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A Data-Driven Decision Framework for Value Retention Strategy Selection in Electric Traction Motor Remanufacturing

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Abstract

Data-driven approaches for selecting the appropriate value retention strategy are of central importance for the implementation of the circular economy. In the context of electric traction drives, rare earth elements and other valuable raw materials are used in the design of permanent magnet synchronous machines and should be recovered using the highest value retention strategy at the end of their first life cycle. This paper presents a data-driven approach in which the selection of the appropriate value retention strategy is based on the condition of the electric traction motor. This is followed by an evaluation using production data and a diagnosis in an evaluation tool. The stages and parameters required to find the appropriate value retention strategy are presented in this paper.

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1. Introduction

The limited availability of key raw materials, combined with the rapid growth of the global population, is already posing major challenges for our society. This rapidly increasing global consumption of resources would have required 1.8 Earths in 2025 to meet humanity's global resource consumption. The circular economy offers a solution: it is an industrial model that decouples production output from resource use and is therefore restorative and regenerative. [1, 2]

From a circularity perspective, the end-of-use phase plays a particularly important role within the product lifecycle. Therefore, it is essential to plan strategies for a potential second or even third life of the product. Since electric traction motors contain valuable materials such as permanent magnets and copper, developing an appropriate end-of-life strategy is highly significant. To successfully implement a circular economy, it is necessary to determine which value retention strategy is most suitable for each product. According to ISO standards, nine resource retention strategies (R-strategies), such as reuse, repair, remanufacturing, and recycling, can be distinguished along the product lifecycle.

Remanufacturing represents the most advanced circular strat-

egy in terms of quality and warranty of the circular product compared to alternative methods. It is the only circular process capable of exceeding the performance and reliability of new products [3, 4]. In the literature remanufacturing is defined as a standardized industrial process in which used products (known as “cores”) are restored to a like-new or even better condition than an equivalent new product [5, 6, 7].

Therefore, the remanufacturing process must be as cost-effective as possible. This is particularly important if the product has a high material value and low added value. For an electric traction motor in this paper, the material value is around 75% [8]. Figure 1 visualizes the value retention in context of remanufacturing.

Against this background, it is of utmost relevance to design remanufacturing processes that are both cost-efficient and capable of being discontinued once they are no longer economically viable. In such cases, the product should be transitioned into a lower-value recovery strategy. While existing approaches already address recycling and initial remanufacturing concepts, there is currently no systematic or data-driven method for selecting the most appropriate strategy. Existing data-driven approaches mainly focus on the production system, as well as production planning and control.

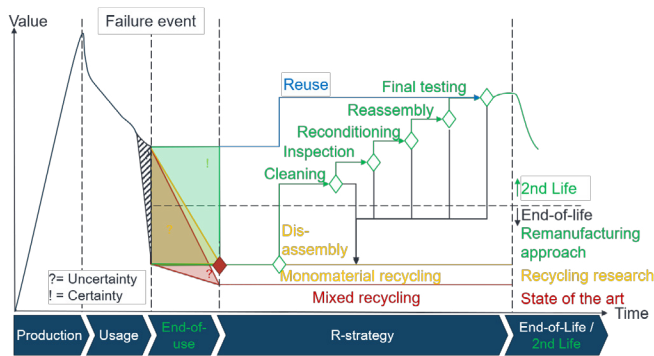


Fig. 1. Value retention in context of remanufacturing adopted from [9]

2. Related Work

To develop a decision-support tool for remanufacturing, a comprehensive review of the existing literature on electric traction motor remanufacturing is required. This review entails identifying the range of potential faults that may occur in electric traction motors, the diagnostic techniques applicable for fault detection, and the implications of these failures at the end-of-use stage. Moreover, it is essential to formalize the knowledge obtained from the initial assessment process, commonly referred to as the end-of-use (EoU) test. To achieve this, the electric traction motor must first be characterized in terms of its design, constituent components, and functional parameters, followed by the establishment of a detailed cost structure encompassing manufacturing, operational, and remanufacturing processes. The subsequent sections therefore examine relevant prior research and methodologies pertaining to these aspects.

