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An Approach for an Integrated Maintenance Strategy Selection considering the Context of the Value-Adding Network

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Abstract

Increasing complexity in manufacturing processes poses new challenges for industrial maintenance. In addition, advanced machine monitoring and lifetime forecasting options expand the tools and maintenance strategies available. Today, maintenance strategy selection is performed sequentially usually based on prioritised machines and components. These selections are optimized locally for each machine isolated, not considering the context of other machines within the value-adding network. To overcome these challenges, this paper presents an approach for an integrated maintenance strategy selection in one-step by an integrated model considering possible machine failures and the context of other machines within the value-adding network in parallel.

Keywords: smart factories; maintenance strategy selection

1. Introduction

The goal of industrial maintenance is to ensure a maximum of production equipment availability while minimizing the costs which arise in the process. The maintenance strategy selected for a specific component is one major factor, both on the availability and the maintenance costs of this component [1]. The implementation of the strategy, for example the frequency of a planned maintenance is also an important factor but builds on the foundation of the selected strategy. New technologies, especially cost effective sensors and more processing power with the option of edge computing are generating industrial big data [2] and allow for sensor based condition monitoring and predictive maintenance to become valid maintenance strategy options for various machines and components [3]. However, the selection of one of the new strategy options results in additional investment and operating costs, which include the need for a specific skillset of maintenance worker. This needs to be considered while selecting these strategies.

The addition of new strategy options has made the already complex maintenance strategy selection process more difficult with even more factors to consider [4]. There are many methods available to select a maintenance strategy, both for general machinery as well as for specific applications, like chemical plants. The specific methods can be used in a narrow application field and are not applicable for other industries or production plants. The selection process for the above mentioned chemical plant for example builds upon the whole production facility to be shut down for a certain time in which all maintenance tasks will be performed [5]. This strategy selection is valid only for a continuous production process where downtime in a single machine would immediately result in a complete stop of production.

Most methods for selecting a maintenance strategy for general machinery, for example in part manufacturing plants, can be used in a wider variety and without special

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circumstances. These methods either consider the production system as a single unit [6] or focus on a single machine without taking the maintenance strategies of other machines into account [7]. Considering the production as a single unit and selecting the best maintenance strategy based on the produced products and company figures can be used to evaluate maintenance strategies in general but does not yield the desired level of detail to make decisions for a single machine or component within the production system. When focusing only on one machine within the production system, the selection of a maintenance strategy is optimized locally for each machine isolated. The context of other machines within the value-adding network is not considering, which leads to two problems:

- The maintenance strategy does not necessarily reflect the maintenance strategy selection of the surrounding machines / components within the production system
- The resources needed for performing the maintenance strategy are only considered for the current machine / component even if they might yield an overall better availability of the whole production system if used somewhere else

Current maintenance strategy selection methods are trying to mitigate the effect of these two downsides by prioritizing the machines and components in the production system and selecting the maintenance strategies in sequence. This procedure helps to reduce the shortcomings but does not fix them.

In this paper, an approach for an integrated maintenance strategy selection, which will consider every maintenance relevant machines and components of the productions system in parallel, will be introduced. The next chapter focuses on the state of the art of maintenance strategy selection. Afterwards the approach and its challenges are described in chapter three and chapter four focuses on the ways to overcome them and the planned implementation of the approach. In the last chapter, a conclusion and future research are described.

2. State of the art and research

Maintenance strategy is a collective term and describes different activities or decisions depending on the context in which it is used. Therefore, the term maintenance strategy is defined in the next paragraph before the state of the art of maintenance strategy selection process will be shown with focus on industrial application and current research in this topic.

The state of the art was researched in different databases (Scopus, Web of Science, Springer, and Google Scholar) using a combination of the following keywords and their synonyms: *industry*, *manufacturing*, *maintenance*, *strategy selection*, *decision making*, and (*indirect*) *costs*. Relevant papers were analysed and forward and backward references of these papers were considered. The state of the art of current research builds on a literature review on the maintenance strategy selection and classifies other relevant papers into the described framework.

