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Adaptive remanufacturing for lifecycle optimization of connected production resources – A literature review

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ABSTRACT

Lifecycle extensions of production resources provide major leverage to the improvement of resource sustainability. This paper presents the results of a systematic literature review on technological fundamentals of intelligent maintenance and remanufacturing approaches as well as affiliated business models. In total, 3,368 paper were identified of which 35 were synthesized. Key findings are that less research activities focus on intelligent remanufacturing than on intelligent maintenance. Moreover, integrated decision frameworks for Prescriptive Maintenance are rare. Beyond that, identified maintenance approaches – most of them focusing on the energy sector – aim at avoiding machine breakdowns rather than ensuring a certain performance level.

1. Introduction

A growing world population along with high global economic performance leads to increasing resource consumption and environmental impacts. An essential solution step is the decoupling of resource usage and economic growth (International Resource Panel and United Nations Environment Programme 2011; Brecher et al., 2011; Reike et al., 2018). In this context, sustainability is enhanced by improving resource efficiency through extended product lifecycles while preserving economic development.

Particularly in industrialized nations, the lifecycle extension of production resources provides major leverage to the improvement of resource efficiency. Common approaches for prolonging the utilization of production resources range from maintenance to remanufacturing, i.e. rebuilding to original specifications (Kampker et al., 2019; Sundin, 2004). Maintenance approaches can be corrective, preventive, predictive or prescriptive, with the latter suggesting specific maintenance actions (Strunz, 2012). Remanufacturing measures are more extensive than maintenance activities and can be applied to entire investment goods or single components. In general, remanufacturing is one of the core elements of a circular economy (Kampker et al., 2016' Kamper et al., 2019; Sauvé et al., 2016). Within the scope of this paper, the term *Adaptive Remanufacturing* (AdR) implies intelligent decisions to enable lifecycle optimization involving measures in the range from maintenance to remanufacturing.

Based on this idea, the concept of AdR is developed within the research project *Adaptive Remanufacturing for Lifecycle Optimization of Capital Goods (ReLIFE).* In this context, adaptivity describes the active and rapid adaptation to sudden, unforeseeable changes in the system environment (Günthner et al., 2017). AdR enables the efficient adjustment of resource performance through the suggestion of economically evaluated maintenance and remanufacturing measures. AdR ensures a predefined performance level through maintenance and remanufacturing measures. Thus, AdR enables new business models for manufacturers, owners and operators of production resources.

A systematic literature review was performed in order to elaborate the state of the art in the field of maintenance, remanufacturing and related business models.

2. Methodological approach

The aim of this systematic literature review is to present the latest state of the art of intelligent maintenance and remanufacturing methods and to identify suitable practical, use case-oriented

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Characteristic	Category			
Focus	Research outcomes	Research methods	Theories	Applications
Goal	Integration	Criticism	Central issue	
Perspective	Neutral representation	Espousal of position		
Coverage	Exhaustive	Exhaustive and selective	Represen-tative	Central/ pivotal
Organisation	Historical	Conceptual	Methodological	
Audience	Specialised scholars	General scholars	Practitioners/ politicians	General public

Fig. 1. Taxonomy of literature reviews according to Cooper (1988).

implementations as well as corresponding business models. The methodology used in this review follows the iterative approach described by Vom Brocke et al., (2009) which comprises five main steps: definition of review scope, conceptualization of topic, literature search, literature analysis and synthesis as well as deduction of research agenda.

Review scope and strategy were defined pursuant to the taxonomy of literature reviews according to Cooper (1988) (cf. Fig. 1) extended by elements of the STARLITE mnemonic (Booth, 2006).

The research focus is on research outcomes and applications with the goal of knowledge integration from a neutral perspective. The conceptually organized review addresses specialized scholars and the coverage is classified as exhaustive and selective. Within the framework of the STARLITE mnemonic, a quantitative literature search, analysis and synthesis was conducted before an affiliated qualitative evaluation was applied to the search results. In the literature search, journal articles and conference proceedings published in English between 1999 and 2019 were collected from the electronic databases IEEE Xplore, Web of Science, Scopus, EBSCO and TEMA.

