Human-Centric PHM in the Era of Industry 5.0

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ABSTRACT

The maintenance industry is undergoing a major transformation as it embraces the shift towards Industry 5.0. The focus of Industry 5.0 is on the integration of human intelligence with advanced technologies. It emphasizes interaction and collaboration between humans and machines and aims to combine the strengths of both. The efficiency of prognostics and health management (PHM) for maintenance in industrial contexts can be enhanced by improving this human-machine interaction and collaboration. This paper investigates the human-centric aspects, with a focus on PHM systems for facilitating the enablement of Industry 5.0 in maintenance. Acknowledging human as an active participant, this study explores their integral role in designing and developing PHM systems. The data collection for this study has been based on available literature, active and passive observations, and unstructured interviews and discussions with experienced industry professionals. As a result of the analysis of collected data, this study identifies and highlights potential areas for research and exploration. The research in these areas can advance the understanding and application of human-centric PHM strategies within Industry 5.0 in maintenance contexts. This is expected to improve the resilience and sustainability aspects of the industrial ecosystem and facilitate the shift towards Industry 5.0.

Keywords— Maintenance, Prognostics and Health Management, Industry 5.0, Human-centric

1. INTRODUCTION

The industrial revolution over the years has led to systematic developments and advancements in all sectors of society. Industries have grown dramatically, starting with the mechanical revolution of the "steam engine" era (Industry 1.0), progressing towards electrical breakthroughs (Industry 2.0), developing further into the computerization and automation era (Industry 3.0), and now towards cyber-physical systems (Industry 4.0) (Leng et al., 2022). Even though Industry 4.0 is still under constant research and development, the concept of Industry 5.0 is being actively defined, discussed, and explored by academia, industry, and policymakers. It aims to extend, complement, and build on the technological advancements of its predecessor, Industry 4.0 (Raja Santhi & Muthuswamy, 2023).

The concept of Industry 5.0 is based on integrating human-centric aspects with advanced technologies for enhanced productivity and operations (Nahavandi, 2019). It emphasizes on human-centric aspects like human-machine collaboration, worker well-being, empowering workers with enhanced decision-making, and personalized/customized systems that can enhance the industry's sustainability and resilience aspects (Adel, 2022; Industry 5.0: Towards More Sustainable, Resilient and Human-Centric Industry - European Commission, n.d.). Unlike its predecessors, where the key factors were automation and technology which gave the idea of the technologies as a partial replacement for humans, Industry 5.0 seeks to integrate the strengths of both humans and machines to optimize industrial processes. In this context, it involves the integration of human intelligence, creativity, and experience, with the capabilities of advanced technologies such as AI, data analytics, IoT, etc. (Ghobakhloo et al., 2023)

PHM leverages data analytics, condition monitoring systems, digital twins, and other advanced technologies to forecast potential failures and issues before they occur, allowing proactive maintenance actions to be taken. This shift towards predictive maintenance, facilitated by PHM, helps minimize unplanned downtime, optimize maintenance costs, and improve overall asset effectiveness (Zio, 2022).

Industry 5.0 will further facilitate PHM in maintenance by focusing on human-centric aspects, which will enable maintenance workers to leverage PHM data and insights to make more informed, adaptive, and resilient maintenance decisions.

The purpose of this study is to advance the understanding and application of human-centric PHM strategies within Industry

5.0 maintenance contexts and make the industrial ecosystem more resilient and sustainable.

The objectives of this study are:

1. To investigate the human-centric aspects of Industry 5.0 in maintenance, focusing on PHM systems.
2. To identify the potential areas for research and exploration for advancing the understanding and application of human-centric maintenance strategies within the context of Industry 5.0.

