# Maintenance-Free Factory

## The Transformation of Maintenance

Wilfried Sihn, Luisa Reichsthaler, Daniel Toth, Linus Kohl, Lisa Greimel

## 1. Introduction

The inspirations for conducting research activities on the Maintenance-Free Factory (M2F) were derived from the contemporary challenges and goals to achieve more sustainable and efficient ways of working in industrial maintenance and production. The increasing complexity and criticality of industrial machinery has made maintenance a fundamental aspect of production management. Unexpected breakdowns can lead to significant risks and consequences, requiring a focus on machine reliability, availability, maintainability, and safety. In particular, asset-intensive industries such as manufacturing companies focus on controlling maintenance costs while achieving these goals (Bousdekis et al. 2015; Golpîra/Tirkolaee, 2019).

Fortunately, with the advent of digital technologies such as the internet of things, artificial intelligence, and predictive maintenance, tools are available to improve the identification and preservation of critical resources. Applying these methods results in efficient maintenance and the ability to identify potential machine failures before they occur. Positive outcomes are reduced downtime, increased production efficiency, and minimized risk and consequences of unexpected failur (Jasiulewicz-Kaczmarek/Gola 2019).

The holistic M2F approach incorporates digital technologies and other existing approaches to create a "future maintenance". To achieve a maintenance-free factory, a theoretical concept has been developed:

- **Digital maintenance processes** – involve using digital technologies to increase the efficiency of maintenance activities and improve machine reliability and availability while reducing costs. This paradigm includes all related approaches, e.g. assistant systems.

- **Data-driven maintenance** – includes all data-based maintenance strategies that lead to predictive maintenance, using digital technologies such as sensors, data analytics, and automation to monitor and optimize machine health and Industry 4.0 approaches, e.g. artificial intelligence.

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- **Decision support system** – describes the bi-directional integration of maintenance planning with production planning, business cases, and models. Future maintenance enables higher productivity and fewer breakdowns through informed decision-making.

- **Maintenance staff** – describes various aspects such as ergonomics, skills management, continuing education and training methods, knowledge management, acceptance of new technologies by maintenance personnel, and work organization and flexibility in general.

- **Sustainable maintenance** – includes relevant aspects of sustainability and resilience in terms of energy and resource-efficient system design as well as aspects of circular economy, optimized life cycle of machinery and equipment and life cycle assessment.

## 2. The necessity of a fundamental change in maintenance

For decades, various approaches have been designed and implemented to optimize maintenance management systems in manufacturing. Increasing digitalization has led to novel data-based maintenance methods and strategies in recent years. Despite plausible benefits for manufacturing companies, maintenance is not yet considered as an enabler and driver of sustainable and resilient production management (Glawar et al. 2022; Sihn et al. 2021).

Advancing digitalization, sustainable legislation at national and international level, and changing employee needs represent current challenges in the industrial context. These challenges have a number of objectives, such as improving the use of resources, practicing efficient energy consumption, minimizing capital expenditure by extending the life of machinery, equipment and spare parts, and changing the expectations placed on production and maintenance personnel. In fact, there is a wide discrepancy in the maturity of the theoretical approaches to maintenance management found in the literature (Simard et al. 2019). Manufacturing processes in most companies have now been optimized to such an extent that only a few productivity gains can be achieved there, but there is still a lot of potential for improvement in the maintenance environment.

Therefore, future maintenance needs a new character under the guiding principle of *"Create value instead of costs!"*.

## 3. Challenges facing the maintenance sector

Initiating the transformation of maintenance from a cost factor to a value-added partner presents companies with the following prevailing challenges:

- **Doubts about the economic efficiency of maintenance**: Maintenance is often perceived as a non-value-adding activity from a current economic perspective (Henke et al. 2019). In this context, reference is made to the lead time of maintenance orders, 75% and 80% of which are reported non-value-added activities (Matyas 2018). This is a result of paper-based processes, a high proportion of failure-oriented maintenance and the associated mostly unplanned interruptions.

- **Lack of data**: Data availability and quality are the key success factors for data analysis projects (Badraddin et al. 2022). Data availability and quality are fundamental for the implementation of predictive maintenance methods or strategies (Nemeth et al. 2019) and are mostly insufficient (Simard et al. 2019). Different failure scenarios need to be identified to enable accurate predictions and relevant patterns that indicate failure need to be derived. In addition, the common strategy of short maintenance cycles of high-cost and critical equipment results in fewer breakdowns but makes it difficult to infer patterns (Singla et al. 2021). Another reason for poor data quality is the organization's incomplete documentation of maintenance activities and poor knowledge management. Systematic maintenance feedback collections a key success factor for implementing data-based maintenance strategies (Schildkamp/Poortman 2015).