The goal of improved resource efficiency in the domain of capital goods is pursued through adaptive maintenance and remanufacturing strategies. This topic was conceptualized by iteratively identifying key research fields, which were structured in the four areas *goal, topic, method* and *domain*. Accordingly, the search terms were condensed into the following search string including Boolean operators and wildcards: (efficien* OR lifecycle OR lifetime OR sustainab*) AND (maintenance OR reconditioning OR remanufacturing OR refurbishing OR overhauling) AND (preventive OR predictive OR prescriptive OR adaptive OR corrective) AND (machin* OR “operating resources“ OR “capital goods“ OR “investment goods“). AND operators were used to exclude publications solely focusing on single areas of the search field in order to increase the thematic relevance.

Literature was searched by applying the previously defined string to titles, keywords and abstracts, resulting in 3368 publications. The affiliating analysis and synthesis of collected publications was conducted in accordance with the PRISMA methodology (Moher et al., 2009). Accordingly, duplicates and formally incorrect records were initially cleared with 2471 publications remaining. The formally correct publications were then clustered through an algorithm analyzing title and abstract. The rejection of thematically irrelevant clusters resulted in 2217 remaining publications. The following screening process was structured as a two-stage review with two assessors independently analyzing the content. A publication was evaluated as thematically relevant, if the four defined areas of the topic were addressed within the publication. In the first screening stage, the reviewers evaluated both title and keywords. In the second screening stage, the abstracts of the 181 remaining publications were analyzed. The intersection of the assessors' selections contained 35 publications which were finally included in the full text synthesis. If a publication was selected by only one assessor, deeper analysis with additional discussion was applied to achieve a concordant decision on selection or rejection. Within the synthesis, central results were revealed in an in-depth content analysis and then structured in thematic categories. These categories are reflected in the structure of Section 3 containing the consolidated review results. In a final step, the research agenda was derived from the key findings and the state of the art forming the basis for the development of AdR within the research project ReLIFE.

3. State of the art on intelligent maintenance and remanufacturing

The sections of this chapter are structured as follows: After an overview of existing intelligent maintenance and remanufacturing approaches, the concept of Condition Monitoring is elucidated. Afterwards, the approach of Predictive Maintenance, which is based on the results of Condition Monitoring, is presented. As for Predictive Maintenance, maintenance measures are applied when monitored machine parameters forecast the need for repair or replacement (Yeh et al., 2011; Li et al., 2009; Reininghaus and Kolbenhub, 2005). The evolutionary step is known as Prescriptive Maintenance. It involves the integration of a decision support system, which proposes specific maintenance actions to be either automatically or manually executed. Finally, sustainable business models are presented and contextualized regarding intelligent maintenance and remanufacturing policies.

Despite the multilayered search string focusing on remanufacturing and the related concepts of overhauling and refurbishing, most publications within the present systematic literature review deal with maintenance topics. Remanufacturing is hardly represented in the context of intelligent strategies or lifecycle optimization. Yet, many maintenance-related strategies and business model have been identified, which can be adapted to the concept of Adaptive Remanufacturing comprising both, maintenance and remanufacturing measures aiming at intelligently prolonging the lifecycle of investment goods.

3.1. Overview and evolution of intelligent maintenance and remanufacturing approaches

There are two widespread general maintenance approaches, which are included in nearly all modern policies. Firstly, run-to-failure maintenance (Yeh et al., 2011), also known as reactive maintenance (Li et al., 2009), is a non-schedule maintenance policy only applied after machine failures (Yeh et al., 2011; Li et al., 2009; Reininghaus and Kolbenhub, 2005). Secondly, Preventive Maintenance is a calendar-based maintenance approach, which is executed during machine operation focusing on the prevention of failures (Yeh et al., 2011; Li et al., 2009; Reininghaus and Kolbenhub, 2005). Several elements influence the successful implementation and application of intelligent maintenance methods. Recent research approaches highlight the potentials of Preventive Maintenance and especially condition-based approaches on reducing costs and efforts in operation and maintenance (Wang et al., 2019; Bot and Azoulay, 2015; Kabir et al., 2015; Franciosi et al., 2018).

