STRATEGY FOR THE DIAGNOSIS AND PREDICTION OF MACHINE FAILURES FOR DEVELOPING AVAILABILITY-ORIENTED BUSINESS MODELS IN CAPITAL GOODS

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Abstract: *Customers demand a guaranteed availability of machine components in capital goods industry. However, manufacturers are not willing to guarantee the demanded availability due to increasing costs based on high risks and uncertainties resulting from missing operational data, insufficient transparency of the machine condition as well as missing information of the customer behavior. In the following paper, a strategy to enable the development of availability-oriented Product-Service Systems (PSS) will be presented. Therefore, a use case focusing on the agricultural industry is regarded. Based on the use case, service-relevant parts will be identified and failure mechanisms of these parts will be determined. The subsequent development of condition monitoring strategies depend on the determined failure mechanisms. In a last step, the strategies will be assessed and the strategy with the highest added value will be chosen for an exemplary implementation, for which an electric motor and a conveyor belt of a potato harvester will be used.*

Keywords: INDUSTRY 4.0, CONDITION MONITORING, AVAILABILITY-ORIENTED BUSINESS MODELS, SMART PARTS

1. Introduction and research gap

In the capital goods industry customers demand a guaranteed availability of machine components. However, manufacturers are not willing to guarantee the demanded availability due to increasing costs based on high risks and uncertainties resulting from missing operational data, insufficient transparency of the machine condition as well as missing information of the customer behavior. Furthermore, the necessary data management to handle a vast amount of data is insufficient. However, to gain competitive advantages and provide availability-oriented services, the development of Product-Service Systems (PSS) in context of Industry 4.0 (PSS 4.0) is an essential approach to solve this issue. The integration of Industry 4.0 technologies [1], e.g. internet technology, smart sensors or business analytics, in PSS enable new forms of value creation, e.g. condition monitoring based on the connectivity of products and services. Implementing condition monitoring requires suitable smart service-relevant components. For identifying the service-relevant components, their failure mechanisms need to be analyzed. Afterwards, the developed sensors will be integrated into the service-relevant components. Based on the smart, communicating components, a smart system can be evolved. Within the smart system concept the sensor data will be saved on and analyzed by a cloud based platform. After analyzing the sensor data online, the gained information about the condition of the machine will be send to the operator of the capital good as well as to the service team. If a failure occurs, the operator and the service team can react on short notice and thus reduce down times.

Capital goods are subject to high requirements regarding availability and productivity [2]. To fulfill the requirements the product needs to be complemented by lifecycle-oriented services within an integrated solution. Those integrated solutions are called Product-Service Systems (PSS). The down time of a machine is related to high costs and service effort. Predictive maintenance can reduce down times and service efforts even before a machine failure occurs [3]. To realize predictive maintenance in times of big data and Internet of Things (IoT), the monitored components need to be smart, that means they are able to make a diagnosis of their own condition in real-time and are able to communicate. One of the objectives is the forecast of wear behavior to detect machine failures in advance. The implementation of such a system can increase the availability of the capital good, but also increases costs for development and realization. To reduce the costs to a minimum, only critical, service-relevant components have to be monitored.

In this contribution, the basis for the identification of service-relevant parts to realize predictive maintenance in an availability-oriented business model are in focus. First, critical, service-relevant components with a high impact on availability need to be identified. Then, concepts for condition monitoring of that components are developed. With the smart components, which additionally are able to communicate, the basis for failure prediction is set. By realizing predictive maintenance concepts, it is possible to offer availability by means of suitable availability-oriented business models.

2. State of the art

According to Mont, Product-Service Systems are defined as systems of products, services, networks of actors, and supporting infrastructure. The aim of a PSS is to increase the competitiveness of the PSS-provider and to satisfy customer needs. Furthermore, compared to traditional business models, PSS have a lower environmental impact [4]. A business model describes how companies generate, deliver and capture value [5]. There are different kinds of business models, which are enabled by PSS: function-oriented, availability-oriented and result-oriented business models. In availability-oriented business models, as only these are considered in the following, the PSS-provider guarantees the availability of a technical product. With this guarantee, the PSS-provider bears a part of the customers manufacturing risk [6]. To realize availability-oriented business models, suitable business model development concepts, smart components with the ability to communicate and a consistent information management are necessary.