- **Lack of flexibility in the maintenance organization**: Although data-driven and AI-based maintenance approaches can provide a better understanding of when a failure might occur, the inflexible work environment makes it impossible to perform the necessary maintenance activities outside of the production process (Fusko et al. 2018). There often are conflicts between production planning and maintenance about whether and when a time slot can be used to perform the necessary maintenance (Cao et al. 2021). After flexibility, business agility is another important part because being able to work with new conditions and implement them as a standard is a major problem for many companies. Therefore, it is necessary to promote maintenance agility and to implement the new working practices efficiently and in the long term (Eckstein 2015).

- **Shortage of skilled workers in industrial maintenance**: Increasing the attractiveness of maintenance is a key lever for addressing demographic change and retaining skilled workers. The lack of appropriate skills for the transition to digital work systems is also an area for action (Kohl et al. 2021).

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- **Lack of prioritization of sustainability and resilience in maintenance**: Maintenance is still seen as a cost generator, not an economically, ecologically and socially sustainable value driver. There is great potential in the areas of resource use and consumption, energy efficiency and environmentally friendly technologies and materials (Jasiulewicz-Kaczmarek et al. 2020).

To address these challenges, various approaches such as total productivity management (TPM), reliability-centered maintenance (RCM) or lean maintenance have been persuaded to optimize maintenance management (Biedermann/Kinz 2019). However, there has not been a shift in industrial environments from maintenance as a cost driver to a strategic competitive factor (Sihn et al. 2021).

## 4. The vision of the Maintenance-Free Factory

The Maintenance-Free-Factory (M2F) vision is to harness the potential of digitalization as a driver of sustainability and enable a fundamental transformation of maintenance to solve environmental, economic and social challenges while securing the future and competitiveness of companies. The concept explores the hidden potential to transform maintenance into an enabler rather than a cost driver along the production line. M2F involves designing production processes to be highly resilient to external and internal disturbances, enabling sustainable planning and operation of flexible production processes.

The challenges listed above require a new understanding of maintenance, similar to what has already been achieved in quality management with the "Zero-Defect-Manufacturing" approach and in setup processes with the "Single Minute Exchange of Die" (SMED) approach. In the future, maintenance will be understood to achieve an overall optimum production time. Special attention will be paid to minimizing non-value-added time.

In analogy to SMED, in which the unproductive setup operations are parallelized and thus extracted from the production process, the concept of the M2F pursues the approach of separating maintenance activities from the production process and extracting them from the productive production time (Sihn et al. 2021).

A M2F is defined as the fundamental maintenance transformation to maximize value-added production time. It therefore implies a factory where production processes are free from maintenance activities.

To realize the vision of M2F a concept has been developed, see Figure 1.

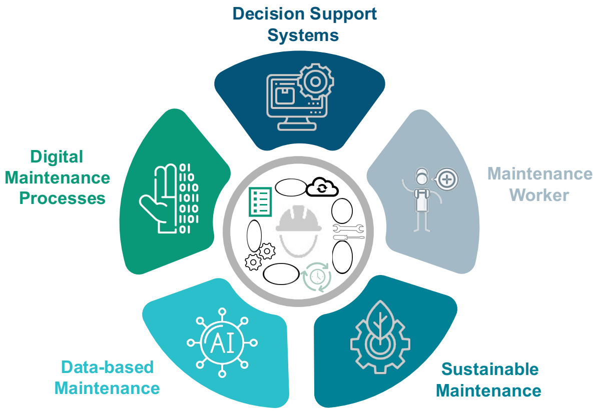


*Figure 1: Concept of the Maintenance-Free Factory*

The concept includes 5 elements, digital maintenance processes, data-based maintenance, decision support systems, maintenance workers, and sustainable maintenance, which are explained in more detail in the following chapters.

## 4.1. Digital maintenance processes

Digital maintenance processes refer to the use of digital technologies and software applications to plan, execute and manage maintenance activities in industrial and commercial environments. These processes use various tools and techniques, such as predictive analytics, artificial intelligence, and the Internet of Things (IoT) to monitor equipment performance, detect potential problems, and schedule maintenance activities in a timely and efficient manner.

Digital maintenance processes are becoming increasingly important for several reasons. Firstly, they can help to reduce downtime and prevent expensive equipment failures by identifying potential issues before they cause significant problems. Secondly, they can improve maintenance efficiency and reduce costs by optimizing maintenance schedules, reducing unnecessary inspections, and streamlining maintenance workflows. Thirdly, they can enhance safety by ensuring that equipment is properly maintained and inspected regularly (Crespo Márquez 2023).

