The Application of Circular Economy Principles through Re-design, Scraps De-manufacturing, and value Chains merge

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Abstract. The literature presents wide gaps in investigating methods and approaches to support the establishment of Industrial Symbiosis. Moreover, the use of composite materials steeply increased in the last decades which are hardly disposable. The present work proposes an eco-design method that guides the reuse and remanufacturing of scraps. The core is the re-design of processes that introduce materials derived from scraps from other value chains. Two cases are investigated: the first concerns the production of panels for the wind sector. Using scraps from the wind blades' trimming almost eliminates the emissions derived from the panel production. Also, the material of a component of an espresso coffee machine has been replaced by scraps from kitchen sinks; this process requires resources only for shredding. The application of the method outlines important factors to consider while finding possible paths to apply Circular Economy principles through Industrial Symbiosis, such as the dismantler's involvement, the importance of sharing information and networking among the actors of the supply chains and the relative distance of cooperating organizations. Future works may focus on the economic evaluation and on strategies for the materials' acquisition.

Keywords: Circular Economy, Design for de-manufacturing, Composite materials, Industrial Symbiosis, Remanufacturing.

1 Introduction

Manufacturers should look beyond their gates and supply chains to make their products and scraps secondary material for different chains. This cannot forget methodologies and tools for de-manufacturing and remanufacturing, applied during design [1]: End of Life (EoL) must constantly induce suggestions and feedback towards previous lifecycle stages, and design in the first place [2]. Circular Economy (CE) is strictly bounded to the concept of industrial symbiosis (IS) to use resources more sustainably than the linear economy. CE requires a whole system to change. IS has a high potential to lower CO2 emissions [3]. The field of research in IS is immature and more research is necessary to demonstrate the economic, environmental, and social benefits and to get practical design insights related to IS [4]. The use of composite materials recently grew steeply [5]; it is extremely difficult to recycle them. A big challenge is the development of approaches and technologies to optimize the waste generated from manufacturing operations and EoL products [6]. It is therefore evident the need to further investigate the question related to the EoL composite treatment scenario and more evident the need for establishing design protocols that positively affect the EoL opportunity of these kind of materials. To obtain the highest environmental benefits and minimum negative impacts from reuse [7], scraps must become secondary input materials, reducing waste treatment costs and increasing the environmental benefits.

1.1 Design for de-manufacturing: the turning point in CE

Today's decisions significantly influence the sebsequent use and disposal of the product [8]. The literature claims ways to improve product designs in terms of circularity [9]. The present work fills the gap of minimal offers available for possible design solutions, especially regarding application-oriented solutions. Besides aiming to reduce the environmental impact, the re-design phase in the current approach seeks to promote a multiple life cycle approach [10]. Three key points of circularity are accomplished [11]: material recirculation, utilization and endurance. The focus of this paper is on circular strategies applied to composite materials. The present paper presents a method of analysis in the context of Eco-design, whose core is to transform scraps and off-specification products into primary materials for manufacturing different goods. Among the main innovations, the focus on composite materials. Secondarily, the establishment of symbiosis among enterprises that are active in different sectors and use several materials (this offers a way out to cannibalization and low demand for remanufactured products); moreover, they are close each other, but not adjoining. However, the method is suitable for non-composite materials too. Differently from the existing literature, the proposed approach aims to apply the scraps also with different functions they were initially conceived for (Section 2). The case study (Section 3) applies the proposed method and identifies a cluster of Italian companies producing different products that can collaborate by working scraps and using them as new raw materials. The environmental benefits for the companies involved are quantitatively evaluated. Results highlight the need for strong cooperation between companies to take advantage of the products' hidden value and are further discussed Section 4, before the conclusion.

2 Materials and method

The proposed approach, shown in **Fig. 1**, aims at supporting enterprises in identifying and evaluating circular strategies for IS with a structured process; it is structured in four main steps. First, the linear lifecycle is assessed, and so are the availability and type of scraps. This enables the second step, the process design, that considers materials, geometries, production processes. Differently from the existing literature, the present approach is particulary intended for composite materials; therefore, the re-design may be helpful to overcome the challenges projected by the scraps feature and the characteristics to be reached by the target component. Scraps properties and their machining, the feasibility of production processes, shape and feature examination, together with environmental analysis results, guide the identification of new applications (step 3). The (prototype) production allows the quantification of the resources employed and emissions produced through standardize methods, as LCA (Life cycle Assessment). **Fig. 1** shows the main steps suggested to have scraps from composite materials acquire new value and avoid unworthy EoL treatments.

