Remanufacturing of electric vehicles: Challenges in production management

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Abstract. Due to the conceptual degrees of freedom in their product structure, electric vehicles offer high potential for remanufacturing-oriented product design. This potential is, however, not realized yet. Remanufacturing as one fundamental element of a circular economy is characterized by specific challenges caused by uncertain information about the condition and the timing of the returning product. By means of a case study within the remanufacturing industry, the effects of uncertainties on remanufacturing operations are examined and different approaches within the field of production management to meet these specific challenges are pointed out. Based on the result of the case study a production management framework outlining fields of action to deal with remanufacturing specific uncertainties is developed. In this context, the requirements for remanufacturing of electric vehicles are derived by analyzing similarities from other industry sectors. In conclusion, a solution approach for the implementation for electric vehicles is presented for strategic, tactical and operational procurement logistics and remanufacturing operations.

Keywords: remanufacturing, electric vehicles, production management

1 Introduction

1.1 Motivation

The concept of a circular economy aims to decouple economic growth from the use of finite resources and the associated negative effects on the environment [1]. Remanufacturing corresponds to the objective of the circular economy since it enables the recovery of product components for further use in order to extend the useful life of products or their components.

The global remanufacturing industry has reached a total size of approximately 110 billion USD per year and creates about 450,000 jobs worldwide [2]. The automotive industry accounts for two-thirds of the remanufacturing market volume, even though remanufacturing

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is currently limited to vehicle components [3]. In other sectors, remanufacturing is executed on the level of the final product and is a central element of the manufacturer's business models.

The growing market share of electric vehicles offers new opportunities to implement remanufacturing at the vehicle level for passenger cars and light commercial vehicles. While vehicles with a powertrain based on an internal combustion engine have a predefined product and functional structure, conceptual degrees of freedom can be used in the design of electric vehicles to implement remanufacturing-oriented product design [4]. Additionally, the components of an electric powertrain are characterized by lower complexity and fewer mechanical interfaces to each other.

Several definitions of remanufacturing exist with slightly different foci. All definitions have in common that remanufacturing is described as an industrial process in which cores are brought into a condition that meets at least the quality and functional requirements of a new product [2, 5, 6]. Cores can also be upgraded to enhance product functionality. Remanufacturing includes re-using, processing or replacing of single components of the returned cores in order to enable a further product life cycle [7].

The generic remanufacturing process begins with the delivery of the cores and storage [8]. After optional cleaning, the product is disassembled. Components, which are technically or economically unsuitable for remanufacturing due to their condition are sorted out. All other cores may need detailed defect diagnosis before the actual reprocessing of the disassembled parts takes place. In reassembly, the processed components are reassembled, if necessary in combination with new parts.

1.2 Problem Statement

Remanufacturing is characterized by additional challenges in comparison to linear value chain production. As discussed in the literature and proven by different studies, the uncertainty about the condition, quantity and timing of returning cores is elementary for these challenges [9]. Varying failure patterns caused by different usage behaviors and multiple external factors lead to the unpredictable timing of product failure and different remanufacturing needs. The more components a product contains, the greater the deviations in causes and times of core returns are.

The combination of a fluctuating number of available cores and varying core conditions results in unreliable forecasts about the availability of remanufacturable cores and spare parts as well as the required production capacity [10]. Moreover, remanufacturers often have to deal with an asymmetry between core returns and market demand since the availability of cores increases during the saturation and degeneration phases of a product's market cycle while demand decreases [11]. Furthermore, depending on the condition of the cores required remanufacturing processes and process times may vary in order to achieve the desired condition [12]. Therefore, it is hardly possible to schedule the process reliably before disassembly and inspection of the cores. Subsequent changes in process and material requirements planning can also occur if further defects are detected during the remanufacturing process that were not detected during quality inspection.

