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Methods and Approaches for Evaluating the Repairability of Mechatronic Systems: A Systematic Literature Review

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Abstract: A suitable way to reduce the environmental impact of a product is to enhance its ability to be repaired. The repairability addresses many areas and is difficult to quantify. The presented systematic literature review aimed to identify and describe approaches for assessing the reparability. Based on developed requirements for the repair of mechatronic systems, existing methods are evaluated. This paper highlights research gaps in the evaluation of methods for increasing the repairability of mechatronic products and initial approaches to close these gaps.

Keywords: Circular Economy, Circular Product Design, Design for Repair, Mechatronics Systems, Sustainability

1 Introduction

One of the greatest challenges of the 21st century is the global climate change. There is a broad scientific consensus that decisive action is needed to counteract climate change, otherwise the negative consequences for the environment, the people but also the economy cannot be estimated. (European Commission, 2023b) Consumer purchasing behavior in particular accounts for a large proportion of the emissions generated. The established and underlying economic model is extremely lucrative and is one of the main drivers of climate change. This economic model is described with the three buzzwords: take, make and waste. Resources are extracted, products are manufactured, used and finally disposed of. Even though the repair of products is a very suitable way of extending their service life and thus reducing the negative impact on the environment. In this context, the Circular Economy (CE) represents a possible solution to counteract further environmental degradation. In general, the CE aims at a more intensive and longer utilization of products, components, and their materials. Within this economic model, there are several strategies that can be used for intensification. These are known as R-strategies and specify how the CE is implemented and how resources can be reused along the value chain. (Ellen MacArthur Foundation, 2015) Mayor R-strategies are for example Reduce, Repair and Recycle. (Potting et al., 2017) Politics has recognized the importance of the CE and has increasingly driven the topic forward. With the Circular Economy Action Plan, the European Commission has presented an extremely ambitious roadmap to transform the European Union in the direction of circular value creation. (European Commission, 2023a) Furthermore, countries are making efforts at national level to establish the CE in law as well. The Repair Index was introduced in France as a national initiative. This index provides end consumers with guidance when choosing new electrical appliances and assesses the repairability of selected product groups. (Ministry of Ecological Transition, 2021) Nevertheless, the repairability of many products can be improved. The European Union has responded to this with the “Right to Repair”. The EU is taking up this law and plans to roll it out across Europe (European Commission, 2024). Policymakers are therefore creating the legal framework for the transition to a CE. In addition to the legal requirements that must be met in the future, many companies have seen the benefits to make their products more circular. However, the development of circular products is by no means trivial but requires a paradigm shift compared to the development of products for the linear economy. (Scholtysik et al., 2022) It is challenging to make reparability measurable and comparable. Manufacturers pursue different strategies and approaches here, making it difficult for the customer to assess which product is better to repair finally.

2 Classification and motivation

Circularity is an indispensable measure for achieving climate neutrality. Therefore, the linear economic model used by companies for decades is being replaced by the circular economy (CE) concept. (Fornasari, 2022) The most used definition of CE comes from the Ellen MacArthur Foundation:

> *"A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. This new economic model seeks to ultimately decouple global economic development from finite resource consumption. A circular economy addresses mounting resource-related challenges for business and economies, and could generate growth, create jobs, and reduce environmental impacts, including carbon emissions. As the call for a new economic model based on systems-thinking grows louder, an unprecedented favourable alignment*

> *of technological and social factors today can enable the transition to a circular economy."* (Ellen MacArthur Foundation, 2015)

