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A Circular Economy Strategy Selection Approach: Component-based Strategy Assignment Using the Example of Electric Motors

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Abstract

The sustainability of industrial processes and products is a core issue of our time. There are several approaches to move from a linear, inherently wasteful economic principle to a circular economy focused on conserving products, resources, and energy. However, selecting which of the circular economy strategies ranging from reuse, repurpose, and remanufacture to recycling is crucial to ensure the economic viability of the product. This contribution proposes an iterative, component-based circular economy strategy selection method that supports product and production planners in choosing the appropriate circular economy strategy. For this approach, the suitability of each component for circular economy strategies is assessed based on identified key properties. In case of no fitting strategy, further component decomposition is devised, and the process is repeated. To further support the design of circular economy strategies, a modular process build set is suggested, enabling the swift composition of the processing sequence. The approach is then applied to the example of an electric motor of a battery electric vehicle. The presented approach allows a quick first assessment of the viability of different circular economy strategies and helps product and production engineers develop product-specific circular economy strategies.

Keywords

Circular Economy; Strategy Selection; Sustainable Production; Electromobility; Product-Process Co-Design;

1. Introduction

Due to rising environmental concerns, the issue of sustainability and the preservation of resources is increasingly seen as a fundamental challenge of industrial production. The classical, so-called linear economy model inherently consumes finite resources and creates non-usable waste. The circular economy (CE) approach conserves the value of products that are no longer in use by restoring their functionality, using them for different purposes, or transforming them into new products. The available circular economy strategies have been described extensively, most comprehensively by the 9R model [1]. Each strategy preserves different aspects of a product, so that the question of which strategy to choose arises. The consensus is to prefer the closest loop possible, thereby retaining as much value inherent in a product and performing the least work [2]. However, deciding what exactly denotes what is possible is difficult, especially since many factors have to be considered, including economic feasibility. This issue is especially prominent when creating the structures to enable a circular economy for an existing or new product. In this case, several different options have to be weighed to find the best solution. This problem is complicated by the complexity of many modern products, especially if individual components are best suited for different CE strategies. While it is technically possible to calculate business cases for each combination of CE strategies, this quickly becomes prohibitively laborious. This paper thus proposes a methodology to determine fitting CE strategies based on an assessment of the properties of the examined product. It further offers an approach to define the necessary industrial processes to facilitate the chosen CE strategies. This overall approach is applied in an exemplary case of an electric car drive, showcasing its potential.

This paper is structured as follows: first, section 2 examines the fundamentals of circular economy and summarizes the current state of research regarding the issue described above. Next, section 3 introduces the methodology for selecting fitting CE strategies and creating matching processes. This approach is then applied exemplarily on an electric drive. Subsequently, section 5 discusses the potential applications and limitations of this approach. Finally, section 6 offers a summary and outlook.

2. Fundamentals of Circular Economy

The extraction and processing of natural raw materials are the cornerstones of today's industrial production. The decreasing cost and increasing efficiency in their extraction and processing have been a basis for the growth of the world economy and the improvement in global living standards for years [3]. Thus, today's manufacturing industry mainly relies on a linear economy model characterized by a "take-make-use-dispose" mindset [2]. To preserve the biodiversity and habitable characteristics of the planet, there are good industrial and societal reasons to increase the use of secondary resources in manufacturing, i.e., through the recovery of materials and resources from end-of-life products [3]. According to a study from the *Circular Economy Initiative Germany*, a complete transition to a circular economy can reduce consumption of natural resources by 50 % until 2050 compared to 2018 [4]. A circular economy is thereby defined as an industrial system, which is restorative and regenerative by design [2], and by means of which products, components, and materials are kept at their highest utility and value along the entire life cycle [5]. In literature, many frameworks already capture the circular economy, of which the 9R model is the most comprehensive [1]. These 9R describe different CE strategies, which include: (1) *refuse*, i.e., preventing the use of raw materials in the first place, through (2) *reduce* and (3) *reuse*, product recovery options like (4) *repair*, (5) *refurbish* and (6) *remanufacture*, to (7) *repurpose*, and lastly (8) *recycle* and (9) *energy recovery* [1]. With every increasing step of the 9R model, the level of circularity, i.e., the volume of raw material extraction and negative environmental impact decrease. A high level of circularity improves economic, social, and ecological value creation. However, feasibility and different characteristics, e.g., product composition, market and competitor situation, or legal and governmental restrictions, need to be considered [2,1].

