Allianz Global Corporate & Specialty

TREND PAPER
PREDICTIVE MAINTENANCE

04 D 2020 ES 01
06 February 2020

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Contacts
AZT-Experts

Thomas Gellermann
+49 89 3800 6236
thomas.gellermann@allianz.com

Stefan Thumm
+49 89 3800 6643
stefan.thumm@allianz.com

Predictive Maintenance Influence on Insured Risks

Following the increasing trend in recent years of using cloud services with artificial intelligence in the private sector, such as voice or image recognition, all industry sectors are strongly investing in digitalization, data collection and analysis, as well as process automation. This industrial initiative is summarized under Industry 4.0. According to a global study of Pricewaterhouse Coopers[1], companies worldwide have invested in Industry 4.0 over $US 900 billion per year in the period 2016 to 2020. The main driver for this trend is the progress in data analytics and predictive technologies.

One important area of application is **Predictive Maintenance (PM)**, which aims to optimize maintenance in a variety of industries, such as production and manufacturing facilities, marine, aviation or power generation. PM is driven by the expectation of decreasing maintenance cost and increasing machinery availability. The question which is discussed in this trend paper is:

Can Predictive Maintenance Systems reduce technical risks?

Available studies about PM are usually quite promising and often driven by business interests. Whereby, experience from users is rare. Allianz Center for Technology (AZT) has performed damage investigations and diagnostic services for more than 85 years. Based on this experience AZT has looked into the question. The presented examples refer to the potential application of PM in the power generation industry.

Development of Maintenance Strategies

Maintenance strategies have been developed over decades according to growing experience and knowledge on degradation mechanisms and improved inspection methods (cf. Fig. 1).

[1] https://www.pwc.by/en/press-releases/industry-4-0.html

Today, usually a mixture of the following maintenance methods is applied:

- *Reactive Maintenance* means operation until failure. If the failure occurs unexpectedly, the time to repair could be long and the required scope of repair might be enhanced. Nevertheless, for uncritical and small machinery, reactive maintenance is still a common strategy.
- *Time Based Maintenance* is done at fixed time intervals according to design, operation regimes and experience. Due to the preventive character of time based maintenance a portion of residual service life time is not used.
- In *Condition-based Maintenance* anomalies are detected by means of different monitoring parameters. Usually, an expert performs the diagnosis and determines the necessary maintenance or repair. It is also a type of preventive maintenance with the goal to detect early signs of a potential failure and to schedule the necessary maintenance in time to prevent unscheduled downtime.
- *Predictive Maintenance* extends condition based maintenance. It is based on continuous machine monitoring and requires methods to extrapolate the development of condition changes in an automated way.

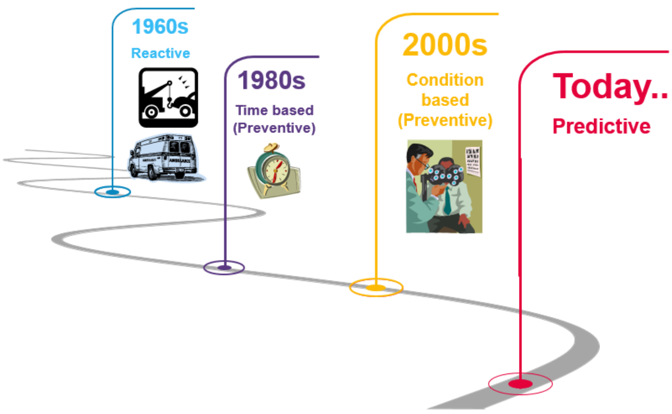

Fig. 1: Development of maintenance strategies

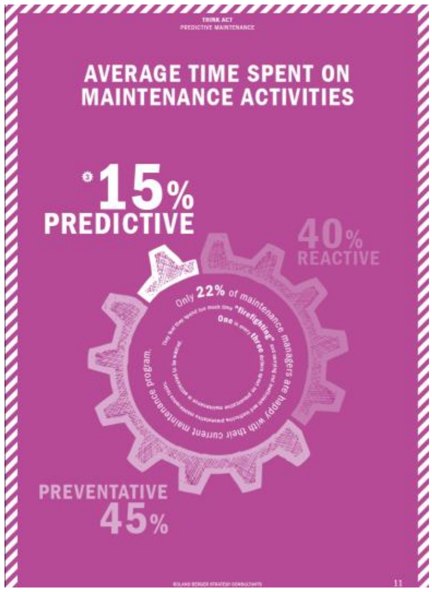

Fig. 2: Share of maintenance strategies in different industries[2]

