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Comparative Analysis Of Maintenance Practices In Industry 4.0 And Industry 5.0: Bridging Gaps

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Abstract

This paper examines how maintenance procedures are changing within the framework of Industry 4.0 and the new Industry 5.0 paradigm. Significant changes in technology, procedures, and tactics have emerged as industries shift from the fourth to the fifth industrial revolution, resulting in pronounced disparities in the approaches taken to Maintenance. This comparative study examines the primary differences between Industry 4.0 and Industry 5.0 maintenance. Integrating digital technology and data-driven methodologies, where predictive maintenance and condition monitoring systems play a crucial role, characterises Industry 4.0. On the other hand, Industry 5.0 presents a more human-centric strategy that emphasises decentralised maintenance teams, AI-enhanced decision-making, and human-robot collaboration. The effect of these modifications on maintenance efficacy, cost-effectiveness, and flexibility in changing industrial settings is assessed in this paper. It also talks about the potential and problems that come with the shift from Industry 4.0 to Industry 5.0, highlighting the necessity of an adaptable and comprehensive approach to Maintenance in the context of the fifth industrial revolution. Ultimately, the paper guides industry participants and decision-makers on handling the challenging shift and reassessing their maintenance plans to be resilient and competitive in this changing environment.

Keywords: maintenance 5.0, industry 5.0, predictive maintenance, industry 4.0, human-centric industry, new trends,

1. Introduction

The evolutionary trajectory of industrial revolutions has shaped our conception of production and maintenance processes inside manufacturing ecosystems. The crucial changes in maintenance methods as we go from the landscapes of Industry 4.0 to the dawn of Industry 5.0 bear witness to this dynamic movement. This study thoroughly examines the disparate aspects of Maintenance during these two crucial industrial eras, in order to identify the challenges and risks posed by this new conception of industry.

The first chapter thoroughly examines Industry 4.0 and explains the fundamental ideas guiding this paradigm change. This chapter lays the groundwork, from its conception and the causes that led to its birth, to a comparative analysis that compares its benefits and shortcomings to those of Industry 3.0 (Cortés-Leal, 2022). In addition, this section explores Maintenance 4.0 by going through case studies that show how advanced maintenance tactics can be used in real-world settings within the Industry 4.0 framework.

As we move into the unknown territory of Industry 5.0, the second chapter explains the forces behind this next stage of the Industrial Revolution. This chapter examines the subtle evolution while closely examining how its benefits and drawbacks compare to Industry 4.0. It focuses on Maintenance 5.0, particularly its introduction, benefits, difficulties, and unique features in the changing industrial landscape.

The third chapter carefully examines the distinctions between Maintenance 4.0 and Maintenance 5.0. By comparing their techniques, technological structures, and strategic perspectives, this section reveals the revolutionary difference that distinguishes these core maintenance methods in the dynamic industrial environment (Massaro, 2022; Mourtzis, 2023; Deshpande, 2023).

The conclusion from the comparative analysis summarises the main ideas of this investigation. It provides insightful analysis and practical recommendations for the future direction of maintenance practices as we move from Industry 4.0 to Industry 5.0.

1.1. Need for the study.

"The Age of Digital Objects" demands pushing the envelope and having the flexibility to react fast without sacrificing stability. This study's goal is to serve as a guide for acquiring adaptive skills and navigating challenging circumstances. The following research questions emerged after conducting a bibliographic study in which several papers were assessed and then integrated with the most relevant keywords selected. They will be employed as input for the literature review:
RQ1: What advances in Maintenance have the fourth industrial revolution brought about?
RQ2: What are the most recent benefits in the digital sector?
RQ3: What role does Maintenance play in the human-robot interface of the digital industry?
RQ4: How are the fundamentals of the digital industry changing in Industry 5.0, and what role do they play in Maintenance?
RQ5: What will be the future criticalities in implementing these changes?
The writers adhered to a review protocol of published articles and reviews while conducting a systematic literature review. This assessment of the literature on the chosen keywords in the digital age will synthesise the body of knowledge, point out knowledge gaps, and offer practical guidance to policymakers, practitioners, and academics. The study uses a descriptive review methodology, and Figure 1 depicts the general organisation of the work.

