A technical and systematic characterization of circular strategy processes

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Abstract. To deal with environmental, economic and social problems linked to high consumption and intense manufacturing, Europe, ecological associations propose scenarios for the implementation of the circular economy, without saying how to implement them. Several circular strategies (CS) (reuse, remanufacturing, recycling...) enable to regenerate a product and its components throughout its life cycle. Currently, these CS are not implemented in a systemic way, but in a punctual and individual way. The objective is to deepen the knowledge of the global implementation of several CS. To achieve this, the paper proposes to characterise each CS according to the requirements of the entering and leaving products. This technical characterisation allows us to analyse their complementarities and interactions. This characterisation will be illustrated by the example of remanufacturing and resynthesis. Then, an analysis of our proposal is carried out to show the contributions in order to have a holistic approach of the regeneration.

Keywords: Circular Economy · Circular strategy · Products regeneration · Holistic approach · Requirement · characterization

1 Introduction

Today, governments are urging more and more companies to adopt a circular economy (CE) through laws, or decrees. Indeed, current issues such as linear consumption through mass customization, fashion effects and obsolescence [1] are not compatible with the objectives of sustainable development (SD). The literature shows that this consumption mode is a source of environmental problems such as the increase in waste, climate change [12] and the depletion of natural resources [15]. In addition, pandemics and wars show how dependent some states are on certain primary resources. [23].

The CE concept based on the pillars of SD is defined by [7]: "A CE is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models.". Through this definition, the consideration of a systemic vision with several regeneration cycles becomes essential to achieve the objectives of CE. The objective of our work over the last few years is to propose a holistic approach of product regeneration (i.e consider the interactions of different systems and stakeholders in a global view) . In Diez 2016, we defined the regeneration paradigm as [11]: “set of actions, natural or technical, to restore a waste or its constituents to an acceptable state (functional and operational) allowing to extend its life cycle”.

In the literature, many works deal with circular strategies (CS), eco-design but there are very few papers that integrate the multiple life cycles and the holistic approach. Thus, a CS standard characterization would help regeneration designers to define an adequate regeneration process for their products in a holistic approach. In order to achieve the SD objectives, a characterization considering environmental, economical and social aspects is necessary. For this first work, only the CS technical aspect is considered. Thus, this article proposes a technical and systematic characterization of CS with a formalization that allows to compare and analyze CS. The final objective is to give a better knowledge of CS to help industrial to adopt CE. This holistic vision will allow them to better apprehend the complexity of CE and the new CE laws implemented by states.

2 Circular strategies state of the art

In literature, the circular strategies (CS) enable to extend the product life and create loops for circular economy (CE) to recover value for a product, subassemblies/components or material that would otherwise be considered as waste [22]. A literature review enabled the identification of several CS: reuse, repurposing, upgrading, reconditioning, remanufacturing, resynthesis, recycling, energetic valorization and landfill. A systematic review was done for each CS. This complete work is not presented in this article, only few references are used by CS. Each selected reference is considered as the best to describe the CS in a holistic view. The objective of this section is to present the technical CS features identified in the literature. The following elements are analyzed:

- **input**: the expected level in the product breakdown structure, and the expected product quantity for carrying out a regeneration.
- **output**: the expected level in the product breakdown structure and its nature: does it have the same purpose and the same composition as the incoming product (i.e. is it identical /different to the incoming product (identical finality and composition) or is it improved (identical finality and different composition by additions/subtractions/modifications))
- **process**: the CS activities and the level of the product breakdown structure that is regenerated. This listed information of the processes will not be developed in the rest of the article but considered as the activities that enable to regenerate an input product.

