

Evaluating a Decision Support System for Assessing the Product Design Disassemblability

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Abstract: In response to the growing need for sustainable practices and resource efficiency, this study explores the integration of production knowledge into product design to enhance disassembly processes, which are crucial for effective remanufacturing and refurbishing. Despite the theoretical framework of Design for Remanufacturing, practical application is limited due to inadequate collaboration between product designers and production experts. Through semi-structured interviews with 14 professionals from various industries, we identify key challenges in this integration and outline user requirements for a proposed hybrid decision support system (DSS). Findings indicate that usability, compatibility with existing processes, and transparency are critical system requirements. Stakeholders express interest in the DSS concept; however, skepticism regarding broader remanufacturing strategies persists. The results emphasize the need to address general prerequisites, such as digitization levels within companies, to ensure successful implementation. This research contributes valuable insights into bridging theoretical frameworks with practical applications in remanufacturing and flexible assembly systems.

Keywords:

Flexible Assembly Systems, Disassembly, Remanufacturing, Human-Centered Design,

1 Introduction

To reduce resource waste and transform into a circular economy, R-strategies are getting more relevant within product life cycle management. [1] presented a framework of ten R-strategies, namely: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover. Not only idealistic motives, but also potential economic benefits are drivers for the application of R-strategies [2]. For instance, in the automotive industry, remanufactured parts can save up to 93 % in CO₂ emissions and 88 % of raw material [3]. However, the products themselves, as well as their production systems, must be adaptable to unlock the full potential of R-strategies. Focusing on the close-to-production strategies of remanufacturing and refurbishing, used products must be partly disassembled to be reassembled with only a few replaced or refurbished parts. However, the quantity and quality of returned products are unknown [4], and it is thus a remaining challenge to determine how disassembly and reassembly are facilitated efficiently. Whether disassembly should be integrated within the existing production system or established as a separate production system relies heavily on product design. Although the theoretical principle of Design for Remanufacturing (DfR) is broadly known, it is rarely used in practice [3]. The collaboration and communication between production experts and product designers regarding remanufacturing is not prioritized by companies, even though the production insights might support targeted design decisions [5]. Given the relevance of this issue, there is a need for research into the obstacles faced by product designers and production experts and the support they

require. Identifying these requirements is the foundation for integrating a future assistance system to take informed decisions on interdependent product- and production system design.

Consequently, this article aims to answer the following research questions:

- How do design engineers and production planners assess a decision support system that is based on the concepts of remanufacturing and flexible dis:assembly system?
- What requirements do design engineers and production planners have for the decision support system?

The publication is structured as follows: Section 2 provides an overview of the related works in the field of decision support systems for remanufacturing at the interface of product design and production planning. Section 3 presents the methodology for this publication, namely the human-centered design approach for a decision support system by means of expert interviews. The results of these interviews were analyzed qualitatively according to Mayring [6] and are presented in Section 4. We discuss our findings and implied consequences in Section 5 and conclude with an outlook for future research opportunities in Section 6.

2 Related Works

Practical guidelines for design for disassembly have been around for more than three decades, for example, Boothroyd and Alting's standard work *Design for assembly and disassembly* [7]. [8] established remanufacturing as a distinct strategy alongside repair, recycling, and disposal, and emphasized the role of product architecture and disassembly effort in determining the economic viability of recovery options. Building on this foundation, surveys on sustainable manufacturing and product recovery synthesized the state of the art on Design for Disassembly (DfD), disassembly planning, and recovery system design [9], highlighting the need for considering the interdependency of product design and production planning. Ijomah and colleagues [10] developed design guidelines specifically for remanufacturing, focusing on issues such as fastening methods, ease of access to critical components, and minimization of damage during disassembly and reassembly. However, many guideline-based approaches remain qualitative or semi-quantitative, and only a subset is linked directly to dynamic performance indicators such as throughput or resource utilization.

