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Evolution from Industry 1.0 to Industry 5.0 in the Context of Machine and Plant Maintenance

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Abstract
The changing needs of modern manufacturing require a re-examination of the maintenance management role in achieving key cost and service benefits. The development of maintenance requirements is supported by the progress of information technology, which provides new opportunities for the implementation of maintenance processes. The aim of the article is to describe the latest trends in the field of maintenance management from the perspective of the challenges of the fourth and fifth industrial revolution as well as economic, environmental, and social challenges. The five stages of the machine maintenance approach, related to the five industrial revolutions, are characterized, along with the advantages and weaknesses of each machine maintenance approach. The operating data in different operating periods were characterized. Digitalization can empower machine maintenance services by using collected data and advanced technologies to monitor equipment health, diagnose faults, predict and prevent failures long before they occur and ensure performance optimization.

Keywords
Predictive Maintenance, Industry 4.0, Industry 5.0, Sustainable Maintenance, digitalization.

Introduction

Modern civilization is mostly a technical civilization, whose inseparable attribute is the use of devices and machines by man. *The operation of machines, as both a science and a practical field, encompasses organizational, technical, economic, and social aspects related to the interaction between people and machines.* These activities concern technical and organizational undertakings in the field of machine use, broadly understood as the maintenance of machinery and equipment. From a technical point of view, operation can be divided into:

1. use – use of technical objects in accordance with their purpose and functional properties,
2. servicing – maintaining technical facilities in a state of fitness and restoring their required functional properties through inspections, adjustments, maintenance, repairs and overhauls.

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Increasing the level of use and operation of machines is not possible without the development of science and operational research. Operation is a fundamental process in the machine operation system. Its effectiveness depends primarily on the rational use of machines, the degree of implementation of the principle of their economical use, the efficiency of living and objectified work, the organization of the use process and the technical properties of the machines. The following technical characteristics of machines determine the process of use: functionality as the ability to perform the intended functions, efficiency, flexibility as the ability to perform multiple functions, degree of readiness understood as durability and reliability, and quality.

An important goal in the construction and operation of machines is to ensure that the facilities operate properly for as long as possible. This is one of the main prerequisites for achieving satisfactory economic results of an industrial enterprise. In the process of use, the physical state of the object changes over time, and the desired physical state is periodically restored to it in the process of renewal. When, for technical or technical-economic reasons, further renewals become ineffective, then it is liquidated. Operation is of great importance as a field of economic practice, because it covers all those problems that concern the use and operation of a single device (machine) and a group of machines, both in the technical and organizational spheres.

Literature review

According to Kobbacy and Murthy (Kobbacy & Murthy, 2008), machine maintenance is an activity aimed at "optimizing the total life cycle of an object, which means maximizing the availability and reliability of a technical facility in order to produce the desired quantity of products with the required quality characteristics on time. Of course, this must be achieved in a cost-effective manner and in compliance with environmental and safety regulations." EN 13306:2017 defines the maintenance of machinery as the combination of all technical and related administrative activities required to maintain equipment, installations, and other physical assets in the desired operational condition or to restore them to that state in which the facility can perform its obligatory functions. The presented definitions indicate the multidisciplinary nature of maintenance activities, which include both technical aspects of the functioning of a technical facility and all operational aspects relating to the facility itself, and all stakeholders and resources involved in maintenance processes. In the narrow sense, maintenance includes all activities related to maintaining a certain level of availability and reliability of a technical system and its components, and the ability of the system to perform functions at the required level of quality. On the other hand, in a broader sense, maintenance also includes decisions at all levels of the company's organizational structure related to the acquisition and maintenance of a high level of availability and reliability of its technical equipment. Therefore, maintenance management must refer to the business objectives of the company, both at the strategic level as well as at the tactical and operational level.

Numerous technological and management changes over the past decades have changed the requirements and content of maintenance. A few decades ago, maintenance was seen primarily as an activity necessary to be performed after failure, and which is impossible to manage. Today, maintenance is widely recognized as a business function of the enterprise (according to (Zonta et al., 2020), maintenance processes collectively account for 15–60% of total production operating costs) and a critical component of asset management. Organizations are increasingly realizing that they can improve customer service efficiency and reliability by planning their maintenance and remediation efforts more effectively. This results in more preventive maintenance activities that are also better aligned with other business functions, such as production planning or inventory control of spare parts and consumables. Over the past 80 years, maintenance has evolved from an activity necessary to repair asset failures to embedded asset technology, to a vital part of profit generation, and to a strategic component of any organization's cooperative partnership. The development of maintenance requirements is supported by the progress of information technology, which provides new opportunities for maintenance and repair activities.

This study is, among other things, the fruit of the author's long-term fascination with the issues considered here. He also results from his own over thirty years of practice as an academic lecturer of the subjects "Machine Operation" and "Fundamentals of Machine Maintenance" and the author of academic textbooks (Legutko, 2002 and Legutko, 2007a) and those intended for education at the technical school level (Legutko, 2004; 2007b; 2009a; 2010; 2013), as well as the author of chapters in the guide inspection of machines and equipment dedicated to maintenance departments in manufacturing companies (Legutko, 2007c; 2007d; 2008a; 2008b; 2008c; 2008d; 2011a; 2011b; 2011c; 2011d). This also includes scientific activity and activity related to the dissemination of its results (Legutko, 2007a; 2007b; 2009b; Jasiulewicz-Kaczmarek et al., 2020a; Legutko, 2023).

From complete unpredictability to limited uncertainty

Industrial revolutions have significantly influenced the definition, organization, and implementation of maintenance functions in an enterprise (Fig. 1). In a reactive approach to the maintenance of production machinery and equipment (*Maintenance* 1.0) is to restore the damaged machine to normal operating conditions. The high costs of unplanned production downtime and the growing requirements for the efficiency of the use of the machine park have resulted in a change in the approach to maintenance, aimed at preventing the occurrence of failures, not just removing them quickly. The concept of a system of planned preventive repairs (*Maintenance* 2.0). Its essence is to perform maintenance activities of machines and equipment at set intervals, often using a checklist of recommendations from the original equipment manufacturer. The automation of production processes and the even greater complexity of machines have paved the way for the next generation.

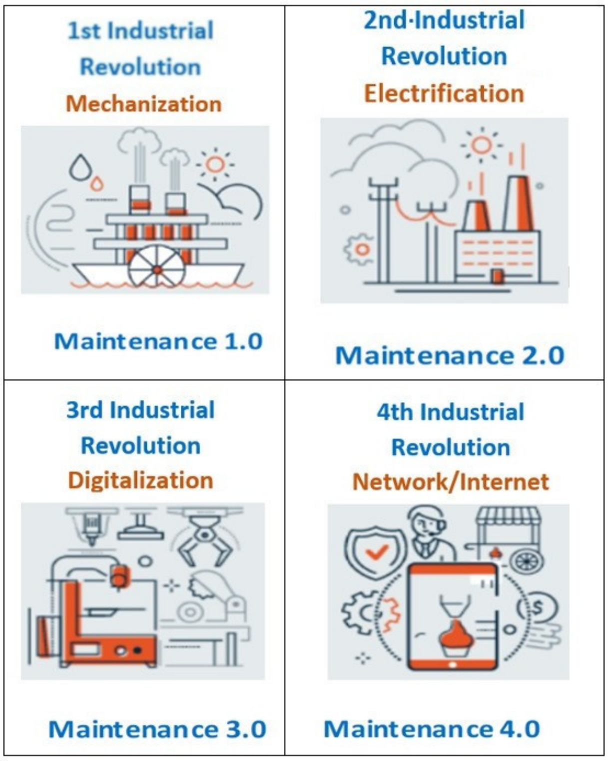

Fig. 1. Industrial revolutions and related concepts for machine maintenance – from *Maintenance* 1.0 to *Maintenance* 4.0 [public domain]

– *Maintenance* 3.0 (also known as *Condition Based Maintenance* – CBM). The company's maintenance function was expected to increase the availability and reliability of the equipment, improve product quality, long machine life and high-cost efficiency. CBM is a maintenance program that recommends maintenance actions (decisions) based on information obtained in the process of monitoring the technical condition of machines. The next generation of CBM (*Maintenance* 4.0), referred to in the literature as *Predictive Maintenance* (PdM), is related to the development of information technologies. The integration of digital technologies into maintenance processes has led to the development of the *eMaintenance* concept. Iung et al. (2009), which is further developed using Industry 4.0 technologies (Johansson et al., 2019; Navas et al., 2020; Turner et al., 2019). In the context of Industry 4.0, maintenance function is often referred to as *Smart Maintenance*, *Intelligent Maintenance*, *Maintenance* 4.0. According to Kinz et al. (2016), "Smart Maintenance means intelligent and learning maintenance management, focusing on continuous improvement." According to Kumar & Galar (2018), "*Maintenance* 4.0 performs predictive analytics and suggests feasible solutions that are primarily applicable to *Industry 4.0*, especially in those aspects of maintenance that involve data collection, data analysis, visualization, and asset decision-making." According to Bokrantz et al. (2020), *Smart Maintenance* is "an organizational project for managing maintenance in manufacturing plants in environments with ubiquitous digital technologies."

