CONNECTING MAINTENANCE MANAGEMENT AND INDUSTRY 4.0 TECHNOLOGY

Azeddine Boulouf, Abdelmalek Essaadi University
Abdelfettah Sedqui, Abdelmalek Essaadi University
Youness Chater, Abdelmalek Essaadi University

ABSTRACT

A new era of business management has begun with the fourth industrial revolution. Indeed organizations are under increasing pressure to undertake projects to harness the potential of new technologies to meet increasingly specific client requirements as industry 4.0 emerges. Maintenance management is also concerned by the fourth industrial revolution. However, its real impact on companies is still poorly understood, as manufacturers frequently perceive maintenance as an additional cost activity. Yet having a new generation of maintenance based on industry 4.0 strongly impacts the value chain. However, there is a shortage of existing research on integrating Industry 4.0 technologies into maintenance management. Thus the understanding of the strategic implications of industry 4.0 for optimizing maintenance management remains limited. This article aims to develop the hidden link between maintenance management challenges and key industry 4.0 capabilities in an industrial environment. Our findings show that maintenance managers do not use all of industry 4.0's tools. The Internet of Things, Big Data and Analytics, Augmented Reality, and Cloud Computing are the most frequently utilized as Industry 4.0 concepts in the maintenance process.

Keywords: Industry 4.0, Maintenance Management, Impact, Smart Manufacturing.

INTRODUCTION

With today's increasing demands on productivity, availability, quality, safety, environment, and the constraints of shrinking profit margins; production, quality, and maintenance overheads can make or break an industrial business. Companies and service providers have taken a giant step towards improving the quality of their products, services and optimizing their processes to maintain their competence and meet the ever-increasing and personalized expectations of the market. Since the development of the concept of preventive maintenance, Total Productive Maintenance (TPM) in 1951 (Chan et al., 2005; Kaur et al., 2012), Condition Based Maintenance (CBM) (Prajapati et al., 2012), lean machines and Overall Equipment Efficiency (OEE) (Fam et al., 2018). Maintenance management policies and strategies have evolved from a focus on organization and quality to meeting customer demands and creating value and intelligent services.

Recently emerging technologies such as the Internet of Things, wireless sensor networks, Big Data and Analytics, cloud computing, embedded systems, and mobile internet are introduced into the manufacturing environment. Germany named the emergence of a new concept Industry 4.0 (Kohler & Weisz, 2016) in 2011. This concept is based on new technologies, such as the Internet of Things or cloud computing. In 2013, the Association of German Telecommunications Companies (BITKOM) identified no less than 104 different definitions, characterizations, and

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descriptions in its Industry 4.0 presentation document (Bidet-Mayer & Ciet, 2016; Blanco-Montenegro, 2007). As our aim in this paper is to analyze maintenance management practices, we have limited the scope of our investigation to the definition of Industry 4.0 by (Kohler & Weisz, 2016), which is a new approach to process control by offering real-time synchronization of flows and enabling unitary and personalized manufacturing of products.

This concept is based on emerging technologies; we have considered those proposed by the Boston Consulting Group (Rüßmann et al., 2015; de Weck et al., 2013). The following is a list of these technologies:

1. Big Data and Analytics (Baum et al., 2018; Sahal et al., 2020; Daily & Peterson, 2017; Lee et al., 2015);
2. Simulation (Liu et al., 2019) (Gallego García & García García, 2018; Guizzi et al., 2019) ;
3. Autonomous Robots (López et al., 2013; Bernardini et al., 2020) ;
4. Internet of Things (Civerchia et al., 2017; Koulali et al., 2018; Cachada et al., 2019; Carneiro et al., 2018);
5. Cloud Computing (Terrissa et al., 2016) ;
6. Cybersecurity (Holtewert et al., 2013; Fan et al., 2019) ;
7. Augmented Reality (Scurati et al., 2018; Ceruti et al., 2019) ;
8. Additive Manufacturing (Haleem & Javaid, 2019; Khajavi et al., 2014) ;
9. Horizontal and Vertical System Integration (Shen et al., 2012)

Although this concept seems more flexible and less expensive, it relies on many technological means that maintenance managers find difficult to deploy. Indeed, industrial companies have specific managerial characteristics that can hinder the adoption of the Industry 4.0 concept in the management of maintenance processes, including.

1. Local management policy
2. Short and medium-term strategy
3. Lack of expertise;
4. Non-functional organization; and
5. Limited resources; and
6. Lack of working methods and procedures.

Many authors, for example Silvestri et al. (2020); Lee et al. (2019), have examined the relevant role of technological development in optimizing maintenance management. Technology influences and interacts with the economic dimension (e.g., enabling new business solutions), with the environment (e.g., providing solutions for nature and resource conservation) and with society (e.g., supporting new patterns of living), in addition to acting as a powerful tool to provide resources to meet the needs of the present generation without impairing the ability of future generations to meet their own needs. In other words, it is not possible to search for solutions to the issue of optimizing maintenance management without considering technology as an integral part of development (Jasiulewicz-Kaczmarek & Gola, 2019).

This paper aims at the one hand to identify the relationships between Industry 4.0 technologies and maintenance management to make new contributions to the knowledge and emergence of a new mode of maintenance management in the era of Industry 4.0. On the other hand, highlight the links between the principles and tools proposed by industry 4.0, such as Big Data and Analytics, cloud computing, Internet of Things, cyber-physical systems, etc., and those presented by the different approaches to maintenance process optimization. There is a particular focus on how certain industry 4.0 technologies improve the implementation of maintenance policies, depending on the capability levels of industry 4.0 technologies. This should improve

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machine availability and ensure asset integrity to overcome current maintenance management limitations.