According to a survey of different industries by Roland Berger Strategy Consultants[2] from 2014 (Fig. 2), 15 % of the time of maintenance activities should have been spent on PM, 45 % on Preventive Maintenance (time & condition based) and 40 % on Reactive Maintenance. We treat the number of 15 % for PM as very optimistic, which is probably caused by a different understanding of PM and the rather blurred transition between Condition based Maintenance and PM.

In contrast to Condition based Maintenance, PM includes anomaly detection, diagnostic analysis and prognostic analysis in a more automated process. PM should point to the cause and severity of the problem and how it most likely is going to develop, ideally predicting the life time and suggesting measures to prevent failures.

This is a challenging goal and not easy to achieve in complex industrial applications.

2 https://www.rolandberger.com/de/Publications/Predictive-maintenance.html

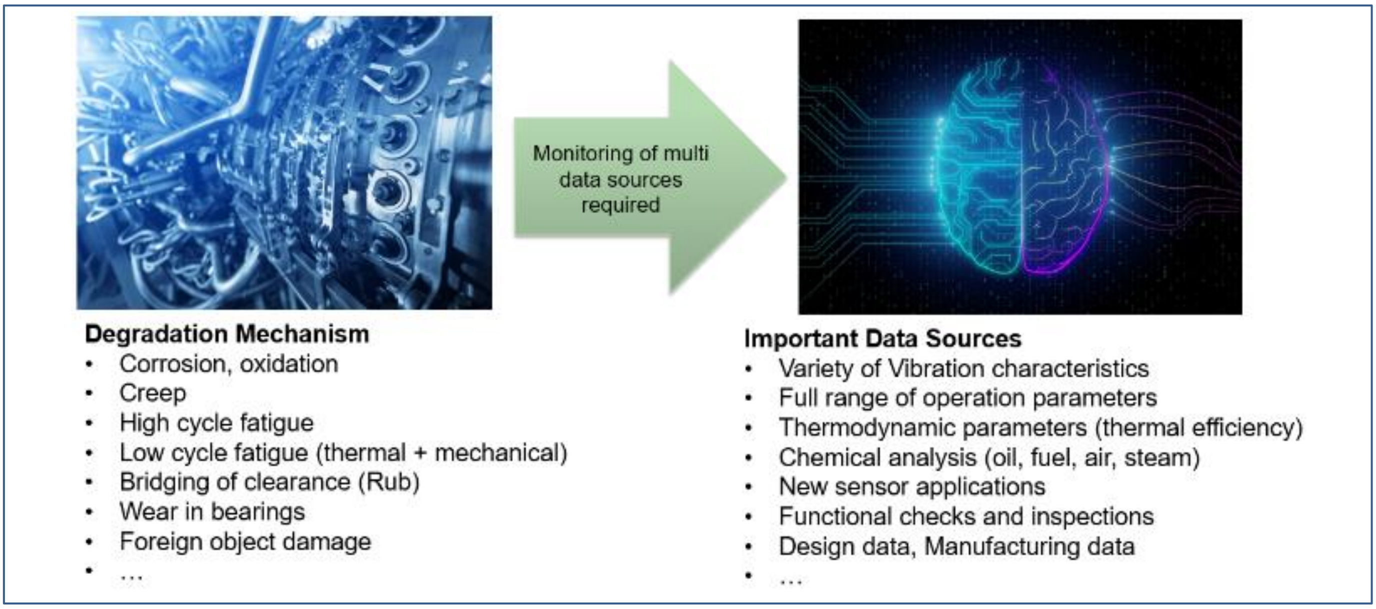

Fig. 3: Examples for degradation mechanisms of gas turbines and important data types for an early detection

Fundamentals of Predictive Maintenance

Formal definition of PM according to DIN EN 13306 „Maintenance terminology":

> "Predictive Maintenance is Condition based Maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of significant parameters of the degradation of the item."