This article deals with the development of smart components. In the following, only the mechanical parts of the machine are focused. In the first step the electronics, the electronic components, the software and the sensor systems are not taken into account. In further steps, the method in this article can be analogically implemented in an adapted form on electronic components as well as on software applications.

In general, a machine consists of multiple components and assemblies fulfilling different functions. To structure the relationship between the components or the functions two perspectives can be differentiated. The first perspective is the functional structure of the machine and the second perspective is the product structure of the machine. The transformation of the functional structure into the product structure and the product architecture are shown in Fig. 1. [7]

The functional structure includes all functions of a machine. Those functions can be divided into main functions and auxiliary functions. The product structure contains all assemblies, sub-assemblies and components. Each component has a specific role for each assembly group and each sub-assembly group has a specific role for the complete assembly group or the entire machine. The functional perspective is analogical to the product structure. Each sub-function is of specific importance for the auxiliary functions, main functions and the overall function. There are one or more linkages between assembly parts, assembly groups and functions. In case of a damaged assembly part or group, hence one or more functions are not properly fulfilled.

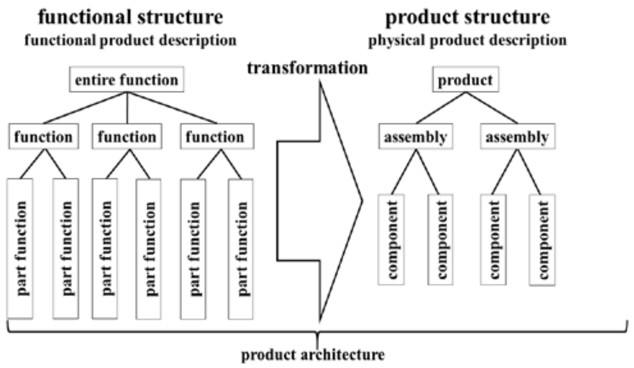

Fig. 1: Product architecture and transformation of function structure in product structure [7]

The availability of the machine will be reduced, if one or more functions are not fulfilled properly. In the context of this article the technical availability is defined as follows: "The availability describes the relative part of time, while a component or a system can fulfil its defined function as required (stipulated by contract main functions). The availability is the ratio of time, in which the systems is functional, to the total time" [8].The availability of the machine is reduced by the non-fulfilment of one or more functions. This implies that one or more failures occurred in the system. According to Eberlin/Hock, there are three categories of failures, early failures, incidental failures and wear failures [8]. Early failures cause machine down times due to failures in the early utilization phase of the machine. Those failures are caused by construction, manufacturing or operating errors. Random failures appear if an unexpected incident happens. Reasons therefore are environmental conditions or wrong operating. The third group of failures are wear failures. These failures generate machine down times due to the common machine wear. Fig. 2 shows the time progress of the sum of the error rate for.

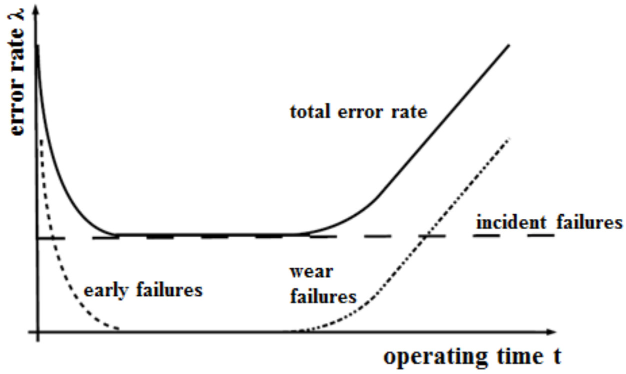

Fig. 2: Bathtub curve with sum of the error rate [8]

To increase the availability of a machine by condition monitoring, predictive maintenance, diagnostics and prognostics these three groups of failures need to be distinguished [9]. For this, the failure mechanisms and failure criteria need to be analyzed.

