Case Study Validation of a Predictive Maintenance Implementation Framework

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1 Introduction

Industrial companies are faced with many tasks in efficiency, sustainability, and customer requirements (Mack et al. 2015). To solve these multiple tasks, reliable processes in production and logistics are inevitable. In a strategy paper of the European Commission, smart and adaptive manufacturing systems play a crucial role in facing the challenges in supply chains (European Commission 2021). This also includes the adaption of smart solutions in the management of reliability and maintenance of production systems, accompanied by large amounts of data to be processed (Feng and Shanthikumar 2018).

The European Standard DIN EN 13306 divides maintenance strategies into four categories. In the **reactive** maintenance strategy, measures are only implemented after failure. This leads to more extended downtimes and no planning or forecasting opportunities. In a **time-based preventive** strategy, the useful lifetimes of parts are defined and documented in a maintenance schedule, and parts are replaced according to this plan. This strategy is characterized by higher maintenance activity and spare parts consumption since the maximum lifetime is usually not reached (Erbe et al. 2005). The **condition-based preventive** maintenance follows the concept of either constant or discrete observation of the object's condition state. The monitoring can be achieved by sensors or manual inspections (Prajapati et al. 2012).

Consequently, parts can be replaced before a breakdown occurs, and the wear reserve can be used to a high extension. The **predictive** maintenance (PdM) strategy extends the CBM, whereas a prognosis of the residual useful life (RUL) allows good planning opportunities for scheduling maintenance activities and

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deploying resources. Furthermore, this strategy aims to inhibit failures and, therefore, production downtimes (CEN 2017; Lei et al. 2018; Ansari et al. 2019).

Although PdM shows high potential in maintenance optimization, the number of implementations in the industrial environment is still comparatively low (Haarman et al. 2018). Therefore, Hoffmann and Lasch (2020) developed a roadmap for a structural implementation process of this maintenance strategy based on literature findings, which has not been applied yet. This paper aims to validate this framework based on a practical case study. The following research questions are considered:

RQ1: Are all relevant aspects included in the implementation framework of a predictive maintenance strategy?

RQ2: In which way and order are the proposed steps put into practice by a maintenance expert team?

The remainder of the article is structured as follows: Sect. 2 provides a short introduction to the roadmap of Hoffmann and Lasch (2020) and gives an overview of the proposed methodology of the validation study. Section 3 shows the practical realization of the analysis phase, Sect. 4 includes the decision-making process, and in Sect. 5, the implementation process is shown. A conclusion is drawn in Sect. 6.

2 Predictive Maintenance Implementation Framework and Validation Methodology

2.1 PdM Implementation Framework

The paper of Hoffmann and Lasch (2020) proposes a generic framework to implement a predictive maintenance strategy in industrial processes. Therefore, technical criteria of this maintenance strategy are considered as well as management-related tasks such as cost–benefit-considerations or decision-making support. The overall aim is to give a structured roadmap to the maintenance management on implementing PdM in an industrial environment that does not require extensive know-how and splits up this assignment into several packages of strategic and tactical tasks.

The general structure is divided into three phases: analysis, decision making, and implementation. This is accompanied by a feedback loop, as shown in Fig. 1. A detailed description of the process is given in chapters three to five.

2.2 Validation Methodology

Since the paper of Hoffmann and Lasch (2020) provides a literature-based theoretical framework for PdM implementation, a practical realization is missing as yet. This paper aims to research the feasibility of the given model to be applied in a practical

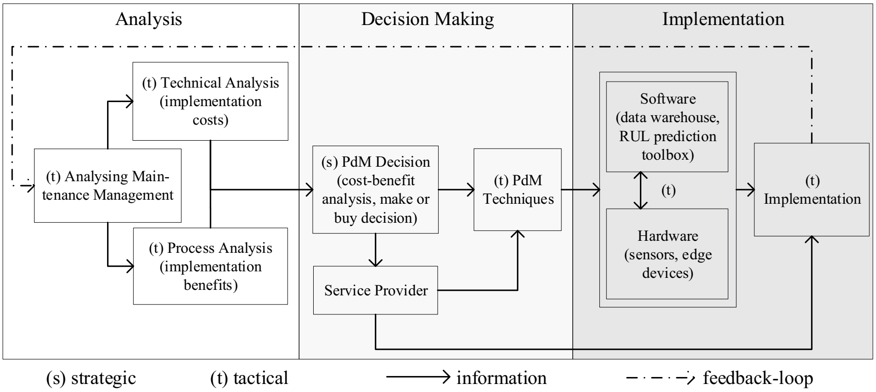


Fig. 1 PdM implementation roadmap according to Hoffmann and Lasch (2020)