Potting et al. have identified nine R-Principles how to implement circular economy. Refuse, Rethink and Reduce belong to intelligent product use and manufacturing, Reuse, Repair, Refurbish, Remanufacture and Repurpose to extension of service life and Recycle and Recover refer to sensible use of materials. The focus of the circular economy is on the R-principle of repair, the fourth R-principle of Potting. Repair is the better alternative to refurbishment and remanufacturing, as this principle involves low energy consumption and the material is preserved. (Potting et al., 2017) The EU Commission focuses on the waste and circular economy primarily on repair together with reuse before recycling or energy recovery (McLaren et al., 2020). The British Standard BS8887-2-2009 has defined repair as follows: **"Repair is the return of a faulty or defective product or component to a usable condition."** (Bakker et al., 2014)**.** The principle of repair in the circular economy is becoming increasingly important (van der Velden, 2021). This is because repair extends the service life of products and reduces the need to buy new products. This allows the consumer to make savings, such as avoiding expenditure on new products, and at the same time increases the sustainability value by avoiding waste. Repair is seen as "green growth" in market-based government interventions that are supported by companies (McLaren et al., 2020). Repair and maintenance of a defective product so that it can be used with its original function. It includes both the repair of non-functional parts and maintenance, for example the replacement of wearing parts (Potting et al., 2017). The main goal is the extension of the service life. Due to the complexity of electrical and electronic devices, there is an increased amount of waste. This is because these products consist of different materials, components and assemblies. Europe reached a new high of 4.7 million items of e-waste in 2020 (Statistisches Bundesamt, 2023). For this reason, the manufacturer in particular must provide a favorable repair process (e.g. non-destructive disassembly). This facilitation is aimed at the product design or the repair environment (e.g. repair instructions). With the help of such indicators, the measurability of a product repair can be operationalized. However, which criteria or factors increase the repair and thus define the requirements for the manufacturer is missing as a scientific basis (Ritthoff et al., 2022).

3 Repairability of mechatronic products: Barriers and challenges

Based on literature research, challenges to repair a product have been collected and been discussed with a focus group. A focus group was established as a method for collecting early feedback. According to Krueger and Casey, a focus group is a set of participants who discuss a topic that has been chosen by the moderator. (Krueger and Casey, 2015) The discussion takes place in a permissive and nonthreatening conversation and does not aim for consensus, but rather to gain participant insights on the topic of discussion. The members of the focus group are scientific employees and company representatives from medium-sized companies. The scientific employees are experienced in the field of product development and have specialist knowledge on the subject of circularity. The represtatives from the companies have at least 5 years of experience in developing mechatronic products and contribute practical experience. Sustainability and Circular Economy are main goals in the strategy of these companies. Factors that counteract repair are shown in Figure 1. This is not an exhaustive list of factors, but reflects not least the challenges faced by the companies involved. While a number of the identified factors may influence each other, the factors can be clustered into the following groups:

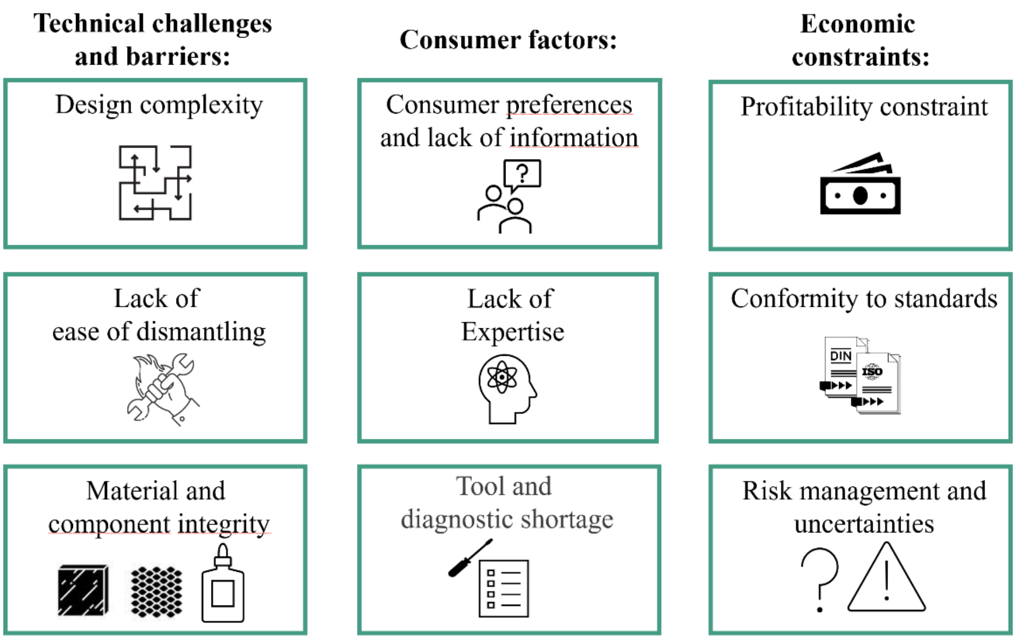

Figure 1: Challenges of repairability

Three major barriers can be identified, which are mutually dependent:

Technical challenges and barriers: The technical specifications, product design and choice of materials have an impact on the lifespan of products. The complex product designs and the inability to disassemble prevent the repair or replacement of components. With the use of connecting elements that cannot be removed non-destructively inferior materials or the use of special tools for assembly and disassembly the repairability of a product is reduced. In addition to these physical characteristics, limited access to repair information and software components plays an important role. The repair and maintenance manuals of the manufacturers are not always accessible to all reuse and repair centers and sometimes must be purchased. Furthermore, products use embedded systems whose software performs important control and regulation tasks. In some cases, access to the software for updates is not provided or manufacturers restrict access. This causes considerable problems during repairs. (Cooper and Giuseppe, 2018; Monier et al., 2016; Perzanowisk, 2022)

Consumer factors: From the consumer side, it is difficult to find qualified, reliable and available repair shops. Another challenge is the willingness of consumers to have the product repaired. Factors such as insufficient income or concerns about the inferior quality of the replacement part are problematic for consumers. The decision to have a repair carried out is hindered by a lack of information. In addition, the costs are often unclear due to the uncertain diagnosis or the cost efficiency is unpredictable if the remaining service life of the repaired product is unknown. Many people lack the necessary knowledge and skills to maintain the products. In addition, the manufacturers of electrical appliances void the warranty once a repair has been carried out. Additionally, consumer preferences for convenience and lack of awareness about repair options contribute to the reluctance towards repair over replacement. (Cooper and Giuseppe, 2018)

Economic contraints: Repairing products faces challenges stemming from supply chain and economic factors. Difficulties in procuring necessary parts or tools, combined with the financial constraints of repair not being financially viable for manufacturers, often impede repair initiatives. A central problem lies in the closed spare parts markets and monopolies in which some manufacturers supply their spare parts exclusively to selected partners. Manufacturers are not obliged to guarantee the availability of spare parts or other relevant materials over the entire life cycle of their products. This hinders competition and the independent repair sector has limited access to original spare parts or compatible components. The availability and prices of spare parts are seen as the biggest problem (Monier et al., 2016). The Waste Electrical and Electronic Equipment (WEEE) Directive (2012/19/EU), which regulates the handling of electronic waste, is a legal obstacle to repairs. Currently, the directive does not define a clear hierarchy for prioritizing repairs. Instead, repair, recycling and raw material recovery are placed on an equal footing, whereby the specified targets can only be achieved through recycling and recovery. Furthermore, the Directive (2012/19/EU) restricts the transportation of defective electronic products within or outside the EU for remanufacturing or recycling once the products are defined as waste (European Commission, 2020). Legislation to prevent the illegal export of waste products classifies electrical products as waste when they are discarded, which places restrictions on their disposal (Dalhammar et al., 2020; Monier et al., 2016). The main aim of trademark law is to promote fair competition and protect consumers. Regardless of their origin, manufacturers have strong incentives to use the provisions of trademark law for imports in order to restrict the flow of spare parts. In order to invoke trademark law, brand presence is required. This explains why companies place logos on internal parts such as batteries, processors and cables to prevent a third party from reproducing them. (Perzanowisk, 2022) Repair endeavors are influenced by risk management considerations and consumer preferences. Concerns about warranty voidance, uncertainties in repair outcomes, and perceived lack of initial quality may deter repair attempts.

4 Research design

4.1 Research objective

What are current approaches for evaluate the repairability? This is very difficult, especially for mechatronic products as an intersection of different specialist disciplines. An overview of the best approaches for developers is missing. The main objective of this SLR is the identification of currently existing methods and approaches for the evaluation of the repair work of mechatronic products. These highlighted approaches are briefly summarized and then evaluated in relation to its requirements.

4.2 Systematic literature review

To fulfill the research objective, we conducted a systematic literature review (SLR), following the eight steps of Xiao and Watson sequentially (Xiao and Watson, 2019). The main goals are the delimitation of the existing evaluation methods and approaches with partly focus on product architecture. Beginning with the planning of the review we formulate three research questions with the three different focus areas according to the research goals.

1. What impact does the product architecture of mechatronic systems have on repairability?
2. What requirements must be considered in the design of mechatronic systems to ensure reparability for circular product design?