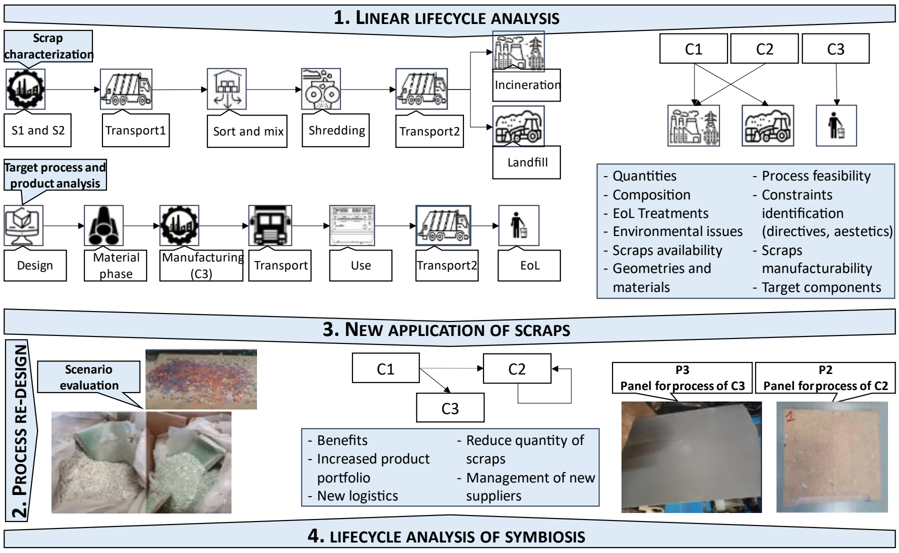

Fig. 1. Valorization of industrial composite materials waste. Light blue-filled boxes stand have general validity; no filled boxes show how the case study applied the approach. Scraps S1 and S2 are produced by Companies C1 and C2 respectively. The new processes involve C2 and C3 to produce P2 and P3 respectively. Network representation adapted from [12]

3 Results

3.1 Scraps characterization

Three companies applied the proposed method from the Marche region in the center of Italy. Two of them (Company 1 and 2 - C1 and C2) made their scraps available to be worked and employed as secondary raw materials in different production processes. C2 turned out to be also a host for circular products, together with C3, which produces professional espresso coffee machines. C1 produces sinks for domestic kitchens. C2 designs and produces wind blades. The scraps (S1 and S2 from C1 and C2's processes respectively) are off-quality products that cannot be commercialized because they do not satisfy the customer quality standards and requirements or process scrap as dust or pieces from Computerized Numerical Control - CNC – machining, trimming scraps, consumables containers. Moreover, their dimensions are often unstable and unpredictable due to process inaccuracy.The environmental burdens are calculated through LCA methodology and tool, deriving from the extraction, production, and disposal of the annual quantity of scraps produced by the companies (Life Cycle Inventory (LCI) for C1 and C2 summarized in **Table 1**).For each waste type, the annual scraps' weight percentages are indicated, together with the material and respective composition, (in brackets, when multiple materials are part of the same waste typology). Sink scraps are fully incinerated after being pre-treated in dismantling centers. In **Table 1** the current disposal scenario is reported, with details of the means of transportation used to move the scraps: the blades' scraps are shredded and compressed, partially incinerated with heat recovery; the remaining is sent to disposal. Similarly happens for the sink scraps that are fully incinerated. Waste is always pre-treated in at least two dismantling centers before incinerating or conferred to a landfill. Enterprises are unaware of what happens to their scraps (nor their product) once they are discarded: what C2 and C3 expect from their scraps is different from what happens. The information was retrieved by interviewing the supplier the companies have contact with. The sorting and mixing phase refers to sorting the scraps collected by the supplier and the mix with scraps of the exact nature that come from other industrial realities.