industrial use case. Therefore, a co-validation based on Yin and McKay (2018) was conducted. The validation team consists of maintenance experts in an automotive industry company as model users and maintenance researchers. This approach was chosen to enable an interdisciplinary validation process and gain new findings for the model based on the practical implementation.

A case study evaluation approach based on the paper of Offermann et al. (2009) was chosen to validate the roadmap. Therefore, the analysis and decision-making phase was conducted in cooperation with the maintenance department of the mentioned automotive industry company. The validation of the implementation phase is based on a maintenance expert interview.

The considered assembly line consists of eleven maintenance objects shown in Table 3, whereas most perform joining processes. The remaining machines execute handling and testing processes. In the following, the proposed steps according to the roadmap of Hoffmann and Lasch (2020) are performed.

3 Analysis Phase

3.1 Maintenance Management

The initial step starts with the analysis of the existing maintenance management. Therefore, the current mix of applied maintenance strategies and their strategic roles, the structure of the maintenance costs, and failure causes are examined. Applied key performance indicators and the existing infrastructure of the information system are further evaluation criteria.

Own employees carry out most maintenance measures, and only a few of them are conducted by machine suppliers due to service contracts. The company follows a preventive time-based maintenance strategy. Therefore, a period of 90 min every week and one maintenance shift every month are scheduled. Maintenance activities are carried out based on a maintenance plan with fixed intervals and work instructions documented based on an ISO 9001 quality management certification.

The accounting department of the company records direct maintenance costs. One problem in this context is that those costs are assigned to working stations instead of classification to the single maintenance objects. The indirect maintenance costs are not captured. This is caused by the management's high priority of delivery reliability. Therefore, the maintenance intensity is high and parts are changed before reaching the wear limit. However, conclusions about the indirect maintenance costs can be partly drawn based on the machine downtimes documented by the maintenance management.

The failure causes are recorded in a detailed manner by the maintenance department. The mean time to repair (MTTR) and up- and downtime monitoring are currently the only implemented KPI considering the maintenance performance. The overall equipment effectiveness (OEE) is introduced as a relevant performance indicator.

The IT infrastructure is based on the SAP PM module. The in-house IT department develops specific solutions for plant condition monitoring. It should be noted that this condition monitoring captures the overall state (operating or down) of a machine but not maintenance-specific features such as vibration.

3.2 Process Analysis

The second step is process analysis, which aims to identify crucial steps within an industrial process that show high potential benefits for implementing PdM. In this context, the process configurations are of particular interest. Parallel and redundant production processes with several machines for the same purpose have a lower risk of a complete process shutdown than serial configurations, where unplanned downtimes can have devastating impacts on the process's reliability and safety. Further potentials of PdM are given at high storage costs for spare parts or production facilities, of which a failure has value-reducing impacts. High failure frequency, downtimes, and failure impacts on output and product quality are analyzed criteria within this step too.

Quantification of the analysis criteria as a sub-process is necessary to conduct the process analysis. Therefore, the expert team defines a weighting of the following features that are necessary for maintenance purposes.

The direct maintenance costs (MC) contain expenses for maintenance measures such as parts, personnel costs, and equipment, based on the accounting department's documentation. The failure frequency (FF) measures the number of failures of a machine per year, whereas the downtime (DO) includes the annual cumulated hours of downtime caused by machine failures. The criterion machine value (MV) measures the negative impacts of a failure on the overall object value.

