Comprehensive Assessment of Remanufacturing Suitability and Enhancement

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Abstract. For many companies, entering the field of circular value creation is a major challenge. They have difficulty in effectively assessing and quantifying the suitability and profitability of their products for remanufacturing and related strategies, which hinders their ability to make strategic decisions and implement necessary improvements. This work therefore proposes a comprehensive set of evaluation criteria to effectively quantify the suitability and profitability of products for remanufacturing and related circular economy strategies and to compare these within the product portfolio. These criteria focus on assessing the remanufacturability of various mechatronic products and evaluating their economic, ecological, and social sustainability. For easy and efficient assessment, a tool has been built that evaluates all criteria and product characteristics and provides recommendations for product improvement. With a remanufacturing score, the application makes it easy to analyse many products and compare their suitability. Additional options, such as the upgradeability of remanufactured products and the integration of remanufactured components into new production, can be used to investigate ways of increasing profitability. This research shows differences in sustainability and remanufacturability across different companies and product-specific potentials for improvement. The application provides companies with a simple assessment of their product's remanufacturing suitability and specific suggestions for improving efficiency.

Keywords: Sustainability Assessment · Circular Production · Remanufacturing · Product Upgrade

1 Introduction

The linear economic model's exclusive focus on efficiency is insufficient to address the finite nature of resources and conflicts with the goals of resource conservation and environmental protection. This highlights the urgent need for a transition to a circular economy [1]. Therefore, the importance of the R-strategies, particularly remanufacturing, to use resources more efficiently, extend the service life of products and minimize waste, is increasing. However, companies currently face challenges in objectively evaluating the suitability of their products for remanufacturing and in quantifying the economic,

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environmental and social benefits. This paper presents a systematic methodology for assessing the remanufacturability of products, with an Excel tool serving as a central component.

2 State of the Art

The objective of a circular economy is to maximise value retention, if possible, first at the product level, then at the component level and finally at the material level [2]. The R-strategies represent the value-preserving processes that aim to maximise product, component and material value retention [3]. This paper generally focuses on the reprocessing of products as presented by Lickert et al. [4]. In detail, the R-strategies remanufacturing, remanufacturing upgrade, reintegration, and refurbishment are examined and enable value retention at the component level.

Remanufacturing refers to the reprocessing of used products or components. During the remanufacturing process, the products are completely dismantled, all components are inspected, worn components are replaced, and, if necessary, modernised. [5, 6] Remanufacturing promises the highest value retention at the component level and a quality level equivalent to a new product [3].

Remanufacturing upgrade combines the remanufacturing of a product with an upgrade process, thus improving product performance as part of the remanufacturing process [7]. In addition to the remanufacturing process, outdated components of the used product are brought up to date by incorporating technological advances and adapting the product to new customer needs [8].

As part of this paper, the R-strategy reintegration is introduced as a further value retention strategy of the circular economy. Reintegration contains the reuse of remanufactured components or assemblies within new production. The component or assembly undergoes a regular remanufacturing process and is afterwards integrated into new production of the subsequent product generation, a product within the same product family or a completely different product. The component or assembly can also be upgraded before reintegrating into new production. This approach can also be found in the work of other researchers. Hegedűs & Longauer [9] describe how, as part of product generation planning, both remanufactured and new components can be used within new production of a subsequent product generation and, according to this concept, the remanufactured components become the raw materials within new production. Following this, Sawyer-Beaulieu and Tam [10] recognise using "factory-approved" remanufactured components and new parts to produce new vehicles. Furthermore, IEC 62309 (DIN EN 62309 (VDE 0050) since 2005) [11], provides a concept to check the reliability, functionality and usage of "qualified-as-good-as-new" ("quagan") components within new products of the electronic, electro-mechanical and mechanical industry. According to DIN EN 62309 (VDE 0050) [11], a "new product" may contain one or more "qualified-as-good-as-new" components. The term "reintegration" for the R-strategy explained above has evolved from Kalverkamp et al. [12], who describe reusing used, but remanufactured components within new production. However, the term is not defined in more detail [12].