This paper is based on the 9R model. However, some alterations are made to accommodate the application in the design of circular value streams. Thus, the options refuse and reduce focussed on product design and resource procurement are foregone. The options repair, refurbish and remanufacture are considered jointly under the term remanufacture, as they are mostly distinguished by the degree of alteration necessary to restore functionality. Energy recovery is considered a non-desirable outcome of the strategy selection but may be necessary in some instances. Accordingly, the CE-strategies considered here are: *reuse*, the use of a functional product in a similar application without significant alterations, *repurpose*, the use of a largely functional product in a different application, *remanufacture*, the restoration of a non-functional product while preserving existing functionality, and *recycle*, the destructive utilization of materials in a product for new products. [6]

While a CE strategy describes the general idea and recovered aspects of a product, the particular CE process sequence still needs to be developed afterward. Unfortunately, there are no universally applicable process chains for CE strategies. On the contrary, many remanufacturing processes, for example, are designed differently and depend on the material, product layout, and different product or market-related criteria [7].

Typical processes for remanufacturing are described by [8], while [9] describe recycling processes. However, while these process chains are different, they still consist of common elementary processes. According to [10], those are the collection and sorting of the waste, the inspection of the individual parts, and finally, the disassembly.

3. CE Strategy Evaluation, Selection, and Process Development

As described above, selecting an appropriate CE strategy for a given product is crucial for achieving sustainability and economic viability. Thus, other methods for strategy evaluation and selection are necessary. There are several comprehensive but complex methods to determine suitable CE strategies. [11] propose a comprehensive multi-criteria decision tool to select suitable CE strategies. [12] assign CE strategies to product instances using Bayesian updating and fuzzy set theory at their EOL. [13] use an analytical hierarchy process and case-based reasoning to determine CE strategies based on similarity and consider both a product and a component level. Several other approaches exist, that examine the feasibility of remanufacturing products [14,15]. [16] present a tool for evaluation of product recycling using the concept of information entropy. Other approaches implement the preference for smaller circles by using a cascade model that prioritizes closer cycles wherever possible [17]. In terms of process development, most contributions are focused on describing relevant processes. [5] highlight the most important system level problems, methods and tools for re- and demanufacturing within the CE context. [18] discuss typical remanufacturing process steps in detail and provide a process sequencing model for cost minimization. [19] determine an optimal remanufacturing process sequences depending on product conditions. While several approaches exist in literature, most are focused on the most comprehensive evaluation. Furthermore, most approaches only consider the selection on the product level, instead of considering different options for each component. Finally, typically, the selection of strategies and their detailing is not considered jointly.

4. Methodology for CE Strategy Selection and Process Development

The selection and development of suitable CE strategies and processes require a comprehensive assessment of the examined product and its components. Furthermore, different options for the CE processes should be considered and assessed before a fitting solution is finalized. Thus, this paper proposes a three-stage approach, based on the selection of relevant CE strategies from the 9R model described in section 2. The approach is shown in Figure 1. The overall process presented here was developed considering the following principles: 1) Use as little information as possible in every step to limit the necessary effort, 2) Generalize concepts where possible to aid applicability in different contexts, and 3) Detail as late as possible.