Evaluating product disassemblability predominantly utilizes absolute metrics, specifically disassembly time, alongside relative indices such as design efficiency and recyclability rates [11], [12]. Foundational methodologies employ predetermined motion-time systems, notably Methods-Time Measurement (MTM) and the Maynard Operation Sequence Technique (MOST), to estimate disassembly effort based on elementary manual operations, positioning, and force requirements [13], [14], [15]. These time-based estimates often feed into broader scoring systems, such as the ease of Disassembly Metric (eDiM) and the Repair Scoring System (RSS), which aggregate diverse criteria, including tool availability, fastener reversibility, and accessibility into quantitative indices [16] (Cordella et al., 2019). Recent advancements integrate these metrics into computer-aided design (CAD) tools and visual representations, such as Disassembly Maps and the Parent-Action-Child model, to optimize disassembly sequences and identify architectural bottlenecks [17], [18], [19].

Despite these advancements, current methodologies largely rely on the assumption of products being in perfect condition, failing to model real-world End-of-Life (EoL) statuses—such as rust, wear, deformation, or fusing—which alter disassembly effort and circularity potential [19], [20]. Furthermore, existing databases for fastener taxonomies are not exhaustive, often necessitating manual modeling for

novel connection types, and the standardization of reference values (e.g., disassembly depth) remains subjective, limiting the robustness of comparisons across different product families [21], [22].

Generating disassembly sequences directly from CAD files attempts to fill that gap. There is a plethora of publications about generating or optimizing disassembly and assembly sequences, yet only a few authors disclose the source code of their approaches. In [23], we performed a systematic literature review about disassembly sequence automation with publicly available code. Geometric approaches utilize collision detection to extract topological constraints and generate AND/OR graphs [24], [25]. Physics-based methods leverage simulation to ensure collision-free paths and gravitational stability during assembly-by-disassembly processes [26], [27]. Concurrently, data-driven approaches employ Graph Neural Networks and point cloud analysis for kinematic constraint prediction [28], [29], next component recommendation [30], and part direction prediction [31].

To gain insight into the real-world performance of a design for remanufacturing, simulations are necessary. Recent work specifically targets flexible process sequencing; Wurster and colleagues [32] employ Reinforcement Learning to enable dynamic, condition-based routing in hybrid disassembly systems where sequences are not fixed in advance. Innovation extends to process control via semantic 3D modeling for automated inspection [33] and factory planning for Matrix Manufacturing Systems, where metaheuristics optimize layout flexibility [34]. However, a holistic simulation framework that simultaneously integrates semantic product perception, dynamic layout optimization, and adaptive sequence control to fully automate the generation of simulation models remains a research gap. In [35], we proposed a framework to extract all feasible (dis-)assembly sequences from CAD files and simulate them on different (dis-)assembly scenarios to receive feedback and iterate for a better design for remanufacturing, as shown in Figure 1. To ensure that the proposed framework is aligned with real-world needs, two questions shaped the approach: first, how practitioners evaluate the proposed framework, and second, what specific requirements they have for such a hybrid decision-making system.

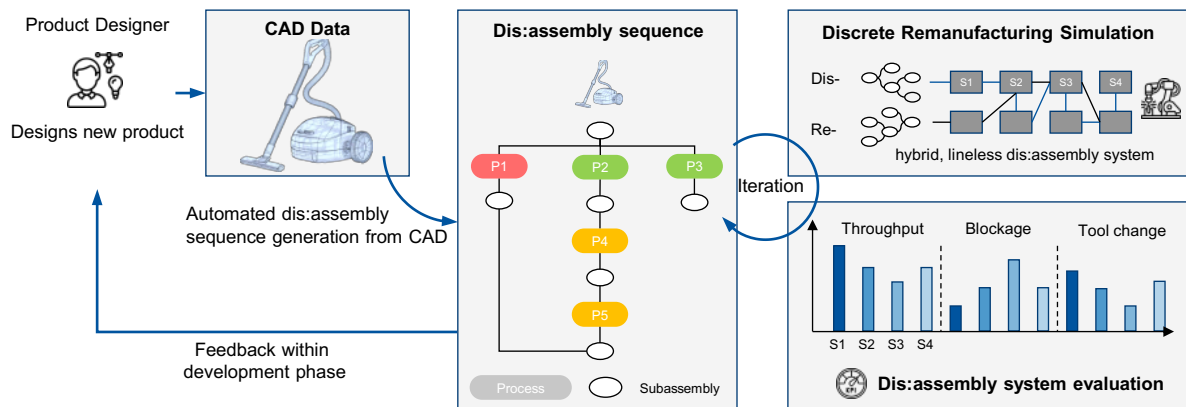


Figure 1: Proposed framework for production-based remanufacturing assessment according to [35].