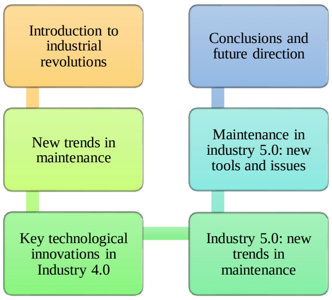


Fig. 1. Article Structure.

1.2. Methodology and structure

Pertinent articles were examined and chosen using the Scopus database, and conference papers were omitted. A systematic review was conducted; Figure 2 depicts the used structure, indicating that the investigation started examining Industry 4.0 technologies. Furthermore, the primary issues discussed are the transition to Industry 5.0, innovations in the maintenance business, and Maintenance in 4.0. The survey's main section contains the responses to the suggested research question. Ultimately, the study's consequences, results, and future research directions were determined. It should be emphasised that the research is restricted to summarising and providing readers with an overview of the most recent and noteworthy developments.

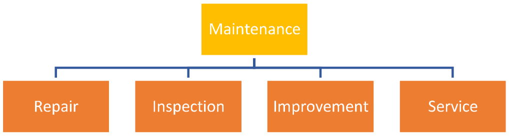


Fig. 2. Maintenance phases.

2. Thematic analysis

2.1. What is Industry 4.0

One important idea that captures the current stage of industrial growth is "Industry 4.0." It aims to put cutting-edge technologies like robotics, digitalisation, IoT, artificial intelligence, and other improvements into practice. This transition aims to establish a highly automated and interconnected industrial setting where machines can speak with one another and make choices on their own. Industry 3.0 gave way to Industry 4.0 in response to the industry's growing need for flexibility, efficiency, and competitiveness. This progress was driven by the desire to streamline processes, shorten production periods, enhance product quality, and enable customisation. As a result, cutting-edge technologies were used, and conventional production methods were altered (Santhi, 2023).

The debate focuses on the changing maintenance procedures in modern industrial environments, where machinery and equipment dependability is essential. Newer solutions are being adopted due to the transformation of old maintenance approaches by technological breakthroughs.

Contemporary manufacturing organisations are acknowledging the significance of Industry 4.0 ideas. This realisation emphasises optimising maintenance procedures because of the financial ramifications, which immediately affect these businesses' profitability. The transition from traditional maintenance techniques to more sophisticated approaches, such as predictive Maintenance, is essential for these businesses to maintain growth and remain competitive in today's marketplaces.

This paper highlights how technology is changing maintenance methods in a significant way. It provides insight into how information and communication technology improvements have fueled the transition from manual inspection methods to computer-aided maintenance systems. This shift denotes a departure from conventional methods towards more data-driven and technologically advanced maintenance tactics.

Inspection, servicing, repair, and improvement are the four basic responsibilities that make up the maintenance process. Within the maintenance framework, each task consists of certain actions. For example, inspection entails evaluating the present state of things and determining the reasons for wear or damage, whereas service is taking steps to keep equipment operating. Repair is about getting things back to working order, whereas improvement is about making things more reliable without changing the important things.

This thorough dissection of maintenance duties highlights the complexity of modern maintenance procedures. It emphasises how companies must keep up with technology developments and use creative solutions to maximise machinery and equipment's durability, dependability, and efficiency in contemporary industrial settings.

2.2. Pros and cons of industry 4.0 compared to 3.0

Compared to Industry 3.0, Industry 4.0 presents significant benefits and difficulties. Enhanced efficiency by integrating cutting-edge technology like artificial intelligence (AI) and the Internet of Things (IoT) is one of Industry 4.0's benefits. This development makes industrial processes more efficient overall and enables for optimised operations. Furthermore, machinery's growing automation and interconnectedness makes more adaptable and customised manufacturing techniques possible. Furthermore, Industry 4.0 makes it easier to handle data by enabling sectors to collect, process, and use real-time data to make well-informed decisions. But there are drawbacks to this change as well. Industry 4.0 deployment involves large equipment and employee training expenditures, significantly increasing implementation expenses.