Preventive Maintenance policies can be divided into the three categories time-based, condition-based and Opportunistic Maintenance (Wang et al., 2019). Time-based measures are scheduled based on equipment-specific knowledge, statistics and legal or internal requirements like quality, whereas condition-based measures are chosen according to current conditions. Opportunistic Maintenance is based on seizing the opportunity of performing maintenance work during planned or unplanned machine stoppages (Reininghaus and Kolbenhub, 2005; Wang et al., 2019; Erguido et al., 2017).

Asuquo et al. (2019) conclude that the decision for one of these high level maintenance strategies depends on the factors of cost, reliability, safety, availability and downtime which need to be interpreted by experts.

3.1.1. Condition monitoring

The monitoring of machine components and systems through sensors is a decisive enabler for maintenance activities. Condition Monitoring (CM) uses sensors to provide information on machine conditions. On this basis, operational efficiency can be improved through reasonable maintenance decisions (Kabir et al., 2015). In order to increase machine availability and system reliability, advanced CM technologies are required, as well as real-time data acquisition and signal processing technologies (Yeh et al., 2011; Denkena et al., 2009; Uhlmann et al., 2013). The CM process can be divided into the steps detection, diagnosis and prognosis of faults (Pattison et al., 2016).

The most commonly monitored condition parameters are vibration (Kabir et al., 2015; Kalra et al., 2019; Kiangala and Wang, 2018; Behera and Sahoo, 2016; Wang et al., 2016), acoustic emissions (Kabir et al., 2015; Kalra et al., 2019; Wang et al., 2016), temperature (Behera and Sahoo, 2016; Denkena et al., 2009), rotational speed (Pattison et al., 2016; Mourtzis et al., 2016) and the level, pressure, temperature and quality of oil (Pattison et al., 2016; Behera and Sahoo, 2016; Ferreira et al., 2017).

Extensometers, pressure and vibration sensors, oil sensors, thermal and ultrasonic sensors are used to monitor these conditions (Kalra et al., 2019; Ferreira et al., 2017). Moreover, wireless sensors allow the monitoring of moving machine parts (Kalra et al., 2019). In order to improve the performance of a CM system, different sensor concepts should be combined in a multi-sensory concept (Behera and Sahoo, 2016; Mourtzis et al., 2016; Fleischer et al., 2006). An intelligent selection and arrangement of sensors within a system ensures maximum diagnostic capability through a minimum number of sensors reducing potential error sources and minimizing system complexity (Fleischer et al., 2006).

Rotary and highly strained components are an important application area for CM (Behera and Sahoo, 2016; Denkena and Jacobsen, 2006). Machine elements like gearboxes, bearings, generators and rotors are often monitored with a focus on vibration and acoustic emissions since they are subject to high mechanical strain. Modern capital goods like wind turbines are usually equipped with sensors allowing the application of CM. Sensor values are aggregated and processed to generate alarms and warnings from the CM system (Kabir et al., 2015; Kalra et al., 2019).

Despite the implementation costs for CM systems, benefits can be realized through reduced operation and maintenance costs (Bot and Azoulay, 2015; Kabir et al., 2015). A potential weakness of CM is reduced reliability due to misinterpretations of sensor signals not fully describing the current machine conditions (Bot and Azoulay, 2015). Study results indicate that only 33% of the participating companies use CM concepts although 67% confirm the importance of failure detection (Denkena et al., 2009). This shows that CM is not yet widely spread throughout industry despite potentials in improving operational efficiency.

