Proceedings of the 35th European Safety and Reliability & the 33rd Society for Risk Analysis Europe Conference
Edited by Eirik Bjorheim Abrahamsen, Terje Aven, Frederic Bouder, Roger Flage, Marja Ylönen
 Published by Research Publishing, Singapore.
doi: 10.3850/978-981-94-3281-3_ESREL-SRA-E2025-P0757-cd

A roadmap to integrate the sustainable impact of Industry 4.0 technologies in maintenance policies

Mouhamadou Mansour DIOP

Université de technologie de Compiègne, Roberval, Compiègne, France.
Polytechnique Montréal, Mathematics and Industrial engineering department, Montreal, Canada.
E-mail: mouhamadou.diop@utc.fr

Amélie PONCHET DURUPT

Université de technologie de Compiègne, Roberval, Compiègne, France.
E-mail: amelie.durupt@utc.fr

Christophe DANJOU

Polytechnique Montréal, Mathematics and Industrial engineering department, Montreal, Canada.
E-mail: christophe.danjou@polymtl.ca

Yacine BAOUCH

Université de technologie de Compiègne, Roberval, Compiègne, France.
E-mail: yacine.baouch@utc.fr

Nassim BOUDAOUD

Université de technologie de Compiègne, Roberval, Compiègne, France.
E-mail: nassim.boudaoud@utc.fr

Maintenance decision-making has traditionally focused on economic criteria, yet the growing demand for carbon neutrality highlights the need to address all three dimensions of sustainability (economic, environmental, and social) within manufacturing industries. Although Industry 4.0 (I4.0) enabling technologies are widely recognized for their potential benefits, their full sustainability impacts remain poorly understood. Existing studies often emphasize their positive contributions but lack precise quantification of both their positive and negative effects. Moreover, these analyses tend to focus exclusively on the use phase, neglecting impacts during manufacturing and end-of-life stages. This article proposes a structured roadmap for evaluating the lifecycle impact of I4.0 technologies on maintenance policies. By considering multiple scenarios, this approach quantifies their effects across all dimensions of sustainability, ensuring that the benefits realized during use outweigh the negative impacts from manufacturing and disposal. To illustrate its applicability, a preliminary use case is presented using a vibration test bench equipped with IoT sensors. Looking ahead, these sensors are set to generate fault data under varying conditions, which will be used to test maintenance scenarios. Additionally, as outlined in the roadmap, a life cycle assessment (LCA) is planned for the sensor to provide a comprehensive assessment of its sustainability impact. This case study serves to demonstrate the roadmap's relevance and its potential to support sustainable maintenance decision-making, laying the foundation for integrating I4.0 enabling technologies into maintenance strategies while avoiding undesirable rebound effects that could compromise sustainability goals.

Keywords: Maintenance policies, industry 4.0, sustainability, economic-environmental and social impacts.

1. Introduction

Industry 4.0 (I4.0), often associated to the Fourth Industrial Revolution, represents a major transformation in manufacturing and industrial operations through the integration of advanced digital technologies Ertz and Gasteau (2023). This revolution is driven by the adoption of cyber-physical systems (CPS), Internet of Things (IoT), cloud computing, big data analytics (BDA), and artificial intelligence (AI), which enable better connectivity and smarter decision-making in industrial processes Waghanna et al. (2024). This convergence of physical and digital technologies creates interconnected and intelligent systems, promising enhanced efficiency, productivity, and flexibility across various industrial sectors Franciosi et al. (2020).

One of the key areas where I4.0 has had a major impact is maintenance, leading to the concept of Maintenance 4.0 Mabaso et al. (2024). Traditional maintenance methods, such as reactive maintenance, are being replaced by predictive approaches made possible by IoT sensors and AI Mabaso et al. (2024); Vrignat et al. (2022). These technologies allow real-time monitoring of equipment to identify potential faults before they cause breakdowns Saraswat and Agrawal (2023).

Moreover, the integration of I4.0 technologies in maintenance also plays a critical role in advancing sustainability goals (Madreiter et al. (2024). Maintenance 4.0 helps industries address environmental challenges and align with global sustainability frameworks by reducing costs linked to equipment failures, conserving energy, minimizing waste, and promoting circular economy practices Turner et al. (2020). Additionally, it enhances workplace safety and supports workforce development by requiring specialized skills for managing advanced digital tools Tomasoni et al. (2024); Almeida et al. (2023).