3. Which indicators can be used to assess the reparability of mechatronic systems?

As the search engine ScienceDirect produced the most hits for the selected search string, the two other search engines under consideration, Web of Science and SCOPUS, were excluded. It is crucial to ensure that all relevant literature is captured in these results. Therefore, different synonyms of architecture are combined with repairability, requirements and circular economy. The search string is formulated below:

(("product architecture" OR "system architecture" OR "product design" OR "product development") AND ("repairability") AND ("indicators" OR "requirements" OR "measurability") AND ("circular economy"))

Figure 2 visualize the elimination of the papers. The longlist of 453 papers based on the search string in the search engine ScienceDirect. With the help of the first research questions the titles are rated with "-1 (irrelevant)", "0 (unclear)" or "1 (relevant)". This removes the articles that are assigned a "-1". If the article is assigned a "0", the relevance of the paper is not clear and will therefore be discussed in a new round. If the title is assigned a "1", it will be kept. (Xiao and Watson, 2019) After all steps with forward and backward search, there were 23 final papers left.

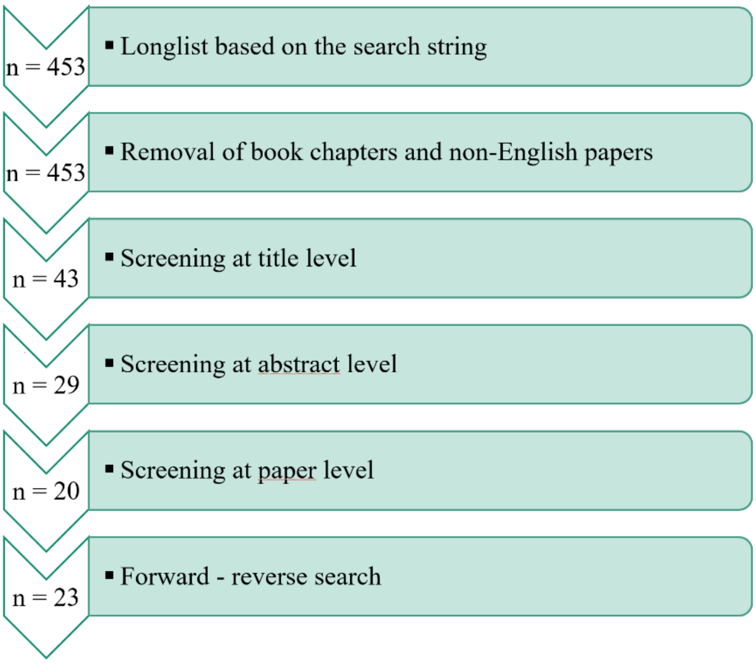

Figure 2: Procedure of Systematic Literature Review

The articles are evaluated with the help of a qualitative content analysis according to Mayring. The aim of this qualitative content analysis is to develop a systematic methodology for interpretation. Structuring to filter the information is the most central content analysis technique. This structure is applied to the amounts with the help of a category system. The text components that are captured by a category are extracted from the material. Which text excerpt can be assigned to a category must be precisely defined. The procedure, based on the categorization theory from general psychology, is based on the three steps definition of the category, anchor example and coding rules. The relevant text passages are searched for and assigned to the defined category. If there is a clear text passage for this category, this is used as an anchor example. If a passage cannot be clearly assigned, a delimitation rule is drawn up. (Mayring P., 2010) This context gives rise to the categories of consumer perspective and industry perspective. The consumer perspective, on the other hand, refers to the demand side of the repair market, with the individual consumer playing a central role. The decision to participate in repair activities is influenced by many factors that can vary for each individual actor. In the case of a defective product, the consumer generally has four options for action. First, he can consult the seller, the manufacturer's repair department or an authorized repair service provider. Alternatively, he can carry out the repair himself. A third option is to go to an independent repairer. Finally, the consumer can dispose of the defective device and purchase a replacement product. (Svensson-Hoglund et al., 2021) This results in three options for action that represent a category. The *perception* perspective focuses on how consumers perceive the need for repairs. The *motivation* perspective looks at the driving forces that cause consumers to opt for repairs. Finally, the *decision* refers to the process a consumer goes through when confronted with a defective product. Rational or emotional decisions can be made and these reflect the individual preferences and needs of the consumer. (Nazlı Terzioğlu, 2021) The industry perspective can be differentiated into *manufacturer*, *state*, *repair service* and *repair café*. The *measurability* of the repair is operationalized through measurable indicators. The indicators that influence repairability can be divided into two categories: those that are aimed at the product design (e.g.

non-destructive disassembly) and those that concern the repair environment (e.g. repair instructions). The most important category from an industry perspective is the *assessment*. The results are presented in the following chapter 4.3.