One of the most frequently referenced operational strategies in the context of *Maintenance* 4.0 is the predictive strategy (PdM), which uses condition monitoring data to detect anomalies (i.e., identify deviations from normal operating conditions) in manufacturing processes, manufacturing equipment, and products, and diagnose (i.e., characterize the existing state of deviations) and forecast (i.e., predict the future evolution of deviations from normal operating conditions, up to failure). The main task of PdM is to forecast the *Remaining Useful Life* (RUL) of a technical facility to effectively use maintenance intervals and optimize maintenance activities. According to the World Economic Forum (Leurent & Boer, 2019), predictive maintenance activities bring various benefits, such as, among others, reducing repair times by 12%, reducing the failure rate of some machines by up to 70%, and reducing maintenance costs by about 30%.

The use of PdM has many advantages, but it also involves overcoming several challenges. On the one hand, the benefits of PdM include improved productivity, reduced system failures, minimized unplanned downtime, increased efficiency in the use of financial and human resources, and optimization of maintenance planning (Leurent & Boer, 2019; Compare et al., 2019; Yoon et al., 2019; Mendes et al., 2023). On the other hand, overcoming challenges requires the integration of data from various sources and systems within the facility, which is important for gathering accurate information to develop predictive models. Another important aspect is the use of artificial intelligence and overcoming challenges such as: acquiring training data, dealing with dynamic operating environments, choosing a machine learning (ML) algorithm that better suits a given scenario, and the need to obtain contextual information related to the execution environment of the production process (Antosz et al., 2021). In addition, it should also be noted that PdM is not always the best solution (Compare et al., 2019). Rather, the opportunity offered by Industry 4.0 technologies in machine maintenance lies in the ability to define the optimal operating strategy for each component of the machine, considering its specificities within the system, e.g., applicable safety and environmental regulations, quality standards, business relevance, physical and functional characteristics, etc.

At the highest maturity level, *Maintenance* 4.0 not only predicts the probability of failure, but also pulls standard maintenance tasks from the library to determine the best actions to avoid failures. The concept of prescriptive maintenance goes beyond simply predicting failures. Based on the analysis of historical and current data, the system predicts the required maintenance actions and determines the course of actions. The main objective of this strategy is to reduce operational risk, eliminate the preventive approach based on planned repairs in favor of a proactive approach and intelligent planning of maintenance activities (Matyas et al., 2017; Silvestri et al., 2020). According to Grijalvo Martín et al. (2021), *Prescriptive Maintenance* is primarily about sharing value with customers through more services and with stakeholders in the company's internal ecosystem through service delivery capabilities.

The innovative approach to maintenance requires mastering both modern technologies and organizational issues related to their planning, implementation and maintenance. From a technological point of view, each of the nine pillars of *Industry* 4.0 (Autonomous/Collaborative Robots (A/CR), *Augmented Reality* (AR), *Additive Manufacturing* (AM), *Big Data & Analytics* (BDA), *Cloud Computing* (CC), *Internet of Things* (IoT), *Horizontal/Vertical Integration* (HVI), *Simulation* (S), and *Cybersecurity* (CS) can play an important role in the maintenance of machines and equipment in the enterprise (Silvestri et al., 2020; Bokrantz et al., 2017). The use of these technologies has a significant impact on maintenance processes and other areas of the company dealing with maintenance, including logistics (spare parts and warehouse management), health, safety and the working environment (information in an intelligent system can be used for ongoing risk monitoring), design (the use of intelligent components can lead to an increase in the reliability of solutions), etc. (Kwon et al., 2016). In summary, the advantages, and disadvantages of individual approaches to machine maintenance can be formulated (Table 1).

From experience to data

EN 13306:2017 defines the maintenance of machinery as the combination of all technical and related administrative activities required to maintain equipment, installations, and other physical assets in the desired operational state or to restore them to the

Table 1
Advantages and disadvantages of each approach to machine maintenance

	Intention	Benefits	Weaknesses
Maintenance 1.0	Servicing is undertaken only in the event of a complete failure of the equipment	No upfront planning and scheduling	Unpredictable equipment availability, shorter equipment life, increased energy costs, and potentially lower production efficiency due to partial failures
Maintenance 2.0	Performing regular maintenance services to avoid partial or total equipment failure. Preventive maintenance can be performed at specific intervals or when a specific condition is met	Increase the availability of production equipment by performing maintenance at specified intervals and within a specified scope	Premature component replacement and servicing can increase costs
Maintenance 3.0	Actions to be carried out, as appropriate, based on information from the monitoring system	Reduction of maintenance activities, only necessary activities are carried out, which leads to reduced costs and rational use of resources	Fatigue damage or uniform wear is not easily detected by CBM measurements
Maintenance 4.0 Predictive	Predict a problem before it occurs and be able to estimate the remaining service life (RUL) of the machine and/or its assemblies	Optimizes resources and reduces costs by predicting the life of machine assemblies to avoid premature replacement and reduce unnecessary maintenance	Given that prediction is probabilistic rather than deterministic, there is a risk of false alarms that could lead to unnecessary maintenance activities

desired operational state. The implementation of these activities and their effectiveness requires appropriate data management, i.e., data collection, data analysis and the use of adequate models supporting decision-making (Knast, 2025). Data in maintenance is needed for a variety of purposes:

1. planning, monitoring, comparing, and evaluating various maintenance activities (e.g., inspections, repairs)
2. building models to support decision-making processes (e.g., defining service intervals, purchasing spare parts and consumables)
3. improvement of activities (e.g., reduction of costs, service time, energy consumption).

Over the years, both the possibilities of acquiring, collecting, and processing data, as well as the scope of their use, have changed (Jasiulewicz-Kaczmarek et al., 2020b).

In the era of *Maintenance* 1.0 data related to the operation of the machines was collected primarily in the operator's memory and was used to support decisions regarding maintenance, repair, and replacement of the machine. Since there were no dedicated technical services in the companies, each maintenance decision was based on the empirical experience of the operator. Operators processed the data manually based on empirical experience.

In the era of *Maintenance* 2.0 the way data is acquired and processed has changed. Specialized departments were established in manufacturing companies to carry out maintenance and repair tasks, and the operators of machinery and equipment in practice did not participate in these activities and had no influence on their scope. Maintenance technicians were increasingly collecting data on their activities. Maintenance managers began to use more systematic methods of documenting (procedures, instructions, maintenance records, etc.) and analyze maintenance data. The raw data was saved in written documents, not in the machine operator's memory. Machine data was used to make decisions about machine maintenance, repair, and replacement. Statistical models have been introduced to analyze the failure rate, determine the frequency and scope of maintenance activities and spare parts. Nevertheless, although scientific methods were increasingly used to analyze data, data was still acquired and analyzed manually. As a result, the utilization rate of service data remained relatively low.

With the next industrial revolution, the role of information technologies and the scope of their application in production processes has increased significantly. This allows companies to *Maintenance* 3.0 They could obtain more data from different functional areas, including production and maintenance. Many factors have influenced these new opportunities.

First, to improve maintenance management (e.g., spare parts management, maintenance planning), companies began to implement IT systems, among others. CMMS (*Computer Maintenance Management System*) was used. Subsequently, OEE (*Overall Equipment Effectiveness*) began to use IT systems such as CAD and CAM to modify and optimize the design of new machines. Third, sensors and computers have been used to automatically control machines. Machine data from operation and maintenance processes began to be collected in computer systems and managed by means of IT systems.

With the advent of *Industry* 4.0 condition monitoring techniques have evolved from visual inspection and manual analysis of data sets to sensors that generate real-time data and advanced data analysis methods. The source of data (i.e., engineering systems vs. human systems) is one of the main differences between traditional and recent data applications. Due to the intensive development of information technology and its applications, as well as the development of sensor technology, maintenance managers have gained many new data sources (e.g., sensors enable continuous measurement, monitoring, and reporting of the current operating status of production equipment and its operating environment). These new data sources generate large amounts of different types of data, called big data, in a short period of time. As such, data-driven approaches have become an important solution for smart maintenance (Cao et al., 2022; Gopalakrishnan et al., 2022; Pawellek, 2013; Chen et al., 2021). Data exploration requires advanced data analysis. Karim et al. (2016) developed the concept of Maintenance Analytics, which consists of four phases: descriptive analytics, diagnostic analytics, predictive analytics, and prescriptive analytics. This approach was used by Ansari et al. (2019) to build another concept known as *Knowledge Based Maintenance* (KBM). According to Lee (2017) "KBM collects data about machines (systems), processes and products, which is then sent to three areas providing overall maintenance strategies, namely i) risk-based maintenance, ii) condition-based maintenance or lifetime maintenance, and iii) *Total Productive Maintenance* (TPM) and *Lean Maintenance* (LM)." Ansari et al. (2019) defines KBM as "a functional unit responsible for i) continuously supporting value generation and ii) facilitating the development and protection of collective smart factory maintenance knowledge, which is enhanced by the sensing, modelling, and representation of need-based or capability-based knowledge." KBM uses a variety of methods (Ansari et al., 2019), including advanced statistics, stochastics, real-time computation and analysis, machine learning algorithms, statistical rules based on "knowledge discovery, prediction, optimization, adaptation, self-learning, and ideally self-learning" (Figure 2).