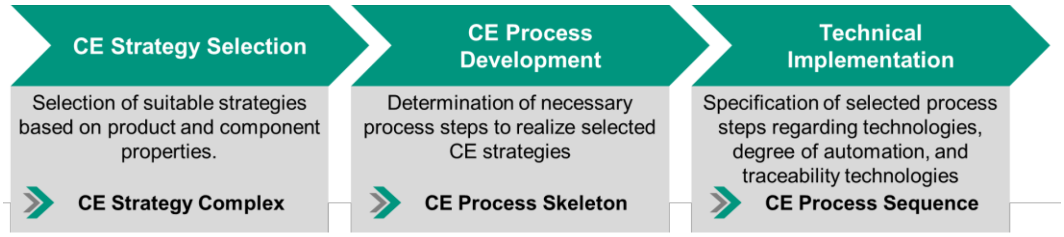

Figure 1: Proposed Three-Stage Process for CE Strategy Selection, Process Development, and Implementation

In the first stage, the fundamental properties of the examined product and its components are assessed. Then, based on this assessment, the suitability of CE strategies for the components is evaluated and a fitting CE strategy complex comprising CE strategies for all components is established. Subsequently, the selected strategies are detailed using a building set of CE processes in stage two. Finally, process variants and automation potentials are considered in stage three, and necessary information exchange technologies are laid out. After this process, a comprehensive concept for designing a circular value chain for a specific product exists. The required steps are specified in the subsequent sections.

4.1 CE Strategy Selection

The first step of the process is the selection of fitting CE strategies for products and components. To assess whether a CE strategy is suitable for a product or component, first, the relevant characteristics of each CE strategy have to be considered. These can then be matched with product characteristics to obtain a suitability score for each product-strategy combination. For the assessment products and components are considered in their average end-of-life (EOL) state. To determine the criteria that describe the suitability of a strategy, first, a qualitative literature study of CE strategy characteristics was performed. With these first results, expert interviews were conducted to weigh the relevance of different criteria using pairwise analysis. The experts were selected from both academia and industry and covered product, production, and circular economy knowledge. Table 1 shows the selected criteria and their respective weights for each CE strategy. In addition to four considered CE strategies, the disassembly of the product or component is also evaluated as an option.

Table 1: CE Strategy Selection Criteria and Respective Weights for each CE Strategy based on Pairwise Comparison

Criteria	**Description**	**Reuse**	**Repur-pose**	**Remanu-facture**	**Recycle**	**Dis-assembly**
EOL Condition	Overall condition of the component at EOL (wear, damage, defects)	0.45	0.38	0.32		0.15
Technical Relevance	Component still usable in its design form, corresponds to the state of the art	0.30		0.14		0.15
Volume	Demand, quantity of products	0.08		0.09	0.08	
Residual Value	Age, material value of the unit	0.08	0.08	0.09		
Applicability	Usability in other applications		0.38			
Conversion Effort	Cost and effort for use in other applications		0.08			
Remanufacturing Effort	Cost and effort for reconditioning the parts to new condition			0.27		
Raw Material Value	Value of the included materials/raw materials				0.45	
Disassembly Effort	Cost and effort of recovering the raw materials/materials				0.23	0.15
Recycling Rate	Recyclable portion / total part				0.15	
Modularity	Possibility of disassembly into functional subunits					0.45
Cycle Preference	Preference for CE strategy	4	3	2	0	1

To perform the selection process each of the criteria need to be evaluated for an examined product, for example using a 0 to 4 scale. Then the overall score $v_{p,s}$ for each product p and strategy s is expressed as

$$v_{p,s} = \sum_{i \in C} c_{p,i} w_{s,i} + 0.1 cp_s \tag{1}$$

Where $c_{p,i}$ is the product specific criteria score, $w_{s,i}$ the strategy specific criteria weight and cp_s is the cycle preference of the strategy. The cycle preference is added to create a preference for smaller cycles as described by [2]. Subsequently, the highest-scoring strategy is selected. If disassembly is selected, the most natural decomposition of the product into components has to be determined. For each of those components, the process is then repeated. If multiple best scoring strategies are within a close range, each option should be considered in more detail. The result of the evaluation model is summarized in a strategy complex, as shown in Figure 2. The model provides a general estimate of the practical utility of all considered CE strategies. The process complex resulting from the evaluation model indicates which CE strategies are targeted for the respective component and its sub-components.