These challenges are dealt with in numerous publications and a variety of solutions is presented. Remanufacturing research to date is characterized by an isolated consideration of the individual problem areas [13]. Due to the high planning complexity of remanufacturing, approaches are necessary that deal with the specific challenges in an integrated framework. Accordingly, only limited theoretical conclusions can be drawn for the implementation of remanufacturing in electric vehicle production. Rather, it is promising to investigate the production management of remanufacturing operations in other industries with regard to the applicability of remanufacturing at the vehicle level. Therefore, the following research question occurs:

Which configuration options in product management for remanufacturing of electric vehicles can be derived from practice in order to meet uncertainty-related challenges?

2 Approach

In order to derive implications for the remanufacturing of electric vehicles, the industry practice is described and analyzed in five companies. The cases are derived in a three-step approach. First, publicly available information was examined in order to select suitable companies. Based on this, a comprehensive literature analysis was carried out with regard to the respective remanufacturing operations. Finally, experts from the production management department were interviewed using a standardized questionnaire.

The products examined in the study show a different level of complexity in order to consider a wide range of different approaches to solving the uncertainties discussed above. The products are becoming gradually more complex from brake callipers, starters, and generators, clutches, printers, combustion engines for heavy-duty trucks and construction machines to gas turbines. All companies, whose remanufacturing operations are examined in this study, are original equipment manufacturers (OEM) of the described products. This is important in order to ensure applicability to the production of electric vehicles since the complexity of remanufacturing products such as electric vehicles can only be controlled by its original manufacturer.

Firstly, as structuring means for the study, a framework is developed, depicting the fields of action for managing the production-related remanufacturing specific uncertainties. The fields of action are differentiated according to their *strategic, tactical* or *operational* character, depending on the planning horizon. Strategic tasks have a rough planning level and are typically carried out by the management for the long term. The tactical management level implements the planning requirements of the strategic level in the medium term and the operational level is responsible for detailed order management.

The management challenges described divide the fields of action associated with remanufacturing into two categories: *procurement logistics* and *remanufacturing operations*. One significant difference compared to conventional systems lies in procurement logistics, since remanufacturing is characterized by exogenous parts availability and therefore the coverage of dependent requirements cannot be completely controlled [12]. Additionally, depending on the core condition, the process steps to be carried out and the process times can vary considerably, which makes the planning of production operations complicated and requires an appropriate strategy.

3 Case study

3.1 Framework

Companies either purchase cores directly from the customer or access third-party service providers such as used parts dealers, scrap yards or core brokers. The multitude of supply sources increases the overall coordination effort and the complexity of procurement logistics. Since there is also a high degree of uncertainty regarding the return time of cores by the customer, close, cross-company cooperation with third-party service providers is necessary for supply chains that are directed backwards, as well as the active involvement of customers in the take-back process [14]. The configuration of the *closed-loop supply chain* represents the increased demands on cooperation with customers and third-party service providers and therefore represents the strategic management field of action of procurement logistics.

In a conventional forward supply chain, manufacturers sell their products directly to their customers or use retailers. Backward material flows typically only occur in connection with product returns, e.g. when the customer asserts warranty claims. In remanufacturing, more extensive requirements are placed on product take-back systems, as returned products are the raw material for production and thus indispensable for the value-adding process. Remanufacturing companies must create logistics systems that work efficiently despite the high number of material sources and the uncertainty regarding the availability of cores. The planning, implementation and control of efficient and cost-effective product flows from the end-user to the original manufacturer, with the purpose of generating added value by restoring the product, is called *reverse logistics* and is on the tactical level of procurement logistics [15].

The operational management task of procurement logistics is to ensure that a number of components tailored to the primary requirement are procured and made available for production. Remanufacturing differs from conventional logistics systems in terms of warehousing, procurement and distribution [16]. Therefore, a reliable forecast of how many reusable components will be available for remanufacturing and how many spare parts are needed cannot be precisely made. For these reasons, the *dependent requirements supply* needs to ensure the availability of cores to be remanufactured.