However, despite these benefits, the sustainable adoption of I4.0 technologies in maintenance policies poses several challenges Franciosi et al. (2020). While their operational advantages, such as cost reduction and improved reliability, are well-documented, their broader sustainability impacts across the entire lifecycle remain underexplored Franciosi et al. (2018); Orosnjak et al. (2021); Madreiter et al. (2024). Then, a more comprehensive understanding of the lifecycle implications of I4.0 technologies is therefore critical for the development of truly sustainable maintenance policies Vrignat et al. (2022).

To address these challenges, this paper proposes a roadmap for integrating and quantifying the sustainable impacts of I4.0 technologies in maintenance policies. The roadmap focuses on evaluating the economic, environmental, and social dimensions of I4.0 sustainability in maintenance policies through a lifecycle perspective.

The structure of this paper is as follows: the next section presents a comprehensive literature review, examining the current state of research on I4.0, maintenance 4.0, and their connection to sustainability. Following this, the proposition section details the development of the proposed roadmap and its illustration through a specific case study. The paper concludes by summarizing key contributions, practical recommendations, and directions for future research in this evolving field.

2. Literature review

This section explores the current state of research on the integration of I4.0 technologies into maintenance strategies, with a focus on their role in promoting sustainability. It aims to understand what has been documented about the impact of I4.0 technologies on maintenance policies for sustainable management, specifically in relation to the three pillars of sustainability: economic, environmental, and social. The key research questions driving this study are:

(i) RQ1: How do Industry 4.0 technologies influence maintenance policies in terms of sustainability outcomes across their lifecycle?
(ii) RQ2: What indicators and/or quantification models are employed to evaluate the impact of Industry 4.0 technologies on the sustainability of maintenance practices?

To address these questions, a systematic literature review (SLR) was conducted to examine current research, highlight gaps, and provide insights. The findings will be used to develop a roadmap to assess the impact of these technologies on sustainable maintenance practices.

2.1. *Methodology*

Two databases are used for the SLR: Scopus and Web of Science. Then, the search was organized around 4 main categories of keywords: digital transformation, maintenance, sustainability, and impact assessment, as identified in table 1. [a]

[a]"*" in some words in table 1 is a truncation operator used to search for all variations of a word from a common root, e.g., "industr*" includes industry, industrial, industries, etc.

Table 1. Groups of keywords.

Digital transformation	Maintenance	Sustainability	Impact
Industr* 4.0	Maintenance	Sustainab*	Impact
Industry 5.0	Asset management	Circular economy	Evaluation
Smart Factory		Life cycle assessment	Quantification
Digital manufacturing		LCA	Measurement
Smart manufacturing		Environmental	Assessment
Industrial Internet		Green	Metrics
Smart production			
Factor* of the future			
Advanced Manufacturing			
Intelligent Manufacturing			
Industr* of the future			
High value manufacturing			
Smart Industry			
Manufacturing 4.0			
Integrated industry			
Digital Factory			
Manufacturing Renaissance			

Moreover, the search was targeted to find articles written in english, and duplicates were removed to ensure the integrity of the dataset.

Next, we applied a filtering based on four exclusion criteria (EC) to narrow down the selection toward the most relevant articles.

(i) EC1 : Conference proceedings or book chapters or books.
(ii) EC2 : Articles that do not establish a relationship between sustainability, industrial maintenance, and Industry 4.0, as they fall outside the scope of this research.
(iii) EC3 : Articles in which the sustainable dimension of Industry 4.0 in the maintenance of industries is neither the main subject nor the secondary subject and is not sufficiently developed.
(iv) EC4 : Articles that do not propose indicators and/or quantification models to assess the impact of Industry 4.0 technologies on maintenance sustainability.

Following that, the selection was performed in two distinct steps. First, the titles, abstracts, and keywords of all articles were screened using the first two exclusion criteria because the third and fourth could not be reliably assessed from these elements alone. The second stage was a full text review for the articles selected at the initial screening. At this stage, the second, third, and fourth exclusion criteria were considered for each article. Articles not available as full texts were also excluded during this stage.

2.2. *Results*

Figure 1 reports the SLR process and its application. At the beginning, 280 papers were identified, 195 from Scopus and 85 from Web of Science. After removing 78 duplicates, 202 papers remained for analysis. In the first screening process, 70 articles were retained (28 conference articles, 42 journal papers), while the second screening reduced it to 7 (6 journal papers, 1 conference article), all published between 2019 and 2024. Table 2 presents the distribution of the selected papers by their year of publication.

Furthermore, 17 papers were found relevant but did not fully meet EC4.

2.3. *Discussion*

The following section summarizes the key findings from the literature review, addressing the research questions and highlighting the most relevant insights.

Table 2. Distribution of the selected papers by their year of publication.