Table 1. LCI scraps and Environmental impacts distribution

SCRAPS/COMPONENTS			**Disposal**	**Transport**
Category	**%**	**Material**		
Company1				
Sink scraps	87%	Mineral + PMMA [a]+ Additives	Incineration	Road, truck
Sink dust	13%	Mineral + PMMA [a]+ Additives	Incineration	Road, truck
Company 2				
Glass fiber scraps	32%	Glass fiber	Landfill (33%) Incineration (66%)	Road, truck
Plastic waste	66%	PVC [b] + Polyamide + Synthetic rubber + Buthacrylate + PET [c] + Epoxy Resin (85%)	Landfill (75%)	Road, truck
		Epoxy adhesive + Glass fiber + Epoxy Resin (13%)	Incineration (25%)	
		Glass fiber + Epoxy Resin + Carob fiber (2%)		
Coating dust	2%	Epoxy Resin + Insulating	Landfill	Road, truck
0-10%	11-20%	21-30%	31-40%	41-50%
51-60%	61-70%	71-80%	81-90%	91-100%

[a] PMMA= Polymethyl methacrylate [b] PVC= Polyvinylchloride [c] PET= Polyethylene Terephthalate

The colors of the cells in **Table 1** quantify the percentage of environmental burden accounted for each lifecycle phase for the Global Warming Potential (GWP) indicator. The material and EoL phases were considered. The material phase is the most impacting (more than 85%, with a peak of 91% for C2), followed by the EoL phase. Wind blades and sink scraps disposal is responsible for about 10% and 15% respectively. Transportation and treatments prior to the final disposal are negligible. For C3 waste pre-treatment impact is lower than 1%. The analysis was carried out with the support of software the SimaPro 8.0, EcoInvent v3.6 database, and results were calculated by the Recipe MidPoint (H) method; and so was the linear lifecycle of the professional coffee machine assessment. The Functional Unit (FU) was the production, use and disposal of a professional espresso coffee machine, daily used in Italy for 5 years to produce on average of 36 coffees per hour. The use phase largely retains the impacts (more than 90% of the overall impacts). The Back Assembly is the second most impacting assembly.

3.2 Process re-design

Wind blades

The geometric features and the manufacturability constraints of the wind blade process scraps did not find any components of C1, C2 or C3. Therefore, alternative treatments have been investigated (**Table 2**). The scraps cannot undergo any chemical process, otherwise their properties change. However, mechanical treatments are allowed. The core material, the blade trim (that comes from the blade finishing process) and the blade root trim (what is left from the finishing of the base of the blade) were shredded so that they were used to obtain new panels as their dimension dropped. However, those are introduced in the wind blade production process with a new function: the panels are employed to make models or mold to be milled; subsequently, prototypes are obtained from them. The panels with secondary raw materials replace sheets of polyurethane polymer (i.e., Eulithe, Ureol) or MDF.

Table 2. Process re-design.

Part	As-is			To-be		
	Mat.	**Man.**	**EoL**	**Mat.**	**Man.**	**EoL**
P2	Eulithe, Ureol, MDF*	Mill	S2	S2	Shredding + cold cure + mill	S2
P3	Aluminum	Mill + coat	S1	S1	Shredding + cold cure + coat	S3

Fig. 2 compares the environmental burden caused by traditional and innovative processes. Please note that the panels milling to produce the molds is neglected, as it is a common phase for both. Regarding the new panels, both the resources employed in shredding and curing are considered.

Back cover

The back cover is a part that presents big dimensions, and its function is mostly aesthetic, as it consists of hiding (from the bartender and the coffee shop customer) and protecting (from dust and other undesired substances) internal components. S1 scraps, especially those of lower dimensions, deriving from the trim of the safety and drain holes and the sink profile, have been shredded and subsequently the back cover obtained from them, through cold cure. The main material composition and environmental impacts are compared in **Table 2** and **Fig. 2**, respectively. All the investigated situations account for a reduction of CO2 emissions and line up as promising measures aimed both at combating climate change and achieving a successful application of the CE principles: what is produced from an industrial process is employed as raw material for a different product, attesting a reduction of natural resources exploiting.