2. METHODOLOGY

This study was conducted using a mixed-method research approach to investigate the human-centric aspects, with a specific focus on PHM systems for facilitating the enablement of Industry 5.0 in maintenance. The methodology followed consisted of the following components:

- Literature Review: A review of existing literature was conducted on Industry 4.0 and 5.0, human-centric aspects, PHM systems, and maintenance efficiency to establish a theoretical foundation for the study.
- Observations: To understand the practical implementations and dynamics of human-machine interactions in industrial maintenance, active and passive observations were made. This included observing industrial professionals utilizing PHM systems in real-world settings to see how they interact with these systems during their daily operations. Observing demonstrations of maintenance systems in laboratory settings during lab visits, which included a diverse audience ranging from students to industry professionals.
- Unstructured Interviews and discussions: Conducted unstructured interviews and discussions with asset managers from companies serving as knowledge partners for rail vehicles and public transport agencies in Sweden. These interviews/discussions were conducted during workshops, seminars, and regular meetings. They provided strategic insights into the adoption and challenges of PHM systems. They additionally provided us with valuable insights from maintenance worker's perspective enabling us to gather firsthand information on their experiences, challenges, and perspectives regarding the integration of human aspects into PHM systems.
- Data Analysis: Qualitative analysis of data collected from literature surveys, observations, and interviews to identify key themes, patterns, and challenges associated with human-centric PHM strategies in Industry 5.0 maintenance contexts.

3. LITERATURE REVIEW

A review of existing literature was conducted on Industry 4.0, and Industry 5.0 in connection with maintenance and PHM systems to establish a theoretical foundation for the study. Since human-centricity is a key factor in moving towards Industry 5.0, we conducted a literature review on human-centric aspects in maintenance and PHM. These considered reviews were from the period 2014 - 2024. To help understand the Industrial Revolution journey, works focusing on the revolutions thus far were also considered. These works dates from 1956 till the present. Key search terms included "Industry 4.0 AND PHM", "Industry 4.0 AND maintenance", "Industry 5.0 AND PHM", "Industry 5.0 AND maintenance", "Human-centric AND PHM", and "Human-centric AND maintenance". In total, the study was conducted with 26 relevant works of literature.

3.1. Industrial Revolutions Leading to Industry 5.0

The Industrial Revolutions, over the years, have helped in shaping the current industrial landscape. Starting in the late 18th century, the first industrial revolution was enabled by the mechanical revolution and the usage of steam power resulting in faster production processes (Martinelli et al., 2021). Subsequently came the 2nd Industrial Revolution, which focused on the electrical revolution for mass production techniques and implementing assembly lines. Industry 3.0 brought the digital revolution with IT and automation transformations which resulted in significant technological advancements and societal changes.

The current Industrial Revolution i.e. Industry 4.0 saw an increase in Cyber-Physical Systems, IoT and AI which focused on the integration of technology with physical assets. The focus has been primarily on the technological aspects, with limited attention paid to the human and social factors within organizations (Moraes et al., 2023). Extending this is the concept of Industrial 5.0, which works alongside the technological advancements till Industry 4.0 but puts humans in the centre of it. Figure **1** shows an advancement of industrial processes from an abstract level.

The revolutionary journey from the first industrial revolution to Industry 4.0, which focused on a technology-driven approach emphasizing digitalization and advanced technologies like digital twins, AI and cybersecurity, laid the foundation for Industry 5.0 (Nagano, 2019). Industry 5.0, as introduced by the European Commission, (*Industry 5.0 - European Commission*, n.d.) represents a shift towards a user-centric and value-driven approach, emphasizing the crucial role of humans in the industrial process and promoting principles of social well-being, sustainability, and human-machine collaboration (Beaudreau, 2018; Verma et al., 2022).

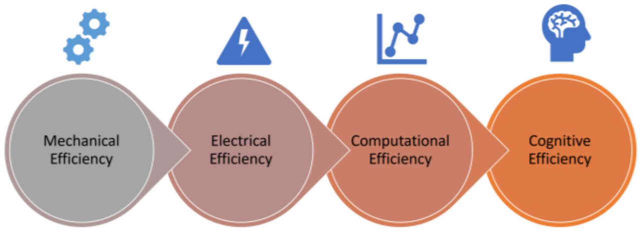

Figure 1: Advancing of Industrial Processes

Industrial revolutions have had significant impacts on maintenance practices, influencing how industries manage and upkeep their machinery and equipment. Table **1** (adapted by (Poór et al., 2019) shows the relationship between industrial revolutions, their enablers and key maintenance facilitators(Coleman, 1956). It is important to note that the mentioned enablers and maintenance facilitators extend and complement their predecessor's enablers and maintenance facilitators respectively.