Main technologies behind a Predictive Maintenance System are pattern recognition, machine learning algorithms, rule based and physical models. The aggregation and interpretation of multiple data types is fundamental. Physical models, also called Digital Twins, simulate the machine behavior (cf. example by GE[3]). They are used to predict potential malfunctions and/or lifetime consumption of components.

Due to complex degradation mechanisms of machinery such as gas turbines, a prediction of the various potential failures is very challenging. Domain knowledge and monitoring parameters from multi disciplines are essential (Fig. 3). Moreover, the variety of detection techniques exhibit different detection periods to failure (cf. schematic in Fig. 4). If the available information sources are combined in one system (Data Fusion), it will improve detectability of failures compared to common Condition Monitoring Systems, which are often based on only a single data source.

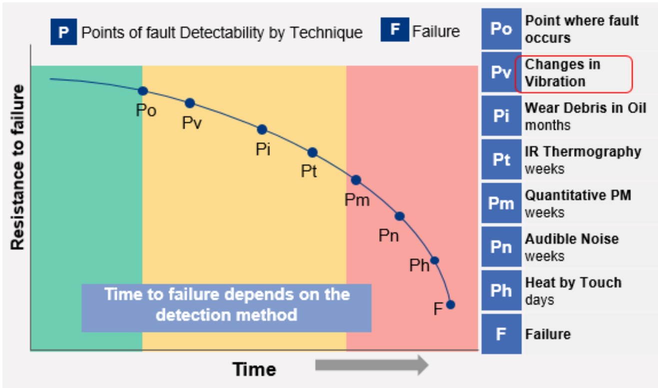

Fig. 4: Schematic presentation of fault development and exemplary periods of failure detection of different monitoring techniques

As mentioned above, thermal turbomachinery, such as gas turbines, are affected by a multitude of degradation and wear mechanisms. The presence and intensity depends on numerous factors, such as operating conditions, environment, design and maintenance. For example overhaul periods of gas turbines are usually defined depending on equivalent operating hours (considering firing temperature) and start cycles (Fig. 5).

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3 https://www.ge.com/digital/sites/default/files/download_assets/Digital-Twin-for-the-digital-power-plant-.pdf

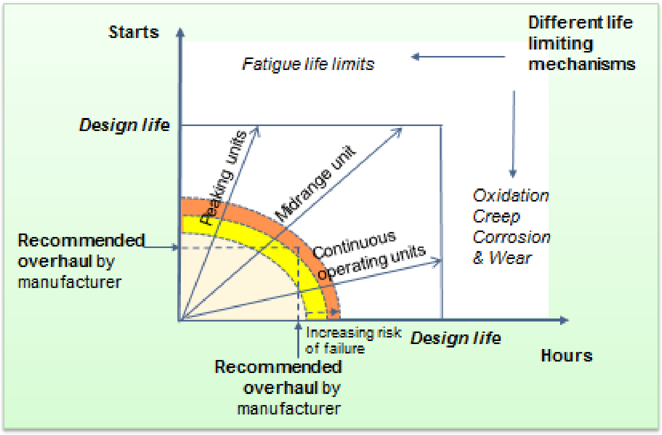

Fig. 5: Schematic presentation of influencing factors on lifetime and overhaul periods of gas turbines

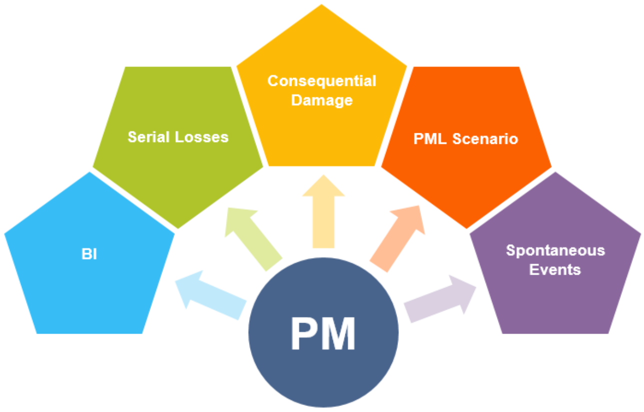

Fig. 6: Potential impact of PM on technical risks

Hot gas path components, rotors and disks of gas turbines have a limited lifetime. Therefore, manufacturers recommend overhaul intervals referring to the specific design and their fleet experience. Degradation mechanisms such as creep, oxidation, corrosion & wear mainly develop over operating time. Fatigue is dominated by start cycles (mechanical and thermal stresses). If overhaul periods are stretched beyond the recommended interval (experience margin) the risk of failures will increase. PM can help to manage the risk, but it needs to be considered which components and degradation mechanisms can be monitored and which cannot. For example, condition changes of rotating blades are difficult to detect.

