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Procedia CIRP 135 (2025) 1234–1239

www.elsevier.com/locate/procedia

32nd CIRP Conference on Life Cycle Engineering (LCE 2025)

Cross-Generational Remanufacturing: Identifying high-potential subsystems through differential analysis of product generations

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Abstract

A critical factor for implementation of the recently developed concept of Cross-Generational Remanufacturing (CG-Reman) – i.e., integrating remanufactured subsystems into new products of the latest product generation for the primary market in a planned and anticipated industrial process – is determining which subsystems of a focal product should be considered prioritized in targeted "Design for CG-Reman" efforts. As one method to identify such potential, we propose the method of a differential analysis, which identifies promising subsystems by assessing the extent, relevance, and baseline impact of each observed change between product generations. Based on empirical studies of two product generations of a kitchen appliance, we developed a framework for conducting such differential analysis along with suitable evaluation criteria. The analysis supports a systematic and applicable assessment of CG-Reman potential and thereby the directed application of CG-Reman.

Keywords: product engineering; product development; remanufacturing; R-strategies; cross-generational; sustainability; circular economy

1. Introduction

Remanufacturing holds strong potential to support the transition to a circular economy due to its high product value retention as well as energy and resource savings [1]. However, as of today, this potential is only exploited to a limited extent due to a variety of key challenges [2]. One of them is balancing design for remanufacturing with customer attractiveness for a given product, which could partly be addressed through a cross-generational approach [3]. Hence, the concept and terminology of Cross-Generational Remanufacturing (CG-Reman) has been presented in [4], along with product and market characteristics that could be suitable. However, not only is the selection of suitable products a challenge, but also determining which subsystems within these products should be prioritized for subsequent Design for CG-Reman efforts. Hence, this paper aims to develop a method to analyze products for identification of high-potential subsystems for CG-Reman.

Building on a summary of the state of research (Chapter 2), Chapter 3 introduces the research approach. The key results of the paper are presented in Chapter 4, while Chapter 5 gives an example of their application in a case study. The paper concludes with a discussion and outlook (Chapter 6).

Our practice-driven investigations lead to a structured approach and a novel method for CG-Reman potential assessment by systematically comparing changes between product generations.

2. Research background

To counteract rising challenges such as climate change and resource scarcity, the concept of a circular economy has been introduced and widely discussed in research and practice [5]. CE aims to decouple value creation from the consumption of finite resources [6]. As a supporting framework, the so-called R-strategies have been established to show different value

10.1016/j.procir.2024.12.124

retention levels for the circularity of resources [7]. One of these strategies, remanufacturing, which is characterized by restoring used products to a quality level that meets at least original equipment manufacturer (OEM) performance from the customer's perspective [8], is considered to provide potential for superior value retention [1]. To proactively design for enhanced ease of this *'conventional'* remanufacturing, a variety of guidelines have been established (e.g., [9, 10]). A product-related key criterion for identifying suitable products for conventional remanufacturing is the residual value of the used product ('core'), followed by more organizational criteria such as core availability and a reverse logistics [11, 12].

Going beyond the consideration of a single lifecycle application of an R-strategy, the concept of multi-lifecycle products has emerged [13]. As a special case of this, CG-Reman is conceptualized as a planned and anticipated industrial process that integrates used subsystems into new products of the latest product generation for the primary market, cf. [4]. Hence, CG-Reman targets subsystem or component-level circularity (cf. [14]), but aims to maintain customer attractiveness through a cross-generational focus. This leads to the challenge to identify those subsystems of a product that should be circulated with CG-Reman. Existing research that has considered similar challenges in adjacent concepts either tackle the topic from an operations research perspective rather than a technical one (e.g., [15]) or take an entire product rather than a component level view (e.g., [16]). In addition, previous work does not focus on multiple product generations. Hence, the question how to analyze which subsystems hold potential for CG-Reman has not been assessed and is a necessary next step for the application of CG-Reman.

3. Research approach

Therefore, the goal of this research is to explore ways to identify subsystems of a product that could be especially beneficial for CG-Reman. To achieve this, we formulated four research questions (RQs). With our first RQ we aim to frame the solution space for potential analyses that could contribute to this goal:

- *RQ1:* What types of analyses might support the identification of product subsystems that are suitable for Cross-Generational Remanufacturing?