On the strategic management level of remanufacturing operations, the fundamental decision must be made for the question to what extent remanufacturing is in line with the corporate strategy. Numerous factors such as revenue potential, the consideration of marketing, the availability of specialists and legislative requirements can influence this decision [17]. Furthermore, a decision must be made about which products are technically and economically feasible for remanufacturing. In addition, a balance must be struck between the availability of cores and the market demand for reclaimed products. Therefore, at the strategic level, the *remanufacturing scope* is defined.

The design of efficient production processes is a success determining factor in the development of remanufacturing systems since both the costs and quality of the processed products as well as the performance of the system are influenced by the choice and design of the production processes [18]. Consequently, the tactical field of action for remanufacturing operations is defined as *production design*.

The operational level of remanufacturing operations is characterized by variable process times and production sequences due to the high inconsistency of the core condition, which is particularly challenging for *inhouse-production planning and control* [9]. Since not all cores have to undergo the same processes in order to be restored to a new condition, it is usually not possible to carry out precise process planning before certainty about the condition of the cores has been achieved. Processing times on the same workstation can also vary depending on the core's condition. Therefore, the scheduling of production processes is more complex than with conventional production systems.

	Procurement logistics	Remanufacturing operations
Strategic	Closed loop supply chain	Remanufacturing scope
Tactical	Reverse logistics	Production design
Operational	Dependent requirements supply	Inhouse-production planning & control

Fig. 1. Framework for production management of remanufacturing-related uncertainties

3.2 Case studies

3.2.1 Case 1: Remanufacturing of brake callipers, starters, and generators

The company in the first case is a multinational technology group with a strong focus on mechanical, mechatronic and electric automotive parts with activities in 60 countries. At the examined production site, remanufacturing of brake callipers, starters and generators is carried out for aftermarket activities. At the location, 300 employees remanufacture more than one million products yearly, handling over 3.000 different types of products.

The cores are taken back via three channels. The first channel is the repurchase from independent workshops. Via agents, the cores are picked up and delivered to one of the regional sorting centres from a network of twelve such stations in Europe where the cores are identified, pre-sorted and evaluated. If the cores meet predefined criteria such as completeness and absence of obvious material eruptions and cracks, the value of the core is credited to the customer. The second option is the direct repurchase from major customers. Contracted workshops are advised to store and forward cores of certain product types. These major customers purchase an agreed quantity of remanufactured products at a reduced price. Lastly, the option of purchasing cores from independent core brokers is used.

The remanufacturing process begins with sorting and inspecting the quality of the delivered cores. If testing and sorting have already taken place at one of the sorting centres before delivery, the cores are stored without checking. The storage time can vary depending on the product type from a few days up to several years. When an order is placed, a corresponding number of cores is removed from stock. Since it cannot be assumed that all components of each product type can be remanufactured due to condition variations, forecasts approximate how many cores of a certain product type are required to meet the existing primary requirement for each product type.

The cores are disassembled non-destructively into their individual components and forwarded to the subsequent processes. Obviously defective components as well as wearing parts and small parts such as screws are directly sorted out and replaced. Components, which in any case have a limited life, are also excluded from reuse. Various cleaning processes like degreasing with technical alcohol and subsequent irradiation with blasting media are carried out depending on the type of component and the degree of contamination. The reusability of the individual components is assessed manually after cleaning. Depending on the test results, mechanical processing is carried out according to a predefined process for each component family. The reassembly follows immediately without intermediate storage. Non-recoverable components are replaced either by equivalent components of the same batch or by new parts. In the last step, a test of the finished remanufactured product as well as packaging and handover to shipping takes place.

3.2.2 Case 2: Remanufacturing of heavy-duty vehicles clutches

The company is a global technology group for automotive systems with activities in 40 countries including a network of fifteen remanufacturing locations in Europe, Asia, North and South America, and Africa. At the analysed plant, 200 employees remanufacture more than 200,000 units per year of a broad variety of different clutches.