The remainder of this paper is structured as follows. Following an introduction, Section 2 covers the challenges and evolution of maintenance management and introduces the new industry 4.0 approach, commonly known as *"smart factories"*, Section 3 presents research methodology perused to conduct the study, and Section 4 and Section 5 investigate the key components of industry 4.0 and technology capability levels for intelligent and connected systems. Section 6 presents the findings and results, as well as a thorough discussion and analysis of them. Finally, Section 7 closes the article with some proposals, and suggestions for future research.

RESEARCH BACKGROUND

Maintenance Management Challenges

Maintenance engineering is a complex exercise that requires mobilizing significant plant resources (budgets, time, operators, etc.) (Nikolic et al., 2017) The simplest basic level of maintenance is corrective (fail and fix) maintenance (also known as fire-fighting), which essentially consists of restoring a production system to its proper working state by repairing the failure when it is detected. This maintenance strategy is unsuitable for smart factories, as unexpected failures strongly impact customer satisfaction (Lee & Lapira, 2013).

Preventive maintenance consists of preventing failures from occurring by periodically scheduling maintenance plans according to the use of the machine and well-defined time intervals. Although preventive maintenance is more appropriate for managers, this type of maintenance has two disadvantages: On the one hand, it has a high maintenance cost (increasingly huge if the machine is critical for the production system), and on the other hand, there is no advanced knowledge of the degradation behavior of the machine to make possible maintenance and design improvements in the future (Lee & Lapira, 2013).

To overcome the weaknesses mentioned above, the maintenance policy has evolved towards predictive maintenance, which has the task of monitoring the state of the processes continuously to decide, taking into account its level of degradation, when a maintenance intervention is required. This maintenance strategy has consensual advantages, such as cost reduction, increased flexibility, operational efficiency of production systems, and improved product quality (Nikolic et al., 2017). Although the concept of predictive maintenance (PdM) is very old (it was introduced in the late 1940s (Prajapati et al., 2012). The emergence of Industry 4.0 technologies such as cyber-physical system, Intenet of Things, Big Data, and Intenet of Service have enabled its successful application by manufacturers (Lee et al., 2014).Predictive maintenance is closely related to Prognostics and Health Management (PHM), which is a discipline that focuses on the degradation mechanisms of systems for the assessment of their health status and the prediction of their reliability and Remaining Useful Lifetime (RUL) to perform informed management of the system's life cycle (Lee et al., 2014). According to (Márquez et al., 2018), PHM should not be considered as a type of maintenance but as a set of methods and techniques that can be employed as inputs to the maintenance function. Therefore predictive maintenance involves methods, tools, and algorithms for monitoring, detecting anomalies, diagnosing the causes of failures, predicting the Remaining Useful Lifetime, and optimizing the maintenance function.

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Despite all the excitement about technological advances in automation, predictive maintenance approaches implemented in real production systems in smart factories have been limited to the application of condition monitoring systems to detect anomalies and the prediction (forecasting) of the time of machine failure. Failure prediction is the most important aspect of preventing and solving persistent maintenance management dilemmas (i.e., lack of availability, process instability, and resource inefficiency). However, the dilemmas mentioned above, which have been considered for several decades as fundamental maintenance deficiencies in production systems, find their causes in inappropriate maintenance strategies, measures, and planning, monitoring, and control models. In other terms, the lack of adequate, complete, up-to-date procedures and mature knowledge is the root cause of most failures. The key missing element is a data and knowledge-based recommendation and decision support system for maintenance management, including planning, monitoring, and control, which not only answers the question 'What will happen when? (i.e. Prediction) but also the significant question 'How should a specific event happen? (i.e., Prescription). In a similar way to predictive maintenance, prescriptive maintenance will continuously analyze data related to an asset's usage and life cycle. Prescriptive maintenance is thus based on a system of sensors linked to software which analyses the functional state of the various materials used. The process provides prescriptions in real-time to improve certain components to increase the life of the equipment by providing an adapted maintenance solution. This is known as a continuous improvement solution. Figure 1 summarizes the development of the maintenance process over time.

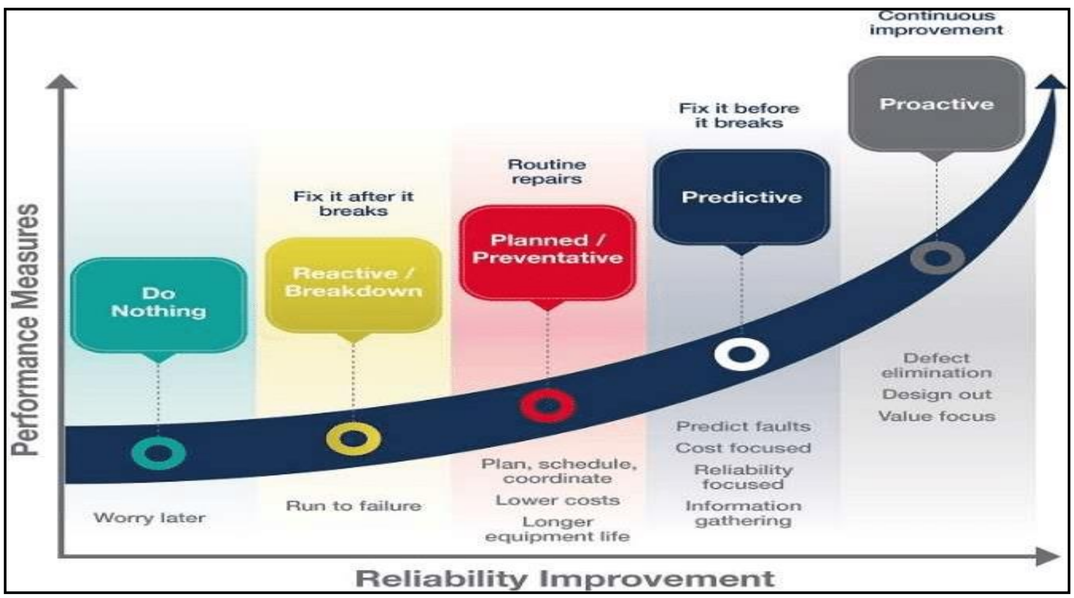

FIGURE 1
DEVELOPMENT OF MAINTENANCE PERFORMANCE

Although no one technique for predicting planning strategies can provide significant results in optimizing the maintenance function, indeed, well-informed decisions based on a reliable prognosis of failure events are needed to continuously improve the performance of maintenance processes and consequently the quality and rapidity of decisions.

