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Closing the Loop Valorization of Industrial Waste of Composite Materials through Re-Design of Products from Detached Value Chains

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Abstract

The literature lacks methodologies to make supply chains of composite materials circular. The proposed approach aims to transform scraps and off-specification products into secondary raw materials. Its novelty is to find innovative applications, instead of re-introducing scraps in the loop they come from. The case study investigates how scraps can be re-worked and re-used as raw material. First, the processes are analyzed; some components are then re-designed to be made of the discarded scraps (composites material). Results reveal that the symbiosis can ensure green, high performing products.

Keywords: circular economy, ecodesign, composite materials, industrial symbiosis, design optimisation

1. Introduction

Organizations are called to the big challenge of launching in the market circular products to meet compliance and demand from customers, but also to promote their brand (Ditlev-Simonsen, 2022). This asks manufacturers to look beyond their gates and supply chains with the goal to make their products and scraps, a secondary material for different chains. This cannot be done without de-manufacturing and re-manufacturing, not only applied at the end of life of the product, but through methodologies and tools since the design stage: End of Life (EoL) must constantly induce suggestions and feedbacks towards previous lifecycle stages, design in the first place. In fact, a correct design and a continuous improvement of the disassembly and EoL phases are key actions to obtain the maximum result (Rossi et al., 2022). Moreover, Circular Economy (CE) requires not only a single enterprise to approach it, but a whole system to change. Inside its own boundaries, a circular organization must harmoniously encompass all its departments; outside, it must simultaneously collaborate with all actors of the product value chain and work to involve that one in other supply chains. The design of industrial and urban symbiosis and especially crucial in the transition of a CE which stressing on waste minimization and recovery at the EoL (Fan et al., 2021).

The focus of this paper is on circular strategies applied to composite materials, i.e. materials made from two or more constituents with significantly different physical and/or chemical properties that, when combined, produce a material with different characteristics from the individual components (Krauklis et al., 2021). The use of composite materials is growing (Job, 2016) and consequently a big challenge for this industrial expansion is the development of approaches and technologies to optimize the waste generated from manufacturing operations and the end of life of products (Mativenga et al., 2017). Three are the main options for treating EoL wastes: landfill, incineration and recycling. Oliveux et al. (2012) calculated the related environmental impact of these strategies obtaining significant negative burdens on the environment for landfilling and incineration treatments, while minor values for the recycling process, e.g. mechanical comminution techniques to reduce the size of the scrap to produce filler materials, chemical degradation to break polymeric matrices into simple chemical constituents (La Rosa et al., 2016). Regarding recycling processes, they present lower Technology Readiness Level (TRL) (Table 1), while landfill and incineration is still the most common route.

Landfill of composite waste is banned in Germany (in 2009) and other EU companies are expected to follow this route; furthermore, when they are incinerated, around 50% of the composite waste remains as ash and must be landfilled (Jacob, 2011).

Table 1. TRL level for EoL treatments for composites

Treatment	TRL	Treatment	TRL
Incineration	9	Recycling	
Fluidized bed pyrolysis and solvolysis	4,2; 2,24	Microwave heating	3
Grinding for CF*	6,3	Grinding for FG*	8,3
Pyrolisis for CF*	8,3	Pyrolisis for FG**	6,25
Landfilling	9		

