Approach for Structured Repairability Assessment for Automated Repair Processes

Hannah Lickert[1(✉)], Tobias Lachnit[2], and Franz Dietrich[1]

[1] Technische Universität Berlin, Institute of Machine Tools and Factory Management, Chair of Handling and Assembly Technology Research, Pascalstraße 8-9, 10587 Berlin, Germany
h.lickert@tu-berlin.de

[2] Wbk Institute of Technology, Karlsruhe Institute of Technology (KIT), Kaiserstraße 12, 76131 Karlsruhe, Germany

Abstract. Repair is a crucial process to recover resources and reduce waste within a circular economy. Automating manual and laborious repair processes has the potential to establish greater economization and efficiency. While research on assessing product repairability exists, there is currently limited research specifically focused on the repairability regarding automated processes. Therefore, this paper investigates the existing knowledge on automation, manual and automated repair processes from theory as well as practical applications, to identify benchmarks for reparability assessment for automated processes. Based on these requirements, solutions, processes, and operating resources are identified. A standardized and structured approach for evaluating the repairability of products for automated repair is proposed. This research also highlights the economic and ecological advantages, as well as the sustainability challenges and potentials of using automated repair processes. Overall, this research contributes to the development of a more sustainable and efficient CE through the advancement of automated repair processes.

Keywords: Repair · Repairability Assessment · Automated repair

1 Introduction

The transition towards circular economy is vital in view of the climate crisis. Currently, the global economy operates only at a circularity level of merely 7.2%, which has also declined nearly 2% over the past five years [1]. While the circular economy framework primarily emphasizes remanufacturing and recycling, the vital role of repair often remains overlooked. Repair, however, constitutes an indispensable component of the circular transformation, offering both economic and ecological advantages [2]. Among the various options to recover value, repair stands out as a process with low cost and labor intensity as well as energy consumption. However, as compared to remanufacturing it involves reduced warranty, reliability, and performance of the product [3, 4].

But the political focus on product reparability is growing. Corresponding measures address the right to repair, assess repairability and facilitating reuse of electronic and

H. Kohl et al. (Eds.): GCSM 2023, LNME, pp. 391–398, 2025.
https://doi.org/10.1007/978-3-031-77429-4_43

electrical waste, such as the the circular economy action plan of the European Commission, the DIN EN 45554 on the assessment of the ability to repair, reuse and upgrade energy-related products and the EU directive on waste electrical and electronic equipment [3, 5, 6]. These regulations highlight the necessity for the effective recovery of electronic and electrical waste to achieve long-term climate objectives.

Regardless of the necessity and feasibility, product repairability depends on the monetary investment required for the repair process, as it competes with product replacement [7]. This is a challenge establishing repair, especially for low-priced products and in countries where labor costs and spare part expenses are high. The integration of automation technologies offers opportunities to reduce manual labor costs and increase the efficiency of the repair process. Nevertheless, economies of scale must be incorporated for automation. Considering the mass production of electronic and electrical products and assuming a product service system or similar business models, the repair of similar products can be centralized in large quantities. Therefore, it becomes essential to explore how repairs can be efficiently performed automated for large quantities, enabling environmentally friendly circular economy practices.

Chapter 2 covers the barriers and limitations for repair in general and the potential for automated repair as well as its current implementation in practice. To create a basis for assessing whether products and processes are suitable for automated repair, a structured approach is developed in Chap. 3. Concluding in Chap. 4, that even though automated repair holds great potential, technical solutions to make automation more versatile are still being developed, which will allow further possibilities in automated repair.

2 Potentials of Automated Product Repair

Although repair is possible and significant efforts have been made by policymakers, manufacturers, and repair initiatives, there are barriers and limitations that prevent repairs from being offered commercially on a large scale. To overcome these barriers the automation of repair processes offers a potential. In order to understand what is intended by automated repair and how this can reduce barriers, the term repair and the existing automation solutions must first be examined. The potential for automating repairs is then derived on the basis of the identified barriers to repair.

The intension of repair is defined by Thierry et al. as: “to return used products to working order” [4]. Meaning, that the”quality of repaired products is generally less than the quality of new products” [4]. General process steps of repair are inspection, disassembly, repair, reassembly, and functional test. These steps can be repeated iteratively until the function of the product is restored, as shown in Fig. 1.

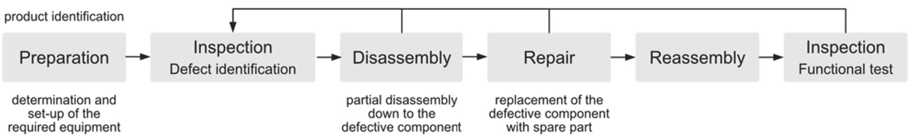

Fig. 1. General process steps of repair

Currently, only repairs by replacement are considered in the examination, meaning repair at the product level including the replacement of defective components and parts with spare parts. This reduces the complexity of the overall process and focuses on the automation potential of (dis)assembly and handling operations.