The cores are procured via three channels. The most important channel is the direct repurchase from major customers who deliver used parts several times a week and in return, they purchase a certain quantity of remanufactured products. The second take-back channel is the purchase of cores from core brokers. Either they receive an order to procure a defined number of a product type or cores are acquired from the existing stock of the respective core broker. Furthermore, cores are supplied directly by workshops. Workshops collect the used parts resulting from the repair of customer vehicles and sell them.

The delivered cores are stored and remanufacturing is only conducted, once a primary purchase order has been received. In the first process step, the cores are categorized according to the extent of defects. The categorized cores are disassembled, which requires controlled destruction of the rivets or welded joints. The separated products are first disassembled and then cleaned of dirt and corrosion by means of a shot-blasting cleaning process. Cleaned components are inspected for defects and, if necessary, sorted out and sent for recycling. Quality control also determines which mechanical treatment processes are necessary to restore the component in mint condition. During the abrasive cleaning process, any identification numbers applied to the surface are removed. The subsequent sorting of the components according to their type requires highly qualified employees who can draw conclusions about the product type on the basis of the component geometries.

The subsequent mechanical processing implements the processing measures defined during quality control as well as adjustments that are necessary due to technical product upgrades. The mechanical processing to be carried out depends on the type of component and the state of wear and includes separating processes such as the removal of burrs and face turning of end faces as well as joining production processes such as the bonding of wear plates. In the last step, the reprocessed components are reassembled and a final functional test is carried out. The cores can go through the entire process several times.

3.2.3 Case 3: Remanufacturing of heavy commercial vehicles combustion engines

One of the world's largest manufacturers of trucks, buses, construction machinery and industrial engines with production sites in 18 countries including remanufacturing sites in Europe, USA and China for transmissions, engines, turbochargers, and hydraulic pumps remanufactures 200 different variants of truck engines with a total volume of about 3.000 units per year for the European and Asian markets at the analysed production site.

Cores are supplied by an external core broker, who supplies the plant once every two weeks. The required number of cores is forecasted from historical data and the order is placed with the core broker without direct order reference. The delivered cores are stored and, as soon as free production capacity is available, fed into the remanufacturing process.

The remanufacturing process starts with the disassembly of the engine. No initial testing of the engine, but a continuous quality test of the engine components during the entire remanufacturing process is executed. Engine components that prove to be defective during dismantling or in subsequent remanufacturing steps are disposed of or recycled accordingly. Among others, surface crack inspections, 3D coordinate measurements and dynamic testing methods are carried out. During disassembly, the components are sorted according to quality and the cleaning process required. Afterwards, the component cleaning is carried out, which is subject to highly varying process times, as the components must be soaked for a long time before the actual, abrasive cleaning process can take place. Cleaned components are then mechanically processed. The processing steps required for processing vary depending on the component group and condition of the respective component.

One major challenge for production planning and control is that the setup and processing times can differ by up to fifteen times depending on the type and condition of the component. Likewise, the recovery rate varies substantially between 10 % and 100 % depending on the component group. Consequently, a very high stock for some components is unavoidable, while other components have to be purchased externally to meet demand.

The components of an individual engine are not reassembled to the same engine but are at first stored. If all components necessary for the fulfilment of an order are in stock, reassembly can take place, otherwise, missing components must first be purchased externally. Finally, the end of line test is carried out, during which the remanufactured engine must meet the same quality standards as a newly manufactured engine.

3.2.4 Case 4: Remanufacturing of printers

The company in case four is a US manufacturer of office equipment including tabletop printers, multifunction devices, commercial production printing systems and printer cartridges. The company operates remanufacturing plants in North and South America, Europe, Australia and Japan.

Used products are mainly taken back via two channels. In particular, commercially used production printing systems and multifunctional systems are replaced by new equipment under lease agreements after a contractually agreed timespan. The second channel is to take back the device directly from the end customer, for example through exchange campaigns, in which the customer is granted a discount on the new device when returning an old product.