As one potential solution, we propose systematically assessing changes that have occurred between two successive product generations, a process that we refer to as "differential analysis". Building on this, we formulated three additional RQs for the differential analysis to guide our study:

- *RQ2:* Which dimensions should be considered for identifying Cross-Generational Remanufacturing potential in a differential analysis?
- *RQ3:* How can changes between product generations in these dimensions be systematically evaluated on a granular physical subsystem level as part of a structured teardown?
- *RQ4:* How can this process be conducted in a reproducible and methodological way?

These questions were addressed through a combination of input from literature (RQ 1,2), expert interviews (RQ 1,2,3) and an iterative applied investigation in a case study (RQ 2,3,4). The latter was focused on the cross-generational analysis through a systematic teardown of two successive generations of a kitchen appliance (cf. Fig. 1). Structured physical teardowns of products have become common in competitive value analyses [17], however, to the authors' knowledge, they have not been specifically directed at identifying and describing granular differences between product generations.

Fig. 1. Example product (kitchen appliance) used for the differential analysis.

The specific product was selected as an example due to its clearly identifiable successive product generations without product variants, its mechatronic nature with sufficient but manageable complexity, its design-relevant exterior for differentiation, and its use as a conventional remanufacturing product. Notably, the older product generation had to be acquired remanufactured, as it was no longer available for purchase through official sales channels and the study had to be conducted without a collaboration with the OEM.

4. Results: Differential analysis as an assessment method for CG-Reman potential identification

The main contribution of this paper is the proposed assessment method to derive CG-Reman potential for subsystems and components. First, we present the context of the proposed differential analysis and its embedding within a broader range of potential analyses (RQ1). Second, we introduce three assessment dimensions to address RQ2, before diving into ways for their evaluation (RQ3). Lastly, we propose a methodology to conduct the differential analysis in an efficient and reproducible manner (RQ4).

4.1. Context of CG-Reman potential identification (RQ1)

We propose that the identification of CG-Reman potential can generally be conducted in several ways, structured along two main aspects. On one axis, potential can be identified from a market-related view, which we termed outside-in, or from a system-related view, which we call inside-out (cf. Fig. 2). On a second axis, both viewpoints can be taken with either a retrospective focus, identifying the inherent potential of the investigated system, or a prospective focus, assessing how future CG-Reman potential might be created. Example analyses within this framework include a retrospective market analysis (outside-in, retrospective), a market trend analysis utilizing methods from the field of strategic foresight (outside-in, prospective, e.g., [18]), or a reference system analysis during product engineering as proposed by [3] (inside-out, retrospective). The differential analysis operationalizes the inside-out perspective, and while in this case study it was conducted retrospectively, there is also potential to apply it to (models of) prospective product generations.

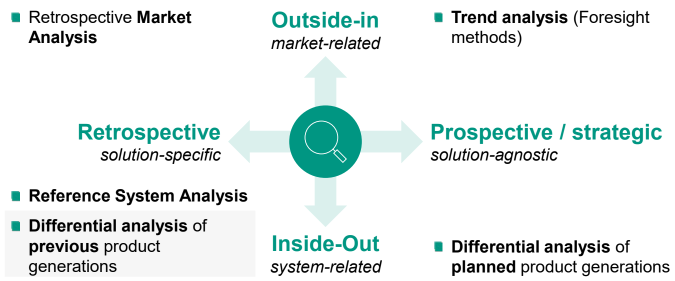

Fig. 2. Overview of possible analyses to identify CG-Reman potential with conducted differential analysis highlighted.

Each of these analyses provides distinct and valuable input, and only a combination of these will yield a holistic view of CG-Reman potential (particularly for subsystems that must be newly developed to respond to market trends). In the following sections, this paper focuses on the differential analysis as a suitable key approach for the system-related view.

4.2. Identification of general assessment dimensions (RQ2)

For the differential analysis conducted in this paper, we analyze engineering changes made between product generations. To derive dimensions for assessment (RQ2), it is first important to understand the goal of this analysis. Since we are not searching for components that could be used for CG-Reman as-is, aspects of conventional reman-suitability (e.g., ease of disassembly, lifetime) are not in focus here. Moreover, risk assessment is not a core element at this stage, as it would already require specific redesign options. Instead, the differential analysis aims to identify fields of action with potential to effectively apply Design for CG-Reman principles.

