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Remanufacturing of electric vehicles: Challenges in production planning and control

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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. Remanufacturing as one fundamental element of a circular economy is characterized by specific challenges caused by uncertain information about the condition of the returning product. By means of a standardized survey within the remanufacturing industry, the occurrence of uncertainties is confirmed and put into relation with challenges in the production planning and control (PPC) of remanufacturing operations. Furthermore, it is shown that strategies to deal with uncertainties currently used cause major inefficiencies that hinder economic remanufacturing of complex products like electric vehicles. Based on the result of the survey the requirements for a remanufacturing specific PPC system are derived from a practitioner's point of view.

Selection and peer-review under responsibility of the scientific committee of the 16th Global Conference on Sustainable Manufacturing (GCSM).

Keywords: Remanufacturing; Production planning and control; Electric vehicle

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1. Introduction

1.1. Motivation

Remanufacturing is one of the fundamental elements of a circular economy. The concept of a circular economy aims to decouple economic growth from the use of finite resources. By conserving ecological resources and sinks, a circular economy protects the environment, reduces the cost of raw materials and energy supply and reverses the dependency on raw material suppliers. [1] Remanufacturing enables the further usage of core components of a product after a first lifecycle and therefore prolongs a products lifespan. A prolonged lifespan leads to longer replacement cycles and results in a reduction of newly manufactured products. This is potentially beneficial from three perspectives. [2] A comparative study shows that carbon emissions over a product's lifecycle can be reduced significantly. [3] Usually, remanufacturing costs for recovering a product to its original condition are lower in comparison to material and production costs of new product. [4] Accordingly, the total costs of ownership can be reduced significantly if the period of observation is extended beyond the normal product life.

SUNDIN defined Remanufacturing as following: [5] "Remanufacturing is an industrial process whereby products referred as cores are restored to useful life. During this process, the core pass through a number of remanufacturing steps, e.g. inspection, disassembly, part replacement/refurbishment, cleaning, reassembly, and testing to ensure it meets the desired product standards." This definition includes that single components of the returned cores can be re-used, processed or replaced. At the same time the product can be upgraded in order to enhance the product quality.

Worldwide, remanufacturing of automotive components such as turbocharger, alternators, starter motors, water pumps, clutches as well as more complex products like automatic transmissions and internal combustion engines account for two thirds of all remanufacturing activities. [6] Although remanufacturing on vehicle level is executed with special purpose vehicles, it does not exist for passenger cars and light commercial vehicles. In other sectors, the continuous use of the core product has been a natural element in the business models for several decades.

Compared to vehicles with conventional powertrains based on an internal combustion engine, electric vehicles have manifold conceptual freedom in the product and functional structure and therefore are more suitable for remanufacturing. An electric powertrain consists of clearly fewer components, each of which has a lower mechanical complexity. The mechanical power transmission interfaces in a conventional powertrain constrain the packaging of components within the vehicle structure, severely restricting easy access to potential remanufacturing modules. [7] Due to fewer components, less effort is required in the disassembly, processing and reassembly of an electric vehicle. Appropriate product design enables functional upgrades. BMW proves the potential of a modular vehicle design with the BMW i3 high-voltage battery retrofit program by including a technology upgrade of the battery. [8]

1.2. Problem statement

Remanufacturing is characterized by additional challenges in comparison to linear value chain production. One core aspect discussed in theory and practice concerning remanufacturing operations is dealing with uncertainties in production planning and control (PPC). With their study GUIDE ET AL. prove the existence of different uncertainties in practice and deduce which fields of action emerge. [9] The described uncertainties can be summarized as timing and quantity of returns, demands for remanufactured products, remanufacturing needs, routing and process times.