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Industry 4.0

After the three previous industrial revolutions caused by the progress of mechanization of the industry with the help of steam machines in the first industrial revolution, electricity, and computers in the second and third industrial revolutions. The rapid development of the internet has pushed manufacturers to introduce smart technologies and the connectivity of objects and actors in the value chain, which has led to a fourth industrial revolution known as Industry 4.0 Figure 2.

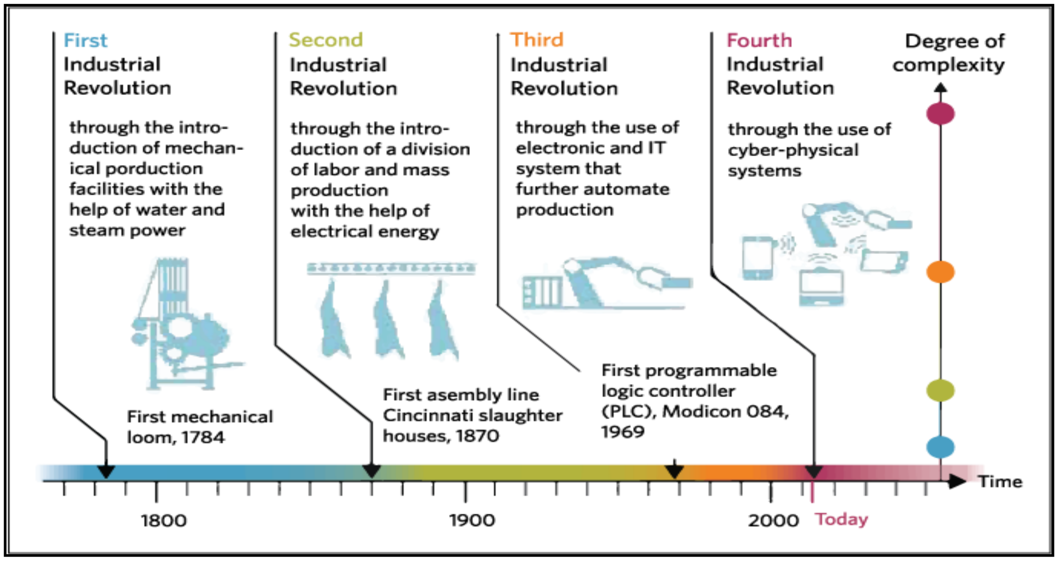

FIGURE 2
THE FOUR STAGES OF THE INDUSTRIAL REVOLUTION

This concept was born at the Hannover Fair in 2011, following a discussion between industry representatives, research, trade unions, and the state. The primary objective of the German initiative is not to increase the automation of production but to make production processes more intelligent by networking machines and humans, this response to the growing need of customers for personalized products. Industry 4.0 refers to the decentralization of business processes brought about by the advances of new technologies. It is characterized by technological innovations such as Augmented Reality, the Internet of Things, Cyber-Physical Systems, and Big Data Analytics. Several strategic initiatives have emerged around the world: "*smart manufacturing*" in the United States, "*internet+*" in China, "*Industrie du Futur*" in France, and "*Industrie 4.0*" in Germany (Porter & Heppelmann, 2015). As Industry 4.0 technologies seem to be taking hold internationally, we decided to connect them with maintenance management.

Industry 4.0 represents a business environment in which employees, machines, and business management systems are connected internally. This industrial interconnection between different processes in the company has enabled intelligent process management and provided new paradigms through the insertion of these technologies into industrial management (Moeuf et al., 2018). Now Industry 4.0 is the key to improving productivity, enhancing economic growth, and ensuring the sustainability of manufacturing companies. Industry 4.0 is based on several

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characteristics, which the European Parliament has listed, that enable horizontal, vertical, and temporal integration of the whole value chain:

1. The interoperability of objects, machines, humans, and IT systems that communicate with each other (Wang et al., 2016);
2. The virtualization of the physical world through a copy in the virtual world from the data collected by the sensors (Terkaj et al., 2015);
3. Decentralization of decision making directly on the cyber-physical systems next to the production (Lee et al., 2015);
4. Real-time capacity and demand management through data collection and analysis, simulation, and priority changes (Michniewicz & Reinhart, 2016);
5. Service orientation to enrich the offer to customers;
6. The modularity of production systems enabling increased flexibility to respond to fluctuations in demand (Seiger et al., 2015).

Thus there are three strategies for the transition to Industry 4.0: products, service, and processes. Hence, the integration of Industry 4.0 tools through the implementation of information and communication technologies within organizations have enabled autonomous, dynamic, and personalized manufacturing (Fatorachian & Kazemi, 2018). Improved inspection systems in operations have improved the nature of the products and services provided by companies significantly (Porter & Heppelmann, 2015). In addition, the adoption of technological innovations in the industrial environment has enabled efficient use of resources, making excellence a key element of smart factories.

LITERATURE RESEARCH METHODOLOGY

To answer the research question pragmatically, it is necessary to carry out a comprehensive literature search. For this purpose, we applied the systematic literature search method as presented by Tranfield. The choice of this method is justified by reproducibility and formality, and it has the advantage of being clearer and guiding the researchers in the analysis and the bibliographic research. Tranfield have extended their literature review method from the medical sector to the management sciences. Finally, the Tranfield method has been used and validated in other management science research.