State of the art electric traction motor

The electric traction motor represents the central drive unit of electric vehicles and consists of four principal subsystems: stator, rotor, housing, and transmission. The stator comprises a lamination stack and a winding system, most commonly realized as a hairpin winding of rectangular copper conductors. In permanent magnet synchronous motors (PMSMs) the rotor contains interior permanent magnet ensuring high torque, high power density and high efficiency [10, 11, 12]. However, these magnets are produced from rare-earth elements, which are costly, entail a high degree of supply-chain dependency, and are associated with a substantial CO₂ footprint [8, 13, 14]. The housing provides structural integrity, accommodates the stator and rotor bearings, protects the internal components from environmental influences, and often integrates the cooling system. The transmission, typically a single- or two-stage gear unit, adapts the motor's high rotational speed to the wheel torque requirements. [10, 11, 15] Due to their high power density, compactness, and low acoustic emissions, PMSMs with hairpin windings currently represent the state-of-the-art solution for automotive drivetrains [12, 16]. Their design and manufacturing characteristics strongly influence both performance and remanufacturing potential, under-

scoring the relevance of systematic end-of-use evaluation in sustainable electric drivetrain production.

Failure modes of electric traction motors and end-of-use testing

PMSMs often face faults and damages classified mainly into electrical, magnetic, and mechanical categories [17]. Electrical faults primarily involve insulation degradation and winding faults such as turn-to-turn short circuits and coil fractures, which compromise motor reliability due to thermal aging [18]. Magnetic faults include demagnetization of permanent magnets, which frequently results from thermal stress, overload, or mechanical impacts, leading to reduced motor performance and increased heating. Mechanical faults affect components like bearings and rotor structures, with common issues including bearing wear, eccentricity, and lamination cracking caused by high centrifugal forces during high-speed operations [19]. Fault diagnosis methods typically leverage current signal analysis and advanced modeling techniques to detect and localize faults such as stator winding shorts or rotor demagnetization, enhancing early detection and mitigating motor failure risks [20]. Identifying and characterizing these fault patterns is essential for an accurate evaluation of the EoU state and for the development of effective remanufacturing strategies.

Characterizing relevant fault patterns is necessary to assess the EoU state and select a suitable remanufacturing strategy. Therefore, the EoU test combines electrical, thermal, and mechanical diagnostics, including DC resistance measurement, high-voltage insulation and partial-discharge testing, open-circuit and short-circuit tests, and cooling-system leakage testing. While these tests determine the functional condition of the motor, an additional decision framework is required to define the appropriate subsequent value-retention strategy.

End-of-use process modeling

More recent research has introduced structured approaches that integrate technical, economic, and environmental criteria. Lachnit et al. propose systematic decision-support tools that combine these dimensions. Environmental aspects are commonly analyzed using life-cycle assessment (LCA) [21]. Broader circularity indicators, such as the Circular Input Rate [22] enable quantification of circularity at sectoral or organizational scales.

A considerable body of literature addresses disassembly. Germani et al. estimate disassembly effort using liaison matrices and cost factors [23]. Mandolini et al. introduce an algorithmic planning method based on level matrices and liaison information [24]. Hansjosten and Fleischer advance the field towards adaptive robotic disassembly of PMSM by integrating digital models, simulation, and planning under uncertainty, including alternative process routes (e.g., milling or drilling) to improve robustness [25].

Design-focused contributions address remanufacturability and strategy selection. Jiang et al. propose a disassembly efficiency index [26], while Fang et al. introduce CAD-based metrics for assessing remanufacturability [27]. Taheri et al. present

a rule-based framework connecting disassembly, cleaning, and fault characteristics [28]. Ahlstedt and Sundin identify design features relevant to remanufacturing [7], while Gharfalkar et al. elaborate terminology and criteria for reuse-oriented strategies [29]. Klein et al. developed a decision tool for assessing the circularity of electric traction motors and supporting R-strategy selection at end-of-life [30]. Further approaches link product condition, uncertainty, disassembly decisions, and economic performance [31, 32]. Although some approaches include decision-tree-based circularity evaluation, they do not provide systematic decision support during remanufacturing execution. [32].