Goals of Predictive Maintenance and potential impact on technical risks

Maintenance of machinery is targeting different goals. The main goals are the increase of availability and profitability and the reduction of risk of failure. But, it is not possible to maximize all of them, and often the players involved follow different interests.

The manufacturer wants to increase the service business and the client retention. The manufacturer is also interested in using the data of PM systems to optimize the design of their product. The operator wants to reduce the maintenance costs and increase the availability, which is somehow a conflict of goals. Insurance is generally interested in reducing the risk of failures. Furthermore, the information of machinery condition from PM systems could help to improve the risk assessment. These optimization goals influence the impact of PM on technical risks.

Potential impact of PM on technical risks

PM could impact the following technical (insured) risks (Fig. 6):

- Business Interruption (BI)
- Possible Maximum Loss (PML) Scenario
- Serial Damage
- Consequential Damage
- Spontaneous Events

In the following the potential impact will be analyzed by means of examples. The BI risk is not specifically covered, because it is directly related to the other risks.

Serial Losses

Wind farms are a good demonstrator for the question as to whether PM could mitigate serial losses. Wind turbines are operated under challenging conditions. AZT has experience from several serial losses which were related to e.g. material quality or weakness of design. By considering a bearing issue, a reliable early detection of a progressing degradation can be used to establish a cost-optimized replacement sequence, and consequential damage can be avoided. Furthermore, a targeted monitoring of high risk units is feasible. These features are already covered by most of the Condition Monitoring Systems (CMS) which are installed on wind turbines and are state of the art for several years (cf. AZT publication on CMS[4]). PM could go beyond. PM could also detect critical turbines in other locations, if the failure pattern is transferred. Serial issues can be better managed and its impact reduced.

[4] https://azt-industry.com/

Consequential Damage

PM can help to detect lifetime reduction, e.g. by use of the above mentioned digital twin. On that basis overhauls could be planned in time and costly consequential damage avoided. As an example, we could consider a compressor blade problem in the first row, e.g. a crack, which could cause a severe damage, if the compressor blade is liberated. Nevertheless, it is very challenging to predict cracks in blades. PM can only predict scenarios, which can be detected from the available data. Thus, planned outages for borescope inspection and overhauls cannot be skipped.

Catastrophic failures and PML scenarios

Some types of catastrophic failures can be avoided depending on the failure mechanism and monitoring technology.

Example A - A shaft fatigue crack of a steam turbine was detected by increased long-term vibration trend of one year (Fig. 7). The turbine was stopped due to the final progression of the vibration. By visual inspection a circumferential shaft crack was detected at the diameter transition from shaft journal to turbine disk.

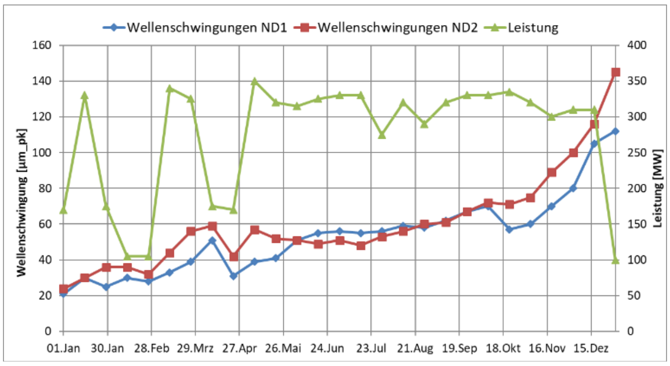

Fig. 7: One year vibration trend of a slowly progressing, fatigue crack at a steam turbine shaft

After opening the crack it turned out, that only ¼ of the shaft cross section has remained (Fig. 8). Thus, the turbine was stopped just in time prior to a catastrophic failure. The fatigue crack was triggered by the notch effect of the small radius at the diameter transition and corrosion. With PM based on vibration data such a potential catastrophic failure can be avoided.