This literature review focuses on articles dealing exclusively with cases of implementation and application of Industry 4.0 tools in maintenance management, as presented by the researchers. The databases searched include Elsevier, Emerald, Springer, Taylor and Francis, and Google Scholar. We considered publications after the official introduction of the Industry 4.0 concept in 2011 and used the following keywords to search abstracts and titles:

Industry 4.0 or Industrie 4.0 or Smart Industry or Smart factory or Digital manufacturing and maintenance management; autonomous robots and maintenance management; collaborative robots and maintenance management; cobots and maintenance management; simulation and maintenance management; Internet of Things and maintenance management; cyber security and maintenance management; cloud computing and maintenance management; Horizontal and Vertical system integration and maintenance management; Augmented Reality and maintenance management; data mining and maintenance management; Big Data and maintenance management; cyber-physical system or cyber factory and maintenance management; Additive manufacturing and maintenance management

In conducting our literature search, we noticed that many authors describe the uses of Industry 4.0 technologies in maintenance processes without specifically referring to "*planning*,

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monitoring, and control" in their abstracts, keywords, or titles. Other authors have reported the implementation of Industry 4.0 technologies without referring to "*Industry 4.0*". Therefore, we decided to conduct separate research on "*Industry 4.0*" to identify the application of Industry 4.0 tools for maintenance management optimization.

Finally, a selection process was used to narrow down the number of articles considered, based on reviewing the article title and abstract. Similarly, articles that included the keywords but were not directly related to Industry 4.0, maintenance management, or manufacturing were not considered. Only full-text articles and journal articles were retained. All other articles were included in the literature review.

Key Components of Industry

The concept of Industry 4.0 is based on the emergence of new technologies. In this section, we present the different technology groups of Industry 4.0 represented in Figure 2. For this purpose, we have exploited a list of nine technology groups proposed by the Boston Consulting Group (Rüßmann et al., 2015). Figure 3 illustrate the different Industry 4.0 technology used in maintenance management.

Augmented Reality

Augmented reality-based systems support various services, including sending repair instructions to mobile devices and selecting parts from the warehouse. Manufacturers can use augmented reality in the maintenance function to provide machine operators with real-time information to improve decision-making and maintenance procedures. Maintenance technicians can diagnose and receive a repair procedure on how to replace a particular spare part of a system that needs repair. This information can be displayed directly in the operators' field of view using augmented reality glasses (Rüßmann et al., 2015; Glas & Kleemann, 2016).

For example, a helicopter stuck in a remote location in Africa needs to deliver food in time. The nearest available mechanic is about 17 hours away and needs almost two hours to repair the helicopter. With the use of an augmented reality window on the pilot's head connected to a central computer that will know all the details of the aircraft. With an augmented reality window on the pilot's head connected to a central computer that will know all the details of the helicopter. The repair action is performed with the help of an augmented reality glass (Rüßmann et al., 2015). Virtual training is one of the practices of augmented reality using a real environment based on 3D data with augmented reality glasses to train maintenance personnel to manage emergency and critical maintenance operations. In this virtual world, operators can learn to interact with machines by clicking on a cyber-representation. They can also change parameters and retrieve operational data and maintenance instructions (Rüßmann et al., 2015).

Additive Manufacturing

In Industry 4.0, Additive Manufacturing methods are widely used to manufacture prototypes with substantial construction advantages, especially for complex and lightweight designs. Additive manufacturing provides the ability to manufacture high-performance spare parts. Decentralized additive manufacturing also reduces transportation costs and inventory levels, which significantly contributes to optimizing maintenance management. Companies that

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integrate Industry 4.0 technologies into their processes are already using additive manufacturing to create new designs that reduce the weight of machine systems, thereby reducing their expenditure on raw materials, energy consumption, and maintenance operations (Rüßmann et al., 2015).

The maintenance process is expected to be faster and less costly through the use of additive manufacturing technologies such as Fused Deposition Method (FDM), Selective Laser Melting (SLM), and Selective Laser Sintering (SLS) to produce spare parts for machines (Haleem & Javaid, 2019). Through the solutions offered by additive manufacturing in spare parts manufacturing, the Overall Equipment Effectiveness (OEE) will be positively impacted so that asset management can meet the challenges faced by the increasing individualization of products and the reduction of time to market. These challenges include increasing digitalization, information technologies penetration, and networking of products, resources, and manufacturing processes (Khajavi et al., 2014).

Cloud Computing

The cloud computing platform serves as the technical support for connecting and communicating several elements of the Industry 4.0 Application Centre (Landherr et al., 2016). Enterprises are already using cloud-based software for some management and analytics applications. However, with Industry 4.0, System 4.0 requires more data exchange between locations and businesses, i.e., achieving a response time of milliseconds or more (Rüßmann et al., 2015). Digital maintenance is a concept of connecting different machines and devices to a single cloud to share information. It can be extended too many machines on a shop floor, not just the entire factory (Marilungo et al., 2017). As a result, machine data and capabilities are increasingly integrated into the cloud, enabling more data control services for maintenance engineering. Also, systems that monitor and control processes and machines can become cloud-based for timely maintenance diagnosis and prognosis (Rüßmann et al., 2015).

Big Data and Analytics

Big data and Analytics are undoubtedly important components of digital transformation. Big data and Analytics are comprised of two major concepts: Big Data and Analytics. In the literature, there is a broad debate on the benefits and outcomes of BDA in the growth and profitability of today's businesses. However, the accelerated evolution of the Big Data Analytics concept in recent years has confused its definition. There is no consensus on a clear and comprehensive description of this composite concept. According to the Forrester definition, Big Data has four dimensions: Volume of data, Variety of data, Speed of generation and analysis of new data, and Value of data (Witkowski, 2017). Analytics based on large datasets have only recently emerged in the manufacturing world with Industry 4.0. It helps to optimize production quality, save energy and improve equipment maintenance interventions.