3. Identification of service-relevant components

In the context of this article, methods to identify the service-relevant components considering the three groups of failures are described. One failure implies one or more unsatisfied functions. The connection between the components and their related functions enables the identification of failures. The identification of service-relevant components can be realized by means of system analysis. Table 1 presents some methods for system analysis.

Table 1: Methods for identification of service-relevant components

	Name of the method
1	Failure tree analysis FTA DIN 25424-1 und DIN 25424-2
2	Event tree analysis DIN 25419
3	Failure Mode and Effects analysis- FMEA IEC 56/1579/CD:2014
4	Cause-effect-diagram
5	Intensity-Relation-Matrix

The fault tree analysis is a deductive method. The reasons for failures are identified based on unwanted incidents [10]. The event tree analysis is an inductive method, which identifies the possible impact of occurring failures. The Failure Mode and Effect Analysis (FMEA) is an analytical method for failure analysis. By application of this method, components, assemblies and subsystems can be analyzed and their possible failures, causes and effects can be determined. [11]

The cause-effect-diagram is used for the basic understanding of the constructive background and structure of the machine. The intensity-relation-matrix is a method for solving of complex problems. It is based on the method of linked thinking and network analysis. Effect intensities between different factors for complex machines or other systems can be estimated. [12]

By application of these methods, the critical components can be determined. The service-relevant components in this paper were chosen by application of the methods listed in Table 1 and of the software Visual-XSel® for calculation and visualization of the results. Based on these components, a machine diagnosis and prediction strategy can be developed.

To reduce the costs to a minimum, only critical, service-relevant components should be monitored and for these components, diagnosis and failure prediction strategies should be developed.

4. Strategies for machine diagnosis for availability-oriented business models

There are four strategies for machine diagnosis for availability-oriented business models. The strategies are shown and compared in Table 2.

Table 2: comparison of the strategies for diagnosis

	1	2	3	4
Strategy for monitoring of	Whole system	Compo-nents	Failure mecha-nisms	Combined
System complexity	low	middle	high	very high
Number of sensors	low	middle	middle	very high
New sensor development needed	no	no	yes	yes
Cost	low	middle	high	very high
Accuracy	low	middle	high	very high
Qualified for availability-oriented business models	no- not enough informa-tion about system condition	yes	yes	no- system complexity and cost to high

Strategy 1: Condition monitoring for prediction of machine failures for the whole system, for example electric motor, gearbox, conveyor belt. It is not possible to locate and monitor one service-relevant component. For this strategy, few sensors are needed. The complexity of the condition monitoring and failure prediction system is low, and the accuracy is low. It is not necessary to develop new sensors. For example, only the rotational speed of an E-motor or the vibration is monitored.

Strategy 2: Condition monitoring for prediction of failures of components, for example bearing, seal, gear, rotor, stator. It is possible to locate the component. It is not possible to determine the failure mechanism. For this strategy, more sensors are needed. The system complexity and accuracy of the failure monitoring are higher. The monitoring task can be solved with existing sensors. For example in an electric-motor the vibration of the bearings is monitored.

Strategy 3: Condition monitoring for prediction of failures based on the failure mechanisms. For example seal-leakage, bearing-vibration, bearing-temperature, bearing-currents, elongation of the conveyor belt. It is possible to locate the service-relevant component and to monitor its failure mechanism for accurate prediction of the failure. The system complexity is high. Many sensors are needed for every component and failure mechanism. The system accuracy is also high. For the monitoring of some failure mechanism new sensors have to be developed and the components have to be modified to be able to communicate, send and receive signals, and determine their own condition. Physical values typical for each failure mechanism need to be defined and monitored.

Strategy 4: Combination of the three strategies. For example monitoring of the whole system and detailed monitoring of service-relevant components and their failure mechanisms. This system has the highest complexity and costs and the best accuracy for condition monitoring and failure prediction.

