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Understanding Decision Making for Reuse, Repair, and Refurbishment in the Dismantling of End-of-Life Heating Pumps

Jan-Philip Kopka[a], Anna Preut[a], Christian Hohaus[a]
a) Fraunhofer Institute for Material Flow and Logistics IML, Dortmund, Germany

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Abstract: The research project "Resource Efficiency through smart Pumps" (ResmaP) aims at increasing the overall resource efficiency of heating pumps with their entire lifespan in mind. While the energy consumption of modern pumps is low compared to previous generations, the resource intensity of the products themselves is increased and the number of different materials used in the parts and components is higher than it previously was. One aspect to increase resource efficiency is prolonging the lifespan through software updates and remote maintenance processes. However, there are cases in which mechanical errors or other physical damage occur that require the exchange of a device. In these cases, the project aims at reusing and refurbishing parts extracted from reclaimed end-of-life pumps. Deciding how to proceed depends on information collected throughout the pump's lifecycle and other factors such as the physical condition of the pump as well as the dismantling process itself resulting in a complex decision-making problem with several steps and decision points. Understanding the decision making for the cycle management process involves three steps: Mapping dismantling processes and identifying decision points helps to understand the processes involved and allows for the following step of Identifying decision problems. For each decision point in the process, the nature of the decision problem at hand is identified. A selection of decision support methods can be applied to support dismantling and recycling decisions and methods for each step. Finally, decision parameters the methods mentioned previously have to be identified and data requirements are derived.

Introduction

The research project "Resource Efficiency through smart Pumps" (ResmaP) aims at increasing the overall resource efficiency of heating pumps with their entire lifespan in mind. One aspect is prolonging the lifespan through software updates and remote maintenance processes. However, there are cases in which mechanical errors or other physical damage occur that require the exchange of a device. In these cases, the project aims at reusing and refurbishing parts extracted from reclaimed end-of-life pumps. Furthermore, the remote surveillance of the pump status will allow for a better error diagnosis leading to a more targeted replacement of parts thus reducing spare part consumption. Deciding how to proceed depends on information collected throughout the pump's lifecycle and other factors such as the physical condition of the pump as well as the dismantling process itself resulting in a complex decision-making problem with several steps and decision points.

In this paper, we aim to identify decision points, classify the corresponding decision-making problems, and offer insight into possible ways to decision making for these points as well as data requirements connected to these.

Decision making for the circular economy

Recently, a variety of work has been published on general decision making within and for the circular economy covering different stages of the product lifecycle such as the product design phase (Diaz et al., 2021) and the evaluation of available end-of-life options in the context of reverse logistics (Alarcón et al., 2020; Lechner & Reimann, 2020). Additionally, a number of relevant case studies have been published that focus on different decision problems and are mostly located in the field of electrical and electronic devices or vehicles (Alfaro-Algaba & Ramirez, 2020; Li et al., 2019; Raihanian Mashhadi & Behdad, 2017).

Previous research identified as relevant to this paper commonly focuses on either a single decision point, a single product, or addresses a strategic decision-making problem covering multiple circular economy alternatives. The decision problem discussed in this paper is a mixture and thus will use insight from different aspects of the referenced papers.

Decision-making problems that can be solved by or supported through computers are often characterized using a 3-by-3 matrix covering structured (the way to obtain the best solution is known), unstructured (both the articulation of the problem itself and ways to its solution are unstructured and unknown), and semi-structured (sitting in between structured and unstructured problems, e.g. deciding on optimal inventory levels in logistics) decisions for operational, tactical and strategic levels (Sharda et al., 2014, pp. 41–43). However, to classify the decision problems at hand, a reduced 2-by-2 matrix covering structured and semi-structured problems for operational and tactical decision levels, is sufficient as can be seen in Figure 2.

