International Journal for Innovative Engineering and Management Research
PEER REVIEWED OPEN ACCESS INTERNATIONAL JOURNAL
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THE VALUE OF PREDICTIVE MAINTENANCE IN THE FOURTH INDUSTRIAL REVOLUTION AND ITS IMPLICATIONS FOR BUSINESSES AND MANAGERS

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Abstract

The emergence of Industry 4.0 enhances the capabilities of predictive maintenance and paves the way for efficient and optimized maintenance operations. Until now, the technical implications of adopting predictive maintenance solutions in Industry 4.0 environments have been reported in various studies. However, the business perspective is usually not considered, although there are significant managerial barriers towards the 4th industrial revolution. In this paper, we present the benefits, business opportunities and managerial implications of predictive maintenance based upon our experience in the design, implementation and deployment of related solutions.

1 Introduction

Industry 4.0 is increasingly gathering the attention of businesses. Since it is still at its dawn, there is a debate about whether Industry 4.0 is a revolution or an evolution with contradictory arguments. One side's arguments – the radical innovation perspective – is summarized by a quote of Oren Harari (McQueen, 2018, p. 117) that "the electric light did not come from the continuous improvement of the candle." The opposite side – the incrementalists – supports that technological innovation is continuous and the concept of a "revolution" is based on a lack of knowledge of the details. This contradiction and tension actually expresses a clash of two worlds with two different cultures: when the world of manufacturing with a long-term perspective meets the world of information technology and data analytics with a disruptive perspective.

Predictive maintenance is a top priority for manufacturers in the 4th Industrial Revolution – Industry 4.0. Since failure of critical assets has been rated as the most significant risk to operational performance, manufacturers are increasingly seeing maintenance as a strategic business function and not as a necessary evil. They now have more alternatives than ever to employ a costly "run until it breaks", or an inefficient "fix it regardless" maintenance strategy. However, predictive maintenance faces several challenges with regards to its practical implementation in the complex and dynamic Industry 4.0 manufacturing environment.

The findings presented in this paper are based upon our experience from the implementation of predictive maintenance projects in various industries such as: oil drilling, automotive, white appliances, aviation and steel industries. The next section introduces predictive maintenance along with its benefits in an Industry 4.0 environment. Section 3 provides managerial and organizational implications of adopting predictive maintenance, while Section 4 summarizes the conclusions.

2 Predictive Maintenance as an Enabler for Industry 4.0

Industry 4.0 has been defined in many ways. Very comprehensively we begin with the following statement that shows the breadth and complexity of the concept.

“Industry 4.0 refers to the integration of Internet of Things (IoT) technologies into industrial value creation enabling manufacturers to harness entirely digitized, connected, smart, and decentralized value chains able to deliver greater flexibility and robustness to firm competitiveness and enable them to build flexible and adaptable business structures, acquiring the permanent ability for internal evolutionary developments in order to cope with a changing business environment as the result of a purposely formulated strategy implemented over time” (Piccarozzi et al., 2018, p.16).

Early definitions had Industry 4.0 including the following pillars: big data analytics, additive manufacturing, autonomous robots, cloud computing, internet of things, cybersecurity, augmented reality, system integration, simulation (Platform Industrie 4.0). For more information, the reader may refer to the documentation of Platform Industrie 4.0 (https://www.plattform-i40.de/).

Predictive maintenance is an indispensable aspect of Industry 4.0 (Roda et al., 2018). It moves beyond breakdown or corrective maintenance – maintenance performed on equipment that has broken down – to time-based or preventive maintenance; maintenance performed on equipment based on a calendar schedule.

Predictive maintenance in the context of Industry 4.0 is a maintenance strategy that uses large amounts of real-time and historical data to detect early anomalies in equipment behavior. It predicts the future equipment health states and potential future failure modes. It formulates proactive maintenance plans to eliminate or mitigate the impact of the predicted failures (Hribernik et al., 2018; Bousdekis et al., 2019).

Predictive maintenance strategies and technologies help manufacturers gain competitive advantage. Maximized operating equipment lifetime, reduced maintenance costs, reduced downtimes, increased knowledge, improved safety, improved plant reliability, efficient maintenance resources utilization, adoption

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of zero-defects strategy, and flexible and optimized process planning are among the most important proven benefits contributing to long-term competitive advantage.

Predictive maintenance is a radical change by specifying failure prediction as the backbone of maintenance operations. The potential of predictive maintenance is clearly visible by utilizing the P-F curve, as shown in Figure 1.