The term automated repair is often used in connection with automated maintenance or refurbishment and can be clearly distinguished from automated program repair in the software field, yet no uniform term usage was found in literature. Using the definition of automation and repair, automated repair is specified in this paper as: Automated product repair is the process by which machines or computer-controlled systems perform partially or fully automated repairs on products to restore their functionality.

Automated repair is being selectively applied in some industries on material, component, and product level. At the material level, the repair of turbine blades by automated laser powder build up welding is an example, or the repair of rotor blades as maintenance of wind turbines [8]. At the component level, the automated repair of electronic components, e.g. circuit boards, is widely applied and already scientifically elaborated in the mid-1990s [9]. At the product level, some applications have been developed for the automotive industry, such as automated tire changing using image recognition and machine learning [10].

2.1 Barriers and Limitations of Repair

A list of factors was compiled that hinder users from engaging in repairs, which are categorized into the general aspects regarding economic and ecological sustainability, product, and process related aspects. The most relevant are explained as follows.

General. The repair must be economically and ecologically sustainable as well as safe and reliable. From an economic point of view, the cost of repair exceeds the customer's profit margin or willingness to invest. In addition, due to an improperly performed repair and bad experiences, some users associate repaired products negatively, while repair is generally considered to be more resource-efficient than other recovery processes. This does not apply in particular and must therefore be individually assessed and verified that the repair is also ecologically beneficial [5, 11]. Maintenance and repair for high-quality products and especially those for commercial use are established, as these products are often designed for longer periods of use, whereas for low-quality products, the effort and cost of repair are not viable. Automation can create economic efficiency for low-priced products in repair through economies of scale.

Product. A significant reason for reduced reparability is the limited availability of spare parts, documentation, and repair information. Also, the product design is crucial, as it often leads to unfeasible or complex repair processes [11, 12]. These aspects become especially important for automation, which raises additional requirements for the design and information set of the product. Furthermore, the product is decisive for the design of repair offers. In addition to repairability, the value of the product and the available quantity play an important role. Obtaining enough defective products is obvious for automation, but knowledge and equipment must also be gained in preparation for manual assembly.

Process. Manual repairs are associated with a high effort of time either a specialized repairer with product-specific knowledge is required, which is often difficult to obtain, or the private repairer must acquire this knowledge, which is limited by his willingness, skills and the effort involved [11]. In addition, quality variance can arise in manual repair depending on the skills of the repairer [13]. These factors can be addressed by automation, but the difficulty in scheduling repair processes presents a challenge. Also, automated resources must achieve a level of flexibility and adaptability that allows for consistent processing across a variety of different repair cases [14].

In summary, several barriers to repair can be identified, including the time required for repairs, the costs associated with manual labor, the need for reliable and consistent quality of repairs. The automation of repair processes enables the economic repair of products in large quantities while maintaining consistent quality [13]. Automated repair is already being applied on the material, component, and product level. However, there is a lack of research establishing general principles, regarding requirements, processes, and development of automated repair applications.

This work aims to give an overview for requirements and an approach to assess the feasibility of automated repair applications on a product-level, to provide fundamentals. Tools exist for assessing the reparability of products and processes for repair are being studied. But product and process required for repair need to be considered coherently, to evaluate whether they can be implemented, automated and thus applied on a large scale. Since circular processes are integrated into closed-loop systems, general criteria are included in the consideration. Thus, for the structured approach, requirements are first specified in the three areas of product, process including equipment and general aspects, derived from literature and the above-mentioned barriers. Proceeding from this, a workflow is created to apply these requirements in a structured manner.

3 Structured Approach to Assess Automated Repair Processes

The developed approach consists of two elements: a list of requirements regarding criteria about the product, process and equipment and general factors related to automated repair; and a workflow as a kind of guide for the sequence and purpose of using the requirements list.

3.1 List of Requirements

The list of requirements was compiled based on literature and derived from the barriers described. The list does not claim to be exhaustive, but since it is quite extensive, only an overview is presented here, and the complete list is assessable via the platform DepositOnce[1] of the TU Berlin.

Product. These requirements address product features concerning general repairability, condition, and automated repair. For example, that the product:

– has documentation, which includes repair instructions and information.

[1] https://depositonce.tu-berlin.de—The file will be published with DOI for the final publication on this platform. For submission, the file was attached to the paper.

– has no contamination or deformation, which affects the process.
– has visible and automated separable connecting elements.

Process and equipment. These requirements relate to general versatility of equipment including software, actuators, end effectors and sensors for process execution, data processing, detection, control, and inspection. for example, that the equipment offers:

– low-effort and reusable programming of the system.
– universal fixture and handling of different product variants.
– automatic recognition of product information, connecting elements and defects.

General. These requirements include economic and ecological criteria. Additional organizational and market factors are included. For example, that:

– the expected number of units and the value added is sufficient.
– the availability of spare parts is given.
– the automated repair is beneficial compared to manual processes, new purchase, or other recovery methods.

3.2 Workflow

In order to assess the feasibility of an automated repair process, several steps are necessary. These steps are divided into product, process, and general factors. Through iteration loops, emerging obstacles can be overcome by the manual execution of a process step, measures to increase sustainability or the redesign of the product. In the following this procedure is illustrated by Fig. 2 and described in detail below.