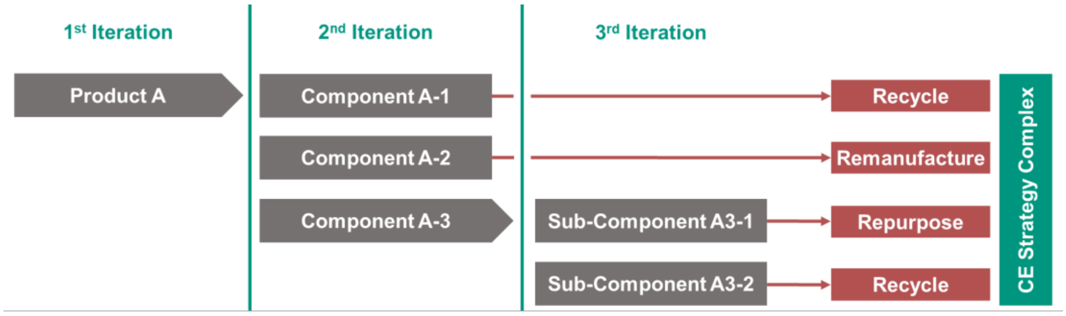

Figure 2: Iterative Selection of Strategies and Resulting Strategy Complex

4.2 CE Process Development

After establishing a CE strategy complex for a given product, a process sequence is developed. As noted in section 2, CE strategies consist of several processes depending on the examined product. It is noticeable that the CE strategies share similar processes and differ mainly in the arrangement, number, or combination of those. Thus, this contribution proposes a modular process build set, containing multiple elementary processes, that enables the swift composition of process sequences. As indicated in section 2, different CE strategies share several elementary processes which can be utilized in the process build set. The considered elementary processes and their relevance for the different CE strategies are shown in Figure 3. The elementary processes are *collection*, *disassembly*, *sorting*, and *inspection*, as proposed by [10]. Additionally, *cleaning*, *repairing*, *material separation*, and *assembly* are included. These elementary processes where identified through a qualitative commonality analysis in CE process descriptions in scientific literature. Even though some other processes exist, the presented elementary processes represent the core of the typical CE strategies. The CE strategy recovery is included in the build set, as it may be necessary for some defective product instances.

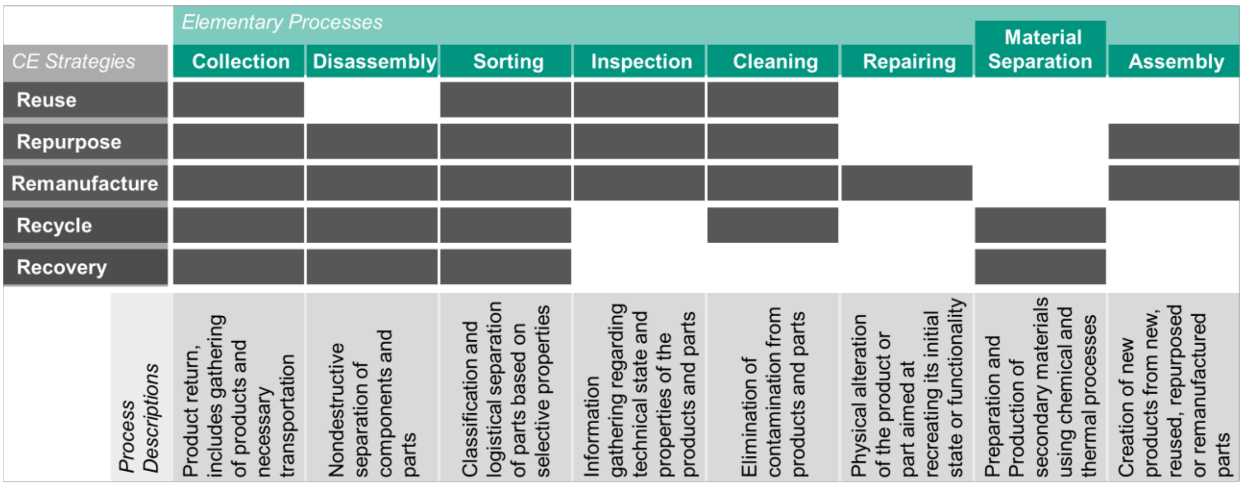

Figure 3: Elementary Processes and their Application in Different CE Strategies

A process skeleton is devised using the strategy complex developed in 4.1 and the relevant elementary processes for each strategy. The resulting process sequence is modelled using the event-driven process chain (EPC). As the previously selected CE strategies only specify the process for an assumed general product instance, an inspection, sorting, and deviation handling needs to be implemented before every CE process.