Based on this fundament, a lot of research has been performed in the last two decades. Three major literature reviews give a comprehensive overview of the state of the art of approaches in PPC for remanufacturing operations until 2014. In 2000, GUIDE ET AL. lays the foundation by discussing approaches dealing with remanufacturing-specific uncertainties. [10] Based on these considerations, LAGE and FILHO updated a review of the state of the art until 2009. [11] GAGNON and MORGAN examined the literature from 2010 until 2014 concerning approaches for dealing with specific challenges in PPC. [12] The individual aspects within the planning and control scope for remanufacturing orders are covered in detail. The effect of and how to deal with uncertainty within the single tasks of a PPC is described comprehensively. However, in literature the complexity of a remanufacturing system is reduced to an extent that the transfer of the findings of previous research to realistic applications is not permissible. [13]

LAGE ET AL. concluded based on a case study that no approach comprehensively fulfils the requirements for an industrial application. [14] GAGNON and MORGAN 2014 found out that remanufacturing companies do not make use of a sophisticated, mathematical heuristic in their scheduling practices even though a majority uses commercial planning software systems for scheduling. In contrast, CLOTTEY's study from 2010 shows that most automotive remanufacturers plan and control their operations manually or by means of desktop software. [15] Only a small proportion of the study's participant use commercial software. Key elements of a PPC like the determination of lead times, routings and batch sizes are mainly calculated based on experience without software-based optimization tools.

Nevertheless, remanufacturing is a profitable business for a wide variety of products, as companies have developed practicable solutions for dealing with uncertainties. [16] This is particularly valid for products with small production volumes or moderate complexity. [17] The more complex the product structure, the greater the uncertainty related challenges. [14] In order to analyse which requirements have to be fulfilled in order to broaden the scope of remanufacturing, the example of electric vehicles is suitable as an object of investigation. Electric vehicles with a product structure consisting of functionally interdependent mechanical, mechatronic and electronic systems are highly complex products with potentially high production volumes.

Understanding the uncertainties affecting the remanufacturing operations and how remanufacturing companies are currently facing these challenges is important for deriving requirements for the PPC for remanufacturing of complex products. Likewise, the effectiveness of current measures needs to be elaborated and the desire for further-reaching solutions must be queried in order to derive the need for action from a practitioner's point of view. Accordingly, the first fundamental question is what information is provided as a basis for planning in the PPC:

Q1: Which level of information is available at the beginning of the production planning?

In case of incomplete information, planning tasks can only be carried out with uncertainty. It has not been investigated how these uncertainties affect the decision-making process of the individual PPC tasks and to what extent adverse decisions are caused by uncertain information:

Q2: How does uncertain information affect the decision-making process within the PPC?

In order to be able to mitigate the effects of uncertain information and the resulting adverse decisions, possibilities for designing the production process exist. Cores can be disassembled completely such that quality controls are conducted for every single part. Furthermore, additional resources can be hold available for unplanned activities or disturbances:

Q3: Which strategies are currently used in production design to counteract uncertainties?

These production design related measures to minimize the influence of uncertainty-related adverse decisions cause inefficiencies in during remanufacturing operations. By means of a specifically designed PPC for remanufacturing operations reaction mechanisms for uncertainties could be helpful:

Q4: For which PPC tasks formalized methods for dealing with uncertainties would be helpful and for which PPC tasks are formalized methods already in place?

2. Explorative survey

2.1. Survey design

An explorative survey was executed based on a questionnaire from June 2017 to August 2017. 512 contacts were requested to participate at international exhibitions as well as from remanufacturing industry networks and an additional online research. The data collection was executed by structured interviews based on a questionnaire and by sending online questionnaires. The data was prepared such as any respondent who answered less than 70 % of all items were not taken into account. At the same time participants that are not directly involved in remanufacturing practices were sorted out by filter questions. N = 62 data entries were left in the data set which corresponds to a response rate of 12,1 %.

The participants of the survey are industry experts by 73 % representing different levels of the remanufacturing value chain including suppliers, original equipment manufacturer (OEM) and remanufacturers. (Fig. 1 a) Supplemented by consultancies, science and research organizations, machines manufacturer and others the survey has a strong focus on the automotive sector in which 89 % of the participants execute their main activities. (Fig. 1 b) With 41 % remanufacturer dominate the survey followed by suppliers (23 %) and science and research organizations. The participants represent a cross-section of different company sizes ranging from small organizations with a revenue per year less than 2 Million USD up to large multinational corporations with more than 2 Billion USD revenue. (Fig. 1 c) With 43 % companies in the area 2 Million USD to 49 Million USD revenue dominate the survey. 40 % of the participant's organizations execute remanufacturing in a medium size series production with 2.000 to 19.999 units per year. While 44 % of the companies' remanufacturing activities are on large scale or mass production level only 9 % remanufacture produce small series. (Fig. 1 d)