Indirect maintenance costs are included in the analysis by considering the influence on the production output (IO) and product quality (IQ). There are no documented

Table 1 Weighted criteria process analysis

Nr.	Criteria	Weight in %
1	Maintenance cost (MC)	20
2	Failure frequency (FF)	30
3	Downtime (DO)	30
4	Machine value (MV)	5
5	Influence on output (IO)	5
6	Influence on quality (IQ)	10

values available for those criteria. Therefore, the expert team estimates the values based on their experience. The weights of the criteria are shown in Table 1.

In this case study, the team considers downtime and failure frequency as the most relevant criteria, whereas machine value, quality, and output are not of high priority. Based on the absolute values of each maintenance object's criteria, a scale is defined by the team, which allows for an assignment to a value from 1 to 10. An exemplary scale for the failure frequency is shown in Table 2. Similar scales exist for the remaining criteria, whereas a higher scale value represents a higher potential factor. As shown in Table 3, the scale values are weighted and summed up afterwards to calculate a value for the PdM potential within the process analysis.

Exemplary calculation of the potential factor of object 1:

$$= 2 * 0.2 + 10 * 0.3 + 7 * 0.3 + 8 * 0.05 + 8 * 0.05 + 8 * 0.1 = 7.1$$

Table 2 Exemplary scale for FF

Value from	to	Scale value
0.0	7	1
7.1	14	2
14.1	21	3
21.1	28	4
28.1	35	5
35,1	42	6
42.1	49	7
49.1	56	8
56.1	63	9
63.1	70	10

Table 3 Values for PdM potential

Criteria	Object type	MC	FF	DO	MV	IO	IQ	$\sum$
Weight (%)		20	30	30	5	5	10	
Object 1	Welding	2	10	7	8	8	8	7.1
Object 2	Welding	1	5	3	8	8	7	4.1
Object 3	Welding	3	7	10	10	8	7	7.3
Object 4	Welding	2	7	10	10	5	6	6.9
Object 5	Welding	2	7	10	10	5	6	6.9
Object 6	Forming	1	1	1	4	10	4	1.9
Object 7	Welding	2	7	3	10	10	4	4.8
Object 8	Rework	1	1	1	2	9	5	1.9
Object 9	Handling robot	10	4	9	6	10	2	6.9
Object 10	Leak test	1	3	5	4	10	9	4.2
Object 11	Optical testing	1	1	1	8	1	10	2.3

3.3 Technical Analysis

The technical analysis concludes the analysis phase, aiming to determine the effort and cost of PdM implementation. If condition monitoring systems are already implemented at the maintenance object, an extension to a predictive system can be installed with comparatively low effort. Also, some existing sensors in the system might be used for PdM purposes. If those two prerequisites are not fulfilled, retrofitted sensors can compensate for that shortcoming. In this context, it must be analyzed whether such an installation of sensors and communication can be done with a moderate effort.

At first, the relevant criteria to estimate the effort of implementing PdM are defined. Usable sensor data (US), which enable RUL prediction, allow minimal implementation effort. If those are not available, sensor costs (SC) and the usable installation space (IS) must be considered. The data transfer (DT) expresses the efforts to extend the IT infrastructure for linking new sensors. Retrofitting (RF) contains necessary hardware changes to fit new sensors to an existing machine. Detecting measuring faults (MF) can be necessary when false signals are delivered due to interferences in the system or damaged sensors.

The priority and weights of the individual criteria are defined by the maintenance experts and shown in Table 4. In this case, the installation space and possible measurement faults are considered the most critical aspects. The scales are configured similar to those in Sect. 3.2, whereas a higher scale value represents a higher effort.

The evaluation considering the implementation effort for PdM of the eleven maintenance objects is done for every criterion and summed up similarly to the process analysis. The results can be seen in Table 5.