4.3 Results

At the end there are the following 17 approaches below:

1. **ONR 19202:2014**

   A durability mark for electrical and electronic appliances was published by the Austrian Standards Organization in 2006. It emphasizes reparability and comprises *40 criteria for white goods and 53 for brown goods*. The criteria are divided into must and should criteria, whereby a graduated scale enables the final assessment of reparability and durability, but the assessment can be subjective. (Ritthoff et al., 2022)

2. **iFixit/Flipsen**

   iFixit is a global support *platform for repairing electronic products evaluated by experienced technicians using a scorecard comprising 26 criteria* covering aspects like information availability, spare parts access and required repair tools. The overall score, ranging from 0 to 10, aims to inform consumers about repairability, with guides for battery, display, and part replacements provided alongside model-specific repairability assessments. (Ritthoff et al., 2022)

3. **ease of Disassembly Metric (eDIM)**

   The ease of Disassembly Metric provides *quantitative data on disassembly time and difficulty*, derived from the Maynard Operation Sequence Technique (MOST) reference time values. It breaks down disassembly tasks and assigns time values but may overlook variations in repair processes. (Ritthoff et al., 2022)

4. **Maynard Operation Sequence Technique (MOST)**

   Maynard Operation Sequence Technique is a predetermined *motion time system* outlining time for basic actions performed by an average worker. It employs letters and indices to represent task types and variations respectively. While enabling systematic analysis of workflows, it overlooks repairability factors and lacks consideration of consumer or technician perspectives directly. (Fazio et al., 2021; Ritthoff et al., 2022)

5. **Unfastening-Effort (U-effort)**

   Sodhi developed the Unfastening-Efford to aid designers in implementing Design for Disassembly (DfD), aiming to *calculate disassembly time for connectors based on physical attributes*. Using the Unfastening-Effort-Index (UFI), it factors in key features influencing disassembly time, like size and shape. Calculations are in seconds for an average worker. While it offers a structured approach focusing on physical properties, it neglects qualitative repairability aspects like spare part availability. (Ritthoff et al., 2022; Vanegas et al., 2018)

6. **Desai & Mital Design-for-Disassembly (DfD)**

   Desai and Mital devised a Design-for-Disassembly (DfD) method to *determine disassembly time based on five factors: force, material handling, tool usage, accessibility of components, and tool positioning*. It employs Method-Time Measurement (MTM) technique to evaluate disassembly tasks by difficulty level. While it aids in identifying and integrating design requirements for disassembly, it lacks detail and overlooks some specific repairability aspects. (Ritthoff et al., 2022; Vanegas et al., 2018)

7. **Philips End-of-Life Costing (ECC)**

   The Philips End-of-Life Costing, developed by electronics manufacturer Philips, *calculates disassembly time using a database with standardized times* for common connector releases and specific disassembly tasks. Times in this method are derived from measurements during actual disassembly sessions, indicating a systematic and objective approach. While utilizing standardized times provides structure, adaptability to diverse contexts may be limited. (Ritthoff et al., 2022; Vanegas et al., 2018)

8. **Kroll Method**

   Kroll devised a design method to *identify disassembly time reduction potentials*, combining MOST (s. approach no. 4) and manual disassembly tests on computers, keyboards, monitors, and printers. It comprises 16 basic disassembly tasks and four difficulty categories. Despite offering a quantitative basis for comparing designs, it prioritizes disassembly time, potentially overlooking qualitative design aspects like eco-friendly materials or modular designs. Yet, it finds application across various electronic products. (Ritthoff et al., 2022; Vanegas et al., 2018)

9. Method Time Measurement (MTM)

The Methods Time Measurement system was the *first publicly available time-motion system*. MTM is used to validate experimental assembly time estimates for design for manufacturability and assembly. It empirically determines the time for individual motion steps and aggregates them for specific tasks. MTM's focus on time data and motion sequences may limit consideration of user-friendliness or parts availability, potentially obscuring conflicts between design aspects. (Syska, 2006)

10. Eco-modular Product Architecture

This *method assesses product modularity* through sequential steps aimed *at facilitating product reuse*. It starts with a Design Structure Matrix (DSM) to depict component relationships. Sustainable modular drivers are identified to group components into modules. The DSM and sustainable values are then transformed into an adjacency matrix and processed using the Markov Cluster Algorithm (MCL). Module similarity and lifecycle similarity metrics are introduced, culminating in End-of-Life Modularization (MEOL) evaluation for product reusability. (Kim and Moon, 2019)