3. Problem Definition

Electric traction motors contain valuable components whose recovery depends on their individual end-of-use condition. Therefore, the selection of a value-retention strategy must consider technical feasibility, economic viability, and process uncertainty. Existing approaches do not sufficiently link initial condition assessment, process-specific value changes, and adaptive strategy selection during remanufacturing.

Both, the cost function and the underlying process framework must then be implemented in a suitable tool. The current cost function focuses on the remanufacturing processes themselves, excluding initial value identification and interconnection between individual processes.

This paper therefore aims to define a process workflow that enables the selection and implementation of an appropriate value retention strategy (R-strategy) for an individual electric traction motor based on defined target criteria. The full workflow is shown in Figure 2.

To demonstrate the applicability of the proposed framework, a structured approach is first established by developing a conceptual framework, followed by an analysis of the required data and available testing methods. Based on relevant literature, a concept is formulated that integrates all accessible product-related information, for instance data provided through a Digital Product Passport (DPP). Subsequently, the current condition of the product is assessed using a dedicated test bench capable of capturing all functional characteristics relevant for evaluating an electric traction drive. Building on this foundation, the following section presents a step-wise execution of the decision-making workflow using an industrially representative electric traction motor, in which each decision stage is examined with regard to technical feasibility, economic impact, and the resulting adaptation of the selected strategy.

Afterwards, an initial R-strategy is selected and subsequently implemented. The selection of the R-strategy must integrate information from the DPP, the functional tests, and expert knowledge regarding the effort associated with each specific R-strategy. The chosen R-strategy is then executed, including the corresponding update of the DPP.

Finally, to ensure the functionality of the electric traction drive

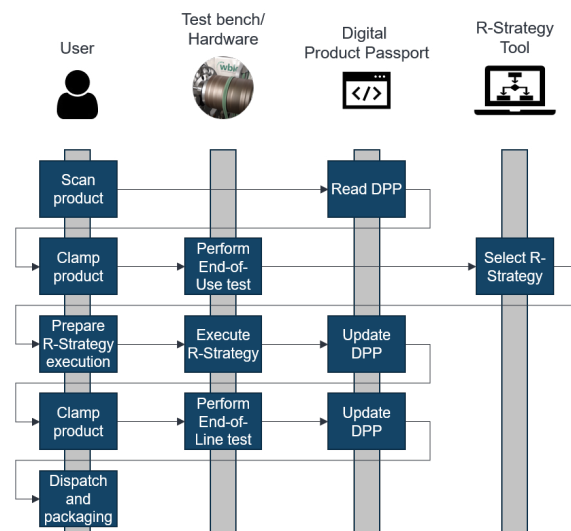


Fig. 2. Process flow for remanufacturing electric traction motors

and to validate any associated warranty claims, a follow-up functional test must be conducted.

4. Decision Framework

This section introduces the essential components of the approach: the DPP, the EoU test, the selection of an appropriate R-strategy using a cost function, and the execution of the chosen R-strategy with particular emphasis on disassembly. The section begins with the presentation of the DPP.

Digital Product Passport (DPP)

The DPP contains lifecycle information on the motor provided by relevant stakeholders. Since no standardized format currently exists, the required dataset was derived from literature, prior information-modeling work, and production-related parameters [33]. Storing this information within an Asset Administration Shell has been shown to be a suitable implementation approach [34].