The literature review shows that CS are developed in a silo view because researchers optimize the CS process activities rather than the life cycle of the

CS	Input	Output	Process	
			Activities	Regeneration level
Reuse [13], [21]		The same input product	diagnostic, cleaning and requalification	
Repurposing [20], [21]		The same input product with another finality		
Upgrading [4], [18], [19]	Product	The same input product but enhanced	diagnostic, cleaning, requalification, replacement, disassembly and Re-Assembly	Product
Reconditioning [14], [4]		The same input product with few different components		
Remanufacturing [2],[10],[15]	Several products sub-assemblies and components	A new product composed with different components	diagnostic, cleaning, requalification, replacement, disassembly, Re-Assembly and reworking	
Resynthesis [8], [9]	Several sub-assemblies and components from different product families	A new product but now for another finality and composed with different components from different product families		Sub-assemblies / Components
Recycling [5], [6], [16], [3]	Several products material	Recycled material	diagnostic, Sort and Separate	Material
Energetic Val. [17]		Energy	Combustion or Methanization	Wastes
Landfill [24]		Wastes	Stock	No

Table 1. CS technical features in the literature

product to be regenerated. Thus, their goal is to regenerate a product with a certain health state only once. Nowadays, CS need to be developed in a holistic vision integrating each other, explaining how to implement them, how to choose a regeneration trajectory between different possibilities and regenerate for several life cycles. In this way, the CE objectives will be achieved, i.e not lose value (recycle a product that could be reused) and preserve the product regeneration potential (regenerate by considering others CS), it's necessary to define a regeneration process in its entirety.

Tab. 1 shows some differences and similarities between CS. For example, several CS have common activities which could enable to pool activities and reduce the regeneration cost infrastructures. In addition, CS as reuse, repurposing, upgrading, and reconditioning expect the same input (a product) but have a different output: the same product regenerated for reuse, the same product with a different finality for repurposing etc. These features, which are sometimes close, show that the papers analyzed in literature are not sufficient to analyze CS and to choose the optimal regeneration for a product according to its health state. Indeed, how to choose a CS between these four CS, knowing that each one expects a product to be regenerated as input? What are the technical features that enable us to say whether a regenerated product is different in its finality and composition? A formalization is necessary to deepen the features identified in the literature, to determine which are the technical elements that allow to specify a regenerated product and especially to be able to position how much one CS is different from another by the formalization. A formalization based on the product requirements baseline is proposed. Indeed, it is according to the product's technical features, reflecting its health state, and the CS's capacity to regenerate a product, i.e if a product can access to a CS or not, to be regenerated.

3 CS characterization and comparison methodology

For regenerating an end-of-life product, a circular strategy (CS) will be chosen according to various economic, environmental, and social constraints, but mainly according to the product's health state. We must also consider the CS's capacity to regenerate the product in order to reach a desired state at the CS's output. So, the product's health state is used to categorize CS, it can be measured according to its initial product requirements.

A requirement is defined by the standard (ISO/IEC 26702:2007) as a "Statement that identifies a product or process operational, functional, or design feature or constraint, which is unambiguous, testable or measurable, and necessary for product or process acceptability". According to [25], a guide for systems engineering, there are several types of requirements: functional, performance...

It is interesting to choose the product requirements to characterize the CS because the requirements are built in the design phase and constitute a commune baseline for a product family. This baseline is then used in the manufacturing phase which uses this baseline to manufacture product instances. As it is illustrated in Fig. 1, when the products leave the factory, they are considered as new, and all their requirements are satisfied. During the use phase, the product's use will degrade the product's health state, and throughout time some requirements will no longer be satisfied, the product becomes a product to regenerate. Then, depending on the product requirements state, a CS is selected and a regenerated product is obtained. Throughout its life cycle, the product is defined by requirements sets that evolve.

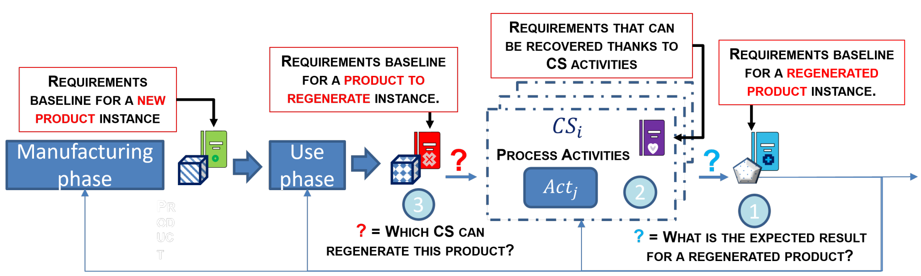

Fig. 1. Origin of the baseline requirements and the formalization method illustration.