Furthermore, Industry 4.0's increased connectedness creates cybersecurity vulnerabilities by opening industrial infrastructures up to possible threats and cyberattacks. Concerns have also been raised on how increased automation may affect jobs, possibly resulting in job displacement as robots take on certain human duties. Furthermore, not every workforce member today possesses the sophisticated technological skills required for Industry 4.0 adoption to be effective. The transition from Industry 3.0 to Industry 4.0 entails weighing these benefits and drawbacks, acknowledging that the assessment frequently depends on an organisation's unique needs and circumstances.

2.3. Maintenance 4.0

The four primary categories (Fig.3) are predictive, preventive, corrective, and opportunistic Maintenance. Corrective Maintenance, also known as reactive Maintenance, entails fixing or replacing malfunctioning equipment after it has broken down. Compared to other forms of Maintenance, this one usually costs more and takes longer since it needs to be attended to right away in order to avoid further damage or safety risks (Aksa, 2021).

On the other hand, preventive Maintenance is a proactive strategy that includes routinely planned maintenance routines to stop equipment failure and increase machinery life. Preventive Maintenance comes in three types: condition-based, performance-based, and time-based. While performance-based preventive Maintenance depends on counter readings, time-based preventive Maintenance entails regular maintenance routines. Condition-based Maintenance only performs repairs when they are absolutely required, in response to predefined circumstances that surpass a threshold or arrive at a specific state (Aksa, 2021; Akkermans, 2024).

A more sophisticated method than the two previously mentioned, known as predictive Maintenance, uses sensor technology and data analytics to forecast when Maintenance is required. This prediction is made using real-time data and machine learning algorithms. This strategy contributes to increased equipment efficiency and lower maintenance costs by enabling the early detection of any faults before they become serious (Aksa, 2021).

Performing Maintenance on a piece of equipment or an asset when the chance presents itself, as opposed to adhering to a defined timetable or waiting for a breakdown, is known as opportunistic Maintenance. The basic concept is to capitalise on circumstances in which Maintenance may be performed without interfering with business operations or resulting in downtime. It entails routine equipment monitoring and Maintenance or repairs carried out during scheduled downtimes, such as planned shutdowns, when the equipment is not being actively used, or during a window of opportunity that has the least negative influence on output.

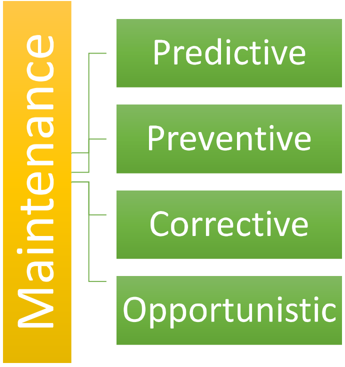


Fig. 3. Main type of Maintenance.

When choosing a maintenance plan, companies must carefully assess their unique demands and operational requirements, as each form of Maintenance has benefits and downsides of its own. Organisations may reap the advantages of enhanced safety, reduced downtime, optimal resource allocation, and improved equipment reliability by implementing the proper maintenance strategy.

Maintenance procedures have changed significantly in the context of Industry 4.0, moving from reactive to proactive and predictive tactics. The path of Maintenance 4.0 is illuminated by insights from seminal studies (Tran Anh, 2018), investigation of predictive Maintenance in Industry 4.0 production enterprises, studies on sensors' role in Industry 4.0 and IIoT (Porokhnya, 2022), and insights into maintenance protocols in the railway industry (Massaro, 2020).

Particular emphasis has been placed on how Industry 4.0 incorporates predictive Maintenance (Tran Anh, 2018). This revolutionary method uses sensor data, IoT, and AI analytics to predict equipment faults before they happen. This boosts operational efficiency by minimising downtime and optimising resource use.

As vital conduits, sensors record real-time data that is necessary for predictive Maintenance. They revolutionise machinery maintenance by easing the transition from reactive models to proactive, predictive ones (Porokhnya, 2022).

Maintenance 4.0's application can be extended beyond manufacturing (Massaro, 2020), highlighting the technology's value in vital infrastructure, such as the railroad sector. Predictive maintenance techniques guarantee operational continuity, safety, and dependability by anticipating and fixing any problems.

2.4. What is Industry 5.0, and why is the transition being made?

These research studies point in the same direction: Industry 4.0 is changing maintenance tactics. They highlight the critical role that sensors, AI, and data analytics play in enabling predictive Maintenance. In line with the principles of Industry 4.0, this paradigm change from reactive to proactive Maintenance ensures operational resilience and efficiency in the modern industrial environment (Fig.4).