*CF= Carbon Fibre **FG= Fiber Glass

It is therefore evident the need to further investigate the question related to EoL composite treatment scenario and more evident the need for establishing design protocols which positively affect the EoL opportunity of this kind of materials. Beauson et al. (2022) outlined needs from the academy and industrial sectors for composites; among them: needs for alternative design solutions for facilitating the EoL processing, identifications of applications for recycled materials and input for the formulation of standards on the use of recycled materials, guidelines to design including EoL consideration, estimation of the second-hand market. Decisions made today significantly influence the use and disposal of the product later. Design strategies can favor the implementation of strategies not only to improve the recyclability level of composite material but also can make possible the re-use of scraps, through the application of design for de/remanufacturing, disassembly rules. The reuse is the second-best option (after reduce) of the European Union's (EU) Waste Framework Directive because it allows obtaining the highest environmental benefits and minimum negative impacts. This could happen by creating circular supply chains, where scraps become input materials, reducing waste treatment costs and increasing the environmental benefits. Supply chains and interfirm relationships have a crucial role in supporting the transition towards CE (Calzolari et al., 2022). Industrial Symbiosis (IS), i.e. synergistic interactions between companies where one's waste(s) can be used as input(s) of another (Baldassarre et al., 2019), represents the most effective enablers toward successful CE, by recovering the value of by-products and waste (Yazan and Fraccascia 2019).

The literature however does not provide enough hints and methodologies aimed to make supply chains of composites materials, circular.

The present paper presents a method of analysis in the context of eco-design whose core is to transform scraps and off-specification products in primary materials for the manufacturing of different goods, also thank to their redesign. The case study applies the proposed method and identifies a cluster of Italian companies producing dissimilar products that can collaborate applying a symbiosis strategy, by working scraps and using them as new raw materials.

First, the process scraps of the first manufacturer are analyzed simultaneously with the high running goods produced by the second. By crossing the obtained results, some specific parts are identified to be made of the discarded scraps. The features of the components are re-design so that the re-use is technologically feasible. Ultimately, a comparison from an environmental perspective between the initial and innovative scenarios is carried out. Results reveal that the symbiosis between manufacturers can ensure the production of green products without giving up on performance. Furthermore, it emerges some possible general design strategies to increase the level of applicability of circular strategies, e.g. simplicity in shape and feature of products.

2. Method

The object of the proposed method is to support companies in the evaluation of circular strategies, through a structured process, which leads them to quantify the environmental benefits of reusing scraps as raw materials. From one side, the company that produces scraps, on the other one, a possible user of these scraps (Figure 1). At first the analysis of the As-Is situation is realized, both for scraps and target products, i.e. the product or the family of products where scraps could be re-use, thus substituting virgin materials. Characterization can start; for the scraps in particular, the following parameters need to be defined or quantified:

- Quantities of scraps produced: to monitor the amount and the variability level and consequently the availability of a specific scrap on a reference target period (e.g. yearly);
- Typology and chemical composition, allowing the identification of mechanical, thermal, physical performances and machining;
- Disposal scenario and EoL treatments for the produced scraps, including all the pre-treatments (e.g. mechanical shredding or manual separation) and intermediate transport prior the effective treatments;
- Environmental impacts related to the involved life cycle phases, i.e. material extraction and pre-processing, transport toward dismantler and EoL treatments.