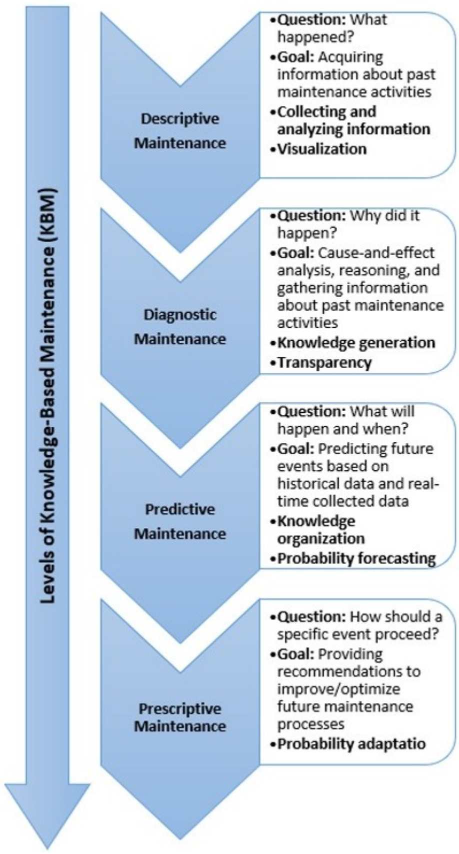

Fig. 2. The evolution of knowledge-based machine maintenance (Jasiulewicz-Kaczmarek et al., 2020c; Ansari et al., 2019)

Given the continuous development of data acquisition and analysis methods, new concepts for data-driven maintenance management will emerge, enabling maintenance managers to improve the efficiency and availability of production equipment, reduce costs and be flexible in approaching customer requirements.

To sum up, from the point of view of the data life cycle, defined as "the process of collecting, transmitting, storing, analyzing, visualizing and using data," the changes in the way data is acquired, stored, analyzed and managed at different periods of machine maintenance (Siddiqa et al., 2016) can be referred to the "data life cycle", as shown in Table 2.

From a single internal customer stakeholder to a network of external customers

The approach has evolved from a single internal customer stakeholder to a network of external customers. Delivering value to stakeholders and a balanced approach to their requirements is a key factor in the competitiveness of companies. Therefore, production paradigms and changing stakeholder requirements were taken as a reference to show the evolution of the scope of maintenance functions. Each change in the production paradigm, and thus a change in the way of "carrying out production", affects all functional areas of the company. Therefore, with the change in production paradigms, the approach to the maintenance of production equipment has changed, from a reactive approach corresponding to artisanal production, through preventive, lean maintenance, Green (*Green Maintenance*), to a contemporary approach in which it is considered a process to be managed from a sustainable perspective.

The concept of *Lean TPM*, also known as *Lean Maintenance*, is a response to Lean Manufacturing's demand for reliable and stable machine operation. Smith and Hawkins (2004) defined *Lean Maintenance* as "a proactive maintenance operation, involving planned maintenance activities through holistic productive mainte-

Table 2
Comparison of maintenance data in the previously used approaches to maintenance (Jasiulewicz-Kaczmarek et al., 2020)

Key Attribute	Maintenance 1.0	Maintenance 2.0	Maintenance 3.0	Maintenance 4.0
Data source	Operator experience	Operator and machine	Operator, Operator, Machinery & Computer Systems	Operator, Service Officer, Information Systems, Data Providers, OEM
Data collection	Manual collection	Manual collection	Semi-automatic collection	Automatic collection via sensors and IoT
Data Retention	Operator memory	Written documents	Database	Cloud
Data analysis	Arbitrarily	With the help of reliability theory	Conventional algorithms	Fuzzy logic, Neural networks, Machine learning, Evolutionary algorithms
Transfer of data	Verbal communication	Written documents	Digital files	Digital files

nance (TPM) practices, using maintenance strategies developed through the application of decision logic, reliability-focused maintenance (RCM), and the practice by authorized (self-contained) teams of activities using the *5S* process, weekly *Kaizen* improvement events, autonomous maintenance and computerized maintenance system management (CMMS) or *Enterprise Asset Management* (EAM)". The concept of *Lean Maintenance* aims to identify losses in maintenance processes and take actions to eliminate or reduce them through appropriate management and continuous improvement. Losses can be identified in various maintenance processes, both those related to the direct implementation of maintenance activities (e.g. repairs, overhauls) and those related to the flow of information (Antosz & Ratnayake, 2016; Jasiulewicz-Kaczmarek & Saniuk, 2018; Ribeiro et al., 2019; Marttonen-Arola & Baglee, 2019). In addition, maintenance losses affect the efficiency of customer service, production, logistics, etc. processes. The extent of the impact of losses therefore indicates many groups of stakeholders within the company who are affected by these losses, as well as those stakeholders with whom cooperation should be undertaken to reduce or eliminate these losses.

In the early 1990s, the concept of Green Maintenance (GMn) was proposed to support the implementation of the *Green Manufacturing* paradigm. *The Green Maintenance* concept focuses on the efficient use of resources (consumables, spare parts, etc.). According to Skoogh et al. (2011), about 30% of energy consumption in industrial enterprises is wasted on machines under repair or idle.

Waste minimization is indicated and the negative impact of production equipment on the environment throughout the life cycle of a technical facility is emphasized, i.e., from design, through production, operation to decommissioning.

As described in (Lewis et al., 2011), "proper maintenance is necessary to achieve optimal energy efficiency, while energy efficiency data is needed for effective maintenance management". Including the environmental dimension in the definition of maintenance obliges managers to consider the impact of maintenance activities on the natural environment in their decisions, identify opportunities to reduce this impact and define, optimize, and link environmental costs with maintenance costs (Lewis et al., 2011; Costantino et al., 2013).

The practical implementation of the *Green Maintenance* concept in a company depends on many factors, both internal (e.g. decision criteria when purchasing new machines/modernizing existing ones, maintenance strategy, the method of planning maintenance works, the repair technologies and materials used, the competence of employees and their awareness) and external (e.g. design features of machines and equipment). Therefore, the inclusion of new requirements (environmental issues) has resulted in the fact that maintenance in its operations must consider potential environmental risks associated with the occurrence of equipment failures, introduce risk analysis tools into the decision-making processes related to the selection of maintenance strategies and proactively integrate the stages of the product life cycle. Meeting environmental obligations towards internal and external stakeholders requires that various departments, such as structural and technology design and production, treat maintenance as a complementary, interdependent function (Ajukumar & Gandhi, 2013; Fraser & Hvolby, 2015).

With the increasing impact of maintenance on various areas inside and outside the company, sustainability challenges have attracted the attention of practitioners and academia alike. Sustainable development is an extremely important challenge for enterprises, and the range of issues it concerns (social, economic, environmental, technical, ethical) contributes to its ubiquity.

The maintenance function plays a key role in promoting sustainability, reducing impact, and integrating sustainability aspects to guarantee specific performance, availability, and quality with limited resources and energy consumption. On the one hand, sustainable maintenance guarantees the compliance of processes and products and reduces their industrial impact on the economy, society, and the surrounding environment. On the other hand, it must be a business-balanced function and limit the own revenue generated during any maintenance activities. According to Franciosi et al. (2020a), "Poor maintenance management leads to significant economic, environmental, and social impacts and obstacles to the sustainable production paradigm."

The economic dimension of sustainable development is one of the main areas that is highly influenced by maintenance (Fraser & Hvolby, 2015). Although maintenance itself is an unavoidable cost (every organization has machinery and equipment that must be kept running), the cost of maintenance activities will not be so high if they are performed at the right time and to the right extent (Jasiulewicz-Kaczmarek et al., 2021a; Zhang et al., 2022).

On the other hand, environmental aspects can be seen throughout the life cycle of technical facilities, in which maintenance plays a key role at each stage of this cycle (Macchi et al., 2016). From this perspective, improperly defined and executed maintenance processes and activities lead to several environmental effects, such as hazardous emissions, inefficient energy consumption, inefficient use of resources, etc. (Al-Turki et al., 2014; Xia et al., 2018).

Building sustainable livelihoods also requires social aspects to be considered. The social dimension of sustainable maintenance concerns, among others, the safety and health of employees, working hours (compliance with legal requirements), financial resources allocated to employee training and investments in new equipment and software to support employees in performing their work (Vrignat et al., 2022). Taking into account the fact that in the near future maintenance employees will need new competences that will allow for the effective use of modern technologies in the implementation of the process of operating complex and automated technical systems, the requirements for appropriate education and training will increase, which may be a critical factor in the success of the company (Jasiulewicz-Kaczmarek & Drożyner, 2013). This applies in particular to the challenges of the fourth industrial revolution (Industry 4.0), to which the concept of maintenance 4.0 is the answer.

The earliest maintenance practices focused primarily on reactive maintenance activities, which most often led to inefficient use of resources and environmental degradation. Currently, the paradigm is shifting towards predictive practices, based on energy (Orošnjak et al., 2023) and sustainable maintenance (SM) (Karuppiah et al., 2021). These practices include not only the strategy of extending the lifespan for profitability, in fact, environmental and social priorities are now at the forefront (Hami et al., 2019). By integrating sustainability principles into maintenance practice (Jasiulewicz-Kaczmarek, 2013), the expected outcome considers minimized negative environmental impact, reduced resource consumption, and increased resilience of physical assets. In fact, SM goes beyond the traditional understanding of maintenance as a simple technical activity consisting of condition monitoring, maintenance activities and planning (Orošnjak et al., 2021). In fact, the interconnectedness between human activities, asset management and the environment are recognised, also considering the importance of sustainability challenges (Samadhiya et al., 2022). Such a holistic approach provides (1) a shift from the traditional perception of maintenance as a "necessary evil" to a "value-added activity" (Orošnjak & Šević, 2023); (2) the transition from short-term financial gain to a long-term perspective; and (3) a better understanding of the impact of maintenance activities on the product life cycle (Taddese et al., 2020). The adoption of SM practices potentially contributes to the *Sustainable Development Goals* (SDGs) (United Nations, 2015) – recommended by the European Commission, promotes the principles of the *Circular economy* (CE) (Elia et al., 2017) and increases social justice (Turner et al., 2022). In addition, MS brings economic benefits in the long run. Namely, by investing in advanced maintenance technologies, organizations can avoid costly repairs, overhauls, and parts replacements, minimize downtime, and improve overall operational efficiency (Singh et al., 2021). In addition, SM internships can create new employment opportunities in sectors such as sustainable energy, renewable energy, and sustainable materials. Therefore, understanding and implementing the SM strategy is essential not only to protect the environment and achieve the global sustainable development goals, but also to promote economic growth and resilience (Kanisuru, 2017).