Hence, the main rationale here is that if a high-value component is observed to have undergone few and/or non-crucial changes, it may be highly suitable to consider for subsequent Design for Cross-Generational Remanufacturing. To systematically capture the influences on CG-Reman potential, we propose three assessment dimensions:

Firstly, the **extent** of the change must be measured. While no change and total intergenerational commonality in a component between subsequent generations might be ideal for CG-Reman potential (cf. [19, 20]), we propose that evidence regarding the proximity to cross-generational commonality (e.g., (limited) compatibility) of a subsystem may also be valuable and should be considered.

Secondly, the reason for the change must be evaluated. While some changes could be critical differentiators for customers (e.g., adding wireless connectivity in the newer generation of the kitchen appliance), others may be purely cost-driven or occur due to operational efficiencies. For CG-Reman, the first type of change may be inevitable due to the primary market aspiration, but the latter type of change may not be necessary and could be deprioritized to facilitate CG reuse of certain subsystems. We call this dimension the **relevance** of a change. This notion can also be linked to obsolescence types that have been investigated in this context, as described by [21].

Lastly, these two dimensions could still result in identifying many small components that would not justify the effort of making targeted design changes as well as engaging in the complex operations of a (CG) remanufacturing process. Hence, the baseline **impact** of a given subsystem should be considered as a key criterion for the effectiveness of a remanufacturing approach (cf. [11, 20]). The impact dimension establishes the contribution of the subsystem to the overall system and can be interpreted (independent of possible changes between generations) in various ways, such as economically, environmentally, or socially. If the impact of a subsystem is high, it will have greater potential for CG-Reman. This dimension serves as a basis for prioritizing the overall CG-Reman effort based on given targets, e.g., set through the company strategy.

In fact, some of these dimensions are already commonly considered in literature (cf. [11, 12]) and practice (as indicated in expert interviews) when retroactively identifying subsystems for conventional remanufacturing of products already on the market (e.g., focusing on high-value cores: impact; limited design change history: extent, no quality-induced changes: relevance). These insights supported the development of the final dimensions during the case study analysis. To summarize, the CG-Reman potential of a focal subsystem or component can be described as a function of the extent of the cross-generational change, the relevance of the change and its (e.g., economic, ecologic, social) impact (cf. (1)). Each of the dimensions can be interpreted as an answer to one of the following questions: '*Why* was it changed?' (relevance), '*What* was changed?' (impact), and '*How* was it changed?' (extent). While the weighting of the dimensions is not deductively given, coefficients can be introduced to adjust the results or set a specific focus (cf. Chapter 5).

$$CGReman\ potential = f\begin{pmatrix}\text{Change } Extent,\\ \text{Change } Relevance,\\ \text{Subsystem } Impact\end{pmatrix} \tag{1}$$

4.3. Evaluation of the general assessment dimensions (RQ3)

To propose an approach to answer the third research question (RQ3), we need to operationalize the assessment dimensions with evaluation mechanisms. While our research focused on a practice-derived approach for the extent evaluation, we also provide a brief overview of possible ways to evaluate the other dimensions based on insights from the empirical analysis of the example product.

Of those dimensions, **impact** seemed the most measurable, given the availability of clear metrics for evaluation. The economic impact of a subsystem can be identified through methods such as an ABC-analysis of its contribution to the bill of materials (BOM) or life cycle costing (LCC). Environmental impact could be estimated through a subsystem-level life cycle assessment (LCA). Similar indicators could also be integrated to include additional impact criteria such as social suitability. Since these fields are generally well-researched, we did not focus on their specific evaluation (cf. [22]). Furthermore, due limited access to OEM engineering data and to simplify the evaluation in our case study, we estimated the impact based on expert input regarding materials used and manufacturing complexity. This was summarized using a three-step scale (low, medium, high) for cost and environmental impact. The authors acknowledge, however, that this could be performed separately and with greater accuracy.

The **relevance** of changes was also estimated by attempting to reconstruct the objectives of the original engineering team. Here, development knowledge and customer understanding are crucial inputs for assessment, which were not available to the authors. As a workaround, our estimate relied on a three-tiered scoring system with the following categorizations for the cross-generational relevance of changes: no change / reason not recognizable or not customer relevant (e.g., cost-driven, production-related) (low), performance improvement without direct customer relevance (e.g., internal performance, reliability) (medium), and customer-critical differentiating function (high).