The literature has shown that some CS can regenerate a product at multiple levels, and the requirement baselines are different according to the product life phase. Thus, the formalization of a requirement baseline $A^{l,k}$ must be defined according to the product breakdown structure level and the product life phase with:

- The l index to define the level of the product's breakdown structure. The l index can therefore take the value in the interval $[1; n]$, with n the level

number in the product's breakdown structure ($l=1$ the product level, for $l \in [2; n-2]$ the different sub-assemblies levels, $l=n-1$ the component level and $l=n$ the material level).
- The k index, to specify the product's life phase: if the product comes from: manufacturing phase N (New), use phase r (to regenerate) or regeneration phase R (regenerated).

Each requirements set can be decomposed according to the requirement type t: $A^{l,k} = \{A_t^{l,k}\}$ with $t=\{F(\text{Functional}), Q(\text{Performance})\}$. In this first work and to simplify, only the F and Q type are used. A requirement is defined as $Req_{j,t}^{l,k}$ with j the requirement ID. A requirement has a textual definition that can have parameters. To illustrate, a new product A leaving the factory has a requirements baseline composed of a F and a Q requirement subset: $A^{l,k} = \{A_F^{l,k}, A_Q^{l,k}\}$ with $A_F^{l,k} = \{Req_{1,F}^{1,N}$:"The system must provide a rotation"$\}$ and $A_Q^{l,k} = \{Req_{2,Q}^{1,N}$: "The nominal speed must be between 1000 and 1500 rpm"$\}$

The requirements sets of a new product ($A^{1,N}$) and regenerated product ($A^{1,R}$) product are compared according to their definition and parameters. For that, The 3 operators are defined:

- $\equiv$ indicates that the 2 requirements have the same definition and the same parameters. Ex: $Req_{1,F}^{1,N} \equiv Req_{1,F}^{1,R}$: "The system must provide a rotation"
- $=$ indicates that the 2 requirements have the same definition but with different parameters. Ex: $Req_{2,Q}^{1,N}$ = "The nominal speed must be between **1000** and **1500** rpm" compared with $Req_{2,Q}^{1,R}$ = "The nominal speed must be between **800** and **1200** rpm"
- $\neq$ indicates that the 2 requirements have different definitions. Ex: $Req_{1,F}^{1,N}$ = "The system must provide a **rotation**" compared with $Req_{1,F}^{1,R}$ = "The system must provide a **translation**"

To compare the requirements sets, augmented same operators are used with the same variables and the requirements number:

- $\equiv$ indicates that the 2 sets compared have the same requirements number, with the same definitions and parameters for each requirement.
- $=$ indicates that the 2 sets compared have the same requirements number, the same definitions but with different parameters for some requirements.
- $\neq$ indicates that the 2 sets compared have different requirements number, and/or with different definitions. In this case, the operator $\sqsubseteq$ is added to specify whether the set, although different, has the common basic requirements of the product family. For example, the set $A_F^{1,N}$ with $A_F^{1,N} = \{Req_{1,F}^{1,N}\}$ and $A_F^{1,R} = \{Req_{1,F}^{1,R}, Req_{2,F}^{1,R}, Req_{3,F}^{1,R}\}$ so, $A_F^{1,N} \neq A_F^{1,R}$ because the product number is different but $A_F^{1,N} \sqsubseteq A_F^{1,R}$ because $Req_{1,F}^{1,N}$ and $Req_{1,F}^{1,R}$ have the same definition.

To categorize CS, the following methodology uses the previous formalization:

- **Step 1**: The starting point of the analysis is to measure the gap between the regenerated product expected and the original product (new). So, the first step consists in comparing both requirements sets, respectively $A_t^{l,R}$ and $A_t^{l,N}$ for each requirement type t.
- **Step 2**: Consists in identifying the requirement type t that could be regenerated by the CS activities.
- **Step 3**: Consists in comparing the requirements sets of a product to regenerated $A_t^{l,r}$ to the regenerated product expected $A_t^{l,R}$ for each requirement type t.

To illustrate this methodology, remanufacturing and resynthesis processes are categorized:

Step 1: the requirements set of a remanufactured product $A^{1,R}$ and a resynthesized product $B^{1,R}$ are compared with an original product $A^{1,N}$.