11. Specific Reconfiguration Complexity Index (SRCI) & Total Reconfiguration Complexity Index (TRCI)

This method employs two metrics to *assess assembly and disassembly complexity in products with an open architecture*. The Specific Reconfiguration Complexity Index evaluates the complexity of each product variant, while the Total Reconfiguration Complexity Index considers the complexity across all variants, factoring in the number of modules and variants. It analyzes assembly and disassembly through product reconfiguration, visualizing results in matrices to identify module dependencies and assembly/disassembly modules with color-coded relationships. (Mesa et al., 2018)

12. Eco-architecture

Eco-architecture delineates a *product's architecture while considering its lifecycle attainment*, dividing it into modules and depicting their interactions. It examines connections between end-of-life (EOL) modules, their geometric arrangement, and physical structure crucial for disassembly and recycling. It aids developers in selecting redesign measures and provides insights into EOL module interactions. The module identification process involves three steps, culminating in the optimization of eco-architecture through linear programming models and AND/OR graph-based methods. (Kwak et al., 2009)

13. The Disassembly Map

The Disassembly Map method *evaluates disassembly processes on a product map*, based on literature review, analysis of seven vacuum cleaners, and using eDiM and MOST. It depicts product architecture using logic representations, action blocks, coding, penalty points, and target indicators. Components are illustrated by circles, with logic representations including sequential dependency and multiple dependency, aiding (re)design for reparability. (Fazio et al., 2021)

14. French Repairability Index

In 2021, France implemented a *regulation mandating manufacturers to label their devices with a special indicator informing consumers about repair possibilities*, in line with the 2018 Circular Economy Anti-Waste Law. This Repairability Index aims to increase repair rates for electronics, covering five specific categories like smartphones, washing machines, laptops, TVs, and lawnmowers. It includes criteria such as availability of information, ease of disassembly, spare parts availability, spare part pricing relative to product cost, and product-specific aspects, integrating constructive requirements while considering consumer and service provider perspectives. (Ritthoff et al., 2022)

15. Joint Research Center (JRC) Analysis

In 2019, the Joint Research Center *developed a repairability assessment system for laptops, vacuum cleaners, and washing machines*, based on insights from CEN-CENELEC-JTC10 and EN 45554. The method includes 12 parameters, assessing both product design and repair processes, with criteria distinguishing essential repairability (must) from upgradability (should). Economic indicators like spare part costs are considered. The systematic approach and adaptation demonstrate its practicality and clarity. (Ritthoff et al., 2022)

16. DIN EN 45554

The Technical Committee developed the European standard DIN EN 45554, featuring a *13-indicator assessment procedure for evaluating repairability, reusability, and upgradeability of energy-related products*. Each indicator, ranging from disassembly depth to spare parts availability, is categorized alphabetically from A to F, with higher values indicating better repairability. Despite its systematic approach and structured assessment, this method overlooks the consumer perspective. (Matarin et al., 2022; Rodríguez et al., 2023; Ruiz-Pastor and Mesa, 2023)

17. Benelux Repairability Criteria

The KU Leuven conducted a study commissioned by the Benelux Union to *quantify the repairability of energy-related products, considering economic impacts from a consumer perspective*. Researchers devised a generic approach based on 24 criteria, evaluating repairability in five steps: product identification, fault diagnosis, disassembly and reassembly, replacement of parts, and restoration of operational status. By combining these steps with indicators, a matrix for assessment was created, allowing for a total of 164 points. The developed repair matrix underwent testing using a washing machine and a vacuum cleaner, considering perspectives from both private individuals and professional repair businesses. (Bracquene et al., 2019; Ritthoff et al., 2022; Ruiz-Pastor and Mesa, 2023)

5 Application of the new design guidelines

5.1 Product architecture

The chosen combination of search terms provides only minimal results for the product architecture, which is part of the first research question: What impact does the product architecture of mechatronic systems have on repairability? It is noted that a modular product architecture has the advantage over an integral product architecture that product components can be exchanged more easily (Fazio et al., 2021). Therefore, the product architecture is also part of the requirements for reparability in chapter 5.2. However, how exactly the modular product architecture is to be designed is not dealt with in these papers due to the limited results of the literature recherche.