The approach to evaluate the **extent** of a cross-generational change for a given subsystem was less clear. To the authors' knowledge and based on a literature search, there are no standardized measures for assessing the extent of changes on a physically observable level. Generally, the idea of CG thinking is based on the model of SGE – System Generation Engineering by Albers et al. [23], which describes changes between generations using three variation types. However, given the detailed level of our investigation, we found it was necessary to go beyond these and develop a framework to evaluate changes on a more granular level for physical subsystems. While experimenting with various approaches, such as 3D scanning and a software-based geometrical deviation analysis, we found that these methods do not provide insights into the quality of a geometrical change.

Based on these findings, we developed a framework for evaluating change extent. The core idea is to qualify the change extent based on the degree of compatibility of the older generation's subsystem with the new generation, ranging from *full equality* (exactly equal), *compatibility* (not equal, but can be integrated as-is), *conditional compatibility* (can be integrated with additional measures, e.g. interface adaption), to *incompatibility* (cannot be integrated). This structure is based on the concept of hard and soft incompatibility [24] and was mapped to the analysis of the geometry and material of the focal subsystem. For geometry, changes were categorized into modifications within the design space (the envelope volume occupied by the subsystem) and at the interfaces (elements interacting with the subsystem's environment, requiring an analysis of the system context). For material, changes were evaluated in terms of substance (engineering matter, e.g. polypropylene) and the surface property (e.g., friction coefficient) parameters. Each of these four categories was assigned a rough equivalent to the previously presented compatibility levels, cf. Table 1. This classification is loosely based on modularization principles and was developed iteratively based on insights gained from its application to the example product.

Table 1. Proposed evaluation scheme for extent of cross-generational change.

Extent of change *(illustrative)*	**Value**	**Geometry**		**Material**	
		Design Space	**Interface** *(system context)*	**Substance** (x0,5)	**Surface** (x0,5)
"Equality"	0	Equal	Equal	Equal	Equal
"Compatibility"	1	Internal change	Compatible	Material type equal	Aesthetic change
"Conditional Compatibility"	2	External change	Compatible w/ adapter	Equal class of materials	–
"Incompa-tibility"	3	New / discontinued	Incompa-tible	Diff. class of materials	Technical change

To derive a comparable result, each compatibility level was assigned a numerical value from 0 (equality) to 3 (incompatibility). The values for each assessed category were aggregated through summation, with the two subcategories for material weighted at only 50% each, as their influence on the change extent was considered lower compared to geometric elements. Consequently, the change extent measured could range from 0 (minimal extent = equality) to 9 (maximal extent). While this approach is expected to provide a useful indication, the scale is not strictly ordinal for individual digits. To align with the prior assessment of other dimensions and facilitate further analysis, the results were grouped into three levels: low (0-2.5), medium (2.5-5.5) and high (6.5-9). The final evaluation scheme resulted from iterative experimentation with the case study product to ensure usability and clear differentiation among individual evaluation levels.