3.1.2. Predictive maintenance

Predictive Maintenance (PdM) models are based on the systematic data collection through sensor signals (i.e. CM). However, PdM goes one step further by applying data analysis techniques in order to predict machine breakdowns and vulnerabilities (Böning, 2019). Several approaches provide mathematical models to predict the remaining useful life (RUL) of a machine (Denkena et al., 2009; Mourtzis et al., 2016; Denkena and Jacobsen, 2006; Paaranan et al., 2018). PdM approaches comprise model-based and data-driven prediction models. In practice, data-driven models are preferable for the monitoring and prediction of complex cyber-physical systems. A hybrid prognostic model combining both methods is proposed where both sensor measurements and machine settings are included in the relating models. An analytical model can be applied, if physical knowledge or experiential information is available. If system effects on degradation are unquantifiable, a data-driven approach should be adopted. Diagnostic models comprise multiple probability distributions for RUL predictions (Wang et al., 2016).

An example for the application of PdM is the analysis and prediction of the RUL of a bender press break. A mathematical prediction model is used for the detection prognosis and diagnosis of machine failure. Expert knowledge is encoded as a set of rules and used to detect and flag possible failures (Ferreira et al., 2017).

Another example for the usage of expert knowledge in PdM is presented within a use case of wind turbines. For the holistic prediction of the RUL and the identification of future condition deteriorations, machine learning methods such as random forests are applied. The predictive phase is interpreted as a classification problem where the state of a turbine is labeled as either anomalous or normal. Classification labels are extracted from past alarm signals and raw sensory data. The reliability is then calculated via a deep believe network. In this context, turbulence intensity is identified by experts as a key variable to predict future degradation of high-risk components like wind turbine gearboxes (Pattison et al., 2016).

In the research project *make-It*, two approaches for predicting the RUL of a machine are proposed. Recorded signals are used to extrapolate wear behavior taking into account future load situations to determine the time of failure. Additionally, failure probabilities are calculated and adapted to the recorded machine conditions (Denkena et al., 2009).

Concepts of PdM are applied in various industries. Use case examples can be found in the heavy machinery industry, the energy sector and in the sectors of consumer goods and machine tools (Yeh et al., 2011; Pattison et al., 2016; Wang et al., 2016; Mourtzis et al., 2016; Ferreira et al., 2017; Yildirim et al., 2019).

3.1.3. Prescriptive maintenance

Prescriptive Maintenance (PsM) is understood as the prediction and automated suggestion of timed decisions regarding specific maintenance actions or action plans, which are based on the monitored current state (i.e. CM) and predicted future conditions (i.e. PdM) of products with the aim of preventing machine failures. A decision framework for PsM may follow an opportunistic approach using planned and unplanned stoppages to perform specifically timed maintenance activities (Wang et al., 2019; Erguido et al., 2017; Cavalcante et al., 2018). (Erguido et al., 2017) present a wind farm example, where Opportunistic Maintenance policies vary according to current weather conditions. A dynamic approach to determine opportunities for maintenance and to increase reliability and performance as well as safety for maintenance workers is described. Maintenance actions can be perfect or imperfect resulting in a state, which is more or less close to the original condition. Decisions are based on a dynamic reliability threshold. Inherent and outsourced maintenance resources as well as repair times and failure modes are included in the decision process. Thus, Opportunistic Maintenance generates potentials regarding wind farm productivity and lifecycle costs.

A recent approach uses the concept of opportunistic replacement for specific parts in a theoretical arbitrary one-component system (Cavalcante et al., 2018). Two opportunistic policies for the replacement of parts are proposed and direct as well as indirect maintenance costs are considered as major decision variables. The authors conclude that the utilization of opportunities for replacements is cost efficient and that it simplifies maintenance planning compared with age-based and scheduled preventive replacements (Erguido et al., 2017; Cavalcante et al., 2018). Opportunistic Maintenance is considered the best policy in cases of little knowledge about machine defects (Cavalcante et al., 2018). This approach can be the basis to remanufacturing activities for single components.