End-of-use (EoU) Test

The EoU test represents the primary procedure for assessing the residual value of the electric traction motor. Consequently, it must include at minimum all characteristics evaluated during initial production. These include: DC resistance measurement, high-voltage insulation testing, partial discharge testing, open-circuit testing, short-circuit testing, and leakage testing of the cooling system. In addition, NVH tests are performed to analyze bearing condition and rotor unbalance. Beyond these performance evaluations, a visual inspection is also mandatory. If the rotor shaft is non-rotatable or if severe damage to the motor housing is detected, the decision tool classifies the unit for direct recycling.

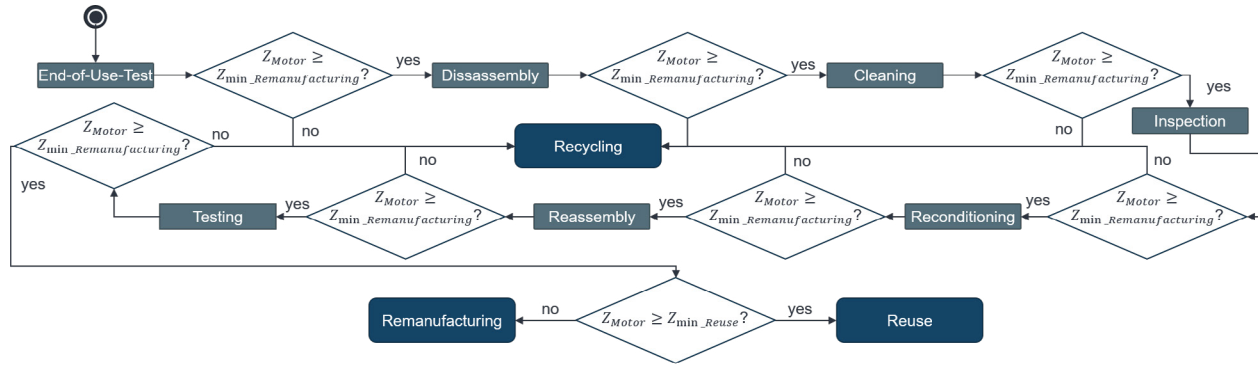


Fig. 3. Evaluation of electric traction motor value during remanufacturing process

Selection of appropriate R-strategy

For the selection of appropriate R-strategy a previously conceptual framework is extended. This framework is focused on disassembly and does not contain a strict process flow for the entire remanufacturing process chain. Especially the EoU test and initial selection of the appropriate R strategy are not considered. This means that the value function has additional terms. The general evaluation process is shown in Figure 3. The implementation is realized with Python using Node-Red as an interface to DPP.

The objective function consistently incorporates the current value of the electric traction motor. To enable further value-adding operations, this value must at all times exceed the minimum threshold required for a motor to remain eligible for remanufacturing. If the value falls below this threshold, the motor is immediately directed to recycling. Conversely, if the motor's value at the end of the theoretical assessment is sufficiently high to permit direct reuse, it is returned to the customer without further processing. Overall, this approach is based on an estimation of the effort associated with the individual processes embedded within the R-strategies, combined with the sequential probabilities of potential transition states. The resulting value function is therefore defined as follows:

$$Z_{\text{Motor}} = Z_{\text{EoU-Test}} + \sum_{i \in \text{R-Process}} (c_i x_i - \Pr(F_i | i) f(\delta_i) c_i \lambda_i x_i) \quad (1)$$

Z_{Motor}	Current value of Motor
$Z_{\text{EoU-Test}}$	Initial value of motor identified in EoU-Test
c_i	Value of part i in R-Process
x_i	Recovery decision for part i , $x_i \in \{0, 1\}$
$\Pr(F_i i)$	Probability of fault mode F_i in part i
$f(\delta_i)$	Diagnostic accuracy level
δ_i	Cleaning outcome
λ_i	Value-loss coefficient associated with δ_i

All monetary parameters are expressed in USD (\$), while probability-related parameters are dimensionless.

Execution of R-strategy

An appropriate process chain is required to implement the selected R-strategy. Since the costs of individual disassembly steps remain insufficiently evaluated, the process is assessed regarding cost efficiency and strategic suitability.