Sustainable machine maintenance is slowly becoming the focus of mainstream research, due to the benefits this practice offers, ensuring the long-term functionality, durability, and profitability of various systems and infrastructures (Jasiulewicz-Kaczmarek et al., 2021b; Saihi et al., 2022; Franciosi et al., 2020b; Sari et al., 2021; Roda et al., 2021). As the world faces unprecedented challenges such as climate change and resource depletion, there is an urgent need to adopt a sustainable approach to maintaining and managing an organization's physical assets (Hanski & Ojanen, 2020). Given that sustainable manufacturing enables the transition from a linear to a circular economy (CE) for efficient resource management and waste reduction (Elia et al., 2017), it is important to consider the interlinkages between maintenance and sustainability. This is particularly important given that CE is considered one of the promising sustainable pathways for industrial companies that aim to reduce resource consumption (Acerbi et al., 2020). Finally, beyond functionality, sustainability, and service life, recent research has begun to highlight the importance of Industry 5.0 for sustainable reliability-focused maintenance (RCM) (Farsi et al., 2021). Recent review studies show that the existing knowledge on sustainable maintenance in *Industry* 4.0 (Samadhiya et al., 2022) and *Industry* 5.0 (Psarommatis et al., 2023), i.e. *Maintenance* 5.0, mainly concerns (Cortés-Leal et al., 2022) research on maintaining worker resilience (Turner et al., 2022). It puts the well-being of the worker at the heart of the production process, enabling the use of advanced technologies that ensure prosperity beyond the workplace. It complements the existing Industry 4.0 approach, by using research and innovation in the service of the transition to sustainable, smart, human-centered manufacturing (Zhang et al., 2023) and the resilience of European industry (Aheleroff et al., 2022). Moreover, the existing work is limited by the lack of emphasis on data-driven reasoning in machine maintenance decision-making, which the authors believe (Vasić et al., 2024) is the missing link in the adoption of sustainable maintenance policies by top maintenance management. This can be attributed primarily to a lack of knowledge and understanding of operational process data, which often goes untapped as maintenance technicians and engineers neglect useful information and knowledge in recognizing the hidden potential of data (Jasiulewicz-Kaczmarek et al., 2020b). In addition, the increased complexity of big data visualization techniques (e.g., multidimensional data visualization) (Jasiulewicz-Kaczmarek & Antosz, 2023) is one of the reasons why the transition from big data to smart data is much more appropriate for data-driven maintenance (Triguero et al., 2019). Finally, given the increase in the number of systematic literature reviews conducted on MS, there is no uniform consensus on existing research on MS (Vasić et al., 2024).

Today's challenges – from Industry 4.0 and Maintenance 4.0 to Industry 5.0 and Maintenance 5.0

The practical challenges of maintenance in *Industry* 4.0 include, among others (Table 3):

1. complexity of industrial systems
2. obtaining and processing data
3. new criteria for optimizing operations and
4. prescriptive maintenance.

Table 3
Maintenance challenges in the Industry 4.0 era

Industry trends	**Consequences for maintenance**
1. jointly optimize multiple criteria (e.g., combining MCDM (*Multiple Criteria Decision Making*) with uncertainty management methods and using big data to obtain more objective information, and *Metaheuristic Search Algorithms* (MSAs) 2. manage unknown dependencies and interdependence between components and subsystems (use of AI (*Artificial Intelligence*) and ML (*Machine Learning*) algorithms, enabling the discovery of previously unknown dependencies. 3. Maintenance challenges in the *Industry* 4.0 era • Industrial systems are complex. • Systems are multifunctional. • The operational environment is uncertain and governed by stochastic processes. • Components and subsystems may exhibit hidden or poorly understood interdependencies.	• The need to manage data and model uncertainty. • The need to extract information about component dependencies from the data.
Advances in Sensors and Sensor Technology.	• Large amounts of data must be processed. • Data are heterogeneous and may require multimodal processing techniques.
Availability of AI algorithms for data mining.	• AI algorithms can estimate the current state of system components. • They can predict future states of those components. • They help assess current operating conditions. • They support forecasting of future operating conditions.
New and more ambitious performance and safety targets.	• One of the criteria is sustainability and environmental impact. • Another criterion is system immunity, such as resistance to electromagnetic interference or cyber threats.
Operation and maintenance are integrated through prescriptive maintenance strategies.	• Information is available on detection, diagnostics, and forecasting. • Operating conditions can be estimated. • Estimations cover both current and future states.

The complexity of technical systems in the context of maintenance and repair activities requires, among other things, the development of methods that allow:

a) jointly optimize multiple criteria (e.g., com- bining MCDM (Multiple Criteria Decision Making) with uncertainty management methods and using big data to obtain more objective information, and Metaheuristic Search Algorithms (MSAs)
b) manage unknown dependencies and interde- pendence between components and subsys- tems (use of AI (Artificial Intelligence) and ML (Machine Learning) algorithms, ena- bling the discovery of previously unknown dependencies.

These considerations require moving away from static maintenance strategies that cannot handle unexpected events and developing dynamic maintenance strategies to adapt in real-time to the changing context. In addition, the widespread use of data-driven approaches in *Industry* 4.0 requires an adequate representation of model and data uncertainty, as poor quantification can lead to suboptimal or even erroneous decisions (Bakon et al., 2022).

Another challenge concerns data collection and processing technology. In this area, it is necessary to assess the suitability of new data, information, and knowledge for maintenance optimization in relation to the investment requirements related to the purchase of sensors and software necessary to carry out analyses and appropriate training of operators (Compare et al., 2022).

The third challenge concerns obligations towards the environment and society. The concept of sustainability and resilience are becoming increasingly critical and must be considered by companies in parallel with safety and economic goals. Despite the importance of these issues, they are not common among practitioners and are usually limited to aspects of qualitative rather than quantitative evaluation (Franciosi et al., 2018). Although *Industry 4.0* includes some energy efficiency and environmental impact targets (Breque et al., 2021), its original concept focuses on improving productivity and economic viability. *Industry 5.0*, which was proposed as an extension of *Industry 4.0*, focuses on the role of research and innovation in supporting industry in the long-term service of humanity, considering the global challenges that have the greatest impact on society. As a result, efforts to improve maintenance efficiency are sure to evolve to include new criteria along with criteria related to efficiency and safety. This requires the definition of measurable quantities to assess the effectiveness of a specific servicing strategy with respect to the resilience and sustainability of the system (Moreno-Sader et al., 2019).

Finally, regarding the fourth challenge, *Industry 4.0* changes the perception of maintenance from monitoring the degradation status of components and predicting their failure to recommending the most appropriate actions to optimally manage the entire system, considering the dynamic production environment in which it is embedded (operational context). This requires the development of an appropriate structure to process all available sources of information, with the accompanying uncertainties, and to manage many system states and possible maintenance actions.

Prescriptive maintenance is gaining popularity among researchers. This is because there is a widespread belief that, firstly, complex service strategies are always the best solution and secondly, that reactive maintenance should always be avoided. Because the most appropriate maintenance strategy should be chosen depending on the characteristics of each component, e.g. functionality, cost, criticality, environmental and safety regulations, and company goals. Therefore, a dynamic and flexible maintenance strategy that can be adapted to the specific conditions of the system and its environment should be preferred. It would therefore be necessary to focus on the development of methods that will require maintenance engineers to draw up a list of possible operational and maintenance actions, without pre-selecting a maintenance strategy for all components under all conditions.

Changes in manufacturing paradigms, automation technologies, and social values are fostering the creation of manufacturing jobs that are characterized by creativity and flexible problem-solving, while also favouring intelligent robots and AI-powered bots that will take on monotonous and dangerous tasks. The production paradigm has evolved significantly under the influence of the revolutionary technological advances associated with the five industrial revolutions. Artisanal manufacturing during the first industrial revolution provided hand-made, customized products at a high cost. This was changed by mass production, which was made possible by dedicated production lines during the Second Industrial Revolution. During the Third Industrial Revolution, computers and flexible manufacturing systems emerged, leading to mass customization. In the age of Industry 4.0, mass personalization, i.e. the flexible production of high-quality personalized products with mass efficiency, is becoming possible through real-time communication and adaptive collaboration. However, increased consumer demand for personalized products with unique values requires human creativity in product development, enhanced by flexible production automation (Knast, 2021). In managing increasingly intelligent automation systems, more than ever, humans need to play a key role. Industry 5.0, driven by societal needs, further strengthens the key role of humans in production.