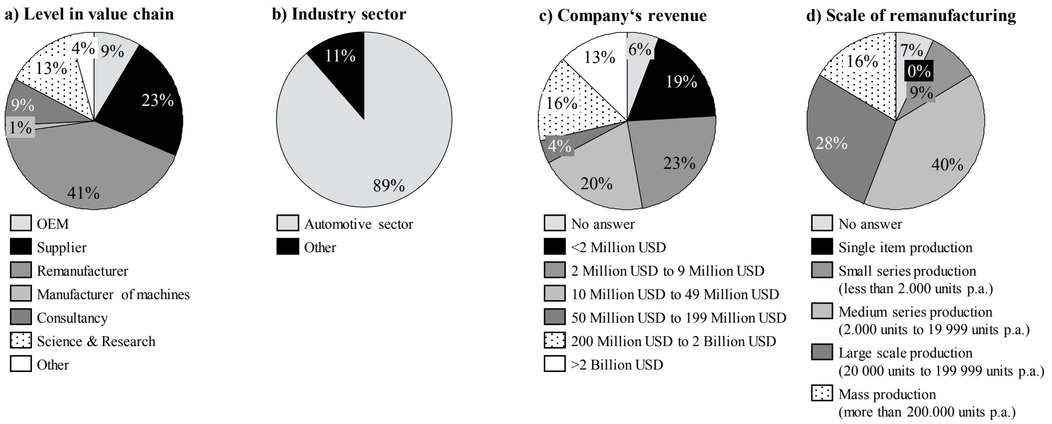

Fig. 1: Sample structure

2.2. Results

Corresponding to Q1 most obvious the information about the condition of the core as well as the timing of the return were evaluated to be very poorly availably for more than 50 % of the participants. The information about the amount of returns within a certain period and the demand for the remanufacturing product is (rather) not available for 37 % and 36 %, respectively. The development of the product technology over a product life cycle is uncertain for 40 % of the participants. (Fig. 2)

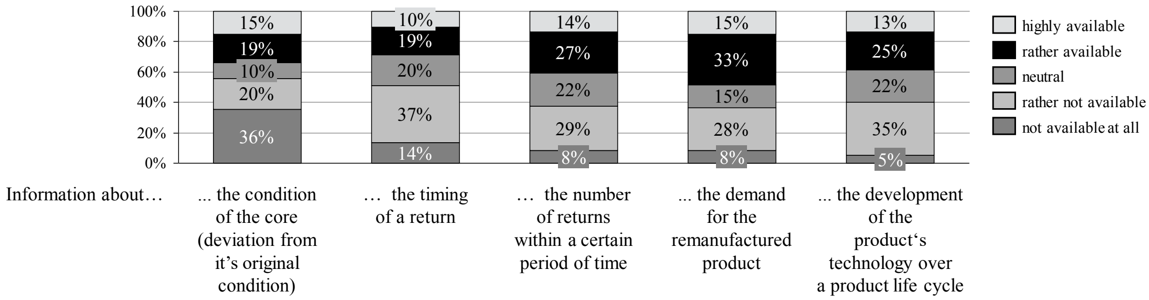

Fig. 2: Information availability in remanufacturing operations

Regarding Q2, the influence of insufficient information on decision-making is examined by means of eight aspects. (Fig. 3) For all aspects, the majority of responses indicate a strong existence. The evaluation of the quality of cores is mostly done based on individual experiences. 35 % do not have to change the work sequence from the initial planning in the course of a remanufacturing at least sometimes. Seemingly defect products are sorted out by mistake by 25 % and (ultimately) defect products are sorted out too late by 41 % often or always, while 35 % and 24 % rarely or never face these inefficiencies, respectively. Compared to the initial planning, there are at least sometimes deviations in process lead times for 78 % of the participants. 16 % have issues with missing parts causing disruptions such as idle times only rarely or never. Production resources are utilized at different extents in a fairly regular manner for a vast majority of the participants (85 %). Also, the profitability of remanufacturing processes changes in the course of a production routine sometimes, often or always for 78 %. Taking into account the unidirectional nature of the scale, meaning that any answer other than "never" implies the existence of the queried phenomenon it is noteworthy that a very low proportion of participants never faces the described challenges.