Year	2019	2020	2021	2022	2023	2024
Number	2	0	0	1	2	2

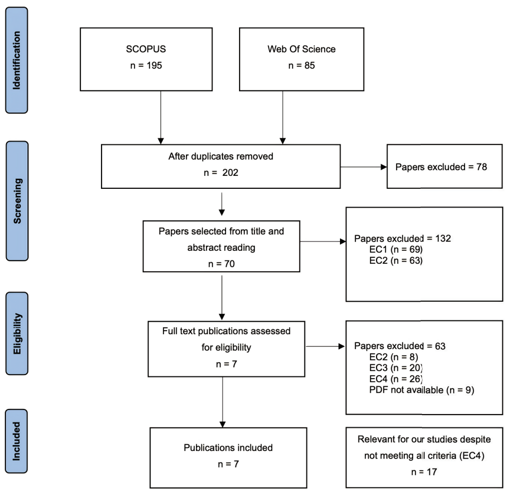

Fig. 1. SLR process and its application

2.3.1. *Answer to RQ1*

The integration of I4.0 technologies into maintenance policies represents a transformative shift in industrial practices, fundamentally revolutionizing asset management and sustainability Chabane et al. (2023); Franciosi et al. (2020).

First of all, these technologies enable predictive maintenance strategies, allowing for timely interventions and preventing costly breakdowns Jena et al. (2024). By leveraging data analytics and machine learning algorithms, maintenance schedules can be optimized based on real-time equipment conditions, minimizing downtime and extending asset lifecycles Narkhede et al. (2024). This shift towards predictive maintenance reduces resource consumption and waste generation, contributing to environmental sustainability Munsamy and Telukdarie (2018). Secondly, I4.0 technologies facilitate remote monitoring and diagnostics, enabling maintenance personnel to access real-time data and insights from anywhere Sénéchal and Trentesaux (2019). This capability improves the efficiency of maintenance operations, reduces travel time and associated emissions, and enhances overall sustainability performance Chabane et al. (2023). For instance, Sénéchal and Trentesaux (2019) discuss a framework for environmentally aware maintenance of cyber-physical systems, enabled by real-time data and diagnostics. Chabane et al. (2023) highlight how resilient and sustainable processes in asset management, supported by I4.0 technologies, contribute to positive lifecycle outcomes.

Furthermore, the integration of technologies such as augmented reality and virtual reality can enhance maintenance efficiency and training and knowledge transfer for maintenance technicians Narkhede et al. (2024); Chabane et al. (2023). This improved training leads to more effective maintenance practices, reducing errors and improving the quality of maintenance work Chabane et al. (2023). Consequently, the lifespan of equipment is extended, and resource utilization is optimized, contributing to both economic and environmental sustainability Patalas-Maliszewska and Losyk (2022). Franciosi et al. (2020) discuss how advanced maintenance services, supported by new technologies, promote sustainability. Moreover, Samadhiya et al. (2023) explore the integration of Total Productive Maintenance and I4.0 within a sustainability context, emphasizing the role of technology in optimizing maintenance for circularity.

Finally, I4.0 technologies support the implementation of circular economy principles in maintenance operations Chabane et al. (2023); Samadhiya et al. (2023). By enabling better tracking and management of spare parts, these technologies facilitate reuse and recycling, reducing waste and promoting resource efficiency. This integration of circular economy principles into maintenance policies contributes to a more sustainable lifecycle management of assets. Munsamy and Telukdarie (2018) discuss the application of I4.0 technologies for achieving business sustainability, including aspects of energy demand in maintenance. However, it is important to note that the successful implementation of these technologies requires careful consideration of human factors and organizational changes Chabane et al. (2023). A human-centered approach to I4.0 implementation is important for achieving sustainable outcomes in maintenance and asset management Chabane et al. (2023).

2.3.2. *Answer to RQ2*

Indicators and various quantification models are employed to evaluate the impact of I4.0 technologies on the sustainability of maintenance practices.

Jena et al. (2024) utilize KPIs such as production volume, downtime, Mean Time Between Failures (MTBF), and Overall Equipment Effectiveness (OEE) to assess the impact of integrating I4.0 technologies with Reliability Centered Maintenance (RCM). Furthermore, they incorporate environmental performance indicators, including energy consumption, carbon footprint, and water consumption, to measure the sustainability improvements. Similarly, Munsamy and Telukdarie (2018) employ a Process Centric Energy Model (PCEM) to analyze the impacts of I4.0 technologies on energy demand, greenhouse gas emissions (GHG) within a maintenance process. Their model demonstrates how integrating technologies like big data analytics, Internet of Things, and CPS can lead to significant reductions in energy consumption and emissions. In addition, Narkhede et al. (2024) emphasize the importance of sustainability measurements to understand the impact of I4.0 technologies across various manufacturing work functions, including maintenance, from the perspective of small and medium-sized enterprises. They highlight the role of these technologies in streamlining processes, optimizing resource allocation, and improving product quality, ultimately contributing to sustainable growth.