The comprehensive collection and evaluation of data from different sources of equipment and production systems as well as company and customer management systems will become the basis for real-time maintenance and production decision-making (Rüßmann et al., 2015). The analysis of previously recorded data from the equipment history is used to discover failures in different machines and predict new failures and other solutions to prevent this from happening again and again in the subsequent production runs (Al-Najjar et al., 2018; Bagheri et al., 2015).

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Simulation

Simulations will be used more in smart factories to exploit real-time data to reproduce a virtual image of the physical world, including machines, products, and people, thus reducing machine set-up times and improving quality and equipment availability (Rüßmann et al., 2015). 2D and 3D simulations can be created for virtual set-up and for the simulation of repair cycle times, energy consumption, or ergonomic aspects of a production facility. The use of production process simulations can not only reduce machine downtime and modifications but also reduce equipment failures during the start-up phase as well as during the nominal production regime (Simons et al., 2017; Souza, 2007). The quality of decision-making can be improved in quick and straightforward ways using simulations. For example, Siemens and a German machine tool vendor have developed a virtual machine that can simulate the machining of parts using data from the physical machine. This reduces the preparation time for the actual machining process by 80%.

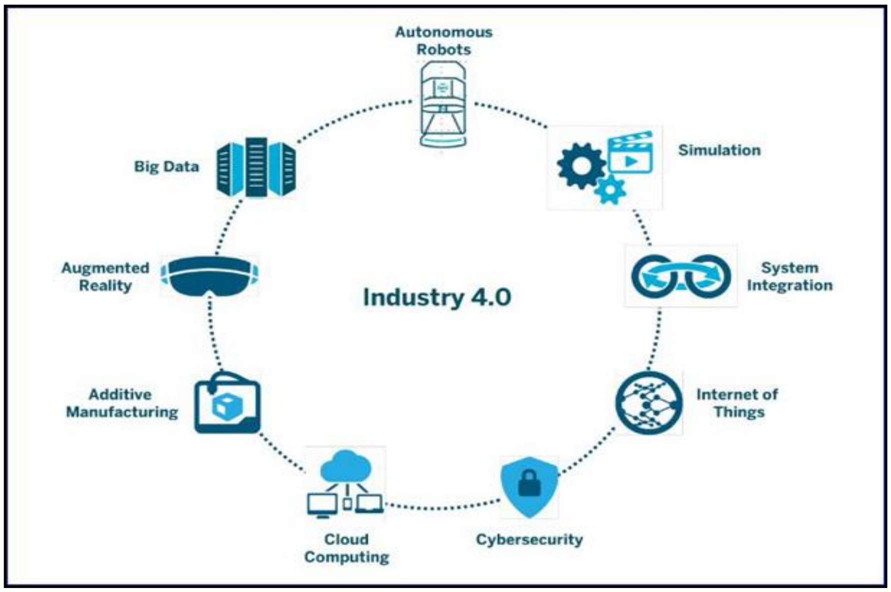

FIGURE 3
THE TECHNOLOGIES USED IN INDUSTRY 4.0

Autonomous Robots

Robots have been around for a long time utilized by manufacturers in various industries to perform complex tasks, but robots have evolved with Industry 4.0 to become even more helpful. They are becoming more cooperative, flexible, and autonomous. Eventually, they may engage with everyone, work safely effectively along with human beings and learn from them. These robots are cheaper and have more features than the robots used in the manufacture of Industry 3.0. An autonomous robot performs more precise autonomous maintenance and works in areas where machine operators cannot work due to a lack of safety. Autonomous robots can perform a given task accurately and intelligently within the prescribed time frame and focus on safety, flexibility, versatility, and collaboration (Bahrin et al., 2016). Autonomous robots

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interact, connect and work together to adapt their actions to maintenance operations automatically. Control units and wireless sensors and allow them to work together closely with the maintenance operators. Computer vision allows safe interaction and recognition of spare parts (Barbosa et al., 2017).

Internet of Things

Today, most factories and machines are usually organized into vertical automation pyramids. There, sensors and field devices with limited, less intelligent automated control flow into the overall control system of the manufacturing process. Only some of the sensors and production machines are found to be networked and use embedded computing. Nevertheless, with one of the most promising Industry 4.0 technologies, more devices - sometimes even unfinished products - will be enhanced with connected and embedded computing using this technology. The Internet of Things is a network of globally interconnected objects with uniform addresses that communicate via standard protocols (Hozdić, 2015). The Internet of Things (IoT) is also known as the Internet of Everything (IoE), which consists of the Internet of Services (IoS), the Internet of Manufacturing Services (IoM), the Internet of People (IoP), an embedded system, and Information and Communication Technology Integration (ICTI) (Neugebauer et al., 2016). Context, ubiquity, and optimization are the three key characteristics of IoT. Context refers to the ability of an object to interact highly with an existing environment and react instantly to changes; ubiquity provides information about the location, physical or atmospheric conditions of an object, and optimization illustrates that today's things are more than just a connection to a human operator's network at a human-machine interface (Witkowski, 2017).

The value chain needs to be intelligent and networked by integrating physical objects, human factors, smart machines, intelligent sensors, maintenance processes, quality, and production lines across the lines of the organization. Software and data are crucial elements for intelligent planning and control of future machines and factories (Valdez et al., 2015). This allows the equipment to communicate and interact with each other and with centralized controllers if required. Decentralizing analysis and decision making allowing a real-time response.

For example, in the case of storage in warehouses, intelligent shelving and pallets will become the engine of modern inventory management. In the case of goods transportation, tracking and tracing become faster, more accurate, and safer (Dutra & Silva, 2016). Bosch Rexroth, a supplier of drive and control systems, equipped a valve production plant with a semi-automated and decentralized production process. Radiofrequency identification codes identify products, and the workplace knows which production steps need to be performed for each product and can adapt to specific operations.