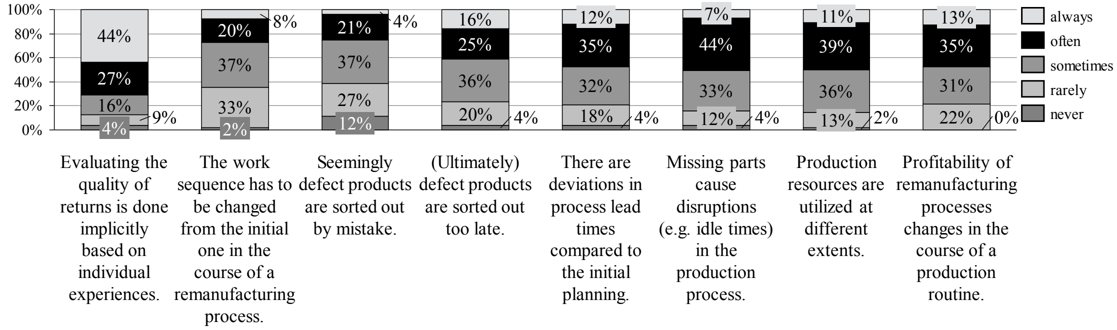

Fig. 3: Decision-making process during remanufacturing operations

Linked to Q3 four strategies of designing the remanufacturing process in order to deal with uncertainties were presented. (Fig. 4) The fact that products are disassembled completely and that the condition of every part is checked individually was confirmed by 84 % and 88 %, respectively. More than half of the responses correspond to strong agreements with these statements. Additional resources tend to be hold ready for unplanned process steps or disruptions (54 %). The limitation of remanufacturing activities to wearing parts was observed to be mostly disagreed upon (56 %).

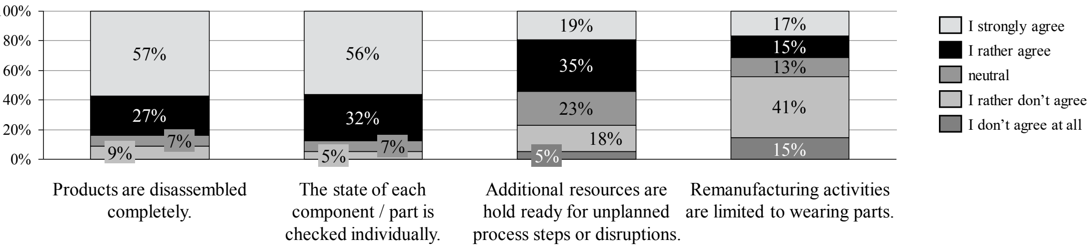

Fig. 4: Remanufacturing production design strategies

Regarding Q4 different aspects were presented all characterizing different methods for reacting to deviations from initial planning in formalized ways. The sample indicated high relevance of the respective aspects. (Fig. 5) For at least 70 % of the participants methods for reacting to changing process lead times and changing availability of production resources as well as methods for integrating unplanned additional processes and integrating unplanned required material are relevant. Highest relevance was confirmed to a continuous re-evaluation of the economic viability of the remanufacturing process and the usage of data from past orders (84 % and 94 %). Methods for integrating unknown product changes are seen relevant by 65 %.

For each aspect between eight and twelve participants indicate that the method was already in place. In total 16 (25 %) participants stated to have at least one method implemented. In relation to the sample composition, remanufacturers are overrepresented while OEM do not occur at all.

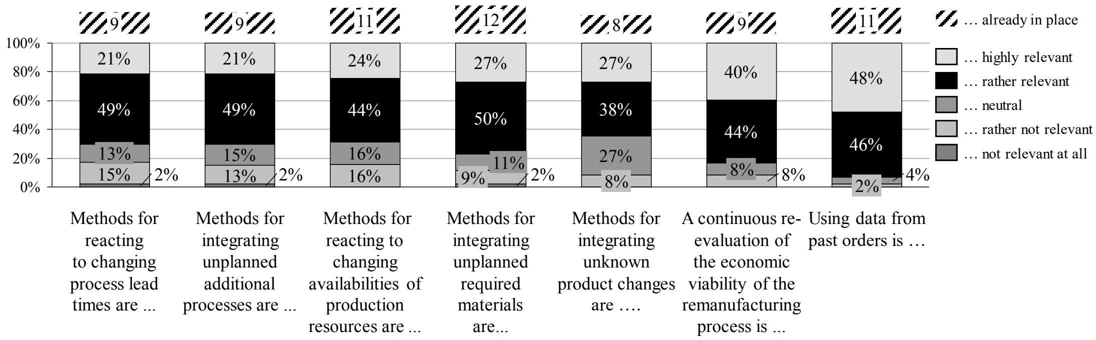

Fig. 5: Formalized methods to react on deviations of the initial planning

3. Discussion

Concerning Q1, the results of the survey confirm the existence of external uncertainties due to a lack of information regarding the cores' condition and the timing of the returns as well as the demand for remanufactured products Accordingly, the results of previous survey can be confirmed.