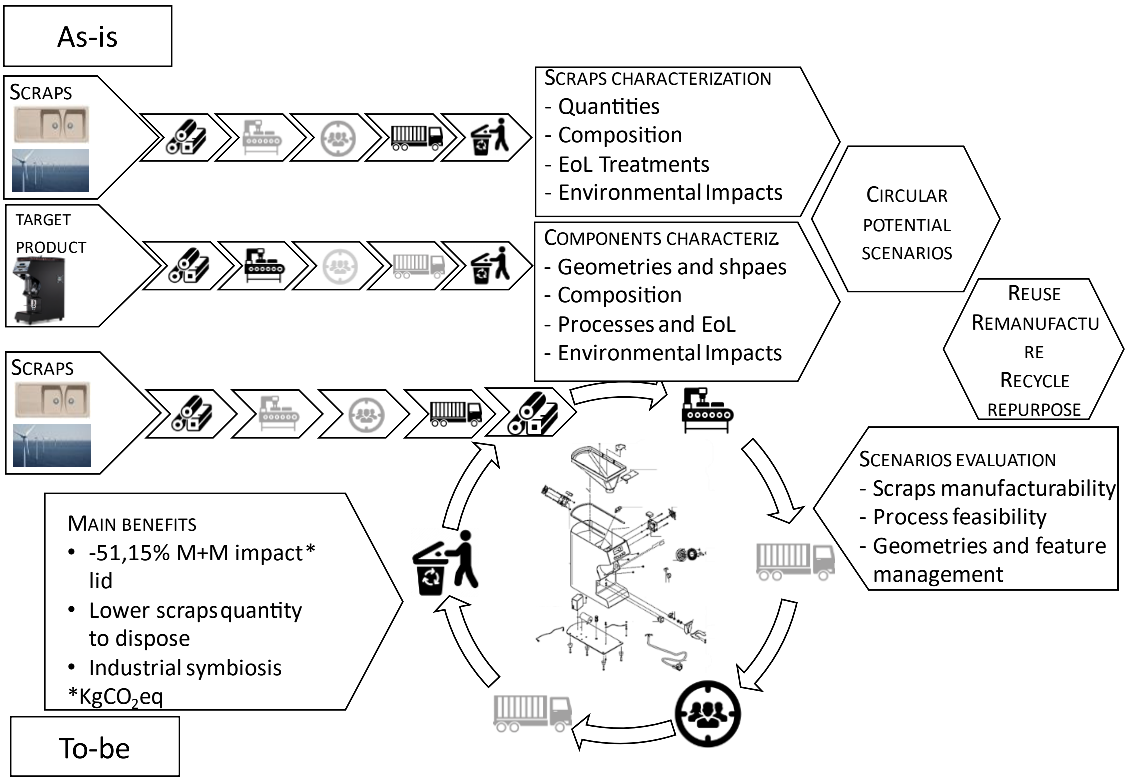

Figure 1. Flow of valorization of industrial waste from composite materials.

The situation is now defined, with the identification of potentiality, e.g. the production of a great amount of a waste typology, or criticalities, e.g. high impacting EoL treatments for specific classes of material. The analysis can start for the product or the product family object of the study, with the analysis of:

- Geometrical properties, feature and shapes for components, to identify parts with higher/lower level freedom degree and therefore suitable for material/shape/thickness modifications (e.g. esthetical vs. functional components);
- Material properties for components and their technical, mechanical, thermal, and physical performances;
- Production processes and EoL treatments for the products' components;

- Environmental impact related to the involved life cycle phases, e.g. material extraction and pre-processing, manufacturing processes, transport toward dismantler and EoL treatments.

All these data collected about the products and scraps, allow from one side to identify the main criticalities in terms of environmental impacts both for components and scraps, and the feasibility of modifications for product components. At this stage the evaluation of alternative circular scenarios can start. Scraps properties and their machining, the feasibility of production processes, shape and feature examination together with environmental analysis results, guide the identification of single or multiple To-Be scenarios. A To-Be scenario foresees the identification of one or more circular strategies to apply for the specific situation. Technical feasibility guides the choice. Then, the evaluation of the To-Be scenario can start by quantifying the environmental benefits obtainable by the implementation of the strategies and comparing the environmental impact of the AS-IS and To-Be situations and evaluating the effort required for:

- Design modification of components and their shapes, which need to allow the application of the circular scenario identified;
- Manufacturing operation needed to make the scarps reusable (e.g. disassembly, finishing operations, etc.) and its application in the specific industrial context.

The environmental benefits of circular strategies need to be verified by the use of quantitative methods and tools (e.g. LCA); the material flow could correspond to higher energy flows and consequently, an impact transfer problem could occur. For this reason, a verification step is needed to validate the choice also under the environmental aspect.

The method claims five main potentialities and strengths: first it aims to give value to scraps made of composite materials, whose disposal is very challenging, and recycling is most of the time an unattainable standard. Secondly, it is compliant with the base principles of CE. In fact, it strictly links the end of life and first stages of products lifecycles. In addition to that, it expects more than a single manufacturer, active in varied sectors, to work together to find sustainable solutions and improvements. This leads to one of the most successful strengths: the symbiosis between distant manufacturers prevents the risk of cannibalization and low demand for remanufactured products that often distress enterprises and hamper circular initiatives. Differently from available works, the proposed methodology is intended to find innovative applications and employment of scraps to existing or new products, instead of re-introducing them in the same loop they were first used.