Horizontal and Vertical System Integration

Most current IT systems for managing business functions are not fully integrated. Companies, suppliers, and customers are rarely closely linked. The same applies to departments such as maintenance engineering, production, and services. Company functions down to the level of production machines are not fully harmonized (Rüßmann et al., 2015). Integration and self-optimization are the two main mechanisms used in industrial organizations. Three aspects of integration essentially define the Industry 4.0 paradigm:

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1. Horizontal integration across the entire value creation network
2. Vertical integration and network production systems;
3. End-to-end integration across the entire product lifecycle.

Fully digital integration and automation of production processes at both the vertical and horizontal dimensions means, in particular, the automation of communication and collaboration within the framework of standardized processes. Companies, departments, maintenance and resources will become more aligned as universal data-integration networks evolve and provide truly automated value chains

For example, Dassault Systèmes and BoostAeroSpace have launched a collaboration platform for the European aerospace and defence industry. The platform serves as a shared workspace for design and manufacturing collaboration and is available as a service in a private cloud. Manage the complex task of exchanging product and production data between multiple partners.

Cyber-Physical System and Cyber-security

Cyber-physical systems are considered one of the key tools of Industry 4.0. Cyber-physical systems technology integrates knowledge from several domains and bridges the gap between the physical and cyber worlds (Meesublak & Klinsukont, 2020). The National Science Foundation (USA) first described the CPS concept in 2006 to integrate computer processing and physical processes. In 2020, cyber-physical systems research focused on the continued seamless integration of physical components and computational, especially in critical areas such as control, data analysis, machine learning, and advanced real-time applications. The cyber-physical systems is an engineering system that connects and integrates both the physical and the cyber (or digital) world with three main essential functions, namely, sensing, reflection (or computation), and action (or feedback control) (Meesublak & Klinsukont, 2020). Today, the Internet of Things can make cyber-physical systems feasible by connecting machines to each other and the monitoring and interconnection of maintenance processes. The information is then sent to the cyber layer for decision making, and appropriate actions are taken.

Lee et al. (2015) propose five levels for cyber-physical systems structure: The 5C architecture, which consists of intelligent connection, data conversion into information, cyber, cognition, and configuration levels. This cyber-physical system structure consists of two main elements: 1) advanced connectivity that provides real-time data flow from the physical space to the cyberspace and feedback from the cyberspace; and 2) intelligent data analysis that builds cyberspace (Jiang, 2018; Kagermann et al., 2013; Kang et al., 2016). The proposed 5C framework provides a workflow that demonstrates how to build a cyber-physical system from data collection to value creation.

Industry 4.0 Technology Capability Levels

Industry 4.0 technologies can support maintenance by deploying different capabilities, depending on the needs of the maintenance system. The level of capability required will vary depending on the complexity of the decisions to be made, the amount of data to be processed, or the autonomy of the systems to make decisions without human intervention. From the perspective of intelligent and connected products, (Porter & Heppelmann, 2015) has proposed four levels of capability. These levels are progressive and are based on each previous level. As

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shown in Figure 4 the capability levels are 1- Monitoring, 2- Control, 3- Optimization, and 4- Autonomy.

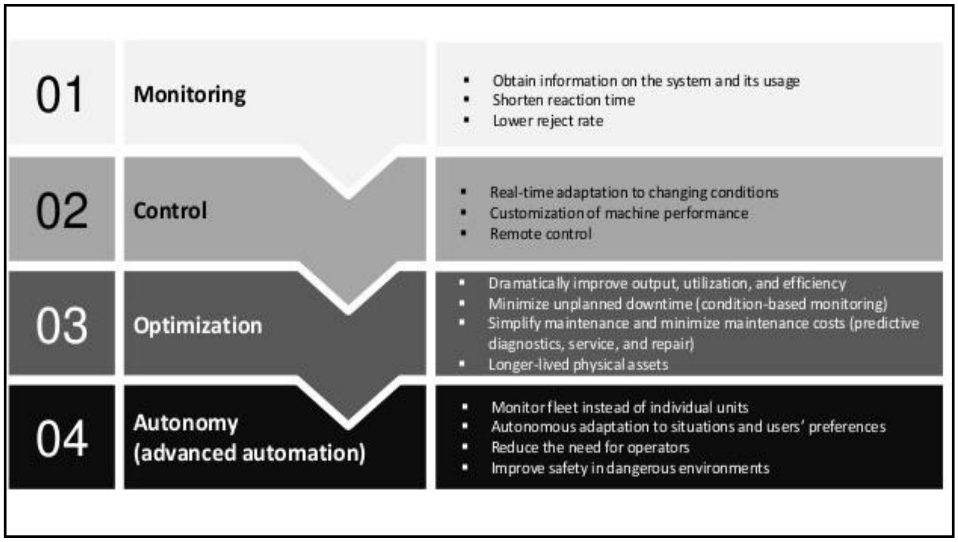

FIGURE 4
CAPABILITIES OF SMART AND CONNECTED SYSTEMS

According to the same authors, the monitoring level allows for monitoring indicators of a machine's operating conditions, safety parameters, preventive or predictive maintenance indicators, or even proactive indicators and production indicators for benchmarking. Different elements and sensors installed at the machines can generate notifications and alerts in case of a situation change or detection of deviation (Moeuf et al., 2018). This level allows for the tracking of the general operating status of the equipment and monitoring of operations and the construction of history. Here, only useful information is transmitted to the operator or manager in charge of the control and inspection process. For the control plane based on historical data, standard system behaviour, and expected performance, the algorithm can detect anomalies. Control, therefore, includes monitoring by incorporating a decision-making loop (Moeuf et al., 2018). The algorithms then respond to specific changes in their environment by taking action (Porter & Heppelmann, 2015).