Table 1: Industrial Revolutions- enablers and key maintenance facilitators

Industrial Revolution	Enablers	Key maintenance facilitators
Industry 1.0	Mechanical Revolution, Steam Power	Visual Inspection
Industry 2.0	Electrical Revolution, Mass production	Instrumental/Tool Inspection, Preventive Maintenance
Industry 3.0	Digital Revolution, Automation	Sensors, CMMS, Predictive Maintenance
Industry 4.0	Cyber-Physical Systems, IoT, AI, ML	Data Analytics (Predictive Analytics), Digital Twins, Condition-Based Maintenance
Industry 5.0	Human-Machine Collaboration, AI, ML	HSI, Advanced Predictive Analytics, AR/VR, Blockchain

3.2. Industry 5.0 and its implications for the maintenance industry

According to the European Commission (*Industry 5.0 - European Commission*, n.d.; *Industry 5.0: Towards More Sustainable, Resilient and Human-Centric Industry - European Commission*, n.d.), implementing Industry 5.0 means placing the well-being of humans at the centre of the industrial processes. It encourages the usage of advanced technologies to focus beyond productivity and efficiency and emphasizes the well-being of the human workforce while considering the planet's resource constraints. It builds on the existing industrial revolution i.e. Industry 4.0 and compliments it while focusing on three key factors, Human-centricity, Sustainability and Resilience (Figure 2).

Industry 5.0 emphasizes the collaboration between humans and machines, focusing on enhancing human creativity and well-being while leveraging advanced technologies like big data analytics, IoT, collaborative robots (cobots), Blockchain, digital twins, and future 6G systems (Adel, 2022; *Industry 5.0 - European Commission*, n.d.).

The impact of Industry 5.0 on the maintenance industry is profound. It implies the usage of modern advanced technologies with a human-centric approach to sustainable and resilient maintenance processes. It involves data-driven decision-making that addresses potential maintenance faults before they lead to breakdowns, optimising operational efficiency, reducing downtime, keeping customers satisfied, and contributing to sustainability efforts by focusing on repair and recycling rather than replacement (Psarommatis et al., 2023).

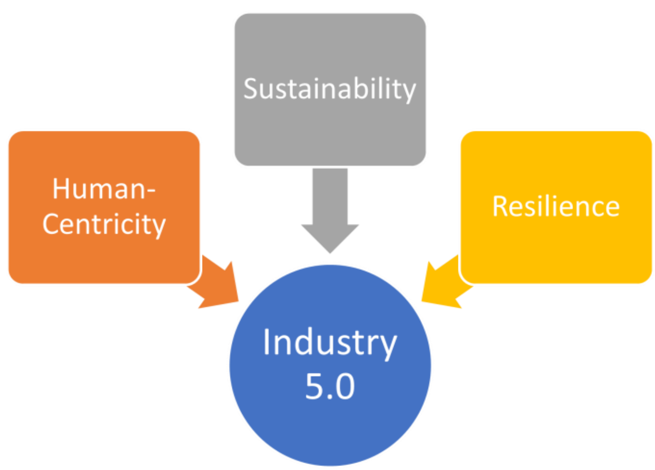

Figure 2: 3 pillars of industry 5.0

3.3. Prognostics and Health Management (PHM) Systems and Industry 5.0

PHM systems are designed to monitor the health of industrial assets. In the context of Industry 5.0, PHM systems can be seen as a cornerstone for the integration of modern advanced technologies like big data analytics, IoT, and A) with human-centric approaches within industrial maintenance practices. It enhances the efficiency and effectiveness of maintenance practices, operational efficiency, and sustainability of industrial operations. (Biggio & Kastanis, 2020) (Adel, 2022).

Industry 5.0 places human well-being at the centre of industrial processes. PHM systems support this approach by empowering maintenance workers with real-time insights and decision-support tools. By providing workers with data-driven insights about equipment health and performance, PHM systems help integrate human intelligence with these insights to make informed decisions, optimize maintenance activities, and ensure the safety and well-being of workers in industrial environments (Kumar et al., 2023).

PHM systems also play an important role in ensuring the sustainability and resilience of industrial maintenance processes. By forecasting asset failures and scheduling maintenance actions at optimum times, these systems help to minimize waste and reduce the environmental impact of manufacturing operations contributing to the sustainability factor(Ghobakhloo et al., 2024). Additionally, PHM systems contribute to the implementation of smart factories, which are a key aspect of Industry 4.0 and Industry 5.0, by providing real-time insights into the health of industrial assets and enabling more efficient and effective maintenance strategies which contribute to enhancing the resilience of the industrial assets (Kumar et al., 2023).