- For remanufacturing, the F requirements are identical to the original product (new) ($A_F^{1,R} \equiv A_F^{1,N}$) and the Q requirements have different parameters (worse performance than the original product) ($A_Q^{1,R} = A_Q^{1,N}$).
- For resynthesis, the requirements number and definitions are different because the product finality has changed (For $t = \{F, Q\}$: $B_t^{1,R} \neq A_t^{1,N}$).

Step 2: Both CS regenerate components and sub-assemblies and are able to recover F and Q requirements because they have the same activities. The difference is that resynthesis regenerates sub-assemblies and components from several other different products.

Step 3: Both CS receive some components and sub-assemblies, which may have requirements not satisfied, but with the CS activities satisfaction will be recovered for F and Q requirements (For $t = \{F, Q\}$: $A_t^{l,r} \neq A_t^{l,R}$ and $A_t^{l,r} \neq B_t^{l,R}$).

The following section analyzes the CS categorization and positions the CS.

4 Discussion

The characterization made it possible to clarify the differences and complementarities between circular strategies (CS). Indeed, by comparing the sets of F and Q requirements of a CS output product, a more relevant positioning is proposed. In addition, the CS characterization confirms that all CS do not enable a complete regeneration of all the product levels in a sustainable way. The next subsection shows the positioning.

4.1 Gap between regenerated product compared to an original product

The CS characterization showed that no CS can achieve the equivalent of an original product but with inferior performance. So the more a regenerated product has different requirements from the original product, the more it is distant.

Therefore, the CS of this regenerated product is more distant from the manufacturing process of the original (new) product. In addition, the more a regenerated product is close to an original product, the higher its health state, and the more likely it would go through a regeneration cycle again. Thus, the shortest gap for a product between an original and regenerated product will be preferred when choosing a CS.

Reuse, reconditioning, remanufacturing and recycling allow to get closer to the original requirements with the difference that the Q requirements have parameters representing their performance intervals lower than the original ones ($A_Q^{l^R} = A_Q^{l^N}$). Thus, to decide which of these four CS used, it is necessary to look at the regeneration activities. It is more advantageous to reuse a product because it requires fewer activities and the product level (l) is the highest (1). However, to be reused, the incoming product must be at product level and all its functional requirements must be satisfied.

For upgrading, the objective is to improve the product by adding, deleting or improving the requirements. Thus, an updated product has different requirements set than the original one, but with the initial functional requirements common to the original product ($A_F^{1^N} \sqsubseteq A_F^{1^R}$).

Other CS such as repurposing and resynthesis completely change the product's finality, which further differentiates the requirements of these regenerated products from the original product ($B_F^{1^R} \neq A_F^{1^N}$). Finally, energy recovery and landfill are even further away, as the output is energy or waste.

Fig. 2 illustrates the above explanations by positioning CS according to the comparison gap between a regenerated product and an equivalent new product. In addition, CS are positioned according to what the CS activities can regenerate.

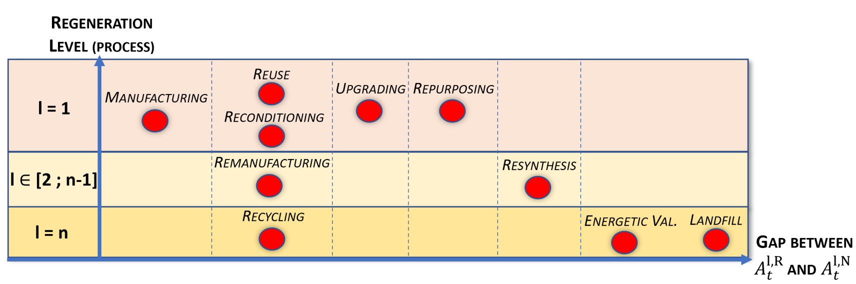

Fig. 2. CS positioning according to the comparison gap between a regenerated product with an equivalent new product and the regeneration level process.

4.2 An analysis of holistic approach

To implement a complete circular economy (CE) it is necessary to regenerate a product at all its levels. From a sustainable development point of view it is obvious that favoring short regeneration loops with few activities with the highest product level like reuse is more advantageous. On the contrary, recycling a product that still has functional and reusable sub-assemblies is a significant loss.