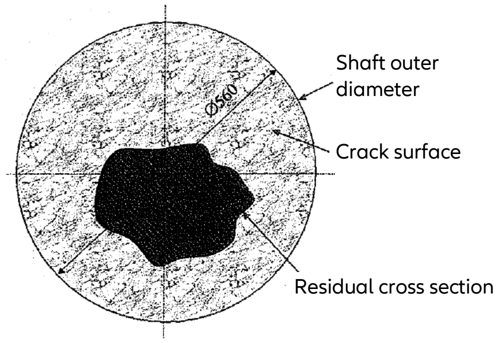

Fig. 8: Fractured shaft cross section shown in grey color

Example B - In another case, the catastrophic shaft fracture of a turbine shaft could not be avoided. The shaft burst during operation (Fig. 9). The observed brittle fracture started from an internal forging defect and developed within milliseconds across the complete rotor length (Fig. 10). It is the biggest fracture surface of a turbine shaft worldwide and can be inspected at the Material Laboratory of AZT (s. virtual Lab tour[5]). The turbine and the machine hall was extensively damaged. One rotor piece with 1300 kg flew over more than 1 km. Fortunately, nobody was injured by this accident.

Such fast growing forced fracture cannot be detected during operation. The measured vibration levels were normal until the event occurred. It was a spontaneous event. Hence, PM cannot avoid such a catastrophic failure. The previously existing internal defect could have only been detected by comprehensive ultrasonic testing during inspections after manufacturing.

Predictive maintenance systems cannot avoid catastrophic failures in every case. Therefore, possible maximum loss scenarios are independent from the predictive maintenance approach.

Fig. 9: Catastrophic failure of steam turbine caused by a sudden rupture of the turbine shaft

[5] https://www.azt-virtual-lab.com/

Fig. 10: Brittle fracture of the turbine shaft

Risk evaluation of PM

According to the examples shown and also many other machine failures that AZT has investigated, the detection and prediction of machinery issues can be very challenging and is not possible in every case. Therefore, the influence of PM on the technical risks depends on the application and the purpose of its use.

For the risk evaluation of PM three categories with a number of sub-criteria have been identified. For reason of limitation in this article, only one sub-criteria for each category is presented below as a short example.

Category 1 - Optimization Goal, sub-criteria:

- Enhanced utilization of component lifetime (stretching scheduled maintenance)
- Avoidance of unscheduled maintenance (mitigation of false alarms & missed detections)
- Plan and preparation of repairs
- Detection and optimization of non-favorable operating conditions

Category 2 - Machinery characteristic and operation conditions, sub-criteria:

- Machinery without scheduled overhauls
- Machinery with serial character and developed lifetime experience, e.g. aero engines
- Machinery with limited component lifetime, e.g. gas turbines
- Other machinery

Category 3 - PM technical level and organizational integration, sub-criteria:

- Defined max. operation periods between overhauls
- Specified responsibilities
- Support and further development of PM System
- Maturity level of PM (use of multi data sources, etc.)

Examples:

- Optimization goal: In case PM is primarily used to stretch scheduled overhauls, this would increase the risk, if the margin of experience is exceeded.
- Machinery characteristic: For machinery without scheduled overhauls, such as wind turbines, PM would produce a risk reduction.
- Organizational integration: If it is the intention to extend overhaul intervals, maximum operation periods between overhauls should be defined and put in place.

In general, when machinery operators change to PM the technical risk is affected and an individual assessment referring to the above categories is advisable.

Conclusion

As demonstrated, PM involves on the one hand potential risk reducing and on the other hand risk increasing factors. Following risk reducing factors have been identified:

→ Reduction of unplanned downtimes/BI losses
→ Reduction of consequential damage
→ Early detection of serial losses

Risk increasing factors:

→ Optimizing capacities or prolongation of use of component lifetime reduces safety factors
→ Catastrophic failures are not or just partially avoidable by PM systems
→ Unmonitored components might get critical, if they are checked less frequently due to extended maintenance intervals

Beyond these effects, there are potential further risks that may arise with the use of PM Systems:

→ Overrating of PM capabilities - blind trust in the systems and less experts available
→ Potentially higher vulnerability against cyber attacks

Summing up, depending on the application PM can reduce the technical risks. However, individual risk assessment of PM systems is required. It should be considered that the PML scenarios of technical risks remains unchanged and risks could also increase.