Cost Model for Evaluation of Industrial Re-Assembly Processes

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Abstract. Manufacturing companies must prioritize resource efficiency to remain competitive in the face of increasing demand for goods. Linear economic models, such as the 'Take-Make-Dispose' paradigm, are no longer adequate for meeting the demands of modern society, ecology, and regulation. The circular economy offers a resource-efficient alternative. In the circular economy, Re-Assembly is a promising strategy within this framework, involving industrial reprocessing of serial products to extend their lifecycle. However, the absence of optimized product designs for reprocessing hinders widespread adoption and economic viability of Re-Assembly processes. Therefore, integrated development across product design, production, and Re-Assembly is crucial to address this challenge. To achieve economic viability, it is necessary to evaluate costs throughout the product lifecycle. To enable companies to make informed decisions regarding the Re-Assembly process, a continuous cost assessment supported by sophisticated cost models is necessary. This paper presents a comprehensive cost model tailored to assess the economic feasibility of industrial Re-Assembly processes. The relevant cost drivers and necessary resources for the reprocessing are identified and used as input for the subsequently developed process-oriented cost model. This cost model is transferred into an optimization model. The model aims to enhance the sustainability and profitability of circular economy practices.

Keywords: Re-Assembly · Cost Modelling · Product and Production Development

1 Motivation

The manufacturing industry faces numerous challenges, including resource scarcity, stringent political regulations, and growing environmental awareness among consumers. This necessitates aligning economic activities with ecological, social, and regulatory requirements [1, 2]. Traditional linear economic models ("take-make-dispose") are inadequate for future challenges, while the circular economy offers a viable alternative [3]. The circular economy aims to decouple consumption and economic growth from natural resource use. The Re-Assembly approach, defined as the industrial reprocessing of complex series products, is key to advancing the circular economy in ecological and economic

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ways. [4, 5] Out of an ecological perspective remanufacturing can reduce emissions by 90% and energy consumption by 56% compared to new production, according to the VDI [6].The reduced material and energy consumption can lead to margins two to three times higher, depending on the product [5]. Forecasts suggest that the economic potential of industrial reprocessing in Europe could reach €90 billion by 2030 [4]. However, the potential of Re-Assembly is hindered by insufficient product design for reprocessing [7]. Designing products for reprocessing maximizes benefits like waste reduction, material and energy savings [2]. Also the production process is not suitable to enable a disassembly of the products, and the process of the Re-Assembly is developed after the first lifecycle of the products, which leads to not applying a Re-assembly at all. Therefore, integrating Re-Assembly development into product development (PD) and production process development (PPD) is essential [8]. Furthermore, it is essential to implement a continuous monitoring and control of costs strategy. As development progresses, the potential for influencing costs diminishes. At the conclusion of the development phase, a considerable proportion of the cost price has already been established. Approximately 70% of the costs of a product are determined during the development and design phase. [9] In the next chapter the integrated development of process and production, the Re-assembly and the process based cost model (PBCM) and optimization modelling as the theoretical basics are described.

2 Theoretical Basics

This chapter will provide an overview of the theoretical basics of Re-Assembly, integrated PD and PPD, as well as PBCM.

2.1 Re-Assembly

Schuh et al. propose that the remanufacturing process can be divided into two levels: the Re-Assembly and the refurbishment process. [5] The Re-Assembly comprises the following steps: disassembly, cleaning, inspection, Re-Assembly and final acceptance. In so-called "Re-Assembly factories," functional and value-enhancing measures are employed to upgrade and qualify used products for subsequent life cycles. [5].

2.2 Integrated Product and Process Development

The aim of the integrated development process is to harmonize PD and PPD. This approach is based on the iterative development process described by Wlecke et al. [10] and the industrialization of remanufacturing in HIP3E by Hermann et al. [8]. The production and assembly processes are largely determined during the product development phase, while constraints on these processes influence PD. Interactions between PD, PPD, and Re-Assembly development must be identified and recorded to resolve conflicts early.

The integrated development process focuses on managing these interactions and is divided into four phases, based on product maturity and production/assembly flexibility. Transition to the next phase requires achieving a certain product maturity and reducing degrees of freedom in production and Re-Assembly. To accelerate development, numerous hypotheses are generated and re-evaluated across phases, leading to their expansion or rejection. [8, 10].