The optimization level allows algorithms to analyze the environment and history data to propose improved outcomes and efficient uses of resources (Porter & Heppelmann, 2015). Using digital dashboards and 3D modeling and simulation of equipment systems, optimal resource utilization, and industrial performance can be optimized in real-time. The system then acts as a decision support system, navigating through a set of suggested actions or alternatives from which an operator or manager can select an action to take.

Finally, system monitoring, control, and decision loops, real-time optimizations can be combined to make the system autonomous (Porter & Heppelmann, 2015), which corresponds to the level of autonomy. The system can then make decisions in real time based on the context of the environment in which it is located. In addition, the system can learn from past decisions or respond optimally to the changes required by industry requirements and constraints (Moeuf et

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al., 2018). This can also include coordination and communication with other systems and products to continuously improve results (Porter & Heppelmann, 2015).

RESULTATS ANALYSIS AND DISCUSSION

Industry 4.0 aims at more flexibility and more links with the customer to satisfy his personalized demand. These are qualities that drive the maintenance department; Industry 4.0 should not impose constraints contrary to the optimization of maintenance management. Unlike other solutions that have already shown their limitations in meeting maintenance management challenges, notably the lean maintenance approach.

The new technologies are much more accessible than other concepts. For example, when you want to exploit Lean Maintenance and Total Productive Maintenance, you have to completely rethink and reconfigure the company's maintenance management model to move to a maintenance process. This transformation is costly and very complex from an industrial perspective. Similarly, some maintenance management continuous improvement methods impose rigid and complex data architectures, freezing the organization. The costs involved in these projects are significant.

Industry 4.0 has advantages linked to the maturity and accessibility of the technologies exploited; the industrials use Cloud Computing; it allows to connect the processes of companies through simple and inexpensive modules, therefore accessible to maintenance managers even with little expertise. The development of a virtual structure, based on Cloud Computing and other technologies such as the Internet of Things and Big Data and Analytics, is also presented by many research works. Cloud computing platforms seem to improve and facilitate collaboration between managers sharing information and knowledge, creating better partnerships and opening new opportunities for managing maintenance interventions.

However, privacy issues related to customer information and maintenance system information are still pervasive. Further research into cyber security should be conducted to provide a means of protecting computer systems and confidential data when Industry 4.0 technologies are implemented (Valdeza et al., 2015) (Table 1a & b).

In addition, the application of Big Data and Analysis in the maintenance process has been widely recognized as a popular method for optimizing resource utilization in companies (Lee et al., 2014). Some authors argue that manufacturers do not consider the potential value within their data (Bi & Cochran, 2014). However, the accessibility and exploitation of the Internet of Things, or another data source such as RFID technology, will increase data sources and data generation without requiring a significant investment. Maintenance managers should exploit data in the future to optimize the costs and times of maintenance interventions without neglecting the safety aspect. It is clear that research is needed to make Big Data and Analysis tools accessible to the industry by formulating clear and practical methods that describe the implementation steps, techniques required, tools, roles, and skills needed.

Big Data and Analytics, cloud computing, and cyber-physical systems create an industrial network, and their combination leads to the birth of intelligent maintenance management. In addition, the new data provided by the widespread use of sensors and Internet of Things allow the development of Big Data analysis and machine learning tools applicable in various fields such as monitoring, diagnosis, and analysis of asset failure trends, hence monitoring and predicting machine failures.

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Table 1a
INDUSTRY 4.0 TECHNOLOGIES ENABLING THE DIGITAL TRANSFORMATION OF MAINTENANCE MANAGEMENT

	Augmented Reality	Additive Manufacturing	Cloud Computing	Big Data and Analytics
Haleem & Javaid (2019)		x		
Khajavi et al. (2014)		x		
Scurati et al. (2018)	x			
Ceruti et al. (2019) Uva et al. (2018) (Masoni et al. (2017) Fernández-Caramés et al. (2018) Gattullo et al. (2019) Roy et al. (2016)	x x x x x x	x		
Terrissa et al. (2016) Fusko et al. (2018) Upasani et al. (2017) Zolotová et al. (2020)			x x x x	
Baum et al. (2018)				x
Sahal et al. (2020)				x
Daily & Peterson (2017)				x
Lee et al. (2015) Ooijevaar et al. (2019) Rødseth et al. (2017) Roy et al. (2016)				x x x x
Holtewert et al. (2013)			x	

Table 1b
INDUSTRY 4.0 TECHNOLOGIES ENABLING THE DIGITAL TRANSFORMATION OF MAINTENANCE MANAGEMENT

	Simulation	Autonomous Robots	Internet of Things	Horizontal and Vertical System Integration	(CPS) and Cybersecurity
Lee et al. (2015)					x
Guizzi et al. (2019)	x				
Liu et al. (2019)	x				
Gallego García & García García (2018)	x				
López et al. (2013)		x			
Bernardini et al. (2020)		x			
Carneiro et al. (2018)			x		
Civerchia et al., (2017)			x		
Koulali et al. (2018)			x		
Cachada et al.(2019) Ooijevaar et al. (2019) Roy et al. (2016) Rødseth et al. (2017) Fusko et al. (2018) Sénéchal (2018) Kans et al. (2016)			x x x x x x x		
Shen et al. (2012)				x	
Holtewert et al. (2013)					x
Fan et al. (2019)					x
Lee et al. (2015)					x

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Augmented Reality is the most advanced technology of Industry 4.0, and this is confirmed by the number of articles dealing with this technology (Figure 5). Augmented reality offers real-time assistance to maintenance operators to diagnose, monitor, train and perform maintenance tasks and operations safely and sometimes remotely. Augmented Reality thus transforms the documentation of procedures and working methods from a pdf and text-based documentation to. Augmented Reality -based support based on graphical symbols that are easy to operate by maintenance operators (Scurati et al., 2018). Finally, Augmented Reality offers many optimized solutions for spare parts inventory management.