Strategy two and three are qualified to be used for the development of availability-oriented business models.

5. Theoretical example

In this chapter, a theoretical example based on literature values is shown. The next example shows how the four strategies for condition monitoring can be used and how they work. Based on the literature, several components and their failure rates could be identified over a few years. In the following, the year 1999 will be analyzed. It was clearly determined that the main failure components of the electric motor are the rotor (1%), stator (2%), bearings (95%) and other parts (2%). Hence the service-relevant components are the bearings, based on the data of the year 1999. The information is shown in Table 3. [13]

Table 3: Failure components in electric motors [13]

Year	1985	1986	1995	1995-1997	1999
Stator	37%	36%	13%	9%	2%
Rotor	10%	9%	8%	6%	1%
Bearing	41%	41%	42%	75%	95%
Other	12%	14%	38%	10%	2%

Fig. 3 shows the failure mechanisms and main reasons for bearing failures in electric motors in general. Because of wrong and aged lubricant, grease missing or too much grease, vibration from motor or load machine, or bearing currents, failures occur. In [14], [15], [16], [17] and [18] examples for condition monitoring of bearings, based on vibration and temperature, are presented.

Based on the information in Table 3 and the Fig. 3, a theoretical FTA (DIN 2542-1 and DIN 25424-2) can be carried out. This is shown in Fig. 4. The Top-Event is the E-motor failure. This kind of failure occurs when the rotor, stator, bearings or other components are not working properly. The failure mechanisms of the bearings in E-motors are shown in Fig. 3. In this case there is information about the service-relevant components and their failure mechanisms.

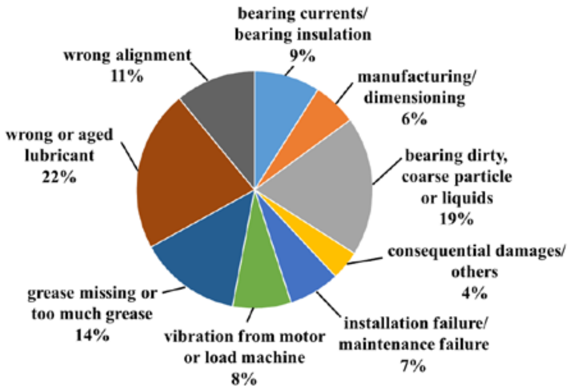

Fig. 3: Overview of mechanisms and reasons for failure of bearings in electric motors [19]

If there is no information about the service-relevant components and their failure mechanism by using of the FTA, FMEA, Cause-effect-diagram and Intensity-Relation-Matrix can be shown, which component and which failure mechanism have to be monitored.

Fig. 4 shows the four condition monitoring strategies based on a FTA structure. If the first strategy is chosen, only the E-motor as a complete assembly will be monitored.

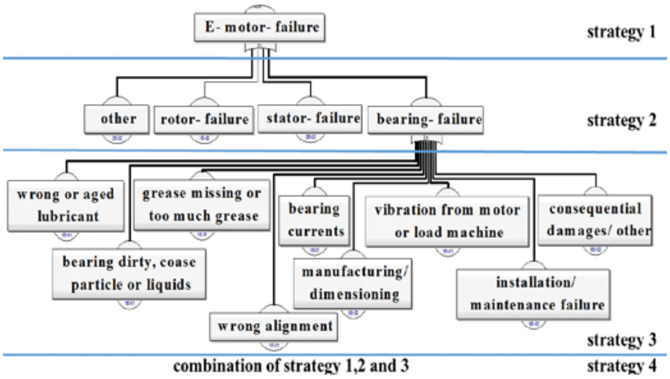

Fig. 4: Example of failure tree analysis with the four strategies

For the second strategy, it is necessary to monitor the bearings, because they represent the service-relevant components. Monitoring failure mechanisms, e.g. bearings failure, is essential for the third strategy. This process is highly complicated and expensive. It is necessary to define some significant physical values for instance temperature, acceleration, distance, length and to measuring them continuously. For the fourth strategy, it is necessary to monitor the main function of the relevant components (e.g. the rotation of an E-motor), the critical service-relevant components- and their failure mechanism characterization (e.g. bearings, their vibration and the physical values, which characterize the failure mechanism of the bearings).