Circular economy processes and decisions for end-of-life heating pumps

The decision-making problem focuses on pumps returned from on-site repair and maintenance operations as well as potentially through take-back systems and may thus be the manufacturer's own or external products. The degree of knowledge regarding the specific product varies accordingly. Additionally, newest generation pumps may contain more lifecycle information collected through their time of operation that can further support decision-making. While the information availability is welcomed in helping to make better decisions, there is also the challenge to identify when a problem is linked to software malfunction instead of hardware failure.

This paper explores the decision-making problems involved in end-of-life handling of pumps in a manufacturer-operated site that accepts both own and external pumps. Generally, the decision-making problem described is not limited to manufacturer-operated sites, but data and information availability will be challenging for independent operators and thus would require adaptions.

While the process at the heart of the project is a dismantling process dealing with a recursive set of decisions covering the degree of disassembly as well as the handling of parts obtained through disassembly, the inclusion of an overarching decision as to which circular economy principle (e.g. refurbishment or immediate recycling) will be applied is integrated as well. While general resource recovery is possible for a majority of the material used in the construction of pumps, the outcome varies based on the material recovery process (plastics are generally recycled to a lesser quality, rare materials are partly lost in the WEEE recycling process, metal recycling often produces lower quality alloys). Additionally, previous value creation may be (partly) reversed in the process when no reuse is practiced. These aspects have to be considered in the decision making as well.

End-of-life decisions (D_1)
- Selection for disassembly
- Selection of appropriate circular economy principle (e.g. direct reuse, direct recycling)

Disassembly decisions ($D_2, \dots, D_n$)
- Degree of disassembly (decided upfront or recursive)
- Handling disassembled parts (e.g. direct reuse, refurbishment, further disassembly)

Figure 1. Circular economy decisions in end-of-life handling of pumps

Figure 1 above illustrates the decisions involved. D_1 as the initial decision is a semi-structured decision problem partly influenced by volatile, external factors addressing the tactical level due to the following considerations:

- The degree of uncertainty regarding the pumps' overall status in cases where the nature of the malfunction causing the end-of-life status is unclear.
- Demand for and market acceptance of refurbished pumps as well as refurbished parts depends on the age of the pump as well as inventory levels and may change over time.
- Direct recycling may economically outweigh other alternatives in times of high demand for end-of-life devices and correspondingly high secondary raw material prices. In these cases, further dismantling may be too cost intensive for the additional economic benefit.

The following disassembly decisions D_2 through D_n are wholly operational and may be structured or semi-structured based on the type of device and part:

- As general demand for refurbished parts and pumps has already been considered in decision D_1 before, there is no need to further include it in these decisions, which means they are from now on entirely of operational nature.
- While the appropriate degree of disassembly may be easy to identify in some cases (e.g. only one malfunctioning part identified upfront), it can be assumed that the more common case will be an iterative decision making process in which dismantled parts are then tested and further handling is decided.
- The handling of parts obtained through disassembly depends on mostly structured information such as their physical condition and operativeness.

Figure 2 below illustrates where the decision problems relevant to this paper are located in the classification framework.

		Planning level		
		operational	tactical	strategic
Type of decision	structured	$D_2, \ldots, D_n$		
	Semi-structured	$D_2, \ldots, D_n$	D_1	
	unstructured			

Figure 2: Decision types and planning levels for the decision-making problems in this paper

Decision parameters and data requirements

Decision parameters

Several decision parameters are to be considered in the decision-making process. As the project "ResmaP" focuses on increasing the overall resource efficiency over the products' entire lifetime, a focus on resource efficiency indicators rather than costs and profits alone seems reasonable. However, economic aspects have to be considered as well in order to ensure that the actual costs are not outweighing the environmental benefits. An additional aspect to be considered is the preservation of previous value creation which can be lost e.g. during recycling processes. Furthermore, inventory levels as well as production of spare parts have to be considered to avoid parts being obtained from a dismantling process only to be stored indefinitely.
As previously discussed, the question whether the manufacturer's own or an external pump is handled in the process, is decisive regarding the amount of information available for disassembly. Compared to own products where disassembly guides are available and costs and value as well as materials of individual parts are known, external products will usually only be disassembled to a lesser degree.
For pumps where more information is available, the decisions can be made based on a broader variety of internal and external factors. Relevant decision parameters in this case are:

- Status of the pump itself and its parts; which includes both the mechanical parts, electronics as well as the software components in the case of newer generation pumps.
- Forecasts on demand for certain parts and pumps in the case of refurbishment of parts and pumps.
- Economic parameters such as dismantling costs and potential revenues for parts and materials.
- Parameters relevant to resource efficiency implications of certain decisions such as the refurbishment and reuse of a component.

Data requirements

Wherever possible, as much lifecycle data from the devices themselves should be utilized in the decision-making process, mirroring the decision parameters mentioned above, particularly including aspects such as the operational conditions (times within and outside of technical specifications), overall runtime and age as well as the pump's repair and maintenance history. This information might be helpful to make decisions (e.g. regarding the degree of disassembly) earlier in the process than is currently possible once enough data has been collected on the accuracy of lifecycle information based decisions. Additionally, this data can be used to optimize future dismantling related decisions.

Additionally, external information is required in order to ensure decision making mainly regarding prices for recycling as well as for secondary raw materials. While the preservation of value creation and resources is crucial, they can only be achieved if dismantling operates on a profit – this is particularly important for potential independent service providers or in cases where the service is subcontracted to external actors.

The most important information which is also most difficultly to obtain are those regarding the resource efficiency of individual decisions. Regarding own products and wherever processes are handled internally, the information required to carry out a proper assessment of the environmental impacts regarding resource efficiency are easier to obtain than for external processes. External processes can be assessed utilizing tools such as LCI databases. However, due to the complexity of the process – particularly when a high degree of dismantling is necessary – the ex-ante modelling of any potential outcome is not feasible. Thus, simplified indicators are to be developed in order to support the decision making in practice.

Decision making methods

For all decision points identified, case-based reasoning (CBR) presents itself as an appropriate tool to support decision making as it can deal with structured and semi-structured problems alike and has previously been used for decision making purposes in remanufacturing (Jiang et al., 2019).

CBR as a method relies on the analysis cases from which conclusions can be drawn based on previous cases. Like other AI methods, CBR will deliver more robust results with an increasing number of diverse cases. As the number of cases that reach decision points D_2 through D_n is likely to be smaller than the total number of cases, the application of an alternative method for these decision points appears to be a reasonable course. Additionally, the data required to assess possible decisions at this point is more structured and the outcome of every decision is more likely to fall into a binary category (e.g. yes/no decisions regarding the continuation of the disassembly process). This suggests the use of either mathematical programming or multi-criteria decision-making techniques for decision support (Sharda et al., 2014, 437-439, 453-455). The final selection of the methods to apply has not been made and will be made after the processes and their respective potential outcomes have been mapped and assessed entirely.

Conclusions

The decision-making problem discussed in this paper encompasses both structured and semi-structured decision problems on operational and tactical levels and thus provides a challenging starting point for a decision system.

The degree of internal information potentially available increases with every new product generation and has the potential to make decision making in this context more effective. However, the generation of environmental indictors for each part and process is a challenge particularly for externally manufactured devices.

Two important aspects regarding information availability are to be emphasized: While internal data on a device's lifecycle becomes more widely available, it is unclear how much of it can contribute to decision making and whether end-of-life decision making can be considered during the earlier stages of product development. Secondly, data availability for external products is a challenge and may also impact more open approaches to the circular economy such as independent refurbishment centers. For both aspects, digital twins are a promising, emerging technology that can help distribute the right amount of information among involved actors.

Finally, a mathematical model for the description of the decision problem has to be developed, tested and transferred to a decision-making system that allows to incorporate both internal and external data for decision making.

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