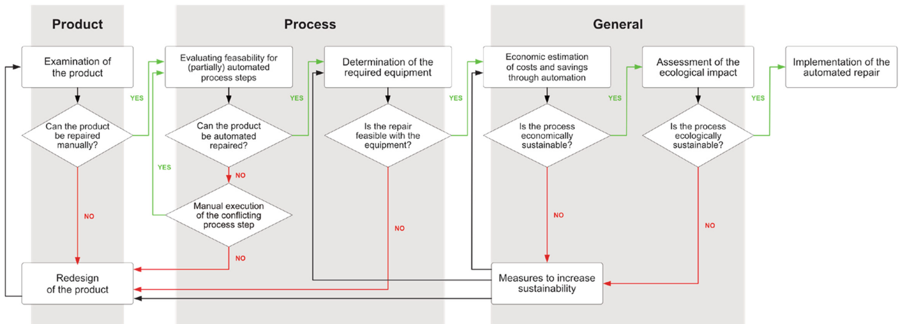

Fig. 2. Workflow to assess the feasibility for automated repair.

Product. During the examination of the product the manual repairability is evaluated. This requires a definition of all repair cases and verification of the availability of appropriate spare parts. It is important to identify and analyze potential product-related obstacles that could affect repair. By examining manual repairability, potential deficiencies in the product can be identified early and appropriate measures can be applied. If it becomes apparent during the evaluation process that manual repair is not feasible, a redesign of the product is required.

Process. For evaluating the feasibility of automating process steps, it is necessary to expand and breakdown the manual repair processes. Subsequently, each individual step of the repair process must be examined regarding its automatability, whereby the following Table 1 can serve as a guide. If it is not possible for certain process steps, manual execution must be considered as an alternative.

Table 1. Assessment of the option to automize the process steps.

No.	Process step	Substep	Automation option
1	Preparation	Product identification Determination of the required operating resources Set up with required equipment	
2	Inspection	Incoming inspection (deformation/contamination) Defect identification	
3	Disassembly	Defect specific derivation of disassembly steps Disassembly step 1 to n Intermediate storage of components Check for complete execution	
4	Repair	Replacement of the defective unit Deposit of the defective unit	
5	Reassembly	Reassembly planning Picking up the components from intermediate storage Resassembly step 1 to n Check for complete execution	
6	Inspection	Functional test	

The determination of the required equipment is aligned with the product to be repaired. Suitable end effectors, such as grippers and screwdriving systems, which are necessary for a successful repair, must be selected. The selection of the appropriate systems depends on both the complexity of the task and the scope of the automated processing.

General. The factors influencing economic efficiency include the costs resulting from processing time for machines and equipment, for manual labor, and for setting up the automated repair. Since the setup costs are dependent on the number of pieces, a quantity estimation should be conducted in advance. Depending on the required accuracy, process times can be estimated by an expert employee, a simulation, or a calculation.

The assessment of the ecological impact is only partially quantifiable. The repair process is usually ecologically sustainable since most of the value is retained, and a completely new product has usually a higher ecological impact. This is also shown by Bracquené's study on the example of laptops [15]. But the process can also entail ecological disadvantages, especially in the case of a failed repair or energy-intensive products. It is necessary to consider the effort of repair in relation to various alternatives, such as buying a new product as well as the expected extension of the product's service life. In terms of automation per se, based on Wang's study, repairs performed by robots compared to human labor is expected to lead to lower environmental impacts [16]. One method to quantify the ecological impact is to perform a life cycle assessment.

The implementation of the automated repair can be realized, presumed that all relevant criteria are met. For this purpose, the corresponding operating resources must be procured, and the system must be set up. After the functionality of the repair process has been successfully confirmed by tests, the serial repair can begin.

4 Conclusion and Outlook

Automated repair holds great potential for ecologically and economically sustainable product repair in large quantities. By automating monotonous and repetitive manual repair tasks, future-oriented, safe, and ergonomic work environments ensuring consistent quality are enabled. Compared to remanufacturing, automated repair offers advantages in terms of efficiency, energy consumption, and cost-effectiveness. It complements existing methods and enhances product circularity. The benefits could drive a greater realization of circular services. To advance automated repair, this study outlines basic requirements for finding new solutions. By integrating repair, automation, and additional criteria into a comprehensive list, the necessary preconditions for automated repair were detected. This facilitates evaluation and measures for users who want to automate product repairs, considering criteria for automated during repair planning and development.

Several obstacles hinder the widespread realization of automated repair. However, integration within a centralized circular economy, alongside remanufacturing, could enhance its role in sustainable value chains. Manual repair still possesses advantages in flexibility, simplicity, and setup requirements. Nonetheless, trends in automation technology, rising wages, and increasing product repairability favor the application of automated repair. Despite its potential, the complexity of automated repair compared to manual repair remains a challenge. Handling the variability of used products and enabling easy programming of different processes are unresolved issues. Intelligent fault detection and functional control are essential for fully automated processes. Further research is needed to advance automated repair and address these complexities.

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