A beneficial data, knowledge and information exchange could happen also with actors in charge of dismantling processes, allowing a detailed modelling of this phase. Manufacturers often do not hold detailed information on this matter, which happens out of their gates.

3. Case study

3.1. As-is

The proposed method was applied by three Italian companies from the Marche region. Two made their scraps available to be worked and employed as secondary raw material in the production of a professional coffee grinder. The scraps are derived from the manufacturing of wind blades (C1) and sinks for domestic kitchens (C2). They were both process scraps (i.e. dust from Computerized Numerical Control - CNC - machining) or pieces that are discarded because they do not accomplish internal quality standards. The As-Is analysis evaluates the environmental burdens, through Life Cycle Assessment (LCA) methodology and tools from the extraction, production, and disposal of the annual quantity of scraps produced by C1 and C2. Table 2 summarizes the Life Cycle Inventory (LCI) data for the environmental assessment of the scraps deriving from processes of C1 and C2. C1 and C2 produce goods made of composite materials; this allows to accomplish the high efficiency of working conditions and durability of products; however, there is not any process able and intended to recycle, re-use or valorized the scraps and waste. About C1, the blade scraps are partially incinerated with heat recovery, the remaining is sent to disposal; prior to that, in both cases, the waste is shredded and compressed. Similarly happens for the sink scraps that are fully incinerated. Waste is always pre-treated in at least two dismantling centers before being incinerated or landfilled.

Table 2. LCI for scraps of companies 1 and 2

#	**SCRAPS**				**Current disposal scenario**	**Mean of transport used**	**Scrap transported [ton*Km]**
	Category	Annual quantity	Material	%			
C1	Fiber glass scraps	32 %	Fiber glass		Landfill	Road, truck	371,01
					Incineration	Road, truck	802,96
	Plastics scraps	4 %	PVC*		Landfill	Road, truck	380,63
		5 %	Polyammide				
		3 %	Rubber	70%			
			Butylacrilate	30%			
		3 %	HDPE**				
		2 %	Nylon				
		6 %	PE***, tubes				
		34 %	Epoxy resin		Incineration	Road, truck	1372,34
		8 %	Epoxy resin	40 %			
			Glass fiber	42 %			
			Carbon fiber	18 %			
		1 %	Epoxy adhesive	50 %			
			Glass fiber	30 %			
			Epoxy resin	20 %			
	Dust from coating	2 %	Epoxy resin	80 %	Landfill	Road, truck	112,57
			Insulation	20 %			
C2	Sink scraps	87%	Mineral	70 %	Incineration	Road, truck	5600
			PMMA****	25 %			
			Additives	5 %			
	Sink dust	13%	Mineral	70 %	Incineration	Road, truck	800
			PMMA	25 %			
			Additives	5 %			

***PVC= Polyvinyl chloride **HDPE= High density polyethylene *** PE= Polyethylene ****PMMA = Polymethyl methacrylate**

Table 3 shows the environmental impact for the scraps produced by C1 and C2 calculated for the following impact categories: Climate change (CC) [kg CO2 eq.], Ozone depletion (ODP) [kg CFC-11 eq.], Human toxicity (HT) [kg 1,4-DB eq.], Water depletion (WD) [m3], Metal depletion (MD) [kg Fe eq.], Fossil depletion (FD) [kg oil eq.]. The analyses were carried out using SimaPro 8.0 and results were calculated by the Recipe MidPoint (H) method. The material phase is the most impacting (more than 85%), followed by the EoL phase. Wind blades and sink scraps disposal are responsible for about 10% and 15% respectively. Transportation and treatments prior the final disposal are negligible. In particular, for C1, waste pre-treatment impact, such as grinding, and compacting, is lower than 1%.