The deviation handling allows for the recovery of specific product instances not corresponding with CE strategy requirements.

4.3 Technological Implementation

Next, the elementary processes need to be specified for use with the particular product or component for the technological implementation. For each elementary process, criteria to help define the suitable process implementation variant were identified. The implementation variants were determined by analysing CE process descriptions and identifying commonly described variants. Based on the recognised variants, influencing criteria on the selection of process variants were determined. Depending on those criteria, a suitable process variant can be selected. As this criteria and variants are significantly more complex compared to the decisions made in 4.1, no deterministic selection scheme is proposed. Instead, the specific criteria serve as the basis for a more comprehensive decision process regarding the variants, utilizing expert knowledge. The relevant criteria for each elementary process and important process variants are shown in Figure 4.

Elementary Process	Selection Criteria	Important Implementation Variants			
Collection	Customer Type, Lifespan, Residual Value, Business Model	Active Collection	Passive Collection		
Disassembly	Connection Types, Variability, Processing Volume	Fastener-based	Specific	Tool free	
Sorting	Variability, Identification Factors, Processing Volume	Material-based	Variant-based	Condition-based	
Inspection	Failure Modes, Product Condition, Variability	Visual	Functional	Model-based	
Cleaning	Product Materials, Contamination Type	Mechanical	Chemical		
Repairing	Failure Modes, Product Materials	Generative	Replacement		
Material Separation	Product Materials, Size, Connection Types	Thermal	Mechanical	Chemical	Density-based
Assembly	Connection Types, Variability, Processing Volume	Fastener-based	Specific	Tool free	

Figure 4: Elementary Processes, Relevant Selection Criteria, and Important Implementation Variants,

Furthermore, each process can be automated to varying degrees, similar to different degrees of automation in linear production. To determine the fitting degree of automation, the variability or the condition of the processed products and components also need to be considered. Historically, the processes of disassembly, inspection, and repair have been challenging to automate, as they are highly dependent on product condition. However, more recently, traceability technologies have emerged that aid product and component identification and facilitate automating inspection by using condition monitoring [20]. To enable this automation in CE processes, implementing a specific traceability system may be beneficial [21]. Also, significant improvements have been made in terms of adaptive robot-based disassembly and repair systems.

With the conclusion of the technological implementation, the first draft of CE processes for an existing or currently developed product is derived. An example of such a process draft is shown in Figure 6. This draft may be used to gauge the viability of CE strategies for a particular product and can serve as a basis for more detailed planning of the overall CE strategy and the necessary processes.

5. Validation

Battery electric vehicles (BEV) have seen rapid growth in the last decade. BEV’s are intended to replace cars with internal combustion engines, reducing personal mobility's environmental impact. As batteries and many electric drives rely on specific, naturally limited resources, designing fitting CE strategies is vital for sustainability. For this paper, the CE strategies for a permanent magnet synchronous motor (PMSM) are selected and detailed. In this case, it is assumed that the majority of the PMSM is still functional at the EOL of the vehicle. The design of PMSM for automotive appliances follows a typical structure consisting of a *casing*, an *external stator*, and an *internal rotor*. The casing is typically manufactured as one-piece casting and is sealed by an endplate. The stator contains copper coil windings with different configurations depending on the winding method. The rotor consists of a solid rotor shaft on which the stacked plates are joined and which is mounted in the housing with bearings. The permanent magnets are attached to the stacked plates by pressing or gluing. [22]