2.1. Maintenance strategies

The European committee for standardization defines maintenance strategy as “management method used in order to achieve the maintenance objective” [8] with examples of outsourcing of maintenance activities and the allocation of resources. When describing a maintenance strategy for a specific machine or component, this broad definition usually is focused on the type of maintenance. If more precise information are available, it is focused on the instance of the type of maintenance [1]. In the document from the standardisation committee, the types of maintenance are broken down into 19 different descriptions and can be categorized according to the graphic in their annex A of the into corrective and preventive maintenance [8]. Preventive maintenance can be further divided in predetermined and condition-based maintenance with predictive maintenance being a subcategory of condition-based maintenance. These categories, with predictive maintenance as its own category in newer publications, are used in the common standard texts [1,3] and publications [9] when referring to a maintenance strategy for a specific machine or component. The other types of maintenance defined in the standardization document and other publications [4,10] can either be placed in one of these categories or describe the way in which the activity is carried out and not the strategy of the activity itself. For example, one type of maintenance is defined as outsourcing of activities. This characterizes, that an external agent will do the maintenance activities; it does not specify the activity itself.

When describing the approach for an integrated maintenance strategy selection in this paper the selection of one of those four categories: corrective, preventive, condition based, and predictive maintenance and the respective instances of these categories will be described. An instance in this case is the detailed elaboration, for example the scope and frequency of preventive maintenance of a component.

2.2. Maintenance strategy selection in the industry

Although the importance of the maintenance strategy selection for the availability of production equipment and the overall maintenance cost is well known [9], a systematically approach is not widespread in the industry. In a benchmark study from 2018 of 134 production companies located in German speaking countries, 61% answered that they used personal and subjective experience to select a maintenance strategy (multiple answers possible) [11]. In another study with its main focus on smart maintenance with 96 participants mainly from maintenance service and mechanical engineering companies only 43% answered that they use either historical or real time data to determine maintenance actions. Other publications and literature reviews also conclude that maintenance strategy selection within companies can be improved. Possible reasons devised by the authors include the highly complicated industrial environment [7] and the unavailability of required information [12].

2.3. Maintenance strategy selection in research

No standard method for maintenance strategy selection that can be applied in every circumstance exists [13,14]. There are many publications focusing on maintenance strategy selection and the optimization thereof, but most publications in this field focus on a specific narrow problem or use-case [14]. None of the examined strategy selection methods provides a solution for the above-mentioned problems. Most of them focus on one machine or component at a time and only are able to include other machines in sequence [15]. The few maintenance strategy selection methods that try to incorporate multiple machines do so in a very narrow scope so that the method is not applicable for general use [16] or focus on a company wide selection [6] without considering the individual machines and components.

Ding and Kamaruddin introduced a classification in their comprehensive literature review [7] in which they classified existing strategy selection and optimization methods in three main groups regarding to the required information. The class ‘Certainty’ consists of methods where all needed information is available, and a single best option exists. The class ‘Risk’ consists of methods where information is available and probability distributions and stochastic algorithms can be used to determine the best maintenance strategy. The publications in this class were divided into three subgroups: mathematical algorithms, simulations, and genetic algorithms with respect to their individual approach. Ding and Kamaruddin called the third class ‘Uncertainty’ because the methods categorized in this class deal with parameters where the future conditions are not known and cannot be derived from probability distributions but have to be ascertained based on subjective probabilities. This class also was divided into three subgroups: heuristic based models, hazard-based models, and the largest multi-criteria-based models. Heuristic based models use logic and experience of the decision maker to guide the maintenance strategy selection process. These methods are usually fast and lend themselves to a variety of conditions but are very subjective. Hazard-based models focus on the failure and its root-cause rather than the economic aspects. Multi-criteria-based models were identified as one of the popular methods for maintenance strategy selection because they allow for conflicting objectives in the decision-making process. There are numerous publications that can be categorized in this sub category [4,17,18].

The focus on multi-criteria-based models for maintenance strategy selection is comprehensible since this method allows for multiple conflicting goals, is easily extendable and can work with different criteria types. This allows not only the evaluation of production equipment availability and costs but also safety issues, added value processes, spare parts availability, feasibility and other factors influencing the maintenance strategy selection [7]. All of the multi-criteria-based models are following the same principle for identifying the best option available: first, the relevant criteria and solution alternatives are identified, second the criteria are weighted and the performance of each solution alternatives is evaluated and assigned a value for each criteria, finally the solution alternatives are ranked based on the weighted sum [17]. In the literature reviews only one existing publication is identified where the maintenance strategy is selected based on an utility theory approach [4].