The European Union presented the *Industry* 5.0 initiative in 2021. According to this concept, it is recognised that the impact of industry should extend beyond jobs to achieve social goals and economic growth to become a resilient source of prosperity, by ensuring respect for the planet's resources in production and placing the well-being of the industrial worker at the heart of the production process. It complements the existing Industry 4.0 paradigm, as research and innovation drive the transition to a human-centric, sustainable and resilient European industry. The human-centred approach in Industry 5.0 puts basic human needs and interests at the centre of the production process, moving from technology-based advances to an entirely human- and social-cantered approach. As a result, the industry will enter a new role. There will be a shift in value from treating employees not as a "cost" but as an "investment". Technology is designed to serve people and societies, which means that the technology used in manufacturing adapts to the needs and diversity of the industry's workforce. A safe and inclusive working environment must be created that prioritizes physical health, mental health and well-being, and ultimately protects workers' fundamental rights of autonomy, human dignity and privacy. However, despite its well-thought-out human-centred concept, its industrial feasibility and technical connotations remain unproven. Industry 5.0 technologies will play an important role in developing industry flexibility and resilience through data collection, automated risk analysis and increased safety. According to the European Commission's report, the new vision for the manufacturing industry should be firmly embedded in social, environmental and political contexts, based on three pillars. The first is human orientation, the second is sustainability, and the third is resilience. Resilience is understood as the ability to respond to disruptive changes. The fourth industrial revolution focuses primarily on technology, while the economy should be shaped in a way that first considers the human situation, and not, for example, the competitiveness of a company, industry or country. Sustainability and resilience are also not new demands, although in the EU definition of Industry 5.0 they have been emphasized as strategic issues. The fifth industrial revolution should bring something completely new to Industry 4.0. Perhaps it is worth seeing in the concept proposed by the European Commission not a new revolution, but a vision of Industry 4.0 even more focused on the role, not so much of the employee, but simply of the human being in the entire social context. Therefore, the labour market and the competences of employees are changing. *Industry* 4.0 has an impact on work and competence profiles, and as a result, new competences will be needed among employees. Technical competence will be much less important in the future, and personal skills will become more critical. Synthetically speaking and outlining the general picture of the development of the production of goods, it can be said that the first industrial revolution used the energy of water and steam to mechanize production. The *Second Industrial Revolution* used electricity for mass production. The Third Industrial Revolution used computers to automate production. The Fourth Industrial Revolution, which is currently underway, uses information technology to connect the physical world with the digital world. The *Fifth Industrial Revolution* is expected to bring man back to the centre of action through the human-cybernetic-physical system for value creation (Fig. 3, Table 4).

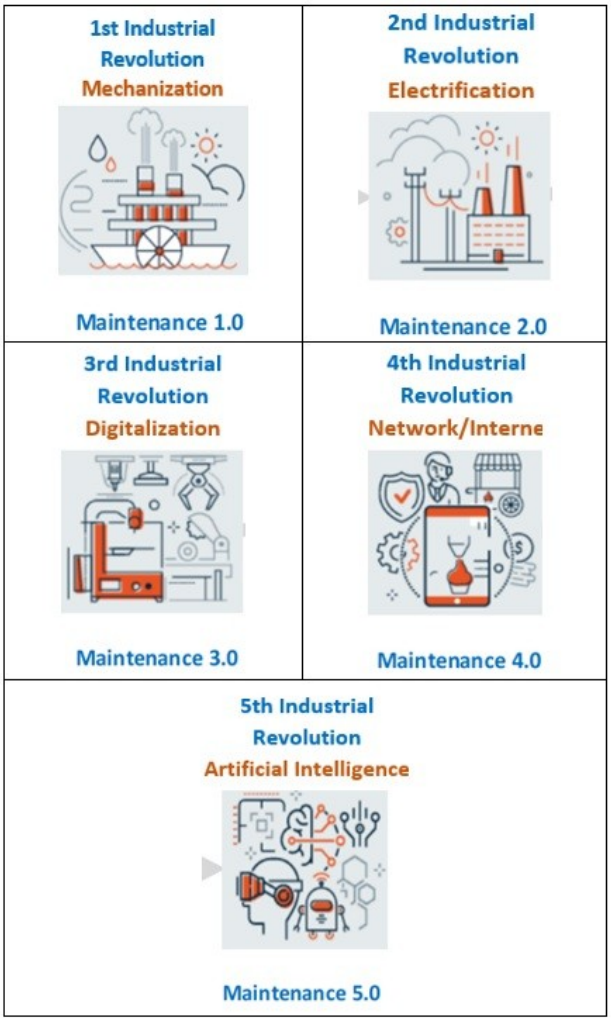

Fig. 3. Machine Maintenance concepts in connection with Industrial Revolutions – from Maintenance 1.0 to Maintenance 5.0 [Public Domain]

Table 4
Maintenance data of machines over different periods including *Maintenance 5.0*

	Maintenance 1.0	**Maintenance 2.0**	**Maintenance 3.0**	**Maintenance 4.0**	**Maintenance 5.0**
Enablers of Technology	Workforce and mechanical loop	Electric motors	Automation	Cyber-physical systems, IIoT, Big Data, cloud computing, 3D printing, etc., mobile devices	Cyber-physical human systems, human-machine, mutual learning, body area, networks, artificial intelligence AI
Maintenance, corrective actions	"Fix when it breaks" Postponed corrective actions: "I act, you fix"	Preventive Maintenance, Condition-Based Maintenance)	"Automation works, you fix"	Predictive Maintenance (predictive analytics)	Advanced analytics and modernization with man-in-the-loop technology
Metric	Number of repairs	Availability, durability, cost	Reliability, availability, repair processability, safety	Productivity, offshoring	Resilience, sustainability, value chain impact
Employee	Manual and cognitive skills of employees	Manager as an employee supporting operators	Computer-assisted and robot-assisted workers	Enriched with technologies: exoskeletons, personal assistants, mobile devices, etc.	Intelligent Machine human-assisted

Industry 4.0 focuses primarily on achieving economic goals through the digital transformation and automation of work processes, while *Industry* 5.0 will also include social and environmental goals and will strive to place the well-being of people at the heart of production systems (Knast & Maciejewski, 2023; Knast & Maciejewski, 2024). Human-centricity, sustainability, and resilience are three of the key features of *Industry* 5.0 (Figure 4) that are not included in the concept of *Industry* 4.0. While *Industry* 4.0 is technology-driven and productivity-focused, *Industry* 5.0 is seen as value-based and human-centered. *Industry* 5.0 does not replace *Industry* 4.0, but improves it, broadening its horizons and adapting it to new needs and constant changes.

The concept of *Industry* 4.0 is concerned with building smart factories through the application of robotics and virtualization in production systems, while *Industry* 5.0 focuses on the synergistic relationship between such systems and people, considering social and ethical issues (Özdemir & Hekim, 2018). *Industry* 4.0 lays the foundations for the Smart Factory, while *Industry* 5.0 is the era of the "Social Smart Factory". The European Commission has announced that *Industry* 4.0 can no longer serve as an adequate framework for sustainable industrial transformation and mitigation of today's socio-environmental crises. It is argued that

Fig. 4. Elements of *Industry* 5.0 not covered by *Industry* 4.0 [https://reputationtoday.in/are-we-ready-for-industry-5-0/]

Industry 4.0 lacks the necessary features to integrate circularity into value chains, promote social well-being, and prevent environmental degradation (Renda et al., 2022). In particular, the European Commission took the initiative in 2021 to formalize the *Industry 5.0* framework. According to this framework, *Industry 5.0* cannot be considered a chronological evolution of *Industry* 4.0. Instead, it complements and expands the benefits of *Industry* 4.0 by introducing environmental protection, a focus on people, and resilience as the main goals. In line with the European Commission's agenda, we define *Industry* 5.0 as a paradigm shift in the management of digital industrial transformation to achieve sustainable economic and socio-environmental development. Although the European Commission's initiative has led to a consensus on the definition of *Industry 5.0*, there are few attempts to operationalize the concept in the literature so far. *Industry* 5.0 is still a technological phenomenon because the delivery of value is based on technological innovation.

Industry 4.0 has been going on for a decade, and the introduction of the concept of *Industry* 5.0 has caused two significant controversies (Müller, 2020). First, industrial revolutions have always revolved around technological innovation, and the pull of environmental and social values of *Industry* 5.0 is shattering this tradition. The latest contribution to the operationalization of *Industry* 5.0 has largely resolved this controversy. Academic and social views articulated on this subject define *Industry* 5.0 as a technopolitical phenomenon (Sindhwani et al., 2022). *Industry* 5.0 is technological in nature because it continues to draw on technological capabilities to deliver anticipated values. *Industry* 5.0 is also political in nature, given that it draws on the regulatory and governance powers of public entities and societal groups to steer the industrial transformation towards human and environmental values [54] (Legutko, 2007a). In addition, *Industry* 4.0 is still developing and has not yet reached its full potential (Agrawal et al., 2022).

As the authors put it synthetically (Verdugo-Cedeno et al., 2023), the *Industry 5.0* initiative aims at the sustainability and resilience of production systems achieved through digital technologies. The *Operator* 5.0 concept derived from such an initiative gained enormous publicity and made the operator a major contributor to value creation in sustainable and resilient human-machine systems. Intelligent service systems are data-driven services that provide intelligent decision-support capabilities for business processes. Despite previous research on multi-technology smart services in different contexts, more research needs to be done on digital twins as enablers of intelligent services at the stages of machine use. Enabling *Industry 5.0*, the *Digital Twin* is a technology that virtually represents physical assets that collect and analyse data from real-world operations to make predictions for decision-making. Simulation-based digital twins generate simulation models that are continuously updated with real-time asset data, improving prediction accuracy.