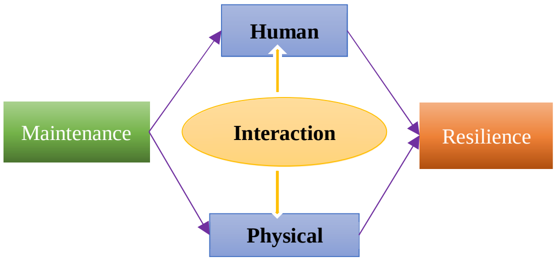


Fig. 4. Human interaction :in the maintenance process.

In January 2021, the European Commission released a report called "Industry 5.0: Towards a Sustainable, human-centric and Resilient European Industry" (https://op.europa.eu/en/publication-detail/-/publication/468a892a-5097-11eb-b59f-01aa75ed71a1), offering a thorough analysis of the necessity of accelerating ongoing transformations using digital and green technologies for both environmental and economic recovery. With a key focus on improving the sustainability and resilience of the industrial sector, this Industry 5.0 vision is positioned as a complement to and extension of the characteristics offered in Industry 4.0. The report outlines a number of Industry 5.0 building components: The industry is considered a force for innovation and revolutionary change. Moreover, digital technologies, such as robots and artificial intelligence (AI) (Škultéty, 2023), are emphasised for enhancing human-machine interactions, highlighting the special value that human workers contribute to the manufacturing floor. Industry 5.0 is meant to create cutting-edge technology with a human focus, empowering and assisting workers rather than displacing them. The report highlights how important European industry is in paving the path for a more environmentally friendly economy. Industry 5.0 is anticipated to profoundly affect society, requiring alterations to industry professionals' jobs and skill sets.

The Industry 5.0 vision also identifies six enabling technologies: customised human-machine interaction, digital twins and simulations, bio-inspired technologies, artificial intelligence, data transmission and analysis technologies, and technologies for energy efficiency, renewables, storage, and autonomy (Nemani, 2022; Chen, 2021).

The goal is to create value by coordinating technical advancement with socially beneficial outcomes, ecological sustainability (such as CO2 reduction and the circular economy), and economic profitability (Hou, 2023). The human-centric design of Industry 5.0 proposes a cooperative interaction between people and robots.

2.5. Differences between Industry 4.0 and 5.0

Industry 4.0 is defined by incorporating digital technologies, such as cloud computing, big data analytics, and the Internet of Things (IoT), into industrial operations(Bhargava, 2022). Process mapping in Industry 4.0 is commonly done with Business Process Modeling and Notation (BPMN), which offers a static picture of the situation when digital sensors and actuation systems transmit data are not under the control of the same PM model. In Industry 4.0, the primary purpose of the Decision Support System (DSS) is to send out online-monitored alarm signals. The major applications of electronic components on manufacturing machinery are in the development of sensors and Human-Machine Interfaces (HMIs) (Massaro, 2022).

Industry 5.0, on the other hand, is a more sophisticated and integrated approach to production management, using artificial intelligence (AI) and smart electronic systems to instantly optimise machine settings and managerial choices. Processes in Industry 5.0 are mapped using decisional logic that is incorporated into the Predictive Maintenance (PM) model. This results in a dynamic process where a calculus unit's real-time automated decisions determine which subprocesses to choose. The Decision Support System (DSS). is a stand-alone system that automatically adjusts machine parameters based on a self-learning methodology (Massaro, 2022). It does this by automatically configuring the best tools and machines for self-adaptive production as well as by implementing DSS-detecting alarms using past sensor data. By manufacturing electronic chips and boards incorporated into manufacturing machines, integrating McCulloch-Pitts neurons with transistors and other electronic components that replicate the AI logic through logic ports, and creating AI logic, innovative, sophisticated electronic systems may be produced (Massaro, 2022).

Industry 5.0 is an increasingly sophisticated and integrated approach to production management. Real-time machine settings and management choices are optimised via the use of AI and sophisticated electronic systems, resulting in a more dynamic and self-adaptive production process.