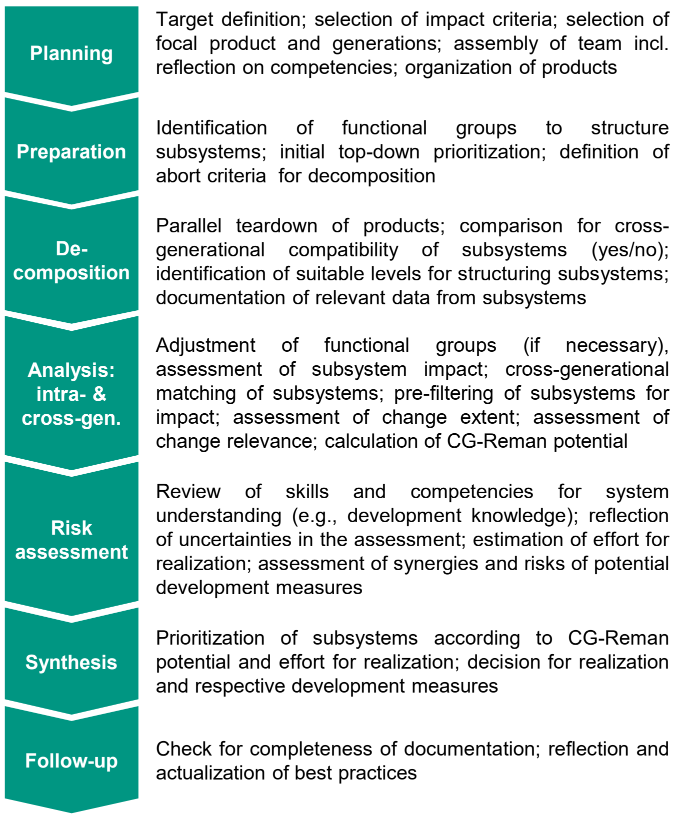

Fig. 3. Procedural framework for conducting a differential analysis to identify CG-Reman potential consisting of seven steps with their key activities.

4.4. Procedural framework for conduction (RQ4)

Based on the empirical insights gained from the practical study, we derived a seven-step general approach to evaluate the CG-Reman potential of subsystems from planning until follow-up, with particular focus on a structured and effective decomposition and comparative analysis. The relevant steps and a selection of their activities are presented in Fig. 3. This framework has been developed in more detail using detailed flowchart notation according to ISO 5807 for each step. Since presenting these details would exceed the scope of this paper, they can be obtained from the authors upon request.

5. Application in the case study

The case study served both as a platform for the iterative development of the concepts and as an example product for validating the approach. The results of the final application are presented below. To identify the CG-Reman potential, the individual assessments (low, medium, high) of the three change dimensions were evaluated in combination. To achieve this, the assessments were first translated into scores from 0 (worst characteristic) to 2 (best characteristic) and then added up to calculate a CG-Reman potential score ranging from 0 (lowest potential) to 6 (highest potential). The distribution of these scores across the 47 disassembled and analyzed subsystems (excluding connectors such as clips and screws) of the example product is shown in Fig. 4. It should be noted that the older product generation was chosen as the baseline, i.e. subsystems that were discontinued were included in the analysis, while new subsystems in the new generation that lacked identifiable predecessors were excluded. The results were finally divided into three categories of potential (low: 0-2, medium: 3-4, high: 5-6) to facilitate the comparison and evaluation.

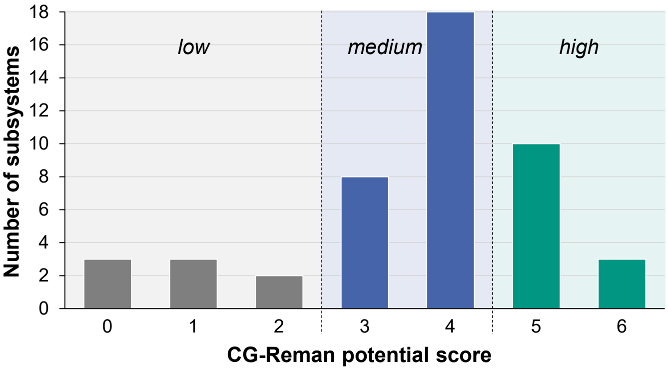

Fig. 4. Distribution of CG-Reman potential scores for the evaluated subsystems (n=47) showing separation into high, medium and low potential.

The results show a clear distinction among the components, with 28 % classified as high, 55 % as medium and 17 % as low CG-Reman potential. These findings can effectively guide the identification of promising subsystems. Examples from the case study are provided in Table 2. These outcomes can be interpreted and explained based on the respective input dimensions. For instance, the main motor meets all three criteria (high-value item, unchanged, not a differentiator) and serves as an ideal starting point for Design for CG-Reman activities. Once this is addressed, lower value items with otherwise favorable characteristics, such as the plastic locking mechanism, could also be targeted. In contrast, high-value items with high performance relevance and many changes, such as the mainboard, are less suitable candidates.

Table 2: Examples of subsystems and their determined CG-Reman potential.

