figure 19. Example of the developed facial mask during the ergonomic test.

4. Discussion

After the LCA and MCI analyses, it is possible to observe that a reduction of 650,000 tons (extending results to one year) in terms of CO_2 eq. emissions can be obtained in Italy by simply choosing reusable devices such as M5 instead of disposable masks such as M3. In this way, benefits at the environmental level and the improvement of the circularity can be appreciated. This decision allows reducing GHGs and also leads to an economic benefit. After the development of the new mask designed by following the proposed methodology and the identified eco-design suggestions, an environmental impact analysis of this innovative prototype was carried out in order to make a comparison with M1 since both are devices with similar characteristics (reusable structure of the mask and disposable filters). For this new mask, the manufacturing process selected was injection molding, based on the guidelines defined above, highlighting the 3D printing process as a criticality. It was verified that the optimized model produced by injection molding using PP as material for the mask structure obtains better results in almost all the indicators studied. Figure 20 shows the normalized results; in this way, the percentage advantage obtainable with the new solution can be inferred. The only category in which the new design has a greater impact is FFP, due to the use of a fossil-based material (i.e., PP). However, these impacts can be mitigated by substituting this type of plastic with a well-known and largely used bio-based plastic (i.e., PLA) [70].

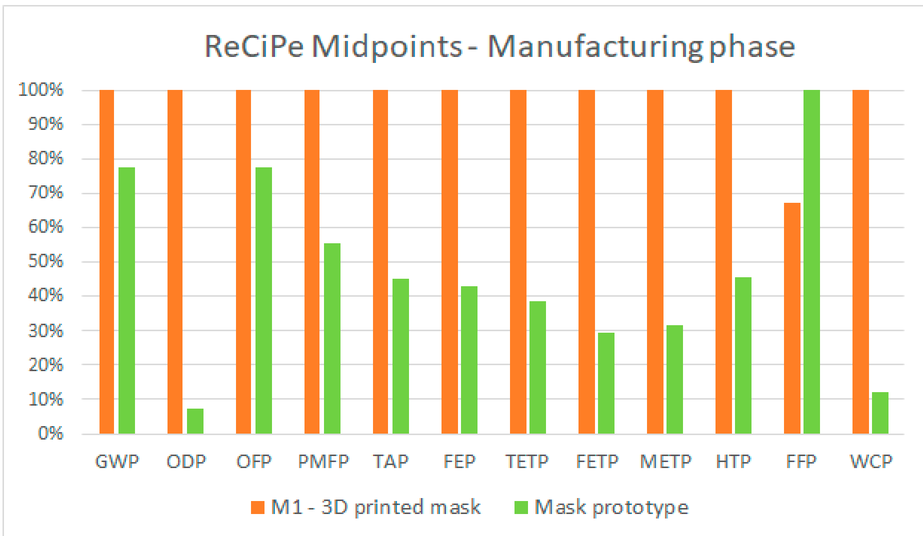

Figure 20. Normalized midpoints for the manufacturing phase (3D-printed mask vs. new mask prototype).

Results for the use phase, when disposable filters are used, are analogous to those ones shown in the mask production phase, confirming the design improvement. In addition, if filters are substituted with washable ones (following the eco-design guidelines that recommend the use of nondisposable filters), the proposed mask prototype has the lowest impact on the use phase of all devices studied, even lower than M5 (see Figure 21). This result is in line with recent work [71] developed on the same subject but using a different metric than LCA (i.e., the environmental impact index (EI)). Indeed, the mentioned work highlights that quilt and cotton are appropriate cloth-from-cotton material for making a nonmedical mask with the highest quality of filtration efficiency and breathability while having the lowest environmental impact, whereas polypropylene fabric is the worst material in terms of environmental impact. Alternatively, another interesting research work [72] tried to investigate the adoption of recycled material from reprocessed FFP2 face masks. The study demonstrated how the reprocessed material has a lower environmental impact and financial burden than new disposable face masks without compromising qualifications and filtration efficiency.

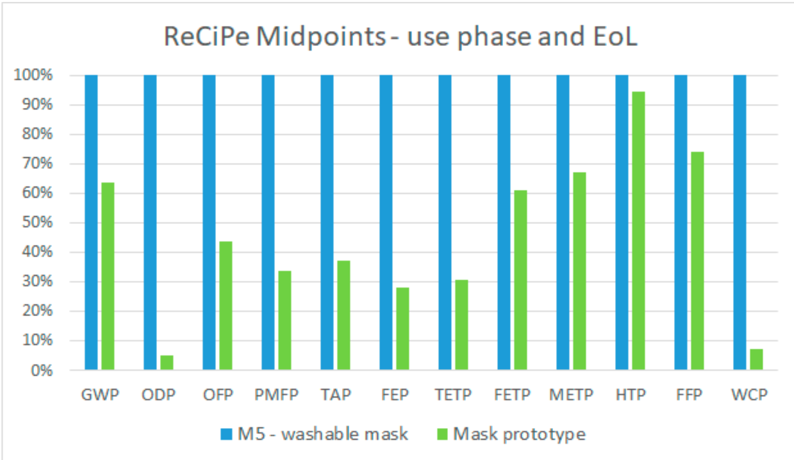

Figure 21. Normalized midpoints for the use and EoL phases (new mask prototype with washable filters vs. washable mask).