In the context of modern production, the idea of "Operator 5.0" highlights the significance of extended reality (XR) technologies, such as augmented reality (AR), mixed reality (MR), and virtual reality (VR) (Mourtzis, 2023; Deshpande, 2023). These immersive technologies provide new avenues for collaborative manufacturing, shopfloor personnel training, and Maintenance assistance. In order to prepare operators for the Operator 5.0 position and to meet the needs of the changing industrial landscape, the Operator 5.0 framework also calls for the creation of novel and efficient training approaches (Ariansyah, 2023).

In addition, the shift to Operator 5.0 entails building trustworthy human-machine relationships in regards to automation, robotics, and artificial intelligence (AI) systems to develop truly resilient and intelligent manufacturing systems that provide operators with new capabilities (Deshpande, 2023).

There is potential for an augmented reality collaborative product design cloud-based platform in the context of modern manufacturing, as evidenced by the exploration of XR technologies in the learning factory. This shows that, in the context of modern manufacturing, XR technologies may help aid maintenance and repair activities (Mourtzis, 2023).

In conclusion, the shift to Industry 5.0 and Operator 5.0 entails utilising immersive technologies like XR to improve training, collaborative product design, and maintenance support in contemporary manufacturing, aiming to equip operators with new knowledge and resources for the changing industrial environment.

3. Maintenance 5.0

The next step in maintenance practices is represented by Maintenance 5.0, or Industry 5.0 maintenance, which combines human skills and cutting-edge technology to optimise maintenance procedures inside the Industry 5.0 framework. In order to accomplish effective, preventative, and data-driven maintenance plans, this method strongly emphasises human engagement with intelligent systems.

Predictive Maintenance (PdM) is crucial in the context of Maintenance 5.0. PdM replaces static maintenance periods with dynamic scheduling of maintenance tasks by utilising sensor technologies, machine learning, and data analytics to anticipate equipment health (Table 1). The just-in-time methodology is supported by this switch to dynamic maintenance intervals, which enables prompt replacements and repairs depending on anticipated equipment failures.

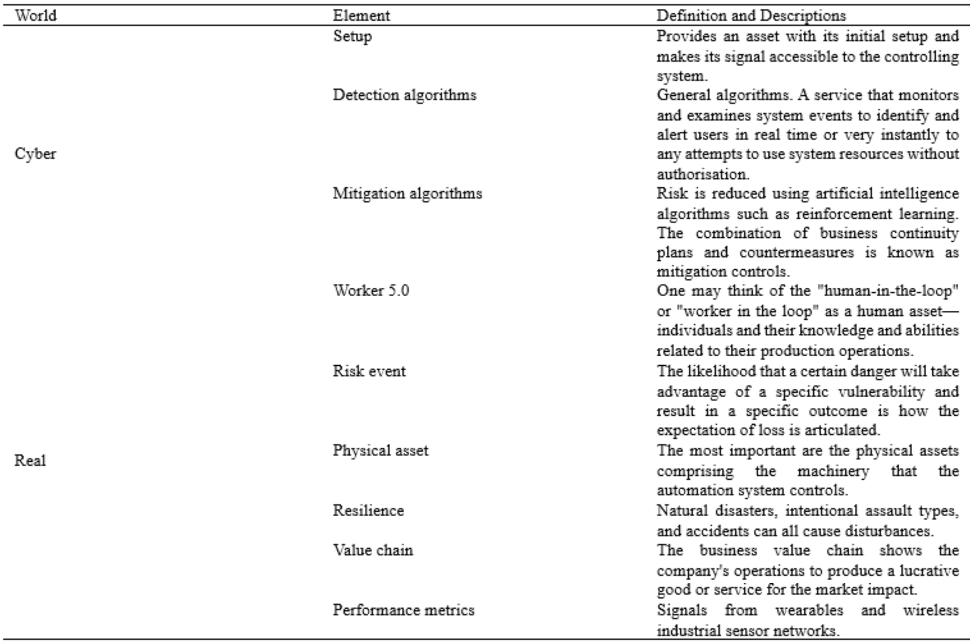
Decision-makers have had difficulty accepting PdM in Industry 5.0 because they frequently oppose incorporating data-driven, system-generated guidance into their daily operations. This opposition emphasises comprehending how decision-makers work is altered by PdM implementation and how this alteration influences their adoption of PdM systems (van Oudenhoven, 2023).