Table 3. Environmental as-is analyses results

	C1				C2		
Impact category	Material	Transport	Electricity	Disposal	Material	Transport	Disposal
CC	2.0E+05	4.7E+02	1.4E+01	2.0E+04	3.5E+05	7.1E+02	6.1E+04
ODP	7.5E-03	8.6E-05	2.0E-06	1.1E-04	6.5E-03	1.3E-04	4.8E-04
HT	6.5E+04	1.9E+02	2.1E+00	1.2E+04	2.2E+04	1.4E+02	6.3E+04
WD	3.9E+03	1.4E+00	9.7E-02	5.3E+01	1.6E+03	2.1E+00	4.8E+01
MD	3.5E+03	1.7E+01	3.5E-01	-8.7E+02	1.6E+03	3.2E+01	1.5E+02
FD	7.5E+04	1.7E+02	4.3E+00	2.1E+02	1.2E+05	2.5E+02	1.1E+03

Simultaneously, the As-Is analysis requires the environmental assessment of the target product, identified as the one that will host the scraps of C1 and C2 as secondary raw materials. The functional unit for the LCA was the production, use and disposal of a professional coffee grinder. Table 4 presents the LCI for the coffee grinder.

Table 4. LCI for professional coffee grinder: material, manufacturing and EoL phases.

Material	Quantity	Manufacturing	Disposal scenario	Flows
Low alloyed steel	42,07 %	Milling; turning; deep drawing;	Recycling	70 %
		Welding arc; wire drawing; zinc coat	Shredding + Sorting	30 %
Stainless steel	2,91 %	Deep drawing	Recycling	70 %
		Turning		
		Section bar rolling	Shredding + Sorting	30%
Aluminum	12,17 %	Turning	Recycling	50 %
		Impact extrusion	Shredding + Sorting	50 %
Brass	0,02 %	Turning	Recycling	25 %
			Shredding + Sorting	75 %
ABS	0,90 %	Injection molding	Shredding + Sorting	100%
Rubber	0,23 %	Injection molding		
Cable	0,77 %	Cable manufacturing		
PVC	0,23 %	Injection molding		
Mylar	0,02 %	Injection molding		
Nylon	1,23 %	Injection molding		
Polycarbonate	2,09 %	Injection molding		
POM	0,13 %	Injection molding		
Copper	4,55 %	Wire drawing		
Electronic board	0,58 %	Wire board printing		
Silicon	0,05 %	Injection molding		
Teflon	0,01 %	Injection molding		
Other	32,18 %	Metal working		

The coffee grinder is composed of several parts and among them, electronic ones are included. For this reason, when it reaches the EoL phase it is treated together with other Waste from Electrical and Electronic Equipment (WEEE). It is first shredded, the smaller parts are sorted according to their composition and sent to different materials flows to be recycled (when possible) or landfilled. The coffee grinder is assumed to be used on a daily basis for 5 years to produce on average 36 coffees per day, in Italy. The analyses were carried out with the support of software SimaPro 8.0 and results were calculated by the Recipe MidPoint (H) method. Figure 2 shows the Material and Manufacturing phase results for the coffee grinder as it is traditionally produced. Over the whole lifecycle, the production and use phases have the highest impacts (up to 90%). Regarding the EoL phase, materials recovery, although not at 100%, allows obtaining credits from the EoL treatment.

The results of environmental analyses, both for scraps and coffee grinder, show several potential improvements; first, avoiding incineration or landfilling of the scraps, would reduce the environmental burden deriving from the actual EoL scenario. Secondly, if they were used in the coffee grinder it would lower the material phase impact.