The returned devices are centrally checked for optical defects as well as for noise and heat generation and vibrations. According to their condition, the cores are sent to different plants. Devices without any signs of wear are centrally stored and prepared for direct reuse while faultlessly working cores with light signs of wear are sent to remanufacturing plants. Non-reusable devices are recycled. The products are completely disassembled and the components are sorted by type. The components are then cleaned using a minimal-abrasive dry ice blasting process, which gently cleans the plastic, glass and precious metal components. Mechanical processing is not carried out. Only painting of the panel components is carried out. Component not suitable for reuse as well as wear parts like seals and bearings are replaced by a new component. Components for which technical upgrades exist are also replaced by the new components.

The tested and partially newly painted components are assembled in the next process step. New and remanufacturing products are assembled on the same line. For the assembly of new devices, no remanufactured components are used. Finally, the latest software is installed for all products and final function tests are carried out.

3.2.5 Case 5: Remanufacturing of constructions machine engines & gas turbines

A US manufacturer of mining machinery, diesel engines and industrial gas turbines and construction machinery remanufactures more than 6,000 of its products including engines, transmissions, hydraulic components and turbochargers at 17 production sites, employing over 4,000 people. In addition to processing its own product line, the company acts as a contract remanufacturer for third-party products and thus offers remanufacturing as a service. At the analysed remanufacturing plant diesel engines from construction machines, gas turbines and military equipment are remanufactured.

The company uses a deposit- or rebate-based take-back system in order to acquire cores. If a customer, or a licensed dealer, buys a remanufactured product, first, the same price as when buying an equivalent new product is paid. This price consists of the actual product price and a deposit for the return of the product. The deposit can be up to 50 % of the price paid and will be refunded to the customer or dealer as soon as the customer returns a similar type of product. If the cores meet all criteria like being complete, having no obvious cracks or break-outs and no independent repair measures have been carried out, the full deposit amount is refunded to the customer. Otherwise, the core will be rejected or the deposit will be repaid partially.

While the engines are returned directly from major customers or via contracted workshops in specifically provided transport boxes the gas turbines are transported to the plant by the customer. The single-item remanufacturing process is triggered by the arrival of a core and begins with an incoming quality check before disassembly. During disassembly, the components are sorted according to type and condition. The process steps are roughly defined for the respective components. The disassembled components lose their affiliation to the original product and are thus reused anonymously, so typically, components of many different products are used in a remanufacturing product. After cleaning and defect detection, all necessary mechanical processing steps are carried out, with the goal to not only restore the original condition but also upgrade the components to the current state of the art. Damaged components are treated with additive processes, to restore worn surfaces or repair microcracks. Ultimately defect components are replaced either by an equivalent remanufacturing part or by a new part. Finally, the engine or the gas turbine is assembled, the product is painted and a final function test is carried out.

3.3 Analysis

Based on the cases described, the following table summarizes the generic options currently available from the OEM remanufacturer to address specific reprocessing uncertainties. The management alternatives described within the six management tasks of the regulatory framework are often found in practice in combination.

Table 1. Generic production management options for remanufacturing-related uncertainties

	Procurement logistics	Remanufacturing operations
Strategic	*Closed-Loop Supply Chain* • Buyback from single customers • Independent core brokers • Long term customer relationships with major customers • Remanufacturing as a service • Contractually agreed repayment • Leasing	*Remanufacturing Scope* • Complete disassembly of cores • Processing of defect parts • Replacement of defect parts • Replacement limited to wear parts • Replacement of old parts with product upgrades
Tactical	*Reverse logistics* • Bulk deliveries from major customers or core brokers • Core collection via sorting centre network • Returns via network authorised dealers or workshops • Core pick-up as part of an integral part of the product-related services • Single item deliveries	*Production design* • Separate remanufacturing facilities • Shared production facility for remanufactured and new product • Flow shop • Job Shop • Fixed-site production • Segmented production
Operative	*Dependent requirements supply* • Make-to-Stock • Make-to-Order • Assembling products from cores and newly produced parts regardless of product history • Product assembly only from own remanufactured or new components • Upgrade of old product versions by (mechanical) processing	*In-house-production planning & control* • Batch production • One-piece flow • Predefined process sequence/times • Variable process sequence/times • Conventional production planning heuristics • Manual definition of remanufacturing requirements

4 Conclusion and outlook

Taking into account the technical, regulatory and market-related boundary conditions, the following management measures result within the six defined fields of action for the qualification of remanufacturing in electric vehicle production. In order to implement the proposed measures, however, further detailed investigations are necessary.