To increase the availability of the machine in times of Industry 4.0, the service-relevant components have to be monitored, the data must be analyzed online and the manufacturer, service team and customer should have access to information about the machine condition. It is possible, that there are no existing sensors for some measurement tasks. Then it is necessary to develop new sensors for the specific tasks. In the following chapter an example of a newly developed sensor for a special measurement task will be presented.

6. Example from the agricultural industry

Focusing on the agricultural industry, the following use case analyzes a potato harvester. To harvest potatoes, there is a short span of time every year and there are rough environmental conditions under which the machines operate [20], [21]. Wear occurs and leads to failures when preventive service is lacking. It is very critical for the customer of the capital good and the manufactures, if a machine failure occurs during the harvest season. To increase the availability of the machine during the harvest season and realize availability-oriented business models it was necessary in the first step to identify the service-relevant components and in the second step to develop a smart sensor concept to determine the condition of these components. By use of system analysis (failure-tree-analysis, cause-effect-diagram and intensity-relation-matrix) it was determined, that the conveyor belt of a potato harvester is the critical component.

After the identification of the critical component, the failure mechanisms of the conveyor belt were determined. After further analysis and experiments in test bench trials, the main failure mechanisms were defined. Results have shown that the elongation of the belt increased slowly according to the applied stress, and can be predicted. Investigations by the manufacturer of the conveyor belts identified the source of break-down as related to the elongation of the conveyor belts. It was possible to use the third strategy for machine diagnosis and condition monitoring for the development of an availability-oriented business model. [22]

The harvester uses conveyor belts to move the harvested potatoes through the machine and to separate them from the ground of the mounds, in which the potatoes are grown in, and other parts of the plant (Fig. 5). The conveyor belts consist of three belts made of hard rubber, which connect bars orthogonal to the conveying direction to build the conveying surface for the potatoes. The three belts are closed by locks. Both bars and locks are made of ferromagnetic metal. [22]

Fig. 5: AMR-Sensor (left [23]), conveyor belt (middle [24]), schematically (right)

The condition of the belts have to be monitored to trigger services just before a failure occurs in order to prevent failure of the conveyer belts in the harvester, avoid unnecessary maintenance and to increase the machine availability.

This was realized by developing of a robust sensor concept, robust signal processing concept, pre-processing concept and a model for signal interpretation. A magnetic measurement principle [25] was chosen to obtain a robust and reliable sensor signal. The AMR-Sensor from Fig. 5 was developed and tested. [22]

In the next steps the sensor will be implemented into the real machine and the condition monitoring strategy three will be tested. The sensor data will be stored in and analyzed by a cloud based platform. After analyzing the sensor data online, the gained information about the condition of the machine will be send to the operator of the capital good as well as to the service team. If a failure occurs, the operator and the service team can react on short notice and thus reduce down times.

7. Conclusion and outlook

In this paper a strategy for the development of availability-oriented business models based on diagnosis and prediction of machine failures is shown. In the first step service-relevant components need to be identified. Methods for this identification are described. After that the failure mechanisms of the components should be determined. When the failure mechanism is known, a strategy for the condition-monitoring of the components based on the failure mechanism as well as smart sensor concepts need to be developed. A theoretical example based on an electric motor and a practical example based on a potato harvester depicted this approach. In the next step, the smart-sensor-concept for the potato harvester will be tested in the machine under real conditions. Based on the smart, communicating components, a smart system can be developed. The sensor data will be analyzed by a cloud based platform. After analyzing the sensor data online, the information about the condition of the machine will be sent to the operator of the capital good as well as to the service team. In case a failure occurs, the operator and the service team could react on short notice and thus reduce down times.

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GEFÖRDERT VOM

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