CG-Reman potential	Score	Examples
High	6	Main motor, cutting knife, kettle retainer
	5	Grille, kettle cover, locking mechanism
Medium	4	Kettle, lower housing, locking motor
	3	Upper housing, kettle base, PCB holder
Low	2	Mainboard, Display
	1	Knob cover, display PCB
	0	Recipe interface, spacer kettle retainer

In this simplest case of evaluation, equal weighting was applied to the three dimensions (relevance, extent, impact), as their importance was deemed equivalent. However, we also conducted a sensitivity analysis to observe changes in the results when placing higher emphasis on relevance and impact (by doubling their scores). Under a double impact weighting, high potential items became more distinct (e.g., motor, knife, retainer), as lower-value items are penalized more heavily. With double relevance weighting, the overall distribution shifted upwards due to the relatively strong polarization in relevance ratings (few with high ratings, most with low). Still, the effects of this weighting are not generalizable and depend on the specific product and its subsystems' characteristics.

6. Discussion and outlook

This paper investigates methods to identify subsystems of a product that may be particularly suitable for targeted redesign for Cross-Generational Remanufacturing. The differential analysis has been introduced as a method that investigates changes between product generations. In this context, three dimensions for change assessment, ways of their evaluation, and a procedural framework for conducting the overall analysis were presented. As part of this, a novel approach to assessing the extent of subsystem changes between product generations was developed. In doing so, the four stated RQs were answered.

Both the specification of assessment dimensions as well as the development of an understanding of the necessary criteria for classifying change extent on a granular subsystem level mark a novel contribution to existing academic concepts (cf. Chapter 2). For practitioners, the identification of suitable subsystems to prioritize for redesign according to CG-Reman requirements is a crucial first step towards adapting such concept in practice facilitated by this contribution.

The analysis conducted here can thus be considered as a first proof of concept, laying the foundation for further refinements and broader application. Based on the insights and limitations of this paper, the next steps for future research can be outlined. First, while it has been conceptually considered, the teardown process and evaluation method need to be validated with other products and product categories to demonstrate reproducibility and adaptability. While the analysis can, in principle, be conducted virtually (e.g., using CAD data, BOM information, system models), some changes may not be as easily identifiable. This is particularly relevant for intricate changes that may result from production processes but could still cause incompatibilities. In our case, the research was conducted during the teardown process, which meant that not all final guidelines (e.g., abort criteria) were adhered to during the analysis. As a result, more individual parts were disassembled than might typically occur, affecting the distribution results of CG-Reman potential. However, this deviation was determined to be non-critical. Nonetheless, the practical applicability of the method should be further validated in follow-up studies.

Second, there is potential to further explore the assessment dimensions and their ability to accurately measure CG-Reman potential, as well as to refine the calibration of their weights and selected threshold values, given their significant influence on the results. The evaluation of the three dimensions can and should be refined (e.g., avoiding aggregation into only three evaluation levels). Additionally, the specific evaluation of the relevance dimension requires further exploration, which was limited in this study due to a lack of development knowledge. The practice-derived, detailed assessment vector for change extent evaluation might provide useful insights for potential design adjustments. Furthermore, the suggested change extent evaluation could be generalized to analyze changes between existing product variants, thereby broadening its application potential to conventional remanufacturing contexts.

Third, on a conceptual level, the combination of the suggested analysis with other methods for identifying CG-Reman potential (cf. Section 4.1) should be explored, especially when considering a greenfield approach rather than cases with existing product portfolios and generation.
Lastly, specific guidelines to support Design for Cross-Generational Remanufacturing (DfCG-Reman) need to be further researched and established, as the presented analyses only identify subsystems with promising potential for CG-Reman. It should be noted that it was purposefully decided not to integrate an assessment of the reasonability or feasibility of redesigning a component for CG-Reman, which might reduce the potential of certain components that face extensive wear (as in our case, e.g., the cutting knife). Similarly, no prioritization was applied for e.g., inner-lying parts over outer-lying parts, which may be less susceptible to negative impacts on their optical function during use. This was done to open the solution space before a later engineering synthesis step that might proactively address these challenges. In general, a component-based rather than a function-based approach was taken to emphasize physical and tangible subsystem thinking for reuse.

Considering these areas for future work, this contribution aids in identifying promising subsystems and paves the way for the successful design of cross-generational remanufacturable products that advance a forward-looking circularity.

Acknowledgements

This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – SFB 1574 – 471687386.