Table 4 Weighted criteria technical analysis

Nr.	Criteria	Weight in %
1	Usable sensors (US)	20
2	Sensor costs (SC)	5
3	Installation space (IS)	30
4	Data transfer (DT)	5
5	Retrofitting (RF)	10
6	Measuring faults (MF)	30

Table 5 Values for PdM implementation effort

Criteria	US	SC	IS	DT	RF	MF	$\sum$
Weight (%)	20	5	30	5	10	30	
Object 1	10	5	9	1	5	8	7.9
Object 2	10	5	9	1	9	1	6.2
Object 3	7	7	2	1	2	2	3.2
Object 4	10	3	5	1	6	6	6.1
Object 5	10	3	5	1	6	6	6.1
Object 6	10	5	3	1	3	10	6.5
Object 7	10	8	5	1	5	3	5.4
Object 8	10	5	5	1	3	10	7.1
Object 9	10	8	3	1	5	6	5.7
Object 10	10	5	3	1	3	10	6.5
Object 11	10	10	8	1	8	10	8.8

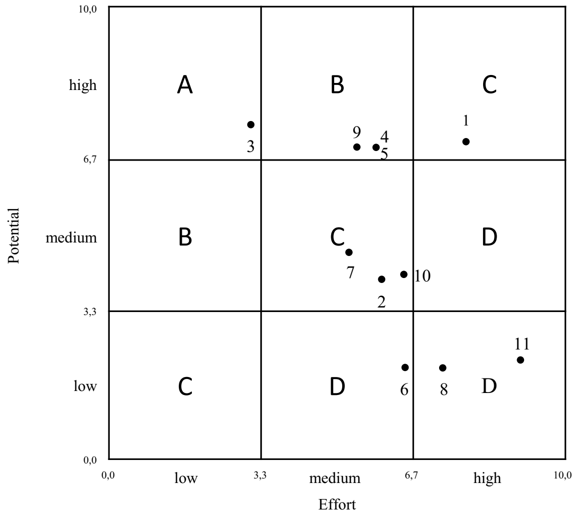
4 Decision-Making Phase

4.1 Decision-Making Matrix

The second phase addresses decision-making. Therefore a 3 × 3 decision support matrix is proposed by Hoffmann and Lasch (2020), in which the results of the process analysis (PdM potential) and technical analysis (implementation effort) are filled in. Depending on the category the maintenance object is assigned to, recommendations about implementing PdM are given based on a cost–benefit consideration. The calculated values for every maintenance object considering PdM potential (Sect. 3.2) and implementation effort (Sect. 3.3) are filled into the decision-making matrix in Fig. 2.

Maintenance object 3 shows a high potential for PdM with a comparatively low effort. Therefore, the implementation is highly recommended for this machine. The main reason is a high number of failures and long downtimes. Furthermore, a missing redundancy makes this machine crucial for the whole production process. On the

Fig. 2 Decision-Making matrix



other hand, necessary sensors for condition monitoring are already implemented, enabling a cost-efficient use of the already continuously measured values. The maintenance objects 4, 5, and 9 are assigned to class B, which implies an advisable implementation of PdM. The potential benefits are very high, but the effort is significantly higher than for the object in the first category. Machines 4 and 5 have a parallel configuration and can be described as redundant. However, they have a high failure frequency, and cost-intensive spare parts are necessary. Object 9 is a handling robot and, therefore, a critical part of the process since a breakdown can also lead to a complete shutdown.

A clear recommendation cannot be given about PdM implementation for those objects assigned to class C. However, a selective consideration is necessary to avoid overfitting. In this case study, maintenance objects 1, 2, 7, and 10 are classified in this category. Machine 1 shows high failure frequency and downtimes. Furthermore, a failure has comparatively high impacts on the output and product quality. Consequently, a PdM consideration seems useful for better process quality, but the implementation is not recommended in the first step under cost-considerations. The remaining objects of class C are characterized by medium potential and effort values, which leads to a lower priority for the PdM implementation.

Objects 6, 8, and 11 have an inconvenient effort-potential ratio and are therefore not suitable for monitoring by a predictive maintenance strategy since this would lead to adverse effects considering the overall maintenance costs. Following this decision-making process, the company's maintenance management decided to start a pilot project to implement PdM for objects 3 and 9.

4.2 Service Provider and PdM Techniques

A strategic decision about outsourcing specific PdM tasks is included in the decision-making phase. To gain further know-how in this field, the expert team makes a strategic decision against outsourcing maintenance tasks in this context. The management assesses that the existing maintenance team can execute all relevant maintenance measures since there is no significant change in operational maintenance tasks to be expected.