2.3 Process Based Cost Modelling (PBCM) and Optimization Modelling

PBCM is a tool for calculating production costs based on technical and operational parameters. It provides transparency regarding the impact of different parameters on overall costs and enables the monetary evaluation of potential optimizations. The model is primarily focused on cost estimation in early development phases and the assessment of alternatives in terms of materials, products and processes. For input product description are used which is transferred into technical parameters. These are modelled in terms of processing times, material and energy consumption, and machine failures. They are combined with company-specific parameters to create the input variables.[11, 12] Optimization models represent an abstraction of reality and are intended to find an optimal solution. The standard form of a linear optimization model comprises three key elements: decision variables, an objective function to be maximized or minimized, and constraints. The decision variables correspond to the decision space of the given decision situation and represent the degrees of freedom that exist and the decisions that are made by the model. [13].

3 State of the Art

The following section presents existing approaches from the literature that address the topic under consideration in this paper, followed by a brief evaluation of the approaches concerning the fulfillment of the objective of this paper.

DING et al. present a cost forecasting method for remanufacturing. Among other things, mathematical formulae for calculating remanufacturing costs are described. The remanufacturing costs are made up of the return costs, the costs in the process steps and the other costs. [14] DU et al. evaluate the recyclability of used machine tools, focusing on technological, economic, and ecological benefits. The initial step is to ascertain the technical feasibility of remanufacturing, followed by calculating costs, including those for returned cores, remanufacturing processes, and overheads. [15] XU et al. propose a procedure for forecasting remanufacturing costs, focusing on automotive components. They recommend a bottom-up approach, starting with delineating prerequisites and selecting a cost calculation method. The analysis focuses on cleaning, inspection, and reconditioning costs. [16] SCHAU et al. analyze life cycle costs for alternator remanufacturing, focusing on costs for both the remanufacturer and the user. This analysis aids in predicting costs, identifying savings, and supporting decision-making. [17] GHAZALLI and MURATA present an integrated evaluation system for selecting End-of-Life (EOL) strategies. The system first selects the EOL strategy at the product level and then determines strategies for individual components. The cost model includes labor costs for disassembly, sorting, cleaning, refurbishment, reassembly, and testing. [18] KRILL and THURSTON present a model for estimating the production, remanufacturing and disposal costs as well as the environmental impact of engine blocks. [19].

In summary, the reviewed approaches in Sect. 3 primarily focus on product remanufacturing, with varying degrees of detail and integration regarding the development of the Re-Assembly.

4 Concept

The cost model for evaluation of industrial Re-Assembly processes is based on the PBCM. It is used to validate the economics of different Re-Assembly hypotheses formulized in the development stage and must be embedded in the validation phase of the development. [8, 10] The results from the cost evaluation are used as a decision-making support. The model is divided in cost drivers and resources as input variables, the mathematical cost model, and the optimization model. For the cost model we assume that the number of returned products equals the number of sold upgrade products, assuming rejects occur only in reprocessing. Also costs which are not related to hypotheses or product manufacturing are excluded.

4.1 Cost Drivers and Resources

The input variables required to calculate Re-Assembly costs are divided into the categories "product-related input variables", "process-related input variables" and "dimensioning the Re-Assembly plant". Input variables derived from literature review [1–19] using the guidelines formulized by KITCHENHAM [20] and supplemented by expert interviews. The interview process includes a preliminary discussion in which the background to the question is specified. The interviews follow a guideline and includes intrinsic and extrinsic follow-up questions as well as interpretative questions [21].

Product-related Input Variables
The product-related input variables refer to the respective product structure of the product hypothesis. The product structure is of significant importance in order to ascertain the proportion of components that can be utilized for reprocessing, the proportion that is generated as scrap following disassembly, and the proportion of purchased parts present within the product. This has a substantial impact on both the costs and the associated production process and the Re-assembly.

Process-related Input Variables
In the development of the Re-Assembly, alternative process chains are defined. In order to evaluate these in economic terms, process input variables need to be defined. These include specification times, personnel and space requirements (workstation and machine based), and acquisition costs.

Dimensioning the Re-Assembly Plant
The evaluation of alternative dimensioning concepts is an essential part of the economic analysis. For this purpose, dimensioning involves forecasting the number of units and different demand scenarios. The goal of dimensioning is to determine the production resource requirements in terms of production equipment, personnel and space required to remanufacture a planned number of items.

4.2 Cost Model

The cost model is applied after the input variables are defined. Periods for economic amortization are taken into account via parameter changes. Following the PBCM processes related costs for the processes in the Re-Assembly must be identified. The Re-Assembly includes the five process steps disassembly, cleaning, inspection, reprocessing, and assembly (see Fig. 1), as well as support processes like transport equipment costs, additional space costs, procurement, disposal, transport, and storage costs.