The R-strategy refurbishing differs from remanufacturing in terms of the achievable quality standard of the product after the process has been carried out. The quality standard for refurbished products is less stringent than for new products. [6].

Existing methods for determining the remanufacturing suitability of products are mainly used in product development. These are intended to identify necessary improvements that can still be implemented in the design process. The evaluation of methods within product development is usually qualitative, for example, using a three level scale (green, yellow, red), and no overall remanufacturing score is automatically displayed [13]. Existing remanufacturing scores based on quantitative key figures of the remanufacturing process steps [14, 15] are very mathematical and theoretical and neglect ecological, social and legal issues as well as market criteria, which are also important for calculating the remanufacturing suitability of a product. A related approach to analyse the suitability for a specific R-strategy based on decision trees is presented by Dvorak et al. [16]. A detailed analysis of methods, assessing the economic profitability of remanufacturing, it is referred to Vogt Duberg et al. [17]. Our approach differs from past assessment methodologies in terms of its comprehensive qualitative and quantitative assessment and its user-friendly application. An integrated financial calculation provides an initial evaluation of the economic viability of remanufacturing.

3 Research Scope

This paper aims to develop a holistic method for identifying and prioritizing products suitable for remanufacturing, including qualitative and quantitative criteria. The evaluation includes technical, economic, ecological, legal and social aspects of remanufacturing. Furthermore, the examination of remanufacturing is extended by evaluating the suitability for remanufacturing upgrade, reintegration and refurbishment. Comprehensive, precisely formulated product criteria enable a well-founded and reliable evaluation of the product suitability for the respective R-strategy. A separate financial calculation is provided within the tool to check the economic viability of the examined R-strategies. The method enables companies to assess existing products in their product portfolios with regard to their remanufacturing suitability. The automated output of the total scores for the various R-strategies contributes significantly to the tool's user-friendliness and understandability.

RQ1: Which technical, economic, ecological, legal and social requirements should a product fulfil to determine its suitability for remanufacturing, and how can companies evaluate these in an effective, quick and efficient way?

Existing methods do not provide specific instructions to increase the calculated remanufacturing score of a product. This deficit will be eliminated in the newly developed method by integrating a toolbox with recommendations for action. These suggestions are intended to enhance the generated remanufacturing score to improve economic and ecological sustainability in the long term.

RQ2: Based on the assessment, which specific guidance can be proposed to improve the remanufacturing suitability of a product?

4 Remanufacturing Assessment

A structured procedure is developed to evaluate the product concerning remanufacturing, as outlined in Fig. 1. Initially, scores for the analysed R-strategies are calculated based on the input data entered by the user. Technical, economic, ecological, legal and social

criteria calculate a comprehensive remanufacturing or refurbishment score. If the user also evaluates the remanufacturing upgrade and reintegration criteria, additional scores for the remanufacturing upgrade and reintegration can be issued. The developed toolbox includes specific control variables based on product properties to improve the beforehand calculated remanufacturing score.