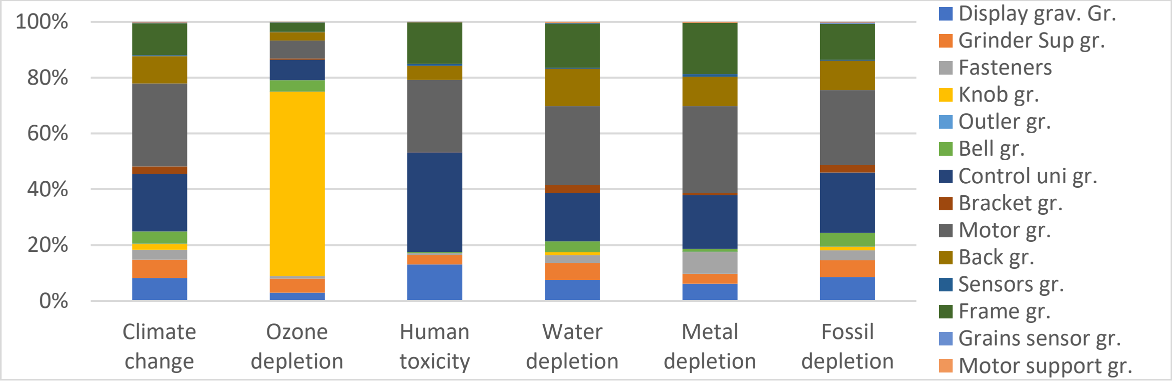

Figure 2. Coffee grinder LCA results, lifecycle (a) and M+M phase (b) [KgCO$_2$eq].

3.2. To-be

The feasibility of circular scenarios is strictly related both to technological and functional constraints: among the first, the possibility to work the scraps with known technologies to obtain the desired shapes; from the functional point of view, it may be hard to balance and optimize volumes and constraints. The scraps deriving from wind blades are either high in one dimension and curve (trimmed part of the blades) or made of materials that do not accomplish the strength, resistance and corrosion parameters for the coffee grinder (i.e. PVC scraps or glass fiber patches). The analysis of the circular potential scenarios that would value the scraps deriving from the production of the wind blades did not identify any processes that would implement those waste in the coffee grinder. Nevertheless, the analysis outlined high potentialities of re-use of the materials such as glass fiber and PVC in other products; in fact, in the case of the wind turbine, those are discarded only because of their dimensions (they are too small for the whole blade) but may be re-used in other processes, since they are still virgin material. A possible shredding or grinding of the blades may obtain very small pieces of blades that may be compressed to obtain insulating panels or shaped to be mold for the production of new blades.

The scraps deriving from sinks have higher flat areas, although they are not very big and not simple sheets (i.e. there are holes for water draining). Their thickness is limited to a few millimeters (less than 1cm). Thanks to their simple shape, three components of the coffee grinder were identified: the buttons plate, the company logo, and the bell lid. The first is a plate in whose holes the buttons fit and thus the grinder is switched to working/off mode; it is also provided with pins and small wings to attach it to the frame; the logo is meant to be attached to the back of the grinder, it is similar to a "v" geometry and presents a simple, curved shape; the lid has the function to cover the coffee beans, thus preventing them to be exposed to light, humidity and dust.

The main technological complication, both for scraps of C2 and C1, is the unfeasibility to modify the shape of the scraps, except with cutting processes. The plastic, composites materials cannot be shaped through extrusion or heat. For this reason, the buttons plate was discarded among the target components; similar considerations were done for the logo that has the aesthetic constraint to follow the rounded shape of the grinder backside. The lid, as shown in Figure 3 (a), had initially a specific shape, intended to couple with the bell and stay stable over it. Figure 3 does not show any knob, useful to handle the lid; it is bonded by a screwed inserted on a hole on the lid. The lid is the dark component; the grey part in the details is the beans bell. Light green and blue sectors are the planes crossed by the section plane: the first for the lid, the blue for the wall of the bell. Off-products sinks were identified as the secondary raw materials for the lid. The bend sides that run over three sides of the lid made the use of the sink unfeasible. Re-design actions modified its geometry, so that neither bending, nor material-adding processes were needed. Figure 3 (b) shows the main modifications: the bent parts were eliminated and substituted with a reduction of thickness around the perimeter of the lid. This ensures the correct positioning of the lid over the beans bell. The hole for the knob is maintained.