Hopes for Industry 5.0

The biggest challenge that *Industry* 5.0 poses to engineering is the transformation of the industrial sector by designing robust, safe, and scalable systems that are human-centered. These solutions will be based on the Industrial *Internet of Things* (IIoT) and cognitive computing. There is currently a lot of interest in implementing *Industry* 5.0 because it is a mindset shift that not only increases the productivity of processes but also reduces uncertainty by keeping physical assets in the required condition from the point of view of their availability. The objectives of *Industry* 5.0 refer primarily to the leading role of humans in the transition from a productivity model to a personalization model. The concept of *Industry* 5.0 treats the employee as an investment, not an expense; besides, it aims to alleviate uncertainty by increasing immunity; and third, it seeks to have an impact on society.

References

Acerbi, F., Polenghi, A., Roda, I., Macchi, M., & Taisch, M. (2020). Exploring synergies between circular economy and asset management. In Advances in Production Management Systems. *The Path to Digital Transformation and Innovation of Production Management Systems*, 695–702. DOI: 10.1007/978-3-030-57993-6_88

Agrawal, R., Wankhede, V.A., Kumar, A., Luthra, S., & Huisingh, D. (2022). Progress and trends in integrating Industry 4.0 within circular economy: A comprehensive literature review and future research propositions. *Business Strategy and the Environment*, 31(1), 559–579. DOI: 10.1002/bse.2861

Aheleroff, S., Huang, H., Xu, X., & Zhong, R.Y. (2022). Toward sustainability and resilience with Industry 4.0 and Industry 5.0. *Frontiers in Manufacturing Technology*, 2, 951643. DOI: 10.3389/fmtec.2022.951643

Ajukumar, V.N., & Gandhi, O.P. (2013). Evaluation of green maintenance initiatives in design and development of mechanical systems using an integrated approach. *Journal of Cleaner Production*, 51, 34–46. DOI: 10.1016/j.jclepro.2012.10.038

Al-Turki, U.M., Ayar, T., Yilbas, B.S., & Sahin, A.Z. (2014). Health, safety and sustainability in maintenance. *Integrated Maintenance Planning in Manufacturing Systems* (pp. 59–69). Springer. DOI: 10.1007/978-3-319-04732-9_4

Ansari, F., Glawar, R., & Nemeth, T. (2019). PriMa: A prescriptive maintenance model for cyber-physical production systems. *International Journal of Computer Integrated Manufacturing*, 32(4-5), 482–503. DOI: 10.1080/0951192X.2019.1616820

Antosz, K., & Ratnayake, R.C. (2016). *Machinery classification and prioritization: Empirical models and AHP-based approach for effective preventive maintenance.* In 2016 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM) (pp. 1380–1386). IEEE. DOI: 10.1109/IEEM.2016.7798099

Antosz, K., Jasiulewicz-Kaczmarek, M., Paśko, Ł., Zhang, C., & Wang, S. (2021). Application of machine learning and rough set theory in lean maintenance decision support system development. *Operation and Reliability – Maintenance and Reliability*, 23(4), 695–708. DOI: 10.17531/ein.2021.4.17

Bakon, K., Holczinger, T., Sule, Z., Jasko, S., & Abonyi, J. (2022). *Scheduling under uncertainty for Industry 4.0 and 5.0.* IEEE Access, 10, 74977–75017. DOI: 10.1109/ACCESS.2022.3197456

Bokrantz, J., Skoogh, A., Berlin, C., & Stahre, J. (2017). Maintenance in digitalized manufacturing: Delphi-based scenarios for 2030. *International Journal of Production Economics,* 191, 154–169. DOI: 10.1016/j.ijpe.2017.06.010

Bokrantz, J., Skoogh, A., Berlin, C., Wuest, T., & Stahre, J. (2020). Smart Maintenance: An empirically grounded conceptualization. *International Journal of Production Economics,* 223, 107534. DOI: 10.1016/j.ijpe.2019.107534

Breque, M., De Nul, L., & Petrides, A. (2021). *Industry 5.0 – Towards a sustainable, human-centric and resilient European industry.* European Commission.

Cao, Q., Zanni-Merk, C., Samet, A., Reich, C., de Beuvron, F.D.B., Beckmann, A., & Giannetti, C. (2022). KSPMI: A knowledge-based system for predictive maintenance in Industry 4.0. *Robotics and Computer-Integrated Manufacturing*, 74, 102281. DOI: 10.1016/j.rcim.2022.102281

Chen, C., Wang, C., Lu, N., Jiang, B., & Xing, Y. (2021). A data-driven predictive maintenance strategy based on accurate failure prognostics. *Maintenance and Reliability*, 23(2), 387–394. DOI: 10.17531/ein.2021.2.19

Compare, M., Baraldi, P., & Zio, E. (2019). Challenges to IoT-enabled predictive maintenance for Industry 4.0. IEEE Internet of Things Journal, 7(5), 4585–4597. DOI: 10.1109/JIOT.2019.2954391

Compare, M., Antonello, F., Pinciroli, L., & Zio, E. (2022). A general model for life-cycle cost analysis of condition-based maintenance enabled by PHM capabilities. *Reliability Engineering & System Safety*, 224, 108499. DOI: 10.1016/j.ress.2022.108499

Cortés-Leal, A., Cárdenas, C., & Del-Valle-Soto, C. (2022). Maintenance 5.0: Towards a worker-in-the-loop framework for resilient smart manufacturing. *Applied Sciences*, 12, 11330. DOI: 10.3390/app122211330

Costantino, F., Di Gravio, G., & Tronci, M. (2013). Integrating environmental assessment of failure modes in maintenance planning of production systems. *Applied Mechanics and Materials,* 295–298, 651–660. DOI: 10.4028/www.scientific.net/AMM.295-298.651

Elia, V., Gnoni, M.G., & Tornese, F. (2017). Measuring circular economy strategies through index methods: A critical analysis. *Journal of Cleaner Production*, 142, 2741–2751. DOI: 10.1016/j.jclepro.2016.10.196

Farsi, M., Mishra, R.K., & Erkoyuncu, J.A. (2021). *Industry 5.0 for sustainable reliability-centered maintenance.* In Proceedings of the 10th International Conference on Through-Life Engineering Services (TESConf 2021).

Franciosi, C., Iung, B., Miranda, S., & Riemma, S. (2018). Maintenance for sustainability in the Industry 4.0 context: A scoping literature review. *IFAC-PapersOnLine*, 51(11), 903–908. DOI: 10.1016/j.ifacol.2018.08.459

Franciosi, C., Di Pasquale, V., Iannone, R., & Miranda, S. (2020). Multi-stakeholder perspectives on indicators for sustainable maintenance performance in production contexts: An exploratory study. *Journal of Quality in Maintenance Engineering*, 27(2), 308–330. DOI: 10.1108/JQME-09-2019-0085

Franciosi, C., Di Pasquale, V., Iannone, R., & Miranda, S. (2020). Multi-stakeholder perspectives on indicators for sustainable maintenance performance in production contexts: An exploratory study. *Journal of Quality in Maintenance Engineering*, 27, 308–330. DOI: 10.1108/JQME-09-2019-0085

Fraser, K., & Hvolby, H.H. (2015). Maintenance management models: A study of the published literature to identify empirical evidence. *International Journal of Quality & Reliability Management,* 32(6), 635–664. DOI: 10.1108/IJQRM-06-2014-0076

Gopalakrishnan, M., Subramaniyan, M., & Skoogh, A. (2022). Data-driven machine criticality assessment – Maintenance decision support for increased productivity. *Production Planning & Control,* 33(1), 1–19. DOI: 10.1080/09537287.2021.1993767

Grijalvo Martín, M., Pacios Álvarez, A., Ordieres-Meré, J., Villalba-Díez, J., & Morales-Alonso, G. (2021). New business models from prescriptive maintenance strategies aligned with Sustainable Development Goals. *Sustainability,* 13(1), 216. DOI: 10.3390/su13010216

Hami, N., Ibrahim, Y.M., Yamin, F.M., Shafie, S.M., & Abdulameer, S.S. (2019). The moderating role of sustainable maintenance on the relationship between sustainable manufacturing practices and social sustainability: A conceptual framework. *International Journal of Engineering and Advanced Technology*, 8, 222–228.

Hanski, J., & Ojanen, V. (2020). Sustainability in strategic asset management frameworks: A systematic literature review. *International Journal of Strategic Engineering Asset Management*, 3, 263.

Iung, B., Levrat, E., Marquez, A.C., & Erbe, H. (2009). Conceptual framework for e-Maintenance: Illustration by e-Maintenance technologies and platforms. *Annual Reviews in Control,* 33(2), 220–229.