Securing the supply of cores in a *closed-loop supply chain* can be achieved through close customer loyalty by means of circular economy business models. A combination of different options is an appropriate solution depending on the targeted customer groups such as private customers or commercial fleet operators. When leasing vehicles, the OEM remains the owner of the vehicle and can set a defined return date for the vehicle in the contract. Furthermore, it is possible to establish a deposit system in which the purchase price is increased with a premium, which is paid back in addition to the buy-back price after the vehicle is returned. Additionally, an OEM can secure a right of repurchase against the reduction of the purchase price in the purchase agreement. Finally, it is possible to offer buy-back prices above market prices on the free used-car market in order to secure returns.

The automotive industry typically works with a network of authorised dealers, through whom the *reverse logistics* of vehicles can be organized. In the case of affiliated contract workshops, it is possible to carry out the (preliminary) assessment of the condition on-site and to calculate the profitability of the order depending on the condition of the vehicle. The advantage is that vehicles can be sorted out directly when remanufacturing is economically or technically unfeasible to avoid expensive transport to the remanufacturing site.

When remanufacturing electric vehicles, it must be ensured that the *dependent requirements* of remanufacturing orders are covered by components of the original vehicle or by new parts. Therefore, components that are removed and intended for further use are assembled into the same original vehicle. In order to be able to carry out product recalls and warranty measures due to technical problems, the traceability of vehicle parts and the identifiability of their technical design must be ensured in the automotive industry [19]. Recalls typically relate to vehicle production periods. If components from different production periods do not match the production date of the vehicle, the definitive assignment of components to vehicles can only be guaranteed by a very complex data management system. Due to the number of components in a vehicle and the fact that vehicles are subject to constant design changes during ongoing production, the effort required to trace the production and usage history for electric vehicles is disproportionate. In addition, remanufacturing practice shows that customer acceptance of remanufacturing increases significantly when the product returns with the same parts. Consequently, spare parts must be supplied from the series production.

The *remanufacturing scope* results from the product structure of electric vehicles, which consists of core elements that are durable under normal conditions of use and components that wear and age. Consequently, disassembling the entire product and testing all components is likely to involve process steps that do not add value if no additional reprocessing needs are identified. In order to implement efficient production, it is important to design a functioning mechanism for reliable identification of defects and wear.

Electric vehicles have a fixed disassembly sequence, which must be reflected in the *production design* in the form of a sequential order of the stations. Consequently, the stations have a fixed assignment of the disassembly tasks. However, to ensure that only the order-related remanufacturing scope is actually taken into account during disassembly, it must be ensured that only the required stations can be approached. In contrast to disassembly at the vehicle level, removed components such as powertrain, battery pack or axles are completely disassembled, cleaned, inspected, processed if necessary and reassembled in accordance with industrial standards. The configuration of the reassembly corresponds to the disassembly in order to enable the same job-related route flexibility. Capacities are designed because of the defect and wear probabilities based on historic values.

In-house production planning and control is characterized by decisions under uncertainty. Only complex data processing concepts are suitable to guarantee the required efficiency within the described production design. First, a reliable identification of defects must be ensured. Machine learning algorithms that can process a large amount of influence data and independently identify complex dependencies are suitable for such a classification task. This information must then be processed within the scheduling process. The aim of scheduling is to utilize production resources as efficiently as possible and at the same time to react robustly to deviations due to extended process times or additional process steps. Simple planning heuristics do not meet these requirements, which is why the use of genetic algorithms to optimize order processing is expedient for the complexity of this task. To ensure the productivity of the remanufacturing system, the profitability of the single orders must be reassessed if there is a major deviation from the initial planning.

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