Predictive maintenance (PdM) which is facilitated by PHM systems monitors the health of industrial assets, predicts potential failures, and optimizes maintenance schedules based on the predicted future state of equipment components. By adopting a human-centric approach to PdM within the Industry 5.0 framework, organizations can enhance decision-making processes, increase trust between decision-makers and predictive models, allocate resources effectively, and improve overall maintenance effectiveness(van Oudenhoven et al., 2023).

Therefore, the integration of human-centric maintenance practices within the principles of Industry 5.0 enables proactive management of maintenance needs, reduces costs, enhances operational efficiency, ensures equipment reliability, and contributes to sustainable maintenance practices by focusing on repair and recycling rather than replacement. This connection highlights the importance of predictive maintenance which is facilitated by PHM systems as a key enabler of Industry 5.0's vision for smarter, more efficient, effective, and human-centred maintenance processes.

3.4. Human involvement in designing and developing PHM systems

In the era of advanced technologies, a human-centric approach to developing PHM systems for industrial maintenance is not just desirable but essential. A human-centric PHM system empowers users with intuitive interfaces, actionable insights, and decision support tools to optimize maintenance strategies ultimately leading to more efficient and effective maintenance activities.

Involving domain experts and their insights into industrial processes, especially maintenance activities, aids in focusing on critical aspects that are prone to failure. Domain experts collaborate with developers early on to define system requirements tailored to operational contexts, and technician knowledge levels (Toothman et al., 2023). Humans can also consider factors like production load, environmental conditions, and other maintenance activities that may influence asset health, which algorithms might overlook (McDonnell et al., 2018).

Humans also play a critical role in selecting the relevant data points for training and monitoring equipment health, ensuring the quality of data used in PHM systems and interpreting system outputs (Siew et al., 2020). Additionally, Usability Engineering and Usability Requirement Analysis are critical areas where specialists ensure that PHM systems meet the maintenance personnel's needs and requirements in a user-friendly manner.

Usability Engineering aspects emphasize visually presenting clear explanations, minimizing cognitive load to enhance usability and ensure effective decision-making for maintenance personnel (McDonnell et al., 2014). This human-centred approach is essential to optimize the functionality and user-friendliness of PHM systems, making them more accessible and efficient for operators.

Usability Requirement Analysis, on the other hand, focuses on identifying and documenting the usability needs and objectives of the system. This involves gathering and analysing user requirements related to usability, accessibility, and user experience, providing a framework for designing and evaluating the user interface.

Customized PHM dashboards can prioritize relevant data points for specific tasks and assets, aiding in quicker issue identification and efficient maintenance actions. Alerts and notifications can also be tailored according to their criticality reducing information overload and ensuring timely response to critical issues(McDonnell et al., 2014).

Another interesting area is to investigate the legitimacy aspect of PHM systems for a necessary understanding of why such predictions were made, fostering trust in the system and the recommendations made by it. It will encourage confident decision-making by the technicians. This comes under the umbrella of Explainable AI for trust and continuous improvement. It enables debugging in case of incorrect recommendations, and human-in-the-loop learning for continuous improvement of algorithms. By understanding the reasoning behind predictions, humans can detect and address these issues, leading to improved accuracy and reliability of the PHM system (Amin et al., 2022; Nor et al., 2021).

4. Results

This research highlights some key insights while integrating human-centric aspects with PHM systems within the context of Industry 5.0 and industrial maintenance.

Following are the findings for the objectives of this study:

Objective 1: To investigate the human-centric aspects of Industry 5.0 in maintenance, focusing on PHM systems.

Industry 5.0 places the well-being of humans at the centre of industrial processes. It emphasizes the collaboration between humans and machines. PHM systems play an important role in this approach, empowering maintenance workers with valuable insights and decision-support tools. These systems when integrated with human intelligence and data-driven insights can optimize maintenance activities and ensure worker safety and well-being.

Integrating human aspects into PHM systems involves real-time collaboration between human operators and machines and the incorporation of human-in-the-loop mechanisms. These possibilities aim to enhance the usability, acceptance, and integration of PHM systems within industrial work environments.