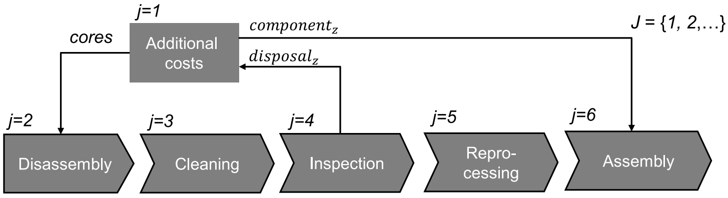

Fig. 1. Processes in Re-Assembly

The control variable j describes the process steps. Re-Assembly costs are calculated from the sum of the individual process costs (see Eq. (1)-(3)):

$$C_{Total} = \sum_{j=1}^{J} C^j_{Process} \tag{1}$$

$$C_{Total} = Total\ costs \tag{2}$$

$$C^j_{Process} = Tota, costs\ in\ j \tag{3}$$

The costs in j are made up of variable and fixed costs. According to the PBCM framework (see chapter 2.3), the variable costs in j result from the sum of material costs, personnel costs and energy costs. Additionally, the fixed costs in j result from the sum of equipment costs, area costs and maintenance costs for each process (see Eq. (4)-(6)):

$$C^j_{Process} = C^j_{variable} + C^j_{fix} \tag{4}$$

$$C^j_{variable} = C^j_{Material} + C^j_{Personnel} + C^j_{Energy} \tag{5}$$

$$C^j_{fix} = C^j_{Equipment} + C^j_{area} + C^j_{Maintenance} \tag{6}$$

For each of the considered process steps of the Re-Assembly (see Fig. 1), corresponding cost functions are developed to calculate the fix costs and variable cost in each respective area. As an example, the cost functions for the disassembly process as one of the process steps are derived in the following. A similar structure was also developed for the other four steps within the Re-Assembly.

Variable Costs for Disassembly

First, the variable costs of disassembly are considered (see Eq. (7)). Since there are no additional *material costs* incurred in the disassembly processes, these are not relevant here. The *personnel costs* consist of the number of stations, the personnel required per station, the annual costs per employee, and a safety factor, accounting for absences due to vacation and illness:

$$C_{Personnel}^{j=Dis} = NOS^{j=Dis} \times N_{Personnel/Station}^{j=Dis} \times S_{Personnel}^{j=Dis} \times p_{personnel} \tag{7}$$

$$N_{personnel/station}^{j=Dis} = Personnel\, requirements\, per\, station$$

$$NOS^{j=Dis} = Number\ of\ disassembly\ stations; \quad S_{Personnel}^{j=Dis} = Safety\, factor$$

$$p_{personnel} = Annual\, costs\, per\, employee\, (incl.\, non - wage\, labor\, costs)$$

The *energy costs* in the case of automated disassembly are calculated according to the following formula (8–9). Since the maximum power is not utilized over the entire usage time but typically at a rate of 0.6 to 0.8 [22], an efficiency factor is considered:

$$C_{Energy}^{j=Dis} = P_{Inst.Power}^{j=Dis} \times k_{Efficiency,Power}^{j=Dis} \times reqOT_{corrected}^{j=Dis} \times p_{Energy} \tag{8}$$

$$reqOT_{korrigiert}^{j=Dis} = ReVol \times CycleTime^{j=Dis} \times \frac{1}{z_G^{j=Dis} \times k_N^{j=Dis}} \tag{9}$$

$$ReVol = Quantity\, produced\, per\, Year; \quad reqOT^{j=Dis} = Annual\ required\ disassembly\ capacity$$

$$CycleTime^{j=Dis} = Disassembly\, target\, time\, per\, product; \quad z_G^{j=Dis} = Time\, degree\, in\, j$$

$$k_N^{j=Dis} = Degree\ of\ utilization\, inj; \quad C_{Energy}^{j=Dis} = Energy\, costs\, (here:\ Annual\ electricity\ costs)$$

$$P_{Inst.Power}^{j=Dis} = Maximum\ installed\ power\ [kW];\ p_{Energy} = Electricity\ costs\ [€/kWh]$$

Fix Costs for Disassembly:

Based on the number of required disassembly stations and the necessary space per disassembly station, the total space requirement is determined. The *space costs* are calculated as the product of the space requirement per station, the number of stations, and the annual space costs per square meter (see Eq. (10)):

$$C_{building}^{j=Dis} = R_{building} \times NOS^{j=Dis} \times Area_{NOS}^{j=Dis} \tag{10}$$

$$R_{building} = Annual\, floor\, space\, costs\, per\, m^2; \quad NOS^{j=Dis} = Number\ of\ disassembly\ stations$$

$$Area_{NOS}^{j=Dis} = Space\, requirement\, per\, station\, in\, m^2$$

The total *equipment costs* are calculated as the product of the annual costs per disassembly station and the number of disassembly stations. The equipment costs include both the costs for machinery and equipment as well as the costs for manual workstations:

$$R_{building} = Annual\ floor\ space\ costs\ per\ m^2$$

$$C^{j=Dis}_{Equipment} = Total\ equipment\ costs$$

$$R^{j=Dis}_{Equipment} = Annual\ equipment\ costs\ per\ disassembly\ station$$

The *maintenance costs* can be initially estimated by multiplying a maintenance factor with the annual equipment costs (see Eq. (11)):

$$\begin{aligned} C^{j=Dis}_{Maintenance} &= C^{j=Dis}_{Equipment} \times Z^{j=Dis} \\ C^{j=Dis}_{Maintenance} &= Maintenance\ costs;\ \ Z^{j=Dis} = Maintenance\ factor \end{aligned} \tag{11}$$

Subsequently, the total costs for each hypothesis must be calculated by applying the different input variables for all functions of the different process steps ($j = 1, \ldots j = 6$) and for each hypothesis. The results allow for an economic comparison to be made, which in turn informs the decision as to whether a hypothesis should be continued or rejected for the next development phase.

Optimization Model
To support the cost modelling a linear optimization model in the direct comparison or integrated consideration of hypotheses formulated. First the cost model is adapted to form of a linear optimization model. Based on this, various decision situations are modelled. For example, the optimization model can be used to determine the profit-maximizing number of units. Binary decision variables are defined for each hypothesis and the cost functions are supplemented by the cost shares of all hypotheses so that a versatile solution space is spanned. The model, considering restrictions, delivers the optimal solution and determines which hypotheses should be developed further or rejected. The main difference between this model and the cost model is that several hypotheses are considered in an integrated manner.

5 Summary and Outlook

In this paper, a cost model is developed to evaluate the economic efficiency of industrial Re-Assembly processes as well as the economic validation of various alternatives. The fundamentals presented suggest that an integrated development of product, production process, and Re-Assembly, as well as early monitoring and control of costs, are important for the development of economical Re-Assembly processes. The cost model is based on input variables derived from the formulation of various development hypotheses. In addition, there is a mathematical cost model and an optimization model that supports the decision-making process. Further work is required to provide a more detailed account of the presented model and validated in industry.

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References

1. Edinger-Schons, et al.: Sustainability transformation monitor (2023)
2. Ellen MacArthur foundation: towards the circular economy (2014)
3. Neugebauer, R.: Handbuch ressourcenorientierte Produktion. Hanser (2015)
4. Parker, et al.: Remanufacturing market study (2015)
5. Schuh, et al.: Green re-assembly upgrade factory (2023)
6. Verein Deutscher Ingenieure e. V.: Ressourceneffizienz durch Remanufacturing (2017)
7. Nasr, et al.: Remanufacturing: a key enabler to sustainable product systems (2006)
8. Hermann, et al.: Industrialization of remanufacturing in the highly iterative product and production process development (HIP3D) (2023)
9. Ehrlenspiel, K.: Kostengünstig Entwickeln und Konstruieren. Kostenmanagement bei der integrierten Produktentwicklung (2013)
10. Wlecke, et al.: Reducing time-to-market in the highly iterative and integrated product and production process development (HIP3D) (2022)
11. Fuchs, et al.: Process-based cost modeling of photonics manufacture (2006)
12. Johnson, M., Kirchain R.: Quantifying the effects of parts consolidation and development costs on material selection decisions: a process-based costing approach (2009)
13. Suhl, L., Mellouli T.: Optimierungssysteme. Modelle, Verfahren, Software, Anwendungen (2013)
14. Ding, et al.: A big data based cost prediction method for remanufacturing end-of-life products (2018)
15. Du, et al.: An integrated method for evaluating the remanufacturability of used machine tool (2012)
16. Xu, et al.: Remanufacturing and whole-life costing of lightweight components lightweight composite structures in transport (2016)
17. Schau, et al.: Life cycle costing in sustainability assessment—a case study of remanufactured alternators (2011)
18. Ghazalli, Z., Murata, A.: Development of an AHP–CBR evaluation system for remanufacturing: end-of-life selection strategy (2011)
19. Krill, M., Thurston, D.L.: Remanufacturing: impacts of sacrificial cylinder liners. J. Manuf. Sci. Eng. (2005)
20. Kitchenham, B.: Guidelines for performing systematic literature reviews in software engineering **2** (2007)
21. Meuser, M, Nagel, U.: Handbuch Frauen- und Geschlechterforschung. Theorie, Methoden, Empirie (2010)
22. Bauer, J.: Controlling für Industrieunternehmen. Kompakt und IT-unterstützt — Mit SAP®-Fallstudie (2006)