Moreover, digital maintenance processes can provide real-time data and insights that can be used to inform decision-making and improve overall business performance. Companies can identify patterns and trends by analyzing maintenance data, optimize maintenance strategies, and make informed decisions about equipment replacement, upgrades, or repairs.

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Overall, digital maintenance processes are critical for modern industrial and commercial operations to improve reliability, reduce costs, enhance safety, and stay competitive in today's rapidly evolving business environment (Karki et al. 2022).

### 4.2. Data-based maintenance

Data-driven approaches seek to improve maintenance strategies by incorporating predictive or prescriptive capabilities (Matyas et al. 2017).

Data-driven maintenance is a proactive approach that uses digital technologies to optimize maintenance activities. It involves using real-time machine data and installing sensors on machines to collect real-time data on its performance, which is then analyzed to predict remaining useful life (RUL) and anticipate any potential breakdowns before they occur. Retrofitting older machines with sensors allows data to be collected from machines that were not originally designed for digital monitoring, contributing to sustainability goals. By analyzing the collected data using machine learning algorithms, models can be developed that predict maintenance needs over time with increased accuracy. This approach can turn unplanned maintenance into planned maintenance, resulting in less downtime and higher machine availability. In addition, downtime can be used for maintenance activities to avoid disruptions to the production schedule (Ansari/Kohl 2022; Jasiulewicz-Kaczmarek et al. 2020).

In summary, the integration of data-driven maintenance and the use of AI methods increases availability, improves product quality, and stabilizes production processes, contributing significantly to the realization of the M2F vision.

### 4.3. Decision Support Systems

Decision Support Systems (DSS) are computer-based tools that help people make decisions by providing access to relevant data and analytical models. The value of a DSS lies in regular backups, documentation, monitoring, testing, updating, and establishing a maintenance schedule. These practices help ensure that the DSS remains functional, reliable, and effective in supporting decision-making. Regular backups and documentation prevent data loss and facilitate problem resolution, while monitoring and testing identify potential issues and bugs that need to be addressed. Updating the DSS software and systems and establishing a maintenance schedule helps ensure that the system remains secure, reliable, and compatible with the latest technologies (Rodríguez-Padial et al. 2015).

Therefore, a radically different understanding of work organization, the production and maintenance environment is required. Such an organization provides the flexibility to remove non-value-added activities from production. For example, downtime caused by material shortages or production interruptions can be used for maintenance activities.

This requires the integration of maintenance planning into the company's production planning and control and an optimized communication between the parties involved. Production gaps, and thus possible maintenance times, are identified in time and filled according to an ideal maintenance strategy. All other maintenance activities take place outside of production time, see Figure 2.

Focusing on planning and predicting maintenance activities to reduce unproductive, unplanned interruptions using appropriate, data-driven methods. The goal is to proactively manage and schedule processes and make decisions about actions to be taken, despite increasing complexity.

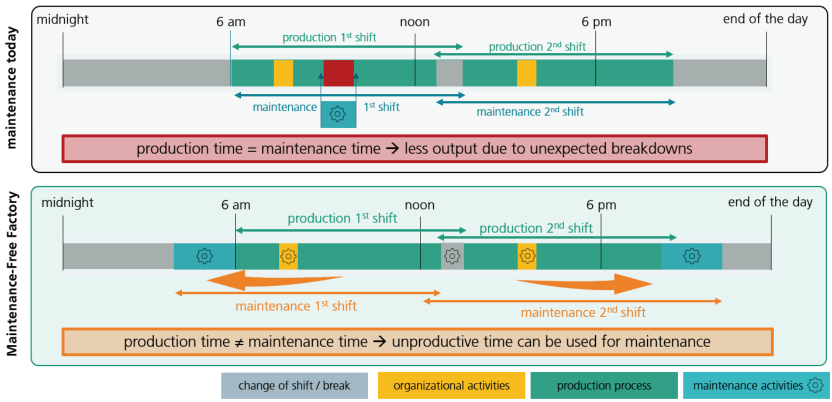


*Figure 2: The Maintenance-Free Factory – when should maintenance be done? (based on Sihn/Greimel, 2023)*

This is accompanied by a change in job descriptions in the industrial maintenance field towards "resilience expert or manager" with a focus on data science competencies. The reduction of short-term operational activities implies an increase in analytical activities and strategic elements. The latter range from knowledge management challenges, changing employee competence profiles and qualifications, to a holistic new work aspect (Glawar et al. 2022; Sihn/Greimel 2023).