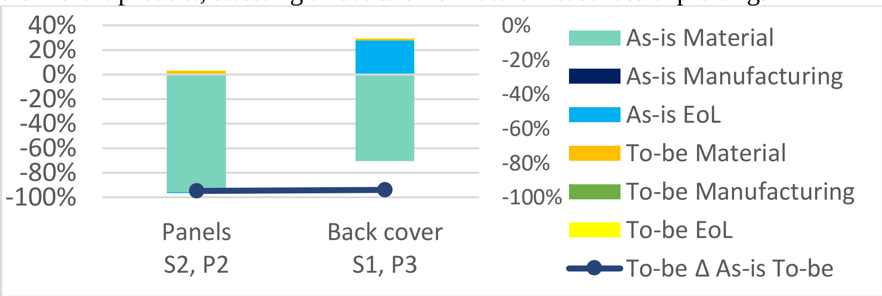

Fig. 2. Environmental impact comparison

4 Discussion

The present work proposed and applied an approach to join detached supply chains to give value to manufacturing scraps; therefore, the companies (C1 and C2) that produce the scraps unlikely phase cannibalization or low demand for remanufactured products, which is often a sore point that distresses enterprises and hampers circular initiatives, if not adequately exploited [13]. It lets enterprises overcome the main obstacles related to the lifecycle extension of composite materials. Furthermore, there are benefits from the environmental point of view in introducing sink scraps as secondary raw materials in the coffee machine. As there was not any waste type suitable for the dimensions of the back cover (part dimensions), and any re-design could not offset this lack, an alternative process has been investigated. In the current state, the prototype has reached high finishing quality. However, the back cover's final appearance differs from the original one. This may hamper customer satisfaction, which expects to coat. Therefore, the back cover made of secondary raw material would be an alternative material for the customer, copper, satin or matte steel options.

The panel almost nullifies its environmental impacts; as it is employed in the process, it is one step toward the net-zero emission aimed by organizations. The benefits are due to avoided impacts related to the: i) extraction of the raw material; ii) EoL treatment and disposal of the scraps; iii) EoL treatment and disposal of P2 and P3. The choice of the target processes is a combination of factors: part and material features, functionalities, design constraints and environmental impacts. Once the waste exits the production plant perimeter, organizations lose any trace of their products and scraps. Direct interviews with downstream suppliers made the picture clear. Data, knowledge and information exchange could bring significant benefits to enterprises. More outstanding communication with actors in charge of dismantling processes improved the detail of modelling the EoL phase, outlining the actors and the steps, and what is done. Future works will focus on the economic evaluation of the proposed de-manufacturing actions that have been explored from technical and environmental points of view. This would be the basis of the supply analysis. In fact, it may be hard to balance and optimize volumes and demand. While process waste might be slightly predictable (if intrinsic to the process), and thus known if the production volumes are known, the off-specification scrap availability is unpredictable and highly variable. Therefore, compensating strategies must be investigated.

S2 has a wide variety of scraps; some are available in a process and heterogeneous state and as virgin materials (i.e., fiberglass or PVC). The latter, rags of various dimensions (order between 1 E-2 to 7E-2 m), are discarded only because of their dimensions (they are too small for the whole blade) but may be reused in other processes since they are still virgin material. Alternative applications (i.e., processes that require smaller patches of fiberglass) can be further investigated.

5 Conclusion

The current approach is based on the milestone that designing for the CE involves giving new meaning to the EoL of products. The method presented in this work enables the valorization of composite materials, whose EoL management is currently highgly inefficient and unsustainable from the environmental perspective. Furthermore, the approach expects cooperation between multiple manufacturers active in different sectors so that they can work together to find sustainable solutions and improvements.

The approach is relatively simple, well-known, and established methods and tools (i.e., LCA). The potential applicability is vast: the growing boom recorded for many industrial markets and applications in the composites industry provide multiple applications; moreover, the approach can also be applied to homogeneous waste materials. The novelty of the proposed method is its purpose of finding innovative applications and employment of scraps to existing or new products instead of reintroducing them in the same loop they were first used. The implementation of the method 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. Chemical and thermochemical decomposition (i.e., pyrolysis, de-polymerization) were neglected, as they belong to the recycling action, which was aside from the focus of the study.

Two cases involved a re-design of production processes: the first concerns the production of panels for the wind sector (P2) (employed as consumables in the wind blades production process). The use of scraps from the wind blades' trimming (S2), after an intermediate step of shredding, almost eliminates the CO2 emission derived from the panel production. Also, the material of the back cover of an espresso coffee machine (P3) has been produced with shredded and cold-cured scraps of sinks (S1). Its production emissions are halved. The results show positive environmental effects. However, the application of the method outlines essential factors to consider while finding possible paths to establish successful IS: dismantler's involvement, information, networking, disassembly, simple shapes and short distances. Future works will focus on the economic evaluation of the proposed de-manufacturing actions and strategies supporting the materials' acquisition. The study might be extended to off-the-shelf components and investigate alternative applications for fiberglass patches and virgin material waste that are discarded only for their dimensions.

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