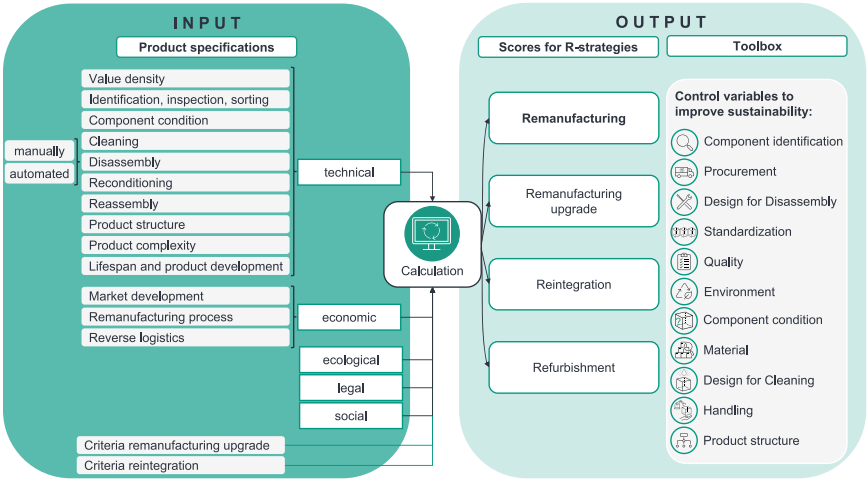

Fig. 1. Structure for the assessment of remanufacturing suitability

4.1 Methodology

Comprehensive evaluation criteria covering the entire process are essential to accurately assess a product's suitability for remanufacturing. A literature review was carried out to identify relevant references. Most of the criteria are based on the following contributions: Herrmann & Vetter [18], James et al. [19], Shabazi et al. [20] and Steinhilper & Hudelmaier [21]. In addition, further key criteria are added with the help of experts. The criteria are split into categories, as pictured in Fig. 1. These categories target the different steps of the remanufacturing process. Some of the criteria are exclusion criteria [22]. If those are not fulfilled, this product's respective strategy is impossible. The tool uses basic functions to assess product suitability for remanufacturing through utility analysis as described by Haag et al. [23]. The suitability of products for remanufacturing is calculated with the help of a utility analysis [23]. For every strategy, a score is displayed to predict the product's suitability. This score is calculated as sum of ratings of the different criteria multiplied by their weights. Finally, a score is calculated for remanufacturing, remanufacturing with product update and reintegration, that indicates the suitability, is calculated.

Furthermore, the tool provides a financial analysis, which allows the estimation of the overall profitability of the remanufacturing process. The key metrics are derived from the process parameters and the associated costs. Figure 2 provides an overview of all calculations, including specific input and output parameters.

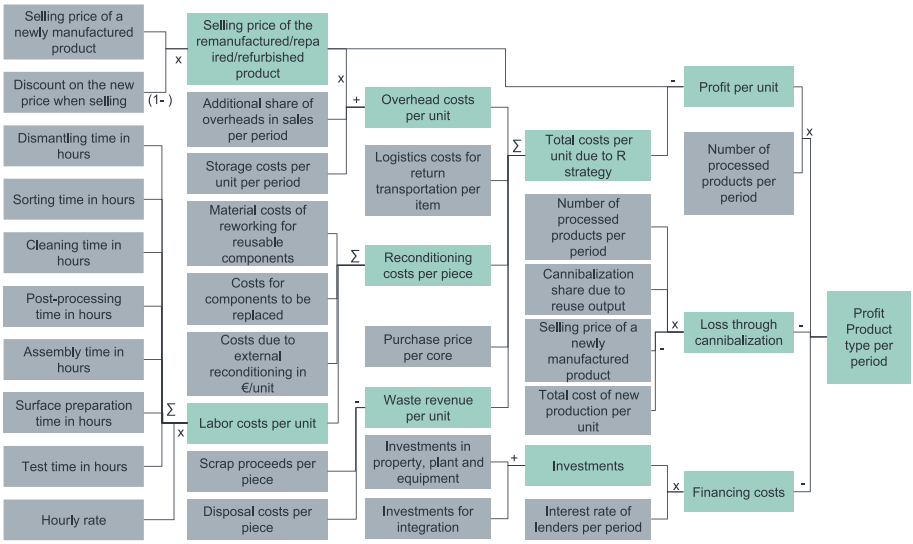

Fig. 2. Overview of financial calculation

After its development the excel tool was tested several times with different products. In this way errors that occurred were eliminated and iterative improvements were made. The exemplary implementation for a product is described in Sect. 5.