The P-F curve is a common way to represent the behavior of an asset before actual functional asset failure has occurred. The curve shows that asset performance or condition declines over time leading to functional failure – the loss of function for which it was intended. In this sense, the failure is considered to be a process instead of an instant event.

A process perspective assumes that failure cause generally takes time to develop before failure occurs. There is a time window – the P-F interval – between the time of the potential failure (P) and the functional failure (F). Potential failure is the point when it is found that the equipment is failing. Functional failure is the point when the equipment actually fails. The point F is typically a distribution of the possible failure times for the failure mode under examination. This distribution is derived from historical data analysis.

Traditional breakdown maintenance occurs after the point F and time-based maintenance is scheduled at specific time intervals in order to avoid F. Predictive maintenance defines visual inspection intervals shorter than the P-F interval in order to assess the condition of the equipment and based upon the expert knowledge.

With the emergence of Industry 4.0, predictive maintenance moves towards its next evolutionary step: the use of sensors and big data processing information systems for placing the P-F interval very close to the point of degradation. This placement is achieved with the exploitation of real-time information that extracts meaningful insights even before the symptoms are visible by humans.

The optimal placement of the P-F interval can be achieved when the abnormal behavior of the equipment is identified – the point that degradation starts. The identification of the transition from the normal state to the dangerous state allows us to predict the future behavior as well as to decide among alternative courses of actions. These actions include perfect or imperfect maintenance of various degrees. The courses of action will occur ahead of time. In this way, the predicted failure impact can be eliminated or mitigated while maintenance operations are optimized.

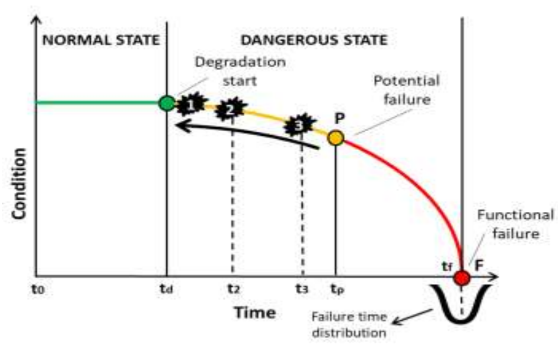

Figure 1: Predictive maintenance in the context of the P-F curve

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The three main predictive maintenance solution functionalities in an Industry 4.0 environment are performed in the early stages of the dangerous state. These functions include: (1) anomaly detection, (2) failure prediction, and (3) decision about maintenance actions – see figure 2.

As shown in Figure 2, the system continuously and indirectly monitors the condition of an asset through sensor measurements of a degradation indicator such as vibration or temperature. As soon as unusual measurements are observed, anomaly detection is performed and an early warning is generated (1). The early warning triggers the failure prediction process. This process utilizes historical data in order to anticipate the future failure. The prediction process calculates the remaining useful life (RUL) and confidence levels (2). The prediction subsequently triggers the decision about the mitigating maintenance actions taking into account the action and the time that minimize the maintenance expected loss (3). Consequently, the maintenance plan is formulated and updated accordingly.

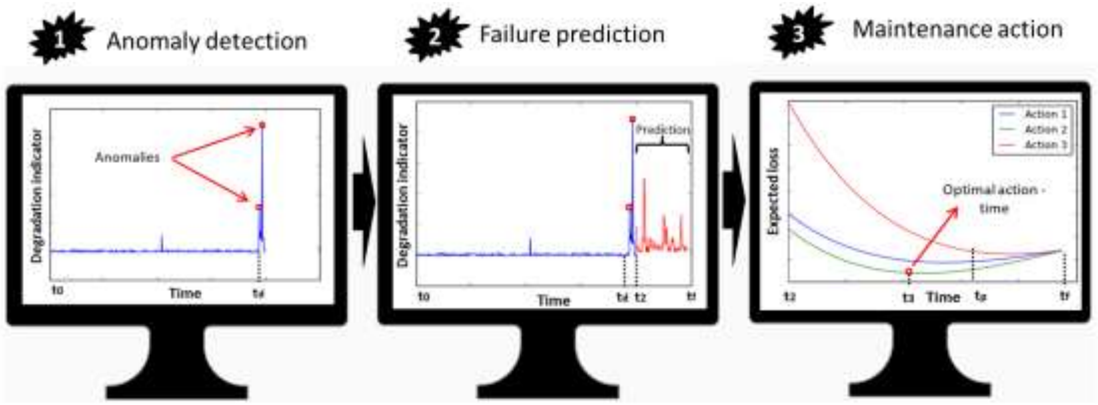

Figure 2: The three main functionalities of predictive maintenance in Industry 4.0