The utility theory approach is described to replicate the total utility function of the decision maker and maximizing it by considering the solution alternatives. The publication itself [19] focuses on a theoretical maintenance decision and decision theory itself and does not yield a practical method for determining a maintenance strategy within a production system without major additional effort.

Thus, no publication could be found to satisfy the stated problems of current maintenance strategy selection methods. The goal of this publication is to close this research gab by building upon the aspects of a multi-criteria-based model, take into account the total utility function of the decision maker with regard to all alternative maintenance strategies for all production objects and all available resources and to present an approach for the method.

3. An approach for an integrated maintenance strategy selection

As outlined in the introduction, the existing maintenance strategy selection methods have two main problems. However, the root-cause of the problems is the same. The methods only focus one machine at a time and do not consider the context of the value-adding network around them. The next subsections introduce additional requirements for an integrated method for maintenance strategy selection based on the findings in the literature. Afterwards, the new approach will be outlined.

3.1. Goal and requirements of an integrated method for maintenance strategy selection

Goal of this approach is to provide the decision maker with recommended maintenance strategies for all maintenance relevant components of a production system with respect to the maintenance strategies selected for all other components of that production system. The decision maker should have an overview of predicted maintenance relevant costs and predicted availability for the whole production system for different valid combinations of maintenance strategies. Considering studies on the forecasted requirements for maintenance support [9] and the conclusions of other publications of methods for selecting maintenance strategies [7] additional requirements for an effective and successful operation within the industry are:

- Easy implementation with interfaces to existing software solutions,
- Recommendation for the (human) decision maker with different options,
- Forecasting and risk-based value contribution calculation,
- Availability / production oriented,
- Flexible / dynamic,
- Self-improving (learning) method / adaptable and
- Automated and resource optimizing.

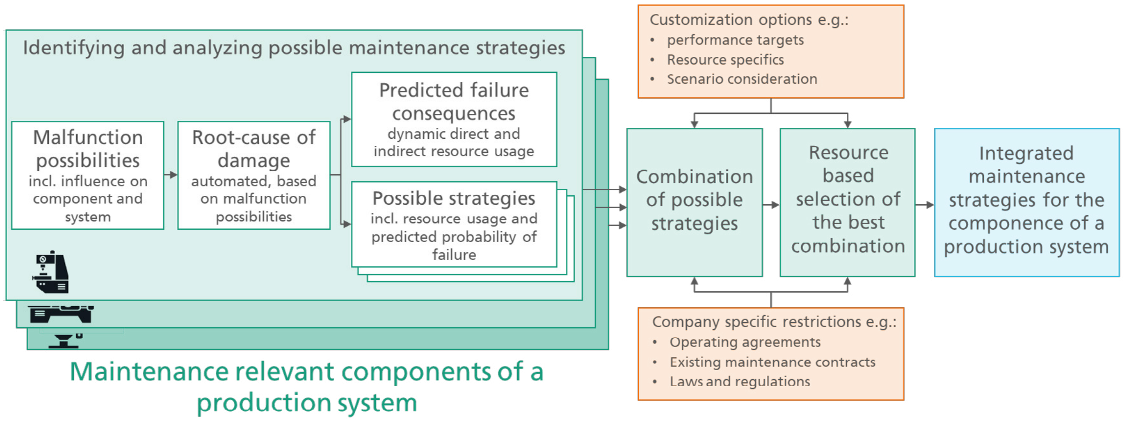

Fig. 1 Schematic of the approach for an integrated maintenance strategy selection

3.2. Integrated maintenance strategy selection

An overview of the proposed approach for an integrated maintenance strategy selection for all maintenance relevant components of a production system is shown in Fig. 1. It consists of three major steps before arriving at the result. Firstly, identifying all possible maintenance strategies for each relevant component with required resources for the implementation of the strategy. In addition, the resulting failure probability of the component when employing this maintenance strategy and the associated resource consumption of a possible failure need to be acquired. The second block illustrates the combination of valid maintenance strategies of all components including their respective resource consumption and failure probabilities and considering the possible influences on each other. After the possible strategies for the components are combined into all existing valid options, the maintenance strategy combination can be selected in accordance to the predicted available resources and the predicted availability of components for the different combinations. The combination step as well as the selection step lend themselves for customization options to better represent the conviction of the decision maker and company specific restrictions.