The influence of PdM adoption on decision-makers' work, and acceptance of system-generated recommendations is further highlighted by the work system viewpoint. The dynamic and problem-solving character of maintenance scheduling is demonstrated by how human decision-makers regularly modify system-generated schedules in light of new information. This highlights the crucial role that human decision-makers play in the maintenance scheduling process.

Research (van Oudenhoven, 2023) offers insightful information about the behavioural elements of PdM deployment and how it affects Industry 5.0 decision-makers. The authors provide a thorough knowledge of the human-system interaction in the context of Maintenance 5.0, shedding light on the potential and problems involved with incorporating PdM into maintenance operations.

Maintenance 5.0 is a paradigm shift toward data-driven and collaborative maintenance methods where human skill and cutting-edge technology combine to optimise maintenance procedures and raise overall operational effectiveness inside Industry 5.0.

Table 1. Cyber vs Real world differences.



World	Element	Definition and Descriptions
Cyber	Setup	Provides an asset with its initial setup and makes its signal accessible to the controlling system.
	Detection algorithms	General algorithms. A service that monitors and examines system events to identify and alert users in real time or very instantly to any attempts to use system resources without authorisation.
	Mitigation algorithms	Risk is reduced using artificial intelligence algorithms such as reinforcement learning. The combination of business continuity plans and countermeasures is known as mitigation controls.
Real	Worker 5.0	One may think of the "human-in-the-loop" or "worker in the loop" as a human asset—individuals and their knowledge and abilities related to their production operations.
	Risk event	The likelihood that a certain danger will take advantage of a specific vulnerability and result in a specific outcome is how the expectation of loss is articulated.
	Physical asset	The most important are the physical assets comprising the machinery that the automation system controls.
	Resilience	Natural disasters, intentional assault types, and accidents can all cause disturbances.
	Value chain	The business value chain shows the company's operations to produce a lucrative good or service for the market impact.
	Performance metrics	Signals from wearables and wireless industrial sensor networks.

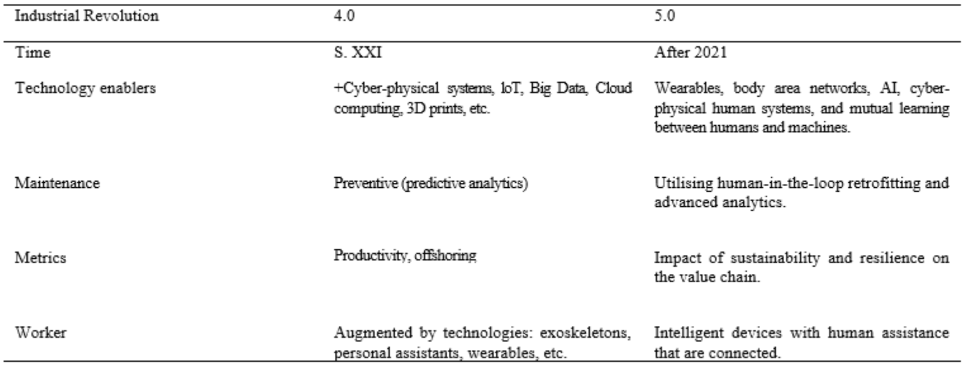
3.1. Comparison between Maintenance 4.0 and Maintenance 5.0

In order to enable predictive Maintenance, condition monitoring, and real-time asset management, maintenance 4.0 focuses on integrating digital technologies like the Internet of Things (IoT), big data analytics, and machine learning. It strongly emphasises using connectivity and sophisticated data analytics to streamline maintenance procedures and reduce downtime (Bokrantz, 2019). However, by adding a human-centric approach, Maintenance 5.0 expands on the idea of Maintenance 4.0. The interaction and cooperation between human decision-makers and data-driven, system-generated guidance are highlighted in Maintenance 5.0. Examining how the nature of decision-makers' jobs evolves and how these changes impact their acceptance of predictive maintenance systems tackles the acceptance challenges associated with deploying data-driven maintenance solutions (van Oudenhoven, 2023).

Research has also explored the difficulties of decision-makers accepting data-driven, system-generated recommendations (van Oudenhoven, 2023). The paper draws attention to the fact that decision-makers frequently reject incorporating data-driven, system-generated advice into their working procedures. It attempts to resolve these issues with acceptance by examining how decision-makers work is altered when predictive Maintenance is implemented and how this alteration influences their acceptance of predictive maintenance systems.