The implementation of predictive maintenance solutions has significant benefits in industry. Below, we briefly describe some use cases from our projects:

Offshore oil drilling: Anomaly detection on the basis of real-time readings of the oil temperature and rounds per minute (RPM) of the drilling machine's gearbox triggers predictions about the drilling machine's gearbox breakdown. Appropriate decisions are then generated. This application led to reduced maintenance costs by up to 38% and to improved safety. These latter benefits are critical in a dangerous work environment that can have sever human and environmental consequences.

Automotive industry: Anomaly detection on the basis of real-time readings about dust level humidity and temperature of moulding machines triggers predictions that headlamp scrap rate will exceed the acceptable threshold. Appropriate decisions are then generated. This application led to increased knowledge with respect to the root causes of the defects and 29% improvement in the scrap rate. This effort facilitates transformation towards a zerodefect strategy.

Production of domestic appliances: Anomaly detection on the basis of real-time readings of the punch vibration, seaming vibration and seaming pressure during the drum rotation in a dryer drum production process. This data triggers predictions about malfunctioning (leading to scraps) or breakdown (leading to downtime) influencing appropriate decision generation. This application and decisions led to elimination of defects by 33%, reduced maintenance costs by 27%. It also led to flexible and optimized process planning by exploiting the available resources.

Aviation industry: Anomaly detection on the basis of real-time readings of temperature, humidity, gyroscope and acceleration of a large transportation jig for wing covers of a commercial aircraft triggered predictions about the time-to-arrival to the maintenance provider as well as its condition. Subsequently, appropriate decisions dealing with optimal maintenance planning, resource allocation and necessary spare parts are generated. In this way, maintenance resources are utilized in an optimal way and the time-to-repair is minimized by up to 22%.

Steel industry: Anomaly detection on the basis of real-time readings of the vibration (acceleration and velocity), tachometer (RPM) and current (Amperes) sensor triggers predictions about the breakdown of the rollers included in the cold rolling machine with appropriate decisions generated. This application leads to maximized operating equipment lifetime by up to 60% and to reduced downtimes due to the timely preparation of the maintenance process in advance.

3 Managerial and Organizational Implications

Even with the advantages of Industry 4.0 predictive maintenance systems across industries, it is not surprising that there are a number of challenges, concerns, and implications facing managers and organization. We bring to the forefront many of these organizational, technological, and economic concerns.

Extracting business insights and knowledge from vast amounts of data through intense employment of IoT technology and Cyber-Physical Systems (CPS) from the industrial value chain is a major technical challenge in Industry 4.0 predictive maintenance (Groger, 2018). Other technical implications include the lack of widespread standard solutions, current cybersecurity technologies risks for corporate data protection, the availability of sufficient and appropriate real-time and historical data, the integration of predictive maintenance solutions with legacy systems, and the difficulties of expert knowledge modelling.

Up to now, most business and scientific interest has focused on the technical implications. Managerial and organizational implications are typically secondary, if even considered. These dimensions may be the most significant barriers for the adoption of

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predictive maintenance solutions (Roda et al., 2018).

Below we summarize the main managerial and organizational implications.

Investment and consulting costs: Novel technological solutions of predictive maintenance are still not well perceived by the industry. Expertise doesn't necessarily exist in most companies. Thus, for quick implementation companies will likely outsource or contract with vendors, consultants, and experts. High consulting costs – since vendors are selling closed and proprietary solutions – and a project's long duration are major concerns.

Even in the case of open source solutions, the consulting costs can be very high and the projects very long given the learning curves. Since predictive maintenance solutions require significant investments, there is the need for extensive cost-benefit analysis and feasibility studies; essentially making the business case.

Digital strategy: Predictive maintenance cannot be implemented in complete isolation since it can have wide-ranging – vertical and horizontal – effects within the organization. It should be embedded into an overall digital manufacturing strategy that is owned and fully supported by top management. This is important not only because of the significant resources and capital investments, but also because there is the need for a clear vision from company leaders who understand the power of new digital technologies; especially powerful predictive tools that can influence their decision making.

Change management: Far-reaching change can be discomforting for the people who make it happen. Effective technological and organizational change management processes are critical. The adoption of new predictive maintenance technological solutions is usually accompanied with a resistance to change from the employees.