3.3. Description of the approach

The approach can be divided into three different steps and the solution, each with their own processes and challenges. In following section, the sub processes in each step will be described and the challenges will be highlighted.

3.3.1. Identifying possible maintenance strategies for each component

The basis of the approach is a detailed list of all maintenance relevant components of a production system. Maintenance relevant in this context means, that the component is under the influence of wear and the maintenance department is responsible for its state. For these components the possible failure options and their influence on the component, the machine, and the production system as a whole need to be collected. Then, knowing all failure options, the root-causes of these failures need to be identified to determine suitable maintenance strategies to prevent these failures from occurring. The challenge of identifying possible failures, their root-causes and the resulting valid maintenance strategies needs to be (at least semi-) automated to work for the numerous maintenance relevant production components.

Having the possible maintenance strategies, the valid and useful instances of these strategies must be identified. Useful in this case means, that it is the lowest consumption of a specific resource for a given production availability. For example, the time-based lubrication of a ball bearing would be a feasible strategy decision for which different instances of this strategy, in this case intervals must be included. Different intervals result in different resource usages and different failure probabilities. Having the lubrication done every day does most likely not improve the failure probability of the component compared to once a week or month. Therefore, the instance of once a day would not be a useful instance of the strategy.

When the possible maintenance strategies for each component and their instances are known, the resource usage of each strategy and its instances needs to be collected and the failure probability of this component in junction with each maintenance strategy instance must be calculated. This task needs to be (at least semi-) automated as well, as it needs to be performed for every valid instance of every possible maintenance strategy for every component in the production system. This calculation of the failure probability is necessary because no maintenance strategy provides certainty that a component does not break down. Even if the breakdown is caused by external factors, like human error, its probability needs to be known. The last process in this step is to identify the direct and indirect resource usage of a possible failure (direct and indirect maintenance costs). Direct resource use would be for example the workhours of the maintenance staff or the spare part used to repair the failure. This information usually is accessible through available data. Indirect resource use consists of the cost of not being able to produce during the downtime of the machine as well as other costs and consumed resources caused by the failure but not associated with its repair. These are more challenging to calculate.

3.3.2. Combination of possible maintenance strategies of the components

The next step after having all possible maintenance strategies for all relevant components of the production system is to combine them. Goal of this step is to list all possible combinations of valid maintenance strategies with their respective production system availabilities and resource allocations. The challenge within this step is to identify the valid strategies with regards to the component's context. For example, to change a ball bearing on a machine, the machine must be stopped. While the machine is stopped, other maintenance activities can be performed without the associated costs of an additional machine stop. These conditions change the overall maintenance costs for all the other components of this machine and make the identification of useful combination difficult. The same problem occurs not only for a machine, but also for a production process with multiple machines (in serial). One machine not producing due to a maintenance activity might have an influence of the production possibility of other machines. This could result in the option of performing maintenance actions on the next machine without interrupting possible production.

3.3.3. Selecting the maintenance strategies for all components

Having all valid and useful maintenance strategy combinations for all relevant components allows the selection process to start. First, all strategy combinations that consume more resources than available are disregarded. Resources can be personalized for a company and might include (skill-based) maintenance personal work hours, storage space for spare parts, (software) operating costs, and all other finite assets. Other personalization, like specific performance targets and special restrictions, can be implemented either in the combination process or in this step. After eliminating the strategy combinations that are not possible with the available resources, all remaining strategy combinations are possible and yield a certain amount of production system availability. The system will provide the recommendation according to the decision makers preferences, for example the maintenance strategy combinations, which maximize the availability of the production system using all available resources.

4. Intended implementation and discussion

In this chapter, the planned implementation in a real-life industrial environment and the methods to be used will be presented. Afterwards, the approach, its implementation, the benefits compared to the state of the art and the challenges are discussed.