To recover the high-value rotor, the housing cover is first removed. The rotor is then extracted and inspected. Direct reuse requires bearing replacement; otherwise, demagnetization initiates material recovery. The complete process chain is illustrated in Figure 4.

The framework was evaluated using an electric traction motor with 33 parts and OEM-based parameters in a Python implementation. The process begins with a DPP scan and EoU test. The initial value was $Z_{\text{Motor}} = 502 \$$, exceeding the remanufacturing threshold of $Z_{\text{min Remanufacturing}} = 500 \$$. Thus, further remanufacturing was considered economically beneficial.

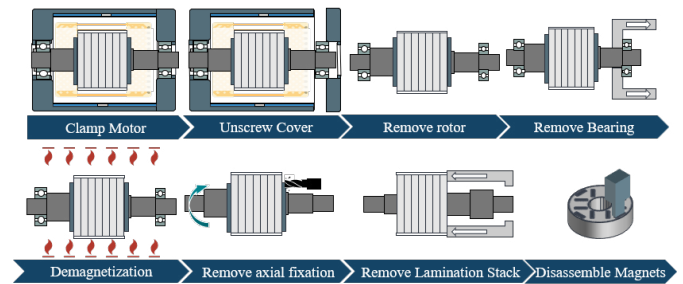


Fig. 4. Process chain for disassembly of permanent magnet rotors

Figure 4 illustrates the sequential disassembly and evaluation workflow applied to an electric traction motor as an industrially representative use case. The process demonstrates the operationalization of the decision framework by linking physical disassembly steps with continuous technical and economic reassessment. The workflow begins with motor clamping, ensuring positional stability and standardized diagnostic and disassembly operations. Initial condition data from documentation and external inspection are incorporated to estimate recovery value and process feasibility.

Subsequently, the housing cover is removed, allowing access to internal components. Following housing removal, structural integrity and contamination levels are assessed. The decision

framework evaluates whether detected deviations increase refurbishment risk or expected value loss beyond predefined thresholds. If acceptable, the remanufacturing pathway is continued.

In the next step, the rotor is extracted, enabling component-level inspection. Rotor removal represents a major decision gate, as it permits assessment of magnetic integrity, shaft condition, and bearing performance. Diagnostic outcomes are integrated into the decision model, which determines whether direct reuse, refurbishment, or component replacement provides the highest retained value. Bearing degradation typically shifts the recovery strategy toward selective refurbishment while maintaining reuse of high-value rotor components.

To enable material recovery where reuse is not feasible, controlled demagnetization is performed. This reduces magnetic forces, ensures safe downstream handling, and minimizes damage risks during separation. The framework reassesses processing costs and safety implications before continuation. Following demagnetization, axial fixation elements are removed, and the lamination stack is extracted to evaluate electrical steel condition and recyclability potential.

Finally, permanent magnets are disassembled, permitting reuse, remanufacturing, or material recovery depending on degradation state and economic assessment. At each disassembly stage, updated diagnostic information, processing effort, and uncertainty levels are fed back into the decision-making workflow. This iterative reassessment enables adaptive strategy selection, prevents economically unfavorable continuation, and maximizes retained product value compared to static disassembly planning.

5. Conclusions and Future Work

This paper presents a concept for the data-driven selection of value-retention strategies for electric traction motors. A suitable process flow for practical implementation is introduced, in which a DPP together with an EoU test is used to determine the residual value of the motor. The motor subsequently progresses through the proposed R-strategy, while the developed evaluation tool continuously verifies whether continuation of the selected value-retention pathway remains appropriate. The approach developed in this paper must now be transferred into practical implementation and applied across the relevant value-retention scenarios for electric traction motors. In doing so, it must be determined to what extent the theoretically identifiable procedures can be predicted in terms of their sensitivity.

CRedit authorship contribution statement

Nicolaus Klein: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Conceptualization. **Sebastian Henschel:** Writing – review & editing, Supervision. **Jürgen Fleischer:** Writing – review & editing, Supervision, Conceptualization.

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