3 Methodology

Participants were recruited via email from companies that are potentially involved in remanufacturing. Each interview included a pre-interview to assess participant suitability. The inclusion criterion was that participants should be able to envision a future where their product might be remanufactured. This criterion led to the exclusion of many potential interview partners, as their companies were not involved or interested in remanufacturing. The final sample consisted of 14 interviewees: 6 from a development perspective and 8 from a production perspective, representing various business sectors, including automotive (suppliers), plumbing, heating and air conditioning, control systems engineering, household appliances, and others. Their experience levels ranged from five to 25 years within their respective

fields. The number of expert interviews conducted is based on the qualitative research principle of data saturation, whereby data collection is terminated as soon as no new significant topics emerge. Empirical studies show that in many qualitative studies, this point is typically reached after between 9 and 17 interviews [36]. We reached saturation after 14 interviewed experts.

Structured interview guidelines were used during the interviews, which included a presentation of our system concept using Figure 1 as a PowerPoint slide. The 23 questions were divided into four blocks: context of use, remanufacturing, flexible assembly and disassembly, and system assessment. The guidelines and visualization were tested for their understandability with a pre-test by a development engineer who was not part of the sample. The interviews were conducted in German and lasted between 45 and 60 minutes, carried out by an engineer and a psychologist. All interviews were audio recorded, transcribed, and analyzed using structured content analysis according to [6]. The analysis was facilitated by MAXQDA, with the coding scheme guided by categories such as user group, requirements, system benefits, and criticisms. These categories were derived from specific questions in the interview guidelines. Additionally, during the analysis process, the category "general prerequisites" emerged as an important aspect alongside system requirements.

4 Results

An overview of the different codes within five categories, along with their frequency of occurrence in the transcripts of the 14 interviews conducted, is displayed in Table 1. Each category is described below, accompanied by relevant quotes.

In the category "user group," seven participants (50%) identified development engineers as the main user group for the proposed system, while four participants (29%) considered production planners to be the primary users. Additionally, six participants (43%) suggested that both the development and production planning departments should collaborate with the system as a team. Other potential user groups mentioned included project leads and product management.

The category "system requirements" was primarily dominated by usability (11 counts, 79%). Within this code group, six participants specifically referred to usability or stated that "it must be as easy to use as possible," emphasizing ease of handling. Other aspects coded under this requirement included efficiency, flexibility, and robustness against errors. Fifty percent of interviewees (7 counts) highlighted the importance of compatibility with the proposed system, mentioning technological compatibility with other tools and file formats, as well as procedural compatibility with existing development processes. Three participants (21%) identified transparency as a key requirement, noting that "you have to find some way to break it down [...] everyone will still demand understanding; I can't imagine it any other way." Additional discussed requirements included data security, demands for a learning system, and aesthetic standards.

When asked about potential benefits of the system, three codes emerged most frequently—each mentioned four times (29%). First was predictive power: interviewees noted that the system allows them to estimate key parameters in advance; one participant remarked, "I can make assumptions in advance about assembly times, which gives me transparency for calculation." The second benefit identified was that the tool supports users amid increasing product complexity, influencing "not only product development but also the whole life cycle." Thirdly, it was noted that the tool would facilitate early consideration of disassemblability during development. Two additional codes were mentioned by two participants each (14%), indicating that the tool could aid collaboration between development and production planning while facilitating R-strategy implementation.

Participants also expressed concerns regarding potential drawbacks of the system. Some felt it might highlight conflicts between objectives faced by development engineers in their daily work (3 counts,

21%), primarily driven by economic considerations such as promised product lifespan and competitive cost structures. Individual criticisms included a lack of focus on refurbishing processes within the concept and concerns about whether the system would function effectively as presented.

The final category—“general prerequisites”—emerged during content analysis rather than being directly addressed in interview questions. This category summarizes conditions within a company that could positively impact implementation but are not direct requirements for using the system. The most frequently cited prerequisite was advanced digitization within companies and their processes (6 counts, 43%). For instance, having a well-maintained database and established standards for managing relevant data would enhance the effectiveness of the tool. Additionally, having products with sufficient complexity was noted as beneficial for effective use of the system (3 counts, 21%). Participants also emphasized the importance of awareness regarding remanufacturing among users as a prerequisite. Finally, two other codes appeared twice each (14%): management support for using the system and strategic alignment towards remanufacturing alongside prioritization and time availability for utilizing it.