Predictive maintenance implementation requires a robust digital culture. This means a culture that prioritizes employee engagement, stimulates experimentation with new technologies and new ways of working. The culture will need to stimulate cross-functional cooperation and is comfortable with data-driven decision-making. Even if decision-making goes against managerial and employee experiences and introduces a new way of thinking. Not surprisingly, such a digital-minded environment can only be cultivated with committed leadership from the top.

Corporate governance strategy: There are different kinds of corporate governance. These differences can include subsidiary companies being centrally managed by headquarters or allowing local management to guide subsidiary company. Modern manufacturing companies are becoming more and more centrally guided.

This fact provides some advantages but also may pose limitations with respect to the adoption of new technologies. For example, getting investment approval for new sensing equipment. In case a subsidiary company wants to implement a new system, it must first check with headquarters if the system in question has enough potential for local but also for worldwide distribution. After positive feedback, the subsidiary company can begin implementation and testing of the new system. There needs to be plans in a project for the additional approval stages in the centralized approach

Organizational structure: Industrial management should consider changes in its organizational structure by promoting cross-functional and interdisciplinary teams, with multiple skills – for example reliability engineers, process technologists, data scientists and IT specialists cooperating. Building effective ways of communication across disciplines and combining the know-how of the maintenance function and the IT department.

An important goal is to create an environment in which IT professionals such as data scientists and business domain experts such as reliability engineers can interact and complement each other. Alternatively, finding resources on the market with the necessary analytics and IT skills for the manufacturing domain remains a challenging task. Obtaining and building these capabilities requires not only talented staff but also a holistic and consistent organizational integration. The involved costs need to be considered and approved for this evolution, if it doesn't already exist in the organization.

Digital and reliability engineering skills development: Success with predictive maintenance depends on skills and knowledge. The vast majority of manufacturing companies do not employ reliability engineers, while even fewer employ data scientists.

Manufacturing companies need to invest in data analytics roles or to introduce new roles that bring complementary skills to those inherent to maintenance processes. Examples would include experts of Industry 4.0 and citizen data scientists. Citizen data scientists create or generate models that use advanced data analytics capabilities, but their primary job function is outside the field of analytics (Gartner, 2016; Gröger, 2018). Building this type of skills and human resources capacity helps to bridge the gap between the world of business and the world of data science.

In the predictive maintenance context, a reliability engineer with appropriate data analytics qualification can play this role. Their skills development can be through the introduction of educational plans combining knowledge on databases, data engineering, statistics and advanced analytics algorithms. The citizen data scientist should also have leadership and human resources management skills in order to lead the cross-functional teams. Their guidance should incorporate strategic digital cultures during the evolution and control of predictive maintenance projects.

Project Management: During the implementation of predictive maintenance projects, there is the need for an efficient project management. Due to the high costs, the required time, the large-scale nature and the complexity of the manufacturing environment, enterprises need to adopt a structured logic taking into account three main factors.

First, they need to perform an asset criticality assessment in order to prioritize the machines and equipment according to their criticality in the manufacturing process. The criticality may be expressed with respect to downtime, cost, safety, contribution to profitability, frequent and massive demand.

Second, they need to identify the most appropriate pilot machines or equipment for experimentation and validation before expanding the predictive maintenance solution to the whole factory.

Third, they should handle the diverse technological levels on the shop floor. Most production environments will be characterized by "smart" and "non-smart" machines. They need to consider the long-term introduction of technologically novel equipment; where legacy systems will need to be merged. The latter may require production processes to temporarily halt, and to fully book capacity on machines. This challenge is a key reason why large enterprises are slow in adopting new technologies.

4 CONCLUSION

The emergence of Industry 4.0 enhances the capabilities of predictive maintenance and paves the way for more efficient maintenance operations. However, the existence and exploitation of huge amounts of data in the manufacturing enterprises features the need for building bridges between two worlds, the world of manufacturing and the world of IT.

Since Industry 4.0 is a revolution on a business level and an evolution on a technological level, a major objective is how to introduce and adapt evolving technologies with successful applications in other domains to the more conservative manufacturing environment. Although predictive maintenance is a significant enabler for Industry 4.0, it still faces several challenges in its practical implementation from both a technical and a business perspective. To this end, managers need to be aware of the major challenges in order to be prepared for the digital transformation of manufacturing and the transition to the 4th industrial revolution.

Acknowledgements

This work is partly funded by the European Commission project H2020 UPTIME "Unified Predictive Maintenance System" (768634).

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