The analysis of all circular strategies (CS) input shows that it is possible that a product does not fulfill any condition to access a CS. For example, if there is a product with a requirement set that does not have the right requirements satisfied to access product-level CS, or sub-assembly-level CS then the product will be regenerated for its material whereas probably several sub-assemblies and components are still functional. A need for a holistic approach in the design phase becomes important in order to plan the different regeneration and avoid skipping regeneration levels.

Thanks to the CS characterization and the expected input requirements (image of the product health state to regenerate) it is possible to position CS by specifying supply chains for the product flow to be regenerated. For example, to avoid switching from reuse to recycling without skipping intermediate CS. Four groupings are proposed:

- **Product from use phase**: The product can be sent to reuse, upgrading and reconditioning.
- **Product, sub-assemblies and components from reconditioning**: The product can be sent to repurposing and sub-assemblies/components to remanufacturing or resynthesis.
- **Sub-assemblies and components from remanufacturing**: The sub-assemblies and components are either sent to other supplier regeneration cycles that can regenerate them or they are sent to recycling.
- **Material from recycling**: The material considered as waste is used as an energy source (energetic valorization) or landfilled if this is not possible.

Fig.3 illustrates these explanations by positioning CS in a holistic approach. To simplify the figure, external cycles of different products that supply some CS with elements to regenerate have not been added. In addition, fig.3 could be instantiated for each element disassembled. Indeed, sub-assemblies are potentially the finished product of a sub-supplier. By defining the access conditions of each CS in adequacy with the CS regeneration capacities and the expected result, it is possible to constrain the regeneration paths to avoid losing value and preserve the regeneration potential of a product throughout its life cycle.

5 Conclusion

According to the need to adopt a circular economy (CE) and the problems highlighted in literature, circular strategies (CS) are implemented in a punctual/individual way and the processes are mostly artisanal, this paper proposes

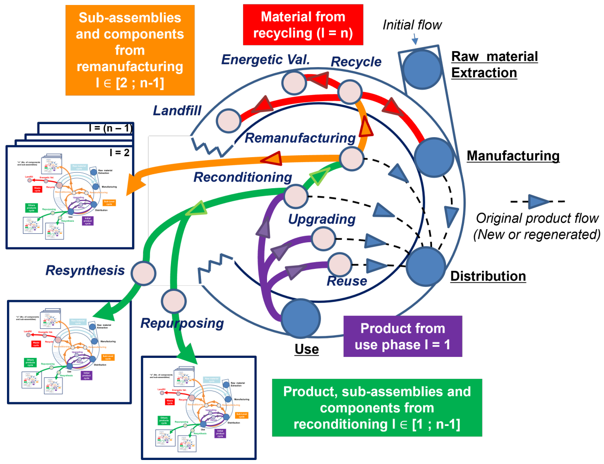

Fig. 3. CS positioning synthesis to avoid value loss and preserve the regeneration potential of a product throughout its life cycle.

to use a holistic vision to define the regeneration process which enables to support the CE. However, in this assumption, it would be necessary to analyze CS to study their differences and complementarities. So technical CS features from review are identified in section 2 and section 3 proposes a formalization to complete the CS characterisation to specify the CS more precisely, to be able in section 4, to position CS according to their technical features. Finally, a possible technical regeneration path is proposed to avoid losing value and preserving the regeneration potential of a product throughout its life cycle. So, this first characterization work raised several questions and perspectives:

This first technical and systematic characterization of CS is a beginning. Indeed, in order to get a CS holistic approach, complementary characterizations from an environmental, economic and social point of view should complete this work. By integrating these elements into the CS categorization it will be possible to choose the optimal CS for a product to be regenerated, with a multi-criteria decision-making system. This system will need to be fed with complementary data (product, market and CS features, ...) [26].

This paper promote the need of a holistic approach to define a regeneration process and implement multiple CS. We therefore propose in the design phase to develop, in addition to the product, a regeneration system that will support the product family throughout the product life cycle. Thus, a product, its manufacturing system and its regeneration system must be co-designed to consider their interactions. So, the CS characterization in Section 3 can be used to determine the outputs, activities, and input conditions of the CS to build the regeneration system. Through this co-engineering, it would therefore be possible to avoid skipping regeneration loops and implement a realistic CE.

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