Jasiulewicz-Kaczmarek, M., & Antosz, K. (2023). *Industry 4.0 technologies for maintenance management – An overview.* Lecture Notes in Mechanical Engineering (pp. 68–79). Springer. DOI: 10.1007/978-3-031-09360-9_4

Jasiulewicz-Kaczmarek, M., & Drożyner, P. (2013). *Social dimension of sustainable development – safety and ergonomics in maintenance activities.* In International Conference on Universal Access in Human-Computer Interaction (pp. 175–184). Springer. DOI: 10.1007/978-3-642-39191-6_20

Jasiulewicz-Kaczmarek, M., & Saniuk, A. (2018). How to make maintenance processes more efficient using lean tools. In R.H.M. Goossens (Ed.), Advances in Social & Occupational Ergonomics. Proceedings of the AHFE 2017 *International Conference on Social & Occupational Ergonomics* (pp. 9–20). Springer. DOI: 10.1007/978-3-319-60372-3_2

Jasiulewicz-Kaczmarek, M., Legutko, S., & Kluk, P. (2020a). Maintenance 4.0 technologies – New opportunities for sustainability-driven maintenance. *Management and Production Engineering Review,* 11(2), 74–87. DOI: 10.24425/mper.2020.133730

Jasiulewicz-Kaczmarek, M., Legutko, S., & Kluk, P. (2020b). Maintenance 4.0 technologies – New opportunities for sustainability-driven maintenance. *Management and Production Engineering Review*, 11(2), 74–87. DOI: 10.24425/mper.2020.133730

Jasiulewicz-Kaczmarek, M., Legutko, S., & Kluk, P. (2020c). Maintenance 4.0 technologies – New opportunities for sustainability-driven maintenance. *Management and Production Engineering Review*, 11(2), 74–87. DOI: 10.24425/mper.2020.133730

Jasiulewicz-Kaczmarek, M., Antosz, K., Wyczółkowski, R., Mazurkiewicz, D., Sun, B., Qian, C., & Ren, Y. (2021a). Application of MICMAC, Fuzzy AHP and Fuzzy TOPSIS for evaluation of the maintenance factors affecting sustainable manufacturing. *Energies,* 14(5), 1436. DOI: 10.3390/en14051436

Jasiulewicz-Kaczmarek, M., Antosz, K., Wyczółkowski, R., Mazurkiewicz, D., Sun, B., Qian, C., & Ren, Y. (2021b). Application of MICMAC, fuzzy AHP, and fuzzy TOPSIS for evaluation of the maintenance factors affecting sustainable manufacturing. *Energies,* 14, 1436. DOI: 10.3390/en14051436

Jasiulewicz-Kaczmarek, M. (2013). Sustainability: Orientation in maintenance management – Theoretical background. In *EcoProduction and Logistics: Emerging Trends and Business Practices* (pp. 117–134). Springer.

Johansson, N., Roth, E., & Reim, W. (2019). Smart and sustainable e-maintenance: Capabilities for digitalization of maintenance. *Sustainability,* 11(13), 1–18. DOI: 10.3390/su11133556

Kanisuru, A. M. (2017). Sustainable maintenance practices and skills for competitive production system. In *Skills Development for Sustainable Manufacturing.* InTech.

Karim, R., Westerberg, J., Galar, D., & Kumar, U. (2016). *Maintenance analytics – The new know in maintenance.* IFAC-PapersOnLine, 49(28), 214–219. DOI: 10.1016/j.ifacol.2016.11.036

Karuppiah, K., Sankaranarayanan, B., & Ali, S. M. (2021). On sustainable predictive maintenance: Exploration of key barriers using an integrated approach. *Sustainable Production and Consumption*, 27, 1537–1553. DOI: 10.1016/j.spc.2021.04.010

Kinz, A., Bernerstaetter, R., & Biedermann, H. (2016). *Lean Smart Maintenance – Efficient and effective asset management for smart factories.* MOTSP 2016 – 8th International Scientific Conference. DOI: 10.1109/MOTSP.2016.7504024

Knast, P., & Maciejewski, R. (2023). *Theoretical and practical foundations of the Industrial Revolution 4.0 and 5.0: Designing educational programs in mechanical engineering with a practical profile for the needs of Industry 4.0 and 5.0 (socio-technical-economic context).* Volume 1. FNCE Scientific Publishing, Poznań. ISBN 978-83-68074-04-8. Available in the Polish National Library catalog

Knast, P., & Maciejewski, R. (2024). *Theoretical and practical foundations of the Industrial Revolution 4.0 and 5.0.* Vol. 2. FNCE Scientific Publishing, Poznań. ISBN 978-83-68074-13-0. Available in the Polish National Library catalog

Knast, P. (2021). Similarities and differences in the process of automating the assembly of rigid bodies and elastic elements of pneumatic tires. *Assembly Technology and Automation,* (3), 25–41. DOI: 10.15199/160.2021.3.4

Knast, P. (2025). Analysis and modeling of design problems in the context of random technological changes. *Assembly Technology and Automation,*, 127(1), 22–53. DOI: 10.7862/tiam.2025.1.3

Kobbacy, K.A.H., & Murthy, D.N.P. (2008). *Complex system maintenance handbook*. Springer.

Kumar, U., & Galar, D. (2018). *Maintenance in the era of Industry 4.0: Issues and challenges.* In Quality, IT and Business Operations: Modeling and Optimization (pp. 231–250). Springer. DOI: 10.1007/978-3-319-96779-5_12

Kwon, D., Hodkiewicz, M.R., Fan, J., Shibutani, T., & Pecht, M.G. (2016). *IoT-based prognostics and systems health management for industrial applications.* IEEE Access, 4, 3659–3670. DOI: 10.1109/ACCESS.2016.2587754

Lee, E.A. (2017). *What is real-time computing? A personal view.* IEEE Design & Test, 34(1), 94–97. DOI: 10.1109/MDAT.2017.2649780

Legutko, S. (2002). *Fundamentals of machine operation* (2nd ed.). WUPP.

Legutko, S. (2004). *Fundamentals of the operation of machines and devices.* School and Pedagogical Publishing House. ISBN 83-02-08998-2.

Legutko, S. (2007a). *Exploitation of machines.* Poznań University of Technology Press.

Legutko, S. (2007b). *Modern approach to machines operation maintenance.* In Proceedings of VIIIth International Scientific Conference Technology Systems Operation '07 (pp. 42–48). Technical University of Kosice.

Legutko, S. (2007c). *Fundamentals of the operation of machines and devices* (2nd revised and supplemented ed.). School and Pedagogical Publishing House. ISBN 978-83-02-08998-5.

Legutko, S. (2007d). Modern approach to machines operation maintenance. *Manufacturing Engineering*, VI(4), 91–95. ISSN 1335-7972.

Legutko, S. (2007e). *Operation of devices and machines.* In Control of machines and devices, 1(4/3.1–4/3.3), 30. FORUM Publishing House.

Legutko, S. (2007f). *Reliability and durability of devices and machines.* In Control of machines and devices, 1(4/4.1–4/4.11), 54. FORUM Publishing House.

Legutko, S. (2008a). *Repairs and maintenance of machines and equipment*. In Control of machines and devices, 2 (5/5.1–5/5.6), 54. FORUM Publishing House.

Legutko, S. (2008b). *Assessment of operational, diagnostic, and repair susceptibility of machines.* In Control of machines and devices, 1(4/5.1–4/5.3), 20. FORUM Publishing House.

Legutko, S. (2008c). *Operation management and maintenance of equipment and machines.* In Control of machines and devices, 1(4/6.1–4/6.5), 54. FORUM Publishing House.

Legutko, S. (2008d). *Computer-aided operation of devices and machines.* In Control of machines and devices, 1(4/7.1–4/7.3), 28. FORUM Publishing House.

Legutko, S. (2009a). *Fundamentals of the operation of machines and devices* (3rd revised and supplemented ed.). School and Pedagogical Publishing House. ISBN 978-83-02-08998-5.

Legutko, S. (2009b). Development trends in machines operation maintenance – Trends in the development of maintenance of devices and machines. *Maintenance and Reliability*, 2(42), 8–16. ISSN 1507-2711.

Legutko, S. (2010). *Fundamentals of the operation of machines and devices* (4th revised ed.). School and Pedagogical Publishing House. ISBN 978-83-02-08998-5.

Legutko, S. (2011a). *Reliability and durability of devices and machines.* In Control of machines and devices, 1(4/4.2–4/4.4), 13. FORUM Publishing House.

Legutko, S. (2011b). *Operation management and maintenance of equipment and machines.* In Control of machines and devices, 1(4/6.2) 13. FORUM Publishing House.

Legutko, S. (2011c). *Characteristics of an exemplary technological process of repair.* In Control of machines and devices, 2(5/5.7), 9. FORUM Publishing House.

Legutko, S. (2011d). *Wear and tear of machine parts.* In Control of machines and devices, 2(5/6), 31. FORUM Publishing House.

Legutko, S. (2013). *Operation of machines and devices*. School and Pedagogical Publishing House. ISBN 978-83-02-13615-3.

Legutko, S. (2023). *Industry 4.0 technologies for the sustainable management of maintenance resources.* In International Conference Innovations in Engineering ICIENG 2022, J. Machado et al. (Eds.), Lecture Notes in Mechanical Engineering (pp. 37–48). Springer. DOI: 10.1007/978-3-031-09360-9_4

Leurent, H., & Boer, E. (2019). *Fourth Industrial Revolution: Beacons of technology and innovation in manufacturing.* World Economic Forum. https://www.weforum.org/reports

Lewis, A., Elmualim, A., & Riley, D. (2011). Linking energy and maintenance management for sustainability through three American case studies. *Facilities,* 29(5/6), 243–254. DOI: 10.1108/02632771111120595

Macchi, M., Farruku, K., Holgado, M., Negri, E., & Panarese, D. (2016). Economic and environmental impact assessment through system dynamics of technology-enhanced maintenance services. *International Journal of Industrial and Systems Engineering*, 23(1), 36–56. DOI: 10.1504/IJISE.2016.078697

Marttonen-Arola, S., & Baglee, D. (2019). Assessing the information waste in maintenance management processes. *Journal of Quality in Maintenance Engineering*, 26(3), 383–398. DOI: 10.1108/JQME-07-2018-0054

Matyas, K., Nemeth, T., Kovacs, K., & Glawar, R. (2017). *A procedural approach for realizing prescriptive maintenance planning in manufacturing industries.* CIRP Annals – Manufacturing Technology, 66, 461–464. DOI: 10.1016/j.cirp.2017.04.019