Objective 2: To identify potential areas for research and exploration for advancing the understanding and application of human-centric maintenance strategies within the context of Industry 5.0.

The identified areas for further exploration within the context of Industry 5.0 and industrial maintenance especially PHM systems include human-system interaction, Explainable AI, Usability Requirement Analysis and Usability Engineering. These areas highlight the need for exploring the dynamics of human-machine collaboration and identifying strategies to optimize human-system interactions for improved maintenance activities and enhanced decision-making. Observations and discussions with maintenance professionals have highlighted the critical role of seamless human-system interaction in enhancing operational efficiency. Additionally, future research will delve into Explainable AI, to enable maintenance personnel to understand the reasoning behind AI-generated predictions and recommendations, fostering trust in the system and facilitating human-in-the-loop processes for continuous improvement. Insights from unstructured interviews and discussions emphasized the importance of transparency in AI systems for maintenance workers. Furthermore, Usability Requirement Analysis will play a pivotal role in identifying and prioritizing user needs and preferences in the context of PHM systems. This area benefits significantly from feedback gathered through interviews and discussions with asset managers. Usability Engineering will play a crucial role in designing user-centric interfaces and interactions for PHM systems in the Industry 5.0 context to enhance the usability and user experience for maintenance personnel. Laboratory observations and real-world use cases have provided valuable insights into the need for creating more effective and user-friendly maintenance systems. Figure 3 shows the key insights of Industry 5.0 within the industrial maintenance context.

The transition to Industry 5.0 introduces several innovative challenges as compared to conventional maintenance activities. These include the integration of advanced technologies which require new skills and training for the users/workers. The focus shifts towards creating more responsive, robust, and resilient maintenance systems.

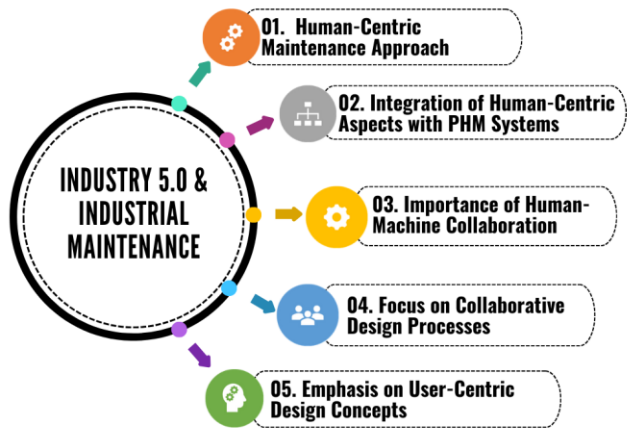

Figure 3: Key insights of Industry 5.0 within the industrial maintenance context

5. Conclusion

The maintenance industry is constantly developing and with the latest industrial revolution i.e. Industry 5.0, the shift is towards a human-centric maintenance approach. The research on industrial maintenance especially the PHM systems within the context of Industry 5.0 is important. It emphasizes the significance of the role of human involvement in optimising maintenance practices. The integration of human-centric aspects with PHM systems also enables industries to improve asset reliability and enhance operational efficiency. Furthermore, the findings emphasize the importance of human-machine collaboration, and data-driven decision-making in realizing the full benefits of Industry 5.0 in maintenance operations. While interviews primarily focused on railway experts, the findings can be extended to various industrial settings, indicating broader applicability. This research highlights the need to focus on collaborative design processes and user-centred approaches to ensure effective human-machine interactions, which are essential for the successful implementation of maintenance practices within the context of Industry 5.0.

The future research will be built on the findings and insights from this research. Future work will focus on achieving a more seamless and efficient human-machine interface, considering human-centric aspects during system design and implementation. As a result, maintenance activities will eventually be more effective and efficient. An important area of research is quantifying the effectiveness and efficiency of such human-centric PHM systems.

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NOMENCLATURE

AI	Artificial Intelligence
IoT	Internet of Things
PHM	Prognostics and Health Management
XAI	Explainable Artificial Intelligence
CMMS	Computerized Maintenance Management System
HSI	Human-System Interaction
AR	Augmented Reality
VR	Virtual Reality

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