5.2 Requirements for repairability

Analyzing these 17 methods provides an answer to the second research question: What requirements must be considered in the design of mechatronic systems to ensure reparability for circular product design? This wealth of barriers results in the following 7 suitable, but not exhausting requirements for methods and approaches to evaluate the repairability.

1. **Disassembly:** The reparability of a product depends largely on the disassembly. An important component is the possibility of non-destructive disassembly, which makes it possible to dismantle the product without damaging it. The availability of special tools also plays a role, as some products may require specific tools to disassemble them. The number of steps required for disassembly is also an important factor, as a high number of steps can make the repair more complex and time-consuming.
2. **User:** The repairability of a product is also strongly influenced by the skill level of the user and their working environment. An experienced technician with access to a well-equipped workshop can often carry out repairs more effectively than an inexperienced consumer without the appropriate knowledge and tools. The work environment, including the availability of space and lighting, can also affect repair capability.
3. **Spare parts:** The availability, price and accessibility of spare parts over the lifetime of the product are critical criteria for repairability. Spare parts should not only be readily available but should also be offered at an affordable price. It is also important that spare parts are also available for older product models to ensure long-term reparability.
4. **Documentation:** Clear and comprehensive documentation about the product and its repair instructions is essential to facilitate repairability. This documentation should not only include disassembly and repair instructions, but also information about the materials, components and circuit diagrams used. Well-structured and easily accessible documentation can make repairs more efficient.
5. **Manufacturer support:** Support from the manufacturer plays an important role in the reparability of a product. This includes both the availability of customer service interfaces and the provision of repair services by the manufacturer. Good manufacturer support can help make repairs faster and more effective.
6. **Warranty**: The warranty conditions of a product can have a negative impact on repairability, especially if repairs result in the loss of the warranty. This can discourage consumers from carrying out repairs themselves or using third-party repair services. The terms of the warranty should therefore be transparent and any potential impact on repairs should be clearly communicated.
7. **Weighting:** One possible approach is to assign a weighting to each criterion based on its importance for the overall reparability of the product. For example, criteria such as the availability of spare parts or documentation could be given a higher weighting, as they have a direct influence on the feasibility and success of repairs.

However, it is important that the weighting of the criteria is transparent and comprehensible. Ideally, the weighting should be carried out in consultation with experts from various relevant areas in order to ensure a balanced assessment. In addition, the weighting should be flexible and can be adjusted according to the specific requirements and characteristics of the product under consideration. For example, in some cases the availability of spare parts may play a greater role than dismantling capability, while in other cases the opposite may be the case. It is important that the weighting method is adaptable to suit the different contexts.

5.3 Assessment of reparability

After describing each approach more in detail in chapter 4.3, an evaluation system is required to determine the repairability of a mechatronic system. This is necessary in order to answer the third research question: Which indicators can be used to **assess the reparability** of mechatronic systems? The existing 17 approaches are the most frequently mentioned methods of the 23 papers in the systematic literature review for assessing the reparability.

The following Figure 3 visualize the evaluation of the 17 methods and approaches according to the 7 requirements disassembly, user, spare parts, documentation, manufacturer support, warranty and weighting. The rating scale is divided into not fulfilled, partly fulfilled and completely fulfilled. The methods are divided into quantitative, semi-quantitative and generic approaches. **Qualitative assessments** define dichotomous indicators that must be fulfilled in order to classify a product as repairable. These assessments therefore represent a checklist that is used to individually check whether the device fulfills or does not fulfill the requirement. No approaches or methods are mentioned in this paper according to the repairability. The checklist with the parameters of the qualitative assessment serves as a basis for **semi-quantitative assessments**. Instead of only checking whether the indicators apply or not, several alternatives are defined for each indicator, which are assigned to a graded evaluation (e.g. repair instructions are freely accessible (1), repair instructions are only freely accessible for authorized repair shops (0.5), repair instructions are not freely accessible (0)). Different scales, such as numerical or alphabetical, can be used. If some indicators are more relevant than others, they can also be weighted. In a **quantitative assessment**, several individual indicators of one or more dimensions are combined to form an index that measures the degree of reparability of the product. A decision must be made according to the included index and how the dimensions are combined with each other (e.g. additive, multiplicative). **Generic approaches** are overarching approaches. These methods strive to develop a superordinate evaluation system. (Ritthoff et al., 2022)