Mendes, D., Gaspar, P.D., Charrua-Santos, F., & Navas, H. (2023). Synergies between Lean and Industry 4.0 for enhanced maintenance management in sustainable operations: A model proposal. *Processes*, 11(9), 2691. DOI: 10.3390/pr11092691

Moreno-Sader, K., Jain, P., Tenorio, L.C.B., Mannan, M.S., & El-Halwagi, M.M. (2019). Integrated approach of safety, sustainability, reliability, and resilience analysis via a return on investment metric. *ACS Sustainable Chemistry & Engineering*, 7(24), 19522–19536. DOI: 10.1021/acssuschemeng.9b04608

Müller, J. (2020). *Enabling technologies for Industry 5.0: Results of a workshop with Europe's technology leaders.* European Commission. DOI: 10.2777/082634

Navas, M.A., Sancho, C., & Carpio, J. (2020). Disruptive maintenance engineering 4.0. *International Journal of Quality & Reliability Management*, 37(6/7), 853–871. DOI: 10.1108/IJQRM-11-2019-0371

Orošnjak, M., & Šević, D. (2023). Benchmarking maintenance practices for allocating features affecting hydraulic system maintenance: A West-Balkan perspective. *Mathematics,* 11, 3816. DOI: 10.3390/math11173816

Orošnjak, M., Jocanović, M., Čavić, M., Karanović, V., & Pencić, M. (2021). Industrial maintenance 4(.0) Horizon Europe: Consequences of the Iron Curtain and energy-based maintenance. *Journal of Cleaner Production*, 314, 128034. DOI: 10.1016/j.jclepro.2021.128034

Orošnjak, M., Brkljač, N., Šević, D., Čavić, M., & Oros, D. (2023). From predictive to energy-based maintenance paradigm: Achieving cleaner production through functional-productiveness. *Journal of Cleaner Production,* 408, 137177. DOI: 10.1016/j.jclepro.2023.137177

Özdemir, V., & Hekim, N. (2018). Birth of Industry 5.0: Making sense of big data with artificial intelligence, the internet of things, and next-generation technology policy. *Omics: A Journal of Integrative Biology,* 22(1), 65–76. DOI: 10.1089/omi.2017.0194

Pawellek, G. (2013). *Integrated maintenance and spare parts logistics: procedures, methods, tools.* Springer. DOI: 10.1007/978-3-642-36246-5

Psarommatis, F., May, G., & Azamfiri, V. (2023). Envisioning Maintenance 5.0: Insights from a systematic literature review of Industry 4.0 and a proposed framework. *Journal of Manufacturing Systems*, 68, 376–399. DOI: 10.1016/j.jmsy.2023.04.007

Renda, A., Schwaag Serger, S., Tataj, D., Morlet, A., Isaksson, D., Martins, F., & Giovannini, E. (2022). *Industry 5.0, a transformative vision for Europe: Governing systemic transformations towards a sustainable industry.* European Commission, Directorate-General for Research and Innovation. DOI: 10.2777/17322

Ribeiro, D.R.S., Forcellini, F.A., Pereira, M., & Xavier, F.A. (2019). An overview about the implementing of lean maintenance in manufacturing processes. *Journal of Lean Systems,* 4(3), 44–59.

Roda, C., Voisin, I., Miranda, A., Macchi, S., & Iung, M. (2021). *Sustainable maintenance performances and EN 15341: 2019: An integration proposal.* In Proceedings of the IFIP International Conference on Advances in Production Management Systems (pp. 1–10). Springer. DOI: 10.1007/978-3-030-72632-4_2

Saihi, A., Ben-Daya, M., & As'ad, R. (2022). An investigation of sustainable maintenance performance indicators: Identification, expert validation, and portfolio of future research. *IEEE Access,* 10, 124259–124276. DOI: 10.1109/ACCESS.2022.3146129

Samadhiya, A., Agrawal, R., & Garza-Reyes, J.A. (2022). Integrating Industry 4.0 and total productive maintenance for global sustainability. *The TQM Journal*, 36, 24–50. DOI: 10.1108/TQM-07-2021-0195

Sari, E., Ma'aram, A., Shaharoun, A.M., Chofreh, A.G., Goni, F.A., Klemeš, J.J., et al. (2021). Measuring sustainable cleaner maintenance hierarchical contributions of the car manufacturing industry. *Journal of Cleaner Production*, 312, 127717. DOI: 10.1016/j.jclepro.2021.127717

Siddiqa, A., Hashem, I.A.T., Yaqoob, I., Marjani, M., Shamshirband, S., & Gani, A. (2016). A survey of big data management: Taxonomy and state-of-the-art. *Journal of Network and Computer Applications*, 71, 151–166. DOI: 10.1016/j.jnca.2016.04.008

Silvestri, L., Forcina, A., Introna, V., Santolamazza, A., & Cesarotti, V. (2020). Maintenance transformation through Industry 4.0 technologies: A systematic literature review. *Computers in Industry*, 123, 103335. DOI: 10.1016/j.compind.2020.103335

Sindhwani, R., Afridi, S., Kumar, A., Banaitis, A., Luthra, S., & Singh, P.L. (2022). Can Industry 5.0 revolutionize the wave of resilience and social value creation? A multi-criteria framework to analyze enablers. *Technology in Society*, 68, 101887. DOI: 10.1016/j.techsoc.2022.101887

Singh, S., Khamba, J.S., & Singh, D. (2021). Analysis and directions of OEE and its integration with different strategic tools. Proceedings of the Institution of Mechanical Engineers, Part E: *Journal of Process Mechanical Engineering*, 235, 594–605. DOI: 10.1177/09544089211040492

Skoogh, A., Johansson, B., & Hansson, L. (2011). *Data requirements and representation for simulation of energy consumption in production systems*. In Proceedings of the 44th CIRP Conference on Manufacturing Systems (pp. 1–3).

Smith, R., & Hawkins, B. (2004). *Lean maintenance: Reduce costs, improve quality, and increase market share*. Elsevier Butterworth-Heinemann.

Taddese, G., Durieux, S., & Duc, E. (2020). Sustainability performance indicators for additive manufacturing: A literature review based on product life cycle studies. *International Journal of Advanced Manufacturing Technology*, 107, 3109–3134. DOI: 10.1007/s00170-020-05290-5

Triguero, I., García-Gil, D., Maillo, J., Luengo, J., García, S., & Herrera, F. (2019). Transforming big data into smart data: An insight on the use of the k-nearest neighbors algorithm to obtain quality data. *WIREs Data Mining and Knowledge Discovery*, 9, e1289. DOI: 10.1002/widm.1289

Turner, C.J., Emmanouilidis, C., Tomiyama, T., Tiwari, A., & Roy, R. (2019). Intelligent decision support for maintenance: An overview and future trends. *International Journal of Computer Integrated Manufacturing,* 32(10), 936–959. DOI: 10.1080/0951192X.2019.1686177

Turner, C., Okorie, O., & Oyekan, J. (2022). XAI sustainable human in the loop maintenance. *IFAC-PapersOnLine,* 55, 67–72. DOI: 10.1016/j.ifacol.2022.07.141

United Nations. (2015). *United Nations Transforming Our World: The 2030 Agenda for Sustainable Development*. United Nations.

Vasić, S., Orošnjak, M., Brkljač, N., Vrhovac, V., & Ristić, K. (2024). Identification of criteria for enabling the adoption of sustainable maintenance practice: An umbrella review. *Sustainability*, 16(2), 767. DOI: 10.3390/su16020767

Verdugo-Cedeno, M., Jaiswal, S., Ojanen, V., Hannola, L., & Mikkola, A. (2023). Simulation-based digital twins enabling smart services for machine operations: An Industry 5.0 approach. *International Journal of Human-Computer Interaction*. DOI: 10.1080/10447318.2023.2254607

Vrignat, P., Kratz, F., & Avila, M. (2022). Sustainable manufacturing, maintenance policies, prognostics and health management: A literature review. *Reliability Engineering & System Safety,* 218, 108140. DOI: 10.1016/j.ress.2022.108140

Xia, T., Xi, L., Du, S., Xiao, L., & Pan, E. (2018). Energy-oriented maintenance decision-making for sustainable manufacturing based on energy-saving window. *Journal of Manufacturing Science and Engineering*, 140(5), 051001. DOI: 10.1115/1.4038655

Yoon, J.T., Youn, B.D., Yoo, M., Kim, Y., & Kim, S. (2019). Life-cycle maintenance cost analysis framework considering time-dependent false and missed alarms for fault diagnosis. *Reliability Engineering & System Safety*, 184, 181–192. DOI: 10.1016/j.ress.2019.01.008

Zhang, C., Zhang, Y., Dui, H., Wang, S., & Tomovic, M.M. (2022). Importance measure-based maintenance strategy considering maintenance costs. *Maintenance and Reliability*, 24(1), 15–24. DOI: 10.17531/ein.2022.1.3

Zhang, C., Wang, Z., Zhou, G., Chang, F., Ma, D., Jing, Y., et al. (2023). Towards new-generation human-centric smart manufacturing in Industry 5.0: A systematic review. *Advanced Engineering Informatics*, 57, 102121. DOI: 10.1016/j.aei.2023.102121

Zonta, T., da Costa, C.A., da Rosa Righi, R., de Lima, M.J., da Trindade, E.S., & Li, G.P. (2020). Predictive maintenance in the Industry 4.0: A systematic literature review. *Computers & Industrial Engineering*, 150, 106889. DOI: 10.1016/j.cie.2020.106889