This solution enables the closure of the loop, linking the value chain of the C2 to one of the Original Equipment Manufacturer (OEM) of the coffee grinder, establishing symbiosis between the two enterprises. What previously was only scraps, now gains new value and life, in a perfect establishment of CE system. Nevertheless, once the re-manufacturing process was identified, according to the proposed method, the environmental evaluation of the new scenario allowed to assess whether those re-manufacturing activities let the companies achieve lower environmental burdens.

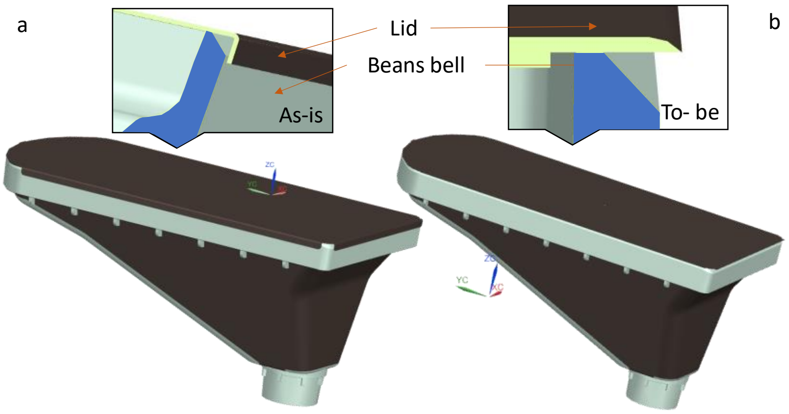

Figure 3. Lid design before (a) and after (b) editing, to employ composites material scraps.

Table 5 shows the environmental benefits in introducing the sink scraps as secondary raw material in the coffee grinder.

Table 5. Environmental benefite between as-is (linear) and To-be (circular) scenario

Impact indicator	As-is Volume [mm3]	As-is impact	To-be Volume [mm3]	Δ Volume	To-be impact	Δ impact	Δ Impacts M+M
CC	7,42E+04	1,85E+00	6,67E+04	-10,14%	9,17E-01	-9,82E-01	-51,15%
ODP		1,53E-07			9,14E-08	-6,12E-08	-59,90%
HT		1,78E+00			1,05E+00	-7,30E-01	-58,92%
WD		2,15E-02			8,33E-03	-1,31E-02	-38,78%
MD		1,77E+00			3,27E-01	-1,44E+00	-18,47%
FD		5,01E-01			2,73E-01	-2,28E-01	-54,44%

The changes in materials (from low alloyed steel) to plastic composites (Mineral + PMMA + Additives) and the re-design (-10% volume) lead to a reduction of more than -50% of overall impacts related to the production of the lid. To these, the avoided impacts of the disposal of the sink scrap must be added (Figure 4); as a result, emissions equal to 1,58 KgCO2eq are avoided per each lid of coffee grinder produced using composite scraps. On the overall group the lid is part of, a reduction of about 20% of impacts are counted. The production of the bell lid in the To-be form consists in working the sink scraps and manufacturing a simpler shape of the bell, which leads to a reduction of volume, compared to the As-is geometry. The use of scraps in the coffee grinder means that a lower volume of scraps must be disposed; the bottom green line in the picture highlights the differential environmental impacts.