In other approaches, the decision process of PsM is considered from an Operations Research point of view (Yildirim et al., 2019; Schutz et al., 2013; Dawid et al., 2016; Bharadwaj et al., 2012; Chen et al., 2012). Here, decision making in maintenance is interpreted as an optimization problem, which needs to be systematically or heuristically solved. Such a heuristic can be a genetic algorithm. In the case of Schutz et al. (2013), the genetic algorithm aims at finding the optimal effectiveness factor for imperfect Preventive Maintenance actions. Other approaches use Markov chain representations, Weibull Proportional Hazards Models, the Bayesian Rule and hidden Markov models to form an equipment residual life model for the definition of optimal maintenance decision criteria (Chen et al., 2012). Maintenance planning in wind farms is interpreted as a routing problem since maintenance and logistics are very expensive in offshore wind farms (Dawid et al., 2016). Yildirim et al. (2019) describe RUL predictions, which are used in model-based mixed-integer programming, utilizing generator loading information to jointly optimize condition-based Preventive Maintenance and unit commitment decisions in power systems. As run-repair-replace decisions are an integral part of the general discipline of asset management, costs and specifically the quantitative risk of maintenance activities need to be considered as well. Therefore, Bharadwaj et al. (2012) argue that the risk of failure is a major indicator for specific maintenance decisions. Accordingly, high-risk components need to be primarily addressed in any system.

Regarding holistic frameworks, several approaches are identified which comprise the complete range from CM to PsM (Bot and Azoulay, 2015; Pattison et al., 2016; Denkena et al., 2009). Maintenance scheduling modules are often part of complex PsM frameworks (Bot and Azoulay, 2015; Pattison et al., 2016). The scheduling of appropriate time windows for maintenance tasks in offshore wind farms for example is interpreted as a multi-variable multi-objective optimization problem (Pattison et al., 2016), which is solved through a memetic algorithm based on current oceanic conditions. Similarly, Denkena et al. (2009) use RUL predictions to analyze technical maintenance criteria. These are used in combination with economic, organizational and logistical conditions to plan maintenance times and to choose the right maintenance service provider for specific maintenance tasks. In the approach of Bot and Azoulay (2015), the minimization of total lifecycle costs (costs for maintenance, failure damage and downtime) represent the optimization objective with the constraint of a fixed minimum availability required. With this objective in mind, the proposed framework targets three variables: The inspection schedule, the Preventive Maintenance schedule and the spare parts inventory (in type and quantity). Concerning the trade-off between maximum availability and minimum maintenance costs, the reliability threshold, on which Preventive Maintenance and Opportunistic Maintenance are conducted, needs to be the central variable of optimization (Wang et al., 2019).

3.4. Sustainable business models based on intelligent maintenance and remanufacturing

This chapter provides an overview of sustainable business models (BM) based on intelligent maintenance and remanufacturing approaches. Bocken et al. (2014) describe eight archetypes for the description and categorization of sustainable business models as well as for the definition of an agenda for the sustainability-oriented development of such BM. Examples of these archetypes are the creation of value from waste, the maximization of material and energy efficiency and the delivery of functionality rather than ownership. The latter is a strategy of increasing popularity according to Sundin et al. (2005). The authors see remanufacturing and upgrading as a vital step to support several services during the functional lifetime of a product. To enable this functionality, the ease of access, handling and separation as well as wear resistance should already be considered during new product development.

Another aspect of sustainable BM is the transformation of economy from linear to circular as mentioned by Bocken et al. (2016). The authors divide the concept of circular economy into two approaches which are not mutually exclusive. The first approach aims at slowing down the circular economy loop by prolonging the utilization period of a machine or resource. The second approach aims at closing the loop between post-use and production by designing products for dis- and reassembly to simplify remanufacturing or upgrading measures.

According to Uhlmann et al. (2017), the concept of CM is of fundamental importance for availability- and leasing-based BM. The authors argue that the role of manufacturers is in a current shift towards that of a service provider. This leads to changing responsibilities between machine manufacturers and their customers. The authors divide innovative data-driven BM in the context of production systems into three categories: Function-oriented, availability-oriented and results-oriented. Through a maintenance contract, the manufacturer provides maintenance personnel in a function-oriented BM, while the customer identifies the need for service. In availability-oriented BM, production system providers are responsible for the machine availability. Thus, they are in charge of identifying the necessity for maintenance. In results-oriented BM, the machine provider assumes the responsibility for production and provides the operating personnel. Thus, the customer only pays for the corresponding result.