To summarise, the primary focus of Maintenance 4.0 is on integrating digital technologies and advanced data analytics to facilitate real-time asset management and predictive Maintenance. On the other hand, Maintenance 5.0 expands on this idea by integrating a human-centric approach and tackling the acceptance issues associated with applying data-driven maintenance solutions (Table 2). In predictive Maintenance and industrial maintenance management, the contrast between Maintenance 4.0 and Maintenance 5.0 highlights the shift from a primarily technologically-driven strategy to a more collaborative and human-centred approach.

Table 2. Differences between 4.0 and 5.0 industrial revolutions



Industrial Revolution	4.0	5.0
Time	S. XXI	After 2021
Technology enablers	+Cyber-physical systems, IoT, Big Data, Cloud computing, 3D prints, etc.	Wearables, body area networks, AI, cyber-physical human systems, and mutual learning between humans and machines.
Maintenance	Preventive (predictive analytics)	Utilising human-in-the-loop retrofitting and advanced analytics.
Metrics	Productivity, offshoring	Impact of sustainability and resilience on the value chain.
Worker	Augmented by technologies: exoskeletons, personal assistants, wearables, etc.	Intelligent devices with human assistance that are connected.

4. **Conclusions**

Several important conclusions may be made from the comparison of maintenance procedures in Industry 4.0 and Industry 5.0:

Industry 5.0 is meant to continue and enhance the features provided by Industry 4.0, with a major emphasis on enhancing human-machine interactions, sustainability, and resilience. This change emphasises the significance of empowering and supporting employees, developing cutting-edge technology with an emphasis on people, and clearing the way for an economy that is more ecologically friendly. In this new context, an adaptive and all-encompassing approach to Maintenance is necessary to move from Industry 4.0 to Industry 5.0. Although Industry 4.0 leverages modern technology to streamline operations and increase efficiency, Industry 5.0 emphasises human-centred and collaborative Maintenance, which calls for changes to industry professionals' roles and skill sets.

Industry 5.0 offers a more human-centric approach with decentralised maintenance teams, AI-enhanced decision-making, and human-robot cooperation. In contrast, Industry 4.0 stresses digital technology and data-driven techniques, notably predictive Maintenance and condition monitoring systems. By combining sensor data, IoT, and AI analytics to allow predictive Maintenance, Industry 4.0 has completely changed maintenance methods. This has increased operating efficiency and decreased downtime. Industry 5.0, in contrast, Industry strongly emphasises combining human expertise with state-of-the-art technology to improve overall operational performance and optimise maintenance operations.

Finally, the comparison of Industry 4.0 and Industry 5.0 maintenance practices highlights how maintenance techniques are always moving and evolving across industrial ecosystems. It offers insightful guidance on managing the difficult transition and reevaluates maintenance schedules for industry participants and decision-makers to stay competitive and resilient in the evolving industrial environment.

To conclude, the writers recommend some propositions for future research on the new trends in the Maintenance of 5.0 industries, in order to guide them in the research of practical solutions for all the future criticalies highlighted in this paper:

RP1: Do autonomous maintenance systems raise ethical implications? Deploying autonomous maintenance systems implies issues regarding decision-making, accountability, and transparency, meaning there's a need to develop guidelines for responsible AI use in Maintenance 5.0

RP2: What is the economic impact of Maintenance 5.0 adoption? Initial investment costs, productivity gains, and long-term financial benefits are all key variables to properly evaluate the feasibility of transitioning to advanced maintenance technologies.

RP3: Are there psychosocial implications of Maintenance 5.0 implementation? Even though the main feature of Industry 5.0 as a whole is the increased role of the human element, there’s still an ever-increasing reliance on technology which is supposed to collaborate with said human element, meaning there’s the need to investigate factors such as employee stress, job satisfaction, and the perception of autonomy.

RP4: What are the major dangers regarding cybersecurity? Implementing so many cyber systems at such a profound level inevitably raises concerns about external attacks, meaning there’s the need for analysing what are the best options for protections of such systems, as well as their economical and infrastructural impact.

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