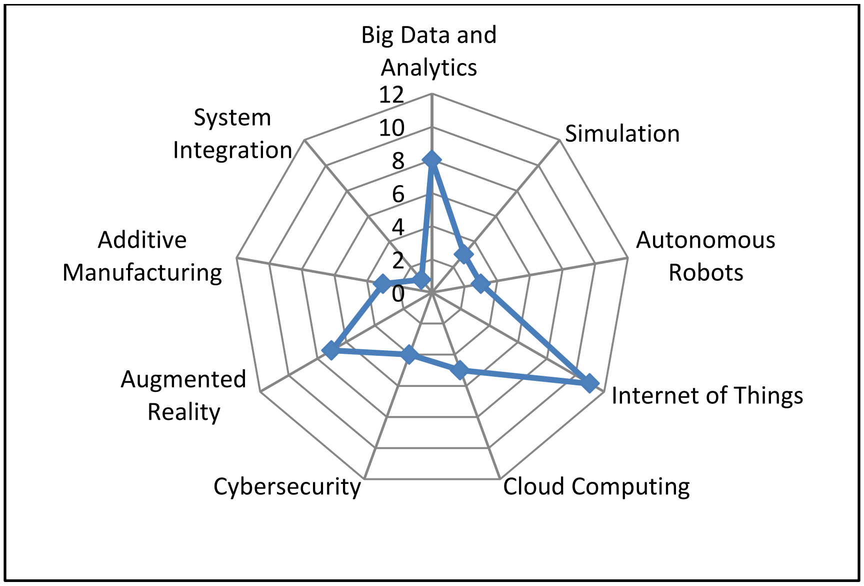

FIGURE 5
PUBLICATIONS RELATED TO INDUSTRY 4.0 TECHNOLOGIES IMPACTING MAINTENANCE MANAGEMENT

Cyber-physical systems are present in machine maintenance through two integration routes: Purchasing new equipment or upgrading existing equipment in the value chain. Thus maintenance managers must target the most critical machines in their manufacturing process and limit investment costs without adding value to the value chain.

Maintenance managers little exploit the capabilities offered by Autonomous robots and machine-to-machine communication. It should be noted that integration is very costly for collaborative robots and cyber-physical systems with a long-term return on investment. Furthermore, these technologies aim to improve flexibility, which is not necessarily the need for processes where flexibility is already strength. Cobots or cooperation between human labor and robots is still limited and should be strongly regulated.

Additive Manufacturing is a growing Industry 4.0 tool in terms of the use of different materials. Its use requires the presence of qualified personnel in the company. Its application for the production of prototypes and spare parts for maintenance still seems to be limited. Additive manufacturing can play a pivotal role in producing small batches of customized products and components and decentralizing part manufacturing, which will positively impact maintenance optimization.

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Systems integration offers the advantage of collecting and integrating data, information, and knowledge for equipment management and maintenance decision-making throughout the life cycle of the equipment. Real-time asset monitoring based on wireless sensors and the integration of facility maintenance management with machine information modeling is attractive information and communication technologies for companies. However, as there are still barriers to the wide application of system integration in maintenance management, more investigation is required for its implementation. System or subsystem-based implementation of intelligent mechanisms can react reactive and proactive to events to improve event robustness and responsiveness. Finally, real-time asset condition monitoring technologies can also pose problems for machine managers. This system requires good real-time information to be collected to provide good decision support

Simulation can provide significant insight into maintenance systems in the same way that it has been proven in the value-adding processes of manufacturing systems and service systems. It is mainly used for evaluation and for combining simulation with optimization approaches or analytical models. In addition, the quality of the data used for simulation is essential for the success of the maintenance process optimization. The mastery of the simulated machine behaviors and an adequate software and hardware infrastructure are necessary. Finally, simulation is time-consuming, which does not always facilitate real-time decision-making in an evolving environment.

Ultimately, we recognize that implementing Industry 4.0 technologies might be an opportunity to improve or even transform maintenance management and grasp new opportunities in the market. Maintenance managers need to move from seeing the maintenance system as a cost to seeing it as an opportunity to transform their business models, to embrace all the potential benefits that lie behind the concept of Industry 4.0. Unfortunately, this literature review reveals that this cost view has primarily encouraged the adoption of low-cost technology groups to achieve faster and cheaper improvements in maintenance processes without substantially transforming maintenance management to Maintenance 4.0.

CONCLUSION AND FUTURE WORK

This paper provides a better understanding of the link between Industry 4.0 and maintenance management by specifically quantifying the Industry 4.0 technologies that enhance maintenance management. A survey of the literature was conducted to determine the connections between industry 4.0 technologies and maintenance management. Subsequently, an analysis of the Industry 4.0 capability levels of the various research papers was used to rank the proposed applications of Industry 4.0 technologies. In addition, the most commonly offered technologies for improving maintenance management are the Internet of Things, Big Data and Analytics, and simulation. In addition, the level of monitoring capability is mainly represented by Industry 4.0 technologies.

Industry 4.0 technologies do not seem to cover the entirety of maintenance management but can enhance maintenance management performance. However, some specific maintenance management principles might be challenged. Nevertheless, Industry 4.0 technologies alone do not replace the pillars of maintenance management, which must be pursued in companies. Therefore, there is a clear need to optimize maintenance management further while improving certain processes with Industry 4.0 technologies, depending on the level of capability targeted.

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Further research is needed to suggest new applications of Industrie 4.0 technologies to further support maintenance management in terms of monitoring, control, optimization, and autonomy. Furthermore, in a manufacturing plant context, it would be relevant to test the extent to which Industry 4.0 technologies improve the implementation of maintenance management and, consequently, the productivity of manufacturing companies.

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