Concerning the maintenance phase for this mask, the use of ethanol for the main structure (mask body) and soap and water for the filters allows combining the advantages of the M1 and M5. This significant benefit is mainly due to the fact that the greatest efforts of the eco-design process are concentrated on the improvement of the use phase.

Summarizing, it is possible to affirm that the usefulness of this type of methodologies and approach to developing new sustainable face masks has been clearly demonstrated by this study. Despite the fact that to date it has only been applied in the context of face masks development, it can be certainly used for the development of other widely used protection devices (e.g., suits, gloves), replicating the process with the needed customizations (e.g., the definition of specific eco-design guidelines, use of appropriate KPIs for each product) and obtaining environmental improvements also in these products.

Finally, some limitations of this study should be mentioned. For example, a univocal EoL scenario was studied. If sanitary landfills would have also been considered an end-of-life scenario, a reduction in impacts could have resulted, especially in the case of M3 and M4 devices, which are the ones that generate the most plastic waste. However, it is clear after studying the results of this research that even if a sanitary end of life had been considered, the values of the circularity index would not have changed since the method used to calculate MCI makes no distinction between landfill types. To avoid this limitation, the circularity study can be extended using other additional indicators. Despite incineration shows high GWP (as confirmed by the study [34]) it is a promising option for the management of this waste compared with landfilling among all the others impact categories.

Lastly, it should also be taken into consideration that the results of the M5 mask vary depending on the material used and the number of times it can be washed without losing filtering properties, this being a key factor for both the environmental and circularity performance.

5. Conclusions

The present paper focuses on the proposal of an eco-design methodology to support designers in the development of environmentally sustainable face masks. The work was performed by using well-known methods for the environmental and circularity analysis of products (i.e., LCA, MCI). Consolidated procedures to formalize useful knowledge on past experiences (i.e., the definition of eco-design guidelines) and to reuse it for product improvement projects (i.e., systematic approach to design with specific constraints due to the pandemic situation) were followed to derive eco-design action in the development of sustainable facial masks. To date, this study can be considered the first attempt in the protection devices sector to contribute to the preservation of the natural environment while facing the world COVID-19 emergency, with a preventive approach to be applied during the design phase. More generally, considering that the risk of future unexpected events such as the COVID-19 pandemic is not null, it can be affirmed that this kind of methodology will be useful each time a very high demand for disposable fossil-based products (as face masks) will be needed to face an emergency situation.

Results obtained with the first methodology step allow having an overview of the environmental performance of five common face masks and lay the foundation for the successive definition of design best practices. Reusable masks (M1 and M5) have clear advantages, compared to disposable products (M2, M3, and M4). However, these products also cannot be considered really sustainable, and different criticalities were identified (e.g., use of fossil-based or impactful materials, open-loop end of life). The proposed redesigned project demonstrated that by starting from the knowledge of the environmental performance of well-known products, it is possible to obtain significantly improved face masks in all the used KPIs by preventing observed criticalities and applying the best design choices concerning material selection, sustainable manufacturing processes, and durability of mask components.

Future developments will regard the following points:

- LCA analysis refinements: an extension of the environmental and circularity analyses, which include additional details (e.g., specific inventory for the nonwoven fabrics manufacturing, the inclusion of the waste collection phase within the system boundaries, etc.) will help in a definition of more specific guidelines and actions;
- LCA analysis scenarios: additional scenarios (e.g., sanitary landfill EoL, different typologies of washable masks, etc.) will allow defining a larger set of design guidelines ad to provide the best solution for policymakers in this complex context;
- Consequential LCA: since the production and disposal of anti-SARS-CoV-2 masks are becoming of global importance for the socioeconomic management of the pandemic, an additional consequential LCA will be able to estimate how the global environmental burdens are affected by the production and use of this product. Consequential LCA could bring some additional important conclusions to couple with the results of this study.

Another direction of research could be the definition of multiobjective design methodologies dedicated to the sustainable development of face masks looking at the promotion of two combined targets: (i) the minimization of negative environmental impacts (as in the present paper) and (ii) the maximization of other performance (e.g., filtration efficiency, cost estimation, etc.).

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su13094948/s1, Excel file.

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

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List of Acronyms

Abbreviation	
BF	Branching flows
BFE	Bacteria Filtration Efficiency
CED	Cumulative Energy Demand
CTM	Conversion-transmission modules
DF	Dominant flow
ED	Ecosystem
EoL	End of Life
EU	European Union
FEP	Freshwater eutrophication potential
FETP	Freshwater ecotoxicity potential
GHG	Greenhouse gas
GWP	Global warming potential
HH	Human Health
HTP	Human toxicity potential
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCE	Life Cycle Engineering
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
M1	Mask type 1
M2	Mask type 2
M3	Mask type 3
M4	Mask type 4
M5	Mask type 5
MCI	Material Circularity Indicator
METP	Marine ecotoxicity potential
ODP	Ozone depletion potential
OFP	Photochemical oxidant formation potential
PE	Polyester
PFE	Particle Filtration Efficiency
PLA	Polylactic acid
PMFP	Particulate matter formation potential
PP	Polypropylene
PPE	Personal Protective Equipment
PU	Polyurethane
RA	Resources
TAP	Terrestrial acidification potential
TETP	Terrestrial ecotoxicity potential
UV	Ultraviolet
WCP	Water consumption potential
WHO	World Health Organization

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