4.2 Tool Structure

Section 4.1 presented the methodology, which is then implemented in the spreadsheet program Microsoft Excel. The tool comprises eight worksheets: (1) an introduction and a brief manual about the usage of the tool, (2) a summary of the results, (3) & (4) sheets for the structured entry of the necessary data for the remanufacturing suitability evaluation as well as the financial calculations, (5) a detailed description of all control variables including goal and recommendations, (6) a sheet to adjust the weights of the criteria, (7) a sheet containing the detailed lists of the references to the criteria and (8) a sheet aiding in the functionality of the tool ("backengine") [24]. The input data is entered in the respective sheets. The user is guided in this process by remarks in the form of input messages. The utility analysis and the calculations are performed automatically with the help of worksheet functions and based on the values put in the weights sheet. The initial values for the weights are based on best practices but are adjustable at the user's discretion. The results are then consolidated and displayed on the results sheet. To aid the user, the most important values are also illustrated as graphs. A message warns that remanufacturing is impossible if one or more exclusion criteria are triggered. The criteria prohibiting product remanufacturing are consolidated in a recommendation section on the results sheets. In addition, improvable control variables are automatically determined and displayed on the results sheet. This is complemented by a function with which one of the control variables can be selected, and the relevant information (from the respective control variable fact sheet) is displayed. As a result, the user can be provided

with targeted suggestions to improve the remanufacturing capability of the products assessed within the tool. The toolbox contains the following eleven control variables: Component identification, Component condition, Material, Procurement, Design for Cleaning, Design for Disassembly, Handling, Standardization, Product structure, Quality and Environment. All fact sheets describe the goal(s) of the respective control variable and key recommendations for action and measures to achieve the goal(s). Furthermore, literature recommendations are provided to deepen the selected improvement potentials, should the tool user require a more profound understanding. This toolbox thus supports the creation of a product with enhanced suitability for remanufacturing.

5 Case Study Validation and Results

For validation, the tool was used to assess electrical construction equipment. An expert of the company conducted a comprehensive evaluation of all product criteria and completed all parameters. This was followed by an evaluation in which any difficulties, problems and ambiguities were discussed with the responsible company employee. In addition, the results generated by the tool regarding the remanufacturability of the product were analysed and discussed with the manufacturer of the product. This process aimed to identify tool errors, user ambiguities and any missing remanufacturing aspects. The company's expert analysed the criteria using its products and validated that they effectively represent the remanufacturing process. The financial calculations proved reliable, closely matching detailed internal analysis results. All findings were subsequently incorporated into the tool. The tool suggests remanufacturing as the suitable R-strategy for the analysed product, excluding remanufacturing upgrade and reintegration due to unmet exclusion criteria. The remanufacturing score is 64.45%, indicating good performance but room for improvement. The product excelled in product criteria and reverse logistics (92%) and Product Structure (83%) but scored lower in identification, inspection, sorting and cleaning (20%). No control variables were flagged for improvement, suggesting that the product performed adequately in all categories with no significant deficiencies. To further improve the product, focus should be placed on areas with lower scores like e.g. the traceability of the product across the value chain. The financial analysis indicates that remanufacturing yields minimal profit, primarily due to the high cost of replacement components. No other anomalies were found in the results.

6 Summary and Outlook

The assessment application facilitates an efficient and quick determination of suitability for remanufacturing based on 188 individual criteria including in particular ecological, social and legal issues. The developed and publicly available tool [24] makes it easy to assess products' suitability for remanufacturing, product upgrade, refurbishment and integration of used components into the new production. The assessment offers specific guidance for improving a product's suitability for remanufacturing by integrating a toolbox proposing targeted recommendations designed to improve the overall remanufacturing score. The tool has been validated and improved in collaboration with several companies. In companies, the tool achieved equivalent results with significantly less

effort than a comprehensive study. The extension to additional R-strategies could be incorporated to further improve the assessment. In addition, the specialization in specific product categories could improve the accuracy. Furthermore, there is a potential to recommend product improvements regarding remanufacturing suitability using artificial intelligence within the tool. Product improvement suggestions were generated in the first trial using a large language model and a substantial dataset. This approach has the potential to quickly provide companies with suggestions for product improvement.

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