Table 1: Overview of the three most frequent codes for each category

Category	Most frequent code		2nd most frequent codes		3rd most frequent codes	
User group	Development engineers	7	Development and production as a team	6	Production planner	4
System requirements	Usability	11	Compatibility with other tools and processes	7	Transparency	3
Benefits	- Predictive power - Support with increasing complexity - Early consideration of (dis-)assemblability	4	- Collaboration between development and production planning - Facilitating implementation of R-strategies	2		
Criticisms	- Emphasizing conflict of objectives	3	- Refurbish process is not considered - Questioning of systems' functionality/performance	1		
General prerequisites	Advanced digitization/infrastructure/interfaces	6	- Awareness - Sufficient complexity of the product	3	- Management specification - Prioritization and time management	2

5 Discussion

This paper evaluates the practical perspectives of design engineers and production planners regarding a hybrid decision support system (DSS) concept aimed at assessing the disassemblability of products during early development stages. We conducted semi-structured interviews in which we presented the system concept and solicited participants' opinions on user groups, system requirements, potential benefits, and criticisms. The results indicate an overall interest from stakeholders; however, there was no consensus on whether development engineers should be considered the primary user group. Some participants suggested that collaboration between development and production teams is essential, while others noted that development engineers often overlook production perspectives.

Regarding system requirements, the anticipated outcome was confirmed, with a strong emphasis on usability. Participants highlighted not only ease of use but also other facets such as efficiency, robustness against errors, and flexibility—elements defined within ISO standard 9241 [37]. A comparison of benefits and criticisms revealed sixteen positive statements versus five negative ones from the sample.

This suggests a favorable view of the system concept, particularly its early consideration of disassemblability and predictive capabilities.

However, it can be argued that participants may find it challenging to criticize such a high-level concept. Additionally, the fifth identified category—general prerequisites—raises questions about relevance for specific industries. The requirement for sufficient product complexity could imply that the system may not be applicable to all companies. Furthermore, concerns regarding digitization highlight the need for good interfaces and data quality—factors that are often difficult to change.

Nonetheless, including general prerequisites in our analysis proved valuable as it illuminated aspects related to company environments rather than just system design. These arguments can be viewed as conditions for successful implementation that must be fulfilled before deploying the DSS.

Overall, the interviews provided insightful perspectives aligned with human-centered design principles—a focus that is often overlooked in practice. It is important to note that while participants did not reject the proposal of the DSS itself, many expressed skepticism towards broader approaches to remanufacturing and flexible matrix assembly upon which it relies. This skepticism may stem from these concepts being relatively unestablished within their industries and thus perceived as highly visionary.

During our recruitment process, we sought companies engaged in either remanufacturing or flexible assembly; however, only three participants reported involvement in remanufacturing practices while two indicated engagement in flexible/matrix assembly—none were involved in both areas. As previously mentioned in our interpretation of codes and categories, not every industry stands to benefit from our system due to varying relevancies tied to product types and sector characteristics.

From a methodological perspective, skepticism toward remanufacturing and flexible assembly concepts could potentially be mitigated by presenting concrete proposals during interviews; tangible topics may resonate more effectively with interviewees. We recommend conducting pre-interviews to assess participant suitability since this might prepare them for what to expect during discussions about remanufacturing and flexible assembly concepts.

Some methodological limitations include a sample that would benefit from including more companies already implementing one of these two main concepts, since many responses were speculative about future possibilities. Additionally, adherence to interview guidelines varied across sessions; consequently, some interviews took on an exploratory nature rather than strictly following established protocols.

6 Conclusion and Outlook

This paper contributes to the discourse on how remanufacturing and flexible assembly can be effectively implemented in practice by utilizing a hybrid decision-making system, highlighting both the potential benefits and relevant challenges. Our methodological approach extends existing literature by providing a practical perspective that has often been neglected, thereby balancing theoretical considerations in previous debates. Future research could focus on specific industries to achieve a more homogeneous sample, allowing for tailored conclusions applicable to different sectors. Additionally, researchers should prioritize involving affected stakeholders early in the development process of decision support systems and maintain collaboration throughout system development.

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