References

[1] Kurilova-Palisaitiene J, Sundin E, Sakao T. Orienting around circular strategies (Rs): How to reach the longest and highest ride on the Retained Value Hill? J Clean Prod 2023;424:138724.
[2] Arnold M, Palomäki K, Le Blévennec K, Koop C, Geerken T. Contribution of remanufacturing to Circular Economy. Mol; 2021.
[3] Albers A, Tusch L, Jäckle M, Seidler M, Kempf C. Circularity in Product Engineering – Towards a Forward-Looking Approach Across Product Generations. In: Marjanovic D, editor. Proceedings of the DESIGN 2024, Glasgow: Cambridge University Press; 2024.
[4] Tusch L, Jäckle M, Albers A. Towards Design for Cross-Generational Remanufacturing: A Literature Review and Concept Proposal. In: Malmqvist J, Candi M, Saemundsson RJ, Bystrom, F. and Isaksson, O., editors. Proceedings of NordDesign 2024; 2024. p. 206–215.
[5] Kirchherr J, Yang N-HN, Schulze-Spüntrup F, Heerink MJ, Hartley K. Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions. Resour Conserv Recycl 2023;194:107001.
[6] Ellen MacArthur Foundation. Growth within: A circular economy vision for a competitive Europe; 2015. www.emf.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf. Accessed 18 December 2024.
[7] Potting J, Hekkert M, Worrell E, Hanemaaijer A. Circular Economy: measuring innovation in the product chain. The Hague: PBL Netherlands Environmental Assessment Agency; 2017.
[8] Ijomah W, Childe S, Mcmahon C. Remanufacturing: A Key Strategy for Sustainable Development. In: Proceedings of the 3rd International Conference on Design and Manufacture for Sustainable Development: Cambridge University Press; 2004.
[9] Ijomah WL, McMahon CA, Hammond GP, Newman ST. Development of robust design-for-remanufacturing guidelines to further the aims of sustainable development. Int J Prod Res 2007;45:4513–36.
[10] Shahbazi S, Jönbrink A. Design Guidelines to Develop Circular Products: Action Research on Nordic Industry. Sustainability 2020;12:3679.
[11] Subramoniam R, Huisingh D, Chinnam RB. Remanufacturing for the automotive aftermarket-strategic factors: literature review and future research needs. J Clean Prod 2009;17:1163–74.
[12] Herrmann C, Vetter O. Ökologische und ökonomische Bewertung des Ressourcenaufwands: Remanufacturing von Produkten. Berlin; 2021.
[13] Go TF, Wahab DA, Hishamuddin H. Multiple generation life-cycles for product sustainability: the way forward. J Clean Prod 2015;95:16–29.
[14] Sakao T, Bocken N, Nasr N, Umeda Y. Implementing circular economy activities in manufacturing for environmental sustainability. CIRP Ann Manuf Technol 2024;73:457–81.
[15] Badurdeen F, Aydin R, Brown A. A multiple lifecycle-based approach to sustainable product configuration design. J. Clean. Prod. 2018;200:756–69.
[16] Umeda Y, Kondoh S, Sugino T, Yoshikawa H. Analysis of Reusability using 'Marginal Reuse Rate'. CIRP Ann Manuf Technol 2006;55:41–4.
[17] Sato Y, Kaufman JJ. Value analysis tear-down. 1st ed. New York: Industrial Press; 2005.
[18] Siebe A. Die Zukunft vorausdenken und gestalten. 1st ed. Berlin: Springer; 2018.
[19] Kim J, Kim HM. Impact of generational commonality of short life cycle products in manufacturing and remanufacturing processes. J Mech Des 2020;142:122001.
[20] Hapuwatte BM, Badurdeen F, Bagh A, Jawahir IS. Optimizing sustainability performance through component commonality for multi-generational products. Resour Conserv Recycl 2022;180:105999.
[21] Asif F, Roci M, Lieder M, Rashid A, Mihelič A, Kotnik S. A methodological approach to design products for multiple lifecycles in the context of circular manufacturing systems. J Clean Prod 2021;296:126534.
[22] Hauschild MZ, Huijbregts MA. Life Cycle Impact Assessment. Dordrecht: Springer Netherlands; 2015.
[23] Albers A, Rapp S. Model of SGE: System Generation Engineering as Basis for Structured Planning and Management of Development. In: Krause D, Heyden E, editors. Design Methodology for Future Products, Cham: Springer International Publishing; 2022. p. 27–46.
[24] Hohenegger J, Bufardi A, Xirouchakis P. A new concept of compatibility structure in new product development. Adv Eng Inform 2007;21:101–16.