## 4.4. Maintenance Worker

Due to the significant increase in digitalization and automation, as well as the complexity of production equipment, the competence requirements for maintenance personnel have changed, both on the front end (i.e. blue-collar workers on the shopfloor) and on the back end (i.e. white-collar workers responsible for planning,

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monitoring, controlling and managing). Maintenance managers in the era of Industry 4.0 face major challenges in reducing unwanted outputs (e.g. $CO_2$ emissions), reducing equipment downtime, lowering costs, meeting desired production lead times and doing all this with less risk to safety and cybersecurity while avoiding damage to the environment. The competence profile of workers is also being transformed by integrating intelligent assistance systems such as conversational AI and physical assistance systems into maintenance work systems. On the one hand, they benefit from technologies that improve work efficiency and quality, for example in documentation (Ansari et al. 2021). On the other hand, they need to become more flexible in terms of knowledge sharing and work-integrated learning (Nixdorf et al. 2021). Considering Industry 4.0 technologies, in particular information and communications technology (ICT) and operational technologies (OT), the ability to collect, analyse and visualize data increases significantly. As a result, maintenance blue- and white-collar workers and consequently business managers can benefit from the value of data in troubleshooting, planning, monitoring and controlling activities. Effective data analysis in the circular value chain enables OEMs and machine users to deepen their understanding of equipment, processes, services, employees, suppliers and regulatory requirements (Jasiulewicz-Kaczmarek et al. 2020).

In the future, people will still be essential to maintain, monitor and ensure the safety of equipment and production machines. In this sense, maintenance and repair tasks will not become redundant in M2F, but their nature will change. New competencies and skills will be required, while some of today's competencies and skills will become obsolete. However, maintenance tasks will increasingly tend towards cognitive tasks and will be strongly characterized by knowledge transfer from experienced workers in production systems (Ansari 2019). Accordingly, the understanding of the role of maintenance will also change, i.e., the entire value chain and the circular ecosystem of maintenance will have to be taken into account.

### 4.5. Sustainable Maintenance

In the future, maintenance will be more than just a set of activities to deal with breakdowns and failures and preserve machinery and equipment. It is more like long-term strategic planning that integrates all phases of a product's life cycle, incorporates and anticipates social, environmental and economic changes, and takes advantage of innovative technologies. The emphasis on adopting environmentally friendly practices, implementing sustainability measures and protecting the environment has continued to grow. National and international legislation, the increasing importance of sustainability, and environmental protection are putting more pressure on industrial companies to focus on sustainable manufacturing practices (Ghafoorpoor Yazdi et al. 2019). Maintenance in a manufacturing company, as a function of great importance, must also contribute to sustainable practices. However, the maintenance process significantly impacts not only the volume, cost of production, and quality of the final product, but alsohe safety of people and the natural environment (El kihel et al. 2022). As a result, in companies that benefit from the so-called good engineering practices, maintenance is not only a cost to be avoided, but mostly an active operation that can become an effective input to the company's development and an integral part of its sustainable development strategy. Therefore, it is necessary to include the category of sustainable development in the processes and activities realized in the area of maintenance of the enterprise's technical infrastructur(Jasiulewicz-Kaczmarek 2013). It requires developing a maintenance strategy and a set of goals consistent with the corporate strategy and the commitment and participation of all employees, as well as knowledge, experience and consistent performance (evolutionary nature of the process). For example, this can save valuable resources by extending machine life and/or reducing energy consumption by increasing machine reliability.

## 5. Summary and outlook

In contrast to existing approaches in the field of maintenance, the revolutionary and challenging M2F approach aims for a holistic view of value creation processes, including the needs of employees, sustainability and resilience requirements, as well as the technical possibilities offered by digitalization.

Thus, the key next steps in implementing the maintenance revolution and research priorities are:

- Data utilization: Consistent implementation of data-based maintenance (predictive / perspective maintenance) to reduce the proportion of malfunctions and convert malfunctions into plannable maintenance activities
- Planning: Integration of maintenance planning into production planning in order to use downtimes consistently and in a plannable manner
- Flexibility: Design a new, flexible working time model in maintenance so that maintenance can occur when production is not taking place.
- Sustainability: Incorporating the sustainability aspect into maintenance in order to carry out activities as resource-efficiently and efficiently as possible and to solve social challenges
- Roadmap: Development of a step-by-step approach for the implementation of M2F in industrial practice.

With the Maintenance-Free Factory, maintenance is to become a driving force for sustainable production management, coordinated and planned within the framework of production activities and thus an integral part of the overall corporate strategy, paving the gap for the paradigm shift towards maintenance as a competitive factor.

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