Regarding Q2, it can be stated that the initial inspections after the return of a core does not provide sufficient information about the core's condition. This information is rather generated successively during the disassembly and reconditioning process. Therefore, the continuously identified remanufacturing needs require the continuous adaption of the initially planned process lead times, production sequence and materials required. Furthermore, the generated information can lead to the conclusion that cores are not able to be remanufactured anymore from a technical or economical point of view and have to be sorted out lately in the process. Unpredictable occurrence of fault patterns can lead to peak demands for specific disassembly and reconditioning resources. The combination of missing information about the timing of core returns and varying remanufacturing needs in different remanufacturing orders potentially causes a highly unbalanced degree of production resources utilization or long waiting times during times of high general demand. Consequently, the profitability of remanufacturing orders changes in the course of the operations due to uncertainty caused disruptions.

In order to deal with these challenges, remanufacturing companies confirm the implementation of the presented production design strategies. (Q3) By applying one of the remanufacturing strategies, one accepts a certain degree of inefficiency in the design of the production itself. Disassembling the entire product and inspecting all components most likely include process steps which are not value adding as long as no additional remanufacturing needs are detected. Planned overcapacity inevitably causes inefficient usage of resources. Sorting out technically processable cores by reducing the remanufacturing scope to wear parts causes opportunity costs in the form of lost revenues.

Even though production design inherent inefficiencies are accepted in order to minimize the vulnerability to uncertainty related disruptions the relevance of additional reactions mechanisms within the PPC is illustrated. (Q4) Particularly, high benefits from remanufacturing specific solutions for production requirements planning, capacity planning and scheduling and an ongoing order profitability assessment are expected. The potential benefits are documented by the fact that remanufacturing companies already have such methods implemented in daily operations.

The comparison of the whole sample (n = 62) with the reduced sample of participants from companies that have implemented at least one of the presented methods (n = 16) shows only minor effects on the answer distribution regarding the decision-making process. (Fig. 3, Fig. 6) Aspect one to three were agreed to by over 60 % of the corresponding participants and is similar with the response behavior of the whole sample. A slight improvement can be detected for the fact that defect products are sorted out too late since it occurs always, often or sometimes for 63 % (0 %, 25 % and 38 %, respectively). Deviations in process times and disruptions caused by missing parts occur a little more frequent in organizations with formalized methods to react to changes. Accordingly, no noteworthy deviations in response behavior can be determined with regard to the occurrence of the change in profitability.

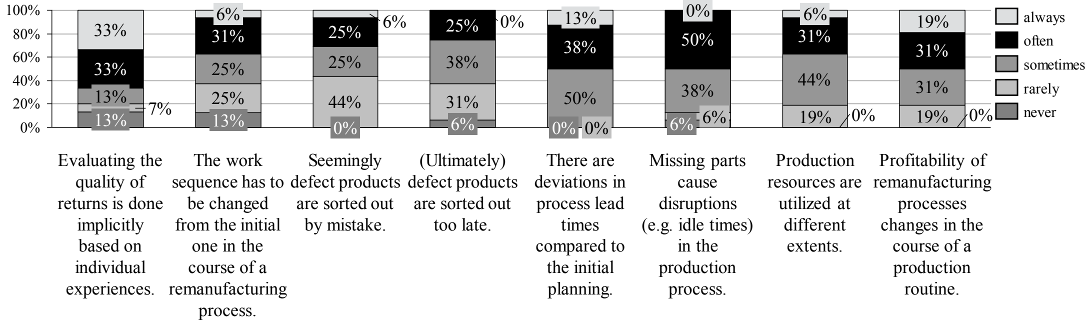

Fig. 6: Decision-making process in companies with at least one formalized methods to react on deviations in place

Regarding the options of designing the production, in order to deal with the remanufacturing specific uncertainties also only little differences within the reduced sample are observable. (Fig. 4, Fig. 7) The companies with implemented reaction methods even more often disassemble the cores completely and check each part individually more often.