The three-step model introduced in section 3 is applied to the PMSM and its components and sub-components. The scoring of the evaluation criteria is established, and the result of each iteration is summarized. The scoring of the individual evaluation criteria was based on information from expert interviews. In the *1st Iteration,* the full EOL PMSM was examined. PMSM in their EOL state are still functional. However, various minor damages can occur to the motor. Due to the contained valuable raw materials such as copper, the raw material value and the recycling rate of the motor are high. Moreover, the overall residual value is high due to the overall good condition and the extensive value-adding processes in the manufacturing process. Although further development of electric drives is expected, technical relevance compared to then low-budget PMSM is conceivable. Due to the design, dismantling to the next smaller sub-components is relatively easy. The result of the first iteration was thus further disassembly. For the *2nd Iteration*, the sub-components casing, stator, and rotor are considered. The casing is made up of predominantly homogeneous materials. Here the residual value of the materials and the good EOL state are dominant. At the end of the evaluation, the casing is eligible for remanufacturing or recycling. The rotor has high residual and material value due to the contained copper, which is easily recyclable. Thus, recycling is selected. The rotor of a PMSM consists of a solid steel rotor shaft that carries the laminated cores with the permanent magnets. The condition and residual value of the rotor can be rated as good. At the same time, the material value of the installed components varies greatly. However, the sub-components can easily be further dismantled. Therefore, the result of the evaluation initiates another iteration. The *3rd Iteration* is conducted for the sub-components of the rotor. These are identified as permanent magnets and rotor shafts with laminated cores. The overall result of the strategy selection is shown in Figure 5.

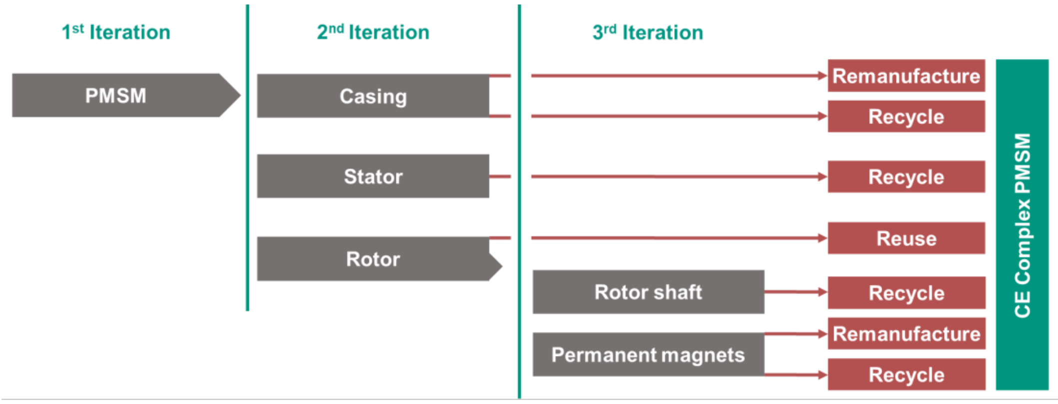

Figure 5: Resulting Strategy Complex for PMSM

The next step was the definition of a more detailed process chain. For this purpose, first the disassembly, inspection, and sorting sequence was connected with each of the strategies. Then each strategy was detailed using the process build set introduced in 4.2. In case the previous step selected multiple potential strategies, the strategy with the highest circle preference was used in the process development. Figure 6 shows the resulting process chain.

To arrive at a detailed process draft, each process step depicted in Figure 6 was further detailed using the methodology discussed in section 4.3. This included the selection of process variants based on product properties. Furthermore, fitting automation levels were selected. To enable a cost-efficient circular economy, a high level of automation is desirable. To facilitate a high degree of automation, a traceability system was planned that allows automated inspection and sorting by offering information on the likely condition of rotor and casing based on usage sensors and identification of product variants. The resulting process chain can be used to plan a circular production system for PMSM. It shows how a first draft of this system can be created with relatively little effort. This draft helps to evaluate whether existing process chains should be reconsidered and guides more detailed considerations of the different available options.