Following the proposed roadmap of Hoffmann and Lasch (2020), the decision about the RUL prediction method is to be made at this point of the process. Deviating from this recommendation, the maintenance team decides to postpone the decision about the PdM techniques to be used since the choice depends on the used software. The planning steps for this implementation pilot project are now explained based on the maintenance team expert interview.

5 Implementation Phase

5.1 Hardware Implementation

Within the third phase, the actual implementation is conducted. Therefore, the required software and hardware must be selected simultaneously for a secure and reliable data transfer and cannot be considered separately from each other.

The most critical task in hardware implementation is choosing the relevant features to be measured to ensure high data quality for condition monitoring. For those maintenance objects where sensors for condition monitoring are installed already (e.g., object 3), an evaluation is necessary whether the monitored features can be used for PdM purposes. To ensure this, a consultation with the machine manufacturer is required. This is also relevant for machines without any installed sensors for condition monitoring purposes yet to gain information about relevant thresholds that indicate the end of life for wearing parts and necessary maintenance measures. The company's sensor supplier and expert is consulted to assess which sensors to select for values to be measured and how to position them.

5.2 Software Implementation

Depending on the existing information system infrastructure and the extent of the expected amount of data, PdM tasks can either be implemented in an existing ERP system or cloud computing solutions combined with IoT-based sensors might be more suitable due to more scalable and flexible options.

In this particular case, two options are considered. The first variant is a predictive maintenance toolbox offered by the existing ERP system provider as an add-on. Therefore, pre-defined algorithms predict the RUL and schedule necessary maintenance measures. This variant reduces the effort of developing algorithms such as artificial intelligence solutions and can be implemented rapidly without extensive knowledge in data engineering.

The second variant contains an extensive in-house development of software for PdM purposes. This requires more effort in the field of data evaluation. Based on the framework of Lei et al. (2018), the process of health prognosis evaluation is split into four steps: data acquisition, health indicator construction, health state division, and RUL prediction. An own software solution requires superior know-how in feature engineering and the configuration of artificial intelligence algorithms frequently used for RUL prediction.

5.3 Implementation in Maintenance Management

A predictive strategy might require adaptions considering the operational targets and organizational structures. Therefore, the implementation phase is concluded by introducing this strategy into maintenance management. To realize the full potential of PdM, a holistic approach that considers production planning and purchasing claims is proposed.

Since the pilot project does not affect the whole production line, only minor changes are expected considering the maintenance management. The weekly timespan for maintenance activities is still used for inspections at the other objects. It is not clear yet, whether the maintenance measures for objects 3 and 9 are still executed in the monthly maintenance shift, or they can be done during the operation time due to the excellent planning opportunities based on the estimated RUL.

Regarding software-variant 1, synergies are expected by including other ERP modules such as production scheduling or material management, which can purchase needed spare parts according to the demand.

A feedback loop is planned to be installed to improve the implemented PdM strategy, aiming for constant optimization and adaptation of the maintenance processes. The feedback information will be embedded into the continual improvement process of the quality management system.

6 Conclusion

Many experts see a contribution of predictive maintenance to more efficient and reliable production processes in the industrial environment. However, the number of successful implementations is still low. Based on a practical case study and expert consultation, this article gives industrial companies a structured suggestion to start making their own experiences and gain know-how in the field of PdM.

The validation study shows that the underlying framework applies to a structured PdM implementation process with few adjustments to the initial version.

In the considered case, the analysis revealed two maintenance objects with high potential and moderate implementation effort, which are feasible for the maintenance management department to start a PdM pilot project.

Regarding RQ1, the expert team recommends implementing a sub-process for quantifying the analysis criteria in phase one. Besides this, the co-validation team sees all relevant criteria included in the framework to give a structured recommendation for action.

Regarding the execution and order of the proposed steps, the decision-making of the PdM techniques is recommended to be shift into the implementation phase since this is dependent on the used software solution, which answers RQ2.

The validation study is done with the limitation that the practical process is performed for the first two phases in the company, whereas the evaluation of the third phase is based on maintenance expert consultation. Further research in practical PdM implementation is still necessary to unfold the advantages for producing companies. Furthermore, plug-and-play solutions are required that offer practitioners the opportunity to get started without high effort.

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