	No.	Approaches and methods	Requirements						
			R1	R2	R3	R4	R5	R6	R7
Semi-quantitative methods	1	ONR 192102:2014	○	○	◑	○	○	○	◑
	2	iFixit/Flipsen	●	●	◑	●	○	○	◑
Quantitative methods	3	ease of Disassembly Metric (eDiM)	●	◑	○	○	○	○	◑
	4	Maynard Operation Sequence Technique (MOST)	◑	◑	○	○	○	○	○
	5	Unfastening-Effort (U-effort)	◑	◑	○	○	○	○	○
	6	Desai & Mital Design-for-Disassembly (DfD)	◑	◑	○	○	○	○	◑
	7	Philips End-of-life Costing (ECC)	◑	◑	○	○	○	○	○
	8	Kroll Method	◑	◑	○	○	○	○	○
	9	Method Time Measurement (MTM)	◑	◑	○	○	○	○	○
	10	Eco-modular Product Architecture	●	◑	○	○	○	○	◑
	11	Specific Reconfiguration Complexity Index (SRCI) & Total Reconfiguration Complexity Index (TCRI)	●	◑	○	○	○	○	◑
	12	Eco-architecture	●	◑	○	○	○	○	◑
	13	The Disassembly Map	●	◑	○	◑	○	○	◑
Generic approaches	14	French Repairability Index	●	●	●	●	◑	○	●
	15	Joint Research Centre (JRC) Analysis	◑	◑	◑	◑	◑	○	◑
	16	DIN EN 45554	●	◑	●	●	◑	○	●
	17	Benelux Repairability Criteria	●	◑	●	◑	●	●	●

R1 disassembly
R2 user
R3 spare parts
R4 documentation
R5 manufacturer support
R6 warranty
R7 weighting

Rating scale
● completely fulfilled
◑ Partially fulfilled
○ Not fulfilled

Figure 3: Approaches and methods

As shown in Figure 3, different approaches cover different requirements. There is no method that completely fulfills all of the requirements. The semi-qualitative methods and quantitative methods only partially meet the requirements. Especially the requirements spare parts, documentation, manufacturer support and warranty are not fulfilled. These requirements are not mentioned in the approaches. The generic approaches have the best overlapping. iFixit, French

Repairability Index, the DIN EN 45554 and the Benelux Repairability Criteria achieve the best results. iFixit is an interdisciplinary approach and the platform combines positive aspects such as accessibility, tools and documentation. Nevertheless, it lacks a guarantee, integration of the developers and the support of the manufacturers. The French Repairability Index considers requirements such as the availability of information on exploded drawings and operating instructions. Dismantling factors, spare parts, availability and the prices of spare parts are also included in the assessment. There is contact with the manufacturers, but without a customer support interface. The warranty requirement is not covered as well. The DIN EN 45554 includes 13 indicators for evaluation, most of it cover the requirements. Requirements such as disassembly depth, tools, working environment, availability of spare parts, types and availability of information are considered. Manufacturer support is partly covered by the consideration of diagnostic support and the warranty is missing. Almost all requirements are covered by the Benelux Repairability Criteria. The availability of information such as repair manuals and maintenance instructions are taken into account, as well as the difficulty of disassembly and accessibility. The availability of service and warranty is also assessed. Both, the perspective of a private individual and of a professional repair company are included in the assessment. The criteria mentioned are evaluated using a weighting system. The service includes the availability of spare parts, warranty and a return system. However, the working environment for the user and the accessibility and price of spare parts are not considered. The applicability for the developer can be improved as well. Finally, none of the methods described can meet all requirements for a systematic approach completely to increase the reparability of mechatronic products.

6 Conclusion and next steps

In the future, companies have to become more sustainable and implement circular economy approaches. This is also motivated by political considerations. The reparability of a product is difficult to assess and quantify, especially for mechatronic systems. The SLR shows the methods and approaches for evaluating the repairability of mechatronic systems. But finally, no approach fits the challenges and requirements perfectly for quantifying the different areas of repairability. This paper presents research gaps according to the assessment of methods to increase the repairability of mechatronic products. For closing these gaps, a new method and approach is necessary. By analyzing every method according to the requirements, it could be possible to take the best points from each approach and synergize them into a new approach. The rethink of some approaches could be helpful as well. These are our next steps for the main goal to evaluate the repairability and will be presented soon.

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