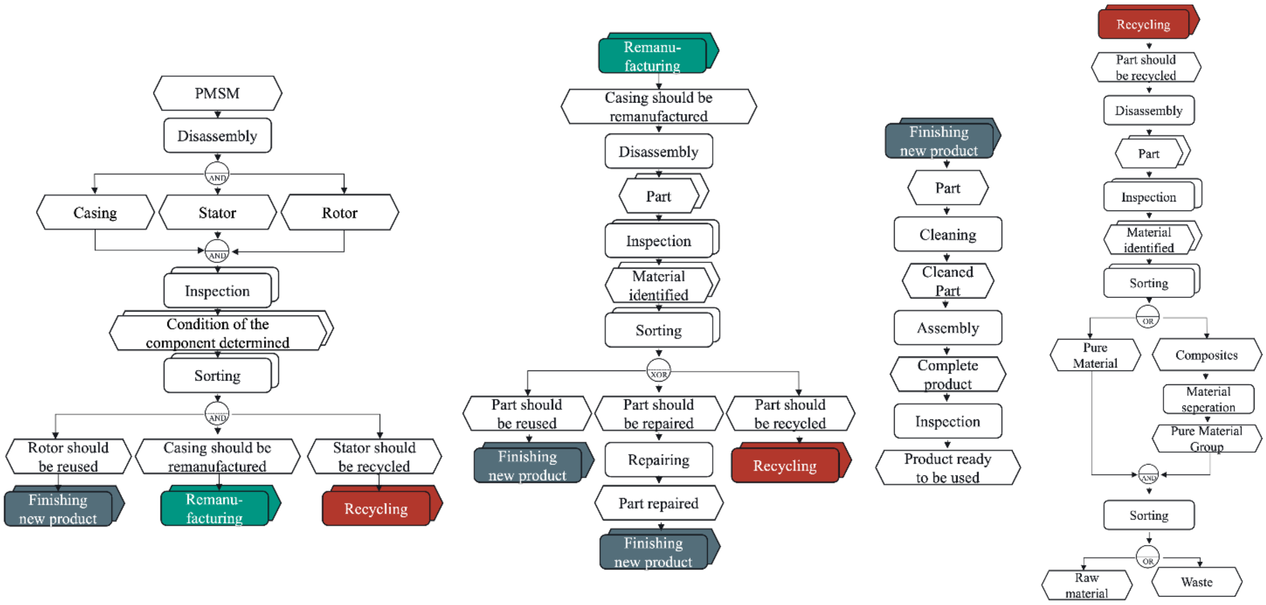

Figure 6: Determined Process Chain for PMSM, Colours Indicate Different Strains of the Process Chain

6. Discussion

Although the approach presented in this paper aims at a comprehensive decision support method for circular economy strategy selection, its utilization and advantageousness are subject to some restrictions. First, the application is most suitable for the system design phase of a circular economy. It assumes many degrees of freedom, i.e., regarding the product design, market and competitor situation, or design of business models and closed-loop supply chains. Moreover, a sufficient return of EOL products in terms of volume and quality is assumed to be profitable. Second, the proposed model only partially considers the organization's specifics regarding its overall business model, capabilities, and influencing factors. Thus, the model may be used to develop an initial CE strategy and process complex that can be refined using more detailed planning procedures. Lastly, the approach relies on subjective assessments of the decision-makers. Although the subjectivity can be reduced, e.g., through comparative analysis and inclusion of multiple perspectives, there remains at least some level of subjectivity, leading to different outcomes for different decision makers.

7. Summary and Outlook

This contribution proposed a methodology for selecting and configuring CE strategies in an early design stage. The methodology combines a comprehensive consideration of product properties with high practicality and may thus limit the effort necessary to derive sensible CE strategies. As many organizations today face the challenge of quickly adapting to a CE paradigm, the proposed method could help focus and guideline the transformation.

In the future, the methodology could be expanded by including a more quantitative analysis regarding the economic and ecological viability of the different options. Additionally, the effect of other criteria on strategy suitability, estimated based on expert interviews here, could be examined empirically. Further research on cross-company traceability technologies is necessary as they have shown significant potential in enabling the automation of CE processes. Finally, a further investigation of product design for CE strategies is essential to enable more effective and efficient CE processes while retaining product performance.

Acknowledgments

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