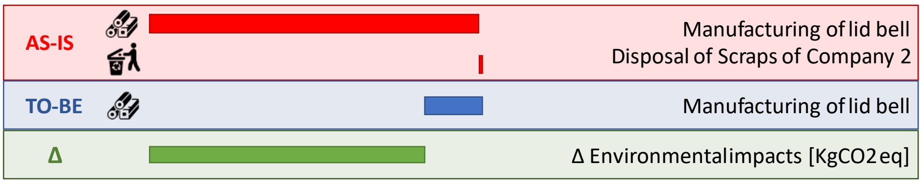

Figure 4. Differential environmental impacts between as-is and to-be scenarios [Kg CO2 eq]

4. Discussion and conclusion

CE requires organizations to look beyond their walls and join their forces with other enterprises, to establish a circular loop of information and material flow, where the quantity of waste thrown away every day is reduced, and the waste becomes secondary new material. This drastic change can only become real with the support of proper design of processes and products. De-manufacturing and re-manufacturing, tother with Design for X, are fundamental technical solutions for an efficient and systematic implementation of the CE and lower the distance between design and EoL phases.

The paper presented a method in the context of eco-design that guides in the choice of which and how scraps can be reused and gain new value, after being discarded. The core of the method is the redesign of components of certain goods so that their material can be substituted with scraps deriving from the value chain of other composite products. This enables the valorization of certain materials (such as composites materials) whose management at the EoL is, currently, extremely inefficient and unsustainable. It represents the first step toward industrial symbiosis, supporting the reuse of scraps as inputs for another company.

The implementation of the methodology identified the first potentialities of establishing relationships among companies acting in different sectors. In the first place, only components and scraps without special treatment were considered and studied to be employed as secondary raw materials. Mechanical, chemical, thermochemical decomposition, etc... (i.e., pyrolysis, shredding, de-polymerization, etc.) were neglected. Secondly, the establishment of flow exchange among companies is important to overcome certain technological obstacles; in fact, treating high performing materials may result extremely costly and energy consuming, and initial performances may not be fully restored (Khalid, 2022); in this case the OEM must either avoid to recycle the material or should look for alternative uses of the virgin waste material to gain value out of it.

This narrowed the potential type of reuse and required a comparison of dimensions, shapes and functionalities between the scraps and the target components. Consequently, any scrap from the first company was not selected. The case study results show great improvements from the environmental point of view; according to the CC indicator, the overall impacts due to the production and disposal of certain components decrease. This is mostly due to:

1. Avoided impacts related to the extraction of the raw material (the new material already exists, and any other resources must be extracted from the geosphere);
2. Avoided impacts related to the EoL treatment and disposal of the scraps; becoming secondary raw material, they do not undergo any EoL processing (i.e. shredding, landfilling, incineration, etc…).

Among the needs and potentialities for a circular system, the method outlined the following design strategies and logistic aspects that contribute to the correct achievement of circular loops:

- *Simply shapes;* the reuse of scraps and off-specification components requires the target components to be as simpler as possible; this is mainly due to the restricted number of feasible processes that can be applied to the waste materials and consequently to the obtained components. For example: plastic composite material can neither be welded nor extruded, otherwise they lose the appropriate conditions and characteristics. The design (or re-design) phase must keep in mind this point.
- *Modularity*; the reuse of scraps require often design modification on components. A modular structure for products minimizes the changes only on functionally related components, thus reducing the time and cost of modifications, while increasing the design flexibility.
- *Simplicity in disassembly;* the reuse of scraps is possible if they are easy to be disassembled and separated from the primary product.
- *Material identifier*; provide materials or an indication on their types, helps who is in charge of analyzing its reusability to understand compatibility, workability and applicability level.
- *Short distances;* the case study involved companies settled in the same district. Proximity is very useful to maintain a strong relationship and lower the environmental burden due to the transport phase.
- *Networking;* as previously stated, the openness of enterprises to establishing new partnerships, even and especially with those from different markets, paves the way to countless innovative solutions that prevent materials to be disposed after the first use, or before (in the case of process scraps).

Future works should more deeply investigate whether the environmental advantages deriving from the re-design of target components and employment of scraps and waste material as secondary raw resources are obtained also on the economic sphere, integrating the environmental and economic sphere.

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