The authors conclude that especially availability-oriented BM require intelligent production systems. Paaranan et al. (2018) give an example for an availability-oriented BM for potato harvesters. Here, machine sellers take responsibility for the machine availability. They are therefore interested in information about the abrasion of specific machine components to plan maintenance activities at the right time and in the right quality. Concerning availability-oriented BM concepts, CM information can be leveraged in different value-inducing ways (Fleischer et al., 2006). Firstly, the manufacturer is able to optimize maintenance services (Paaranan et al., 2018; Schutz and Rezg, 2013) and spare parts inventories (Bot and Azoulay, 2015). Secondly, data about machine failures can be used in a manufacturing firm, such as research and development, to improve future products. Lastly, information can be used to run machines at a maximum, but at the same time wear-resistant performance level which increases value for customers and manufacturers (Fleischer et al., 2006). This is especially relevant for expensive capital goods with a long service life as a big part of the revenue is generated by after-sales services (Uhlmann et al., 2013).

Moreover, there are leasing-based BM (Schutz and Rezg, 2013) which are often availability-oriented aiming at ensuring a minimum, contractually predefined availability. This is achieved through preventive actions performed when a predefined reliability threshold is reached or through improving actions restoring the machine to a previous, better state when a failure occurs outside the reliability threshold (Schutz and Rezg, 2013). Especially for leasing-based BM, transparency and security are of great importance (Noack, 2018).

Relevant BM are primarily availability-oriented with manufacturers increasingly developing into service providers selling minimum machine performance levels instead of the machine itself. Thus, intelligent maintenance and remanufacturing decisions based on machine conditions are gaining in importance to prolong and close the loop of a circular economy and hence to enable sustainability for industrial machines.

4. Conclusion and outlook

The goal of this systematic literature review was the identification of state-of-the-art methods and use case-oriented, practical implementations of intelligent maintenance and remanufacturing approaches. Based on these approaches, an overview of possible BM concepts, which create and deliver value for machine manufacturers and operators, was given.

In the presented review, 3368 papers were found via the predefined search string, whereof 35 full texts were examined in detail. The findings were structured in the three sections *condition monitoring*, *predictive maintenance* and *prescriptive maintenance* representing the most relevant thematic clusters. Only 3 of 35 reviewed publications address integrated approaches covering CM, PdM and PsM. Especially for CM and PdM, several use cases were identified. These show in detail how specific machine components can be intelligently monitored and how the RUL can be predicted. For decision prescription, strategies like Opportunistic Maintenance, route and schedule optimization as well as holistic frameworks were identified. Common use cases with affiliated current research activities are (offshore) wind farms (8 publications) as well as heavy machinery (9 publications) such as press breaks, mining and harvesting machines. Regarding related BM, the analyzed literature focuses on availability- and functionality-oriented BM comprising CM, prediction and decision support for capital goods. For circular economy BM, the particularities already need to be addressed during product development.

A research gap was identified for intelligent remanufacturing approaches, since intelligence and adaptivity were only present in the domain of maintenance. In addition, identified PsM strategies only intend to prevent breakdown, not to ensure a certain minimum performance level. Besides that, a major part of use cases focuses on wind farms and the energy sector with only few papers specifically covering production resources. While most of the publications only cover segments of intelligent maintenance, an obvious lack of integrated intelligent decision frameworks for maintenance and remanufacturing has been determined. Therefore, future research will further develop these PsM strategies, focusing on integrated, intelligent maintenance and remanufacturing frameworks. Based on these findings, a novel approach for Adaptive Remanufacturing will be developed and implemented within the ReLIFE project. The approach will be based on PsM, extended by the aspect of contractually defined minimum performance levels of capital goods. On this basis, novel BM concepts will be developed to raise economic potentials on the basis of AdR. Moreover, AdR is expected to enable significant enhancements in resource efficiency by prolonging lifecycles of capital goods.

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