4.1. Planned Implementation

The approach described needs to be (at least semi-) automated to be able to incorporate the numerous maintenance strategy selection for all maintenance relevant machines and components. Based on this insight and on literature reviews of other implementation of specialised software solutions in a manufacturing context [16,20], a software toolkit is planned. The software toolkit will be organized in independent modules, which contain individual solutions that work together to solve the challenges raised in the description of the approach. Interfaces to databases or other production and maintenance software can be implemented within the modules as needed. The interfaces between the different modules will be defined considering their individual necessities. The modular structure allows for implementing and independently testing the individual solutions. In addition, it allows a simple change for different modules.

To simplify and accelerate the identification of the failure possibilities and their root-causes, a standard component database can be set up. In addition, information provided by the part manufacturer can be also used to collect failure options. Moreover, the component related information gained will be enriched by historical data from the production system. Each past failure event and its root-cause will be incorporated into this module. This ongoing increasing data base also allows the maintenance selection to improve over time. Historical data from the production system in general will be one of the most used information sources and builds the foundation of the planned implementation.

Possible maintenance strategies for each failure root-cause can either be determined by a heuristic approach or also based on historical data. The required resources to implement the instance of the maintenance strategy can be calculated using experience from similar maintenance activities. The challenge in this module is to predict the failure probability of the component when employing each maintenance strategy. This can be achieved by simulation of the wear processes for each component and the influence of the maintenance strategy on this wear. The simulation can either be augmented by or replaced with experience of failure frequencies within the production system. This can be experience both from the specific and from comparable objects. The more company and component specific information of a maintenance strategy is available, the more accurate the predictions will become.

Computing the direct and indirect resource requirements for and unplanned failure of the component also uses historical data from the production system if available. In addition, the direct resource requirements can be ascertained by predicting the work hours needed, checking the price of the required spare parts and by accumulating other possible resources required. It is more difficult to calculate the indirect resources required because they depend on the structure of the production system. Indirect resources are consumed because of the failure but that are not associated with its repair. Commonly the largest contribution to this is lost production time. Additional efforts to mitigate the effect of the component failure on the production system also are considered an indirect resource. A simulation of the production system and its workflows allows simulating the downtime of all relevant objects and ascertaining the needed information.

To combine all possible strategies to determine the valid and useful strategy combinations, the predicted availability will be contrasted with the resource consumption. For each defined resource, every combination will be checked if another strategy combination achieves equal predicted availability while conserving more of the resource. After this only resource and availability, combinations are considered that are more efficient in at least one resource. These tasks will be done automatically by using sorting and comparing algorithms. The selection process will be aided by a user interface in which the preferences of the decision maker can be specified. Based on the settings different maintenance combinations will be presented. This can be either resource consumption or availability-oriented settings.

4.2. Discussion

The feasibility of this approach depends on the availability and quality of the required information. Especially historical data of the production system will be used to determine the strategy selections. Accumulating the required information in an effective way, will be the main challenge for this approach. In addition, the quality of the information must be taken into account. To be able to use this approach for different companies will be an additional challenge. For this, interfaces for production and maintenance software as well as to other databases are required for the different modules. Self-improvement by updating and enhancing the information must be implemented in all steps of the approach to be able to identify where user input is required to add and/ or override existing bad data. The validity and feasibility of this approach still has to be proven by implementing it within a real-life industrial setting. The possible benefits compared to the state of the art outweigh the above-mentioned challenges. In addition to solving the two problems mentioned in the introduction an automated maintenance strategy selection would save time of highly skilled labours. Moreover, system wide policy decisions would be based on detailed oriented decisions for all machines and not just the most expensive or vulnerable as done today.

5. Conclusion and outlook

In this paper, an approach for an integrated maintenance strategy selection was presented. First, the problems of existing selection methods were outlined, and the state of the art and research was listed. Based on this, the goals and requirements of an integrated strategy selection were defined, and the approach and its challenges were presented. Afterwards the intended implementation was described and discussed.

The presented approach is able to satisfy all expressed goals and requirements for selecting integrated maintenance strategies. The two problems of existing maintenance strategy selection methods are addressed. Some further requirements, such as the easy usage, interfaces to existing software and self-optimization, depend heavily on the specific implementation of the approach but are considered as well.

Next steps will be to implement the solutions for the different modules and the framework connecting them. The module development will be done in close cooperation with different industries to enable the solution to be used in general and not to be industry specific. The framework to incorporate the different modules will be implemented simultaneously. The overall approach for an integrated maintenance strategy selection then needs to be verified in industrial setting.

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