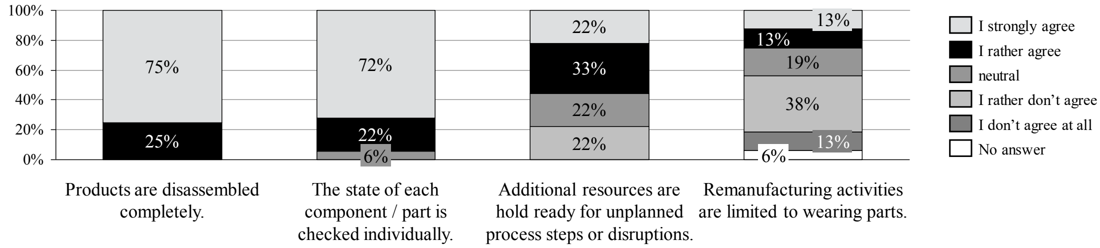

Fig. 7: Remanufacturing production design strategies in companies with at least one formalized methods to react on deviations in place

Summarizing can be stated that currently implemented methods to react on changes in the PPC do not help avoiding production design inherent inefficiencies. In order to guarantee a functioning remanufacturing, order processing compromises in the production design still are necessary to deal with insufficient information caused uncertainties.

4. Conclusion and Outlook

The discussed remanufacturing industry insights have a considerable influence on the remanufacturing of complex products like electric vehicles. With regard to uncertain information, the following conclusions can be drawn. (Q1) While mechanical signs of wear and damage can in many cases be determined by a simple visual or functional check, fault detection in mechatronic and electrical systems can be much more difficult. Even for OEM, most control units provide only limited access to the recorded usage data since suppliers typically do not provide open communication interfaces. While fault messages are transmitted, in most cases the reason behind errors remains unclear in the first place. The fault patterns of the interrelated systems overlap during usage of the products, making condition determination and defect prediction even more difficult. Complexity increases further as environmental factors such as usage behavior and environmental conditions during the vehicle lifecycle leads to significantly different signs of wear and failure patterns. As a result, recurring fault patterns are even more difficult to derive.

Due to the difficulty of identifying the remanufacturing needs, the planning basis for PPC is highly uncertain. (Q2) The less reliable information is available, the more deviations from the initial planning are to be expected. At the same time, the sensitivity of a production system's efficiency to such disruptions increases with the complexity of the production processes potentially resulting in a significant reduction in profitability. Consequently, the requirements for planning and controlling order processing increase with the complexity of the product structure.

Furthermore, the options for dealing with uncertainties by an adequate production design as it is common practice are very limited for vehicle level remanufacturing operations. (Q3) Firstly, from an economic point of view complex product structures with several thousand individual parts and combined frictional, positive and adhesive connections cannot be disassembled completely. Secondly, holding additional resources available contradict the automotive industry's standards of efficient and lean production. Lastly, reducing remanufacturing to wear parts excludes a majority of returning products since interrelated fault patterns lead to a vast number of possible component conditions and fault combinations.

To enable remanufacturing of complex products like electric vehicles, an integrated PPC system is required that is able to manage uncertainties and the resulting system dynamics. (Q4) Crucial elements are the generation of condition information and dynamic scheduling as well as continuous re-evaluation of the profitability of remanufacturing orders. An accurate initial condition assessment prior of the actual remanufacturing operations is of particular importance. Since an electric vehicle cannot be completely dismantled during remanufacturing, it is impossible to check the vehicle components individually. Therefore, a comprehensive upfront assessment of the components condition is required in order to derive the remanufacturing operations needed. This assessment must be able to process different input variables from various sources like status information, error messages, lifecycle data from control units and sensors as well as individual worker evaluations. Due to the described complexity of fault detection in electric vehicles, incorrect evaluations cannot be avoided. Therefore, the scheduling logic has to consider uncertainties regarding potentially incorrect condition assessment resulting in unplanned or differing processes and additional material requirements. At the same time the resulting dynamics needs to be managed in order to minimize production disruptions causing a loss of profitability.

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