Beyond KPIs and energy models, other quantitative methods are also used. Patalas-Maliszewska and Losyk (2022) propose a Fuzzy-TOPSIS approach to assess maintenance sustainability levels integrated with I4.0 technologies. This method provides a structured framework for evaluating the impact of these technologies on various sustainability criteria. Sénéchal and Trentesaux (2019) emphasize the importance of considering environmental factors during maintenance decision-making within CPS. They suggest using data generated by CPS to make more environmentally aware choices, contributing to sustainable maintenance practices. Moreover, Chabane et al. (2023) highlight the need to integrate the impact of industry changes, including the adoption of I4.0 technologies, into the asset management process to balance economic activity with environmental responsibility and social progress. While Samadhiya et al. (2023) examine the mediating role of the circular economy in the relationship between total productive maintenance and I4.0 within a sustainability context, their study focused on its impacts in Indian industries, using questionnaires distributed to professionals in the field.

2.3.3. *Literature gaps and research opportunities*

Despite the benefits of I4.0 technologies for maintenance sustainability, significant gaps remain in understanding the broader implications of I4.0 technologies. Key challenges include the sustainability of their manufacturing processes and the quantification of lifecycle impacts Patalas-Maliszewska and Losyk (2022). In particular, the manufacturing phase is underexplored, with limited focus on both the positive and negative effects, highlighting opportunities for further research and practical advancements. Also, social metrics remain underrepresented in most frameworks Franciosi et al. (2020).

Then, the future research proposed in this article is developing more holistic and integrated assessment frameworks that evaluate the full lifecycle impacts of I4.0 on maintenance strategies. Existing models often focus on specific aspects of sustainability, such as energy efficiency or waste reduction, but a more comprehensive approach is needed to capture the interconnection of economic, environmental, and social dimensions.

Furthermore, further research should explore the social dimension of sustainable maintenance, including the impact of I4.0 technologies on worker safety, job satisfaction, and community well-being.

Lastly, the distribution of the selected papers by their year of publication (table 2) clearly shows that the topic is recent and currently relevant but yet not fully addressed.

3. Proposed roadmap

I4.0 significantly impacts sustainable maintenance practices across multiple dimensions Almeida et al. (2023). However, the SLR reveals critical gaps in understanding and evaluating the sustainability impacts of I4.0 technologies on maintenance. To fill this gap, the proposed roadmap, illustrated in figure 2, provides a structured approach for evaluating the sustainable impact of I4.0 technologies on maintenance policies.

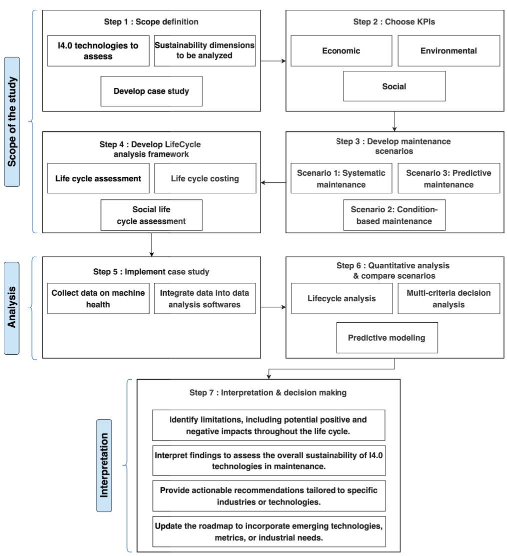

Fig. 2. Roadmap for evaluating the sustainable impact of I4.0 technologies on maintenance policies

This roadmap is organized into seven distinct stages.

Step 1: Clearly define the scope of the analysis by identifying the I4.0 technologies to be assessed; specifying the dimensions of sustainability, economic, environmental, and social; and develop a case study relevant for focusing the analysis.

Step 2: Choose KPIs, such as cost, GHG emission, and worker safety, to measure the impact across the defined sustainability dimensions.

Step 3: Develop three maintenance scenarios: systematic maintenance, condition-based maintenance and predictive maintenance powered by real-time data analytics.

Step 4: Apply a lifecycle framework to evaluate the impacts of these I4.0 technologies in maintenance across their entire lifecycle, including production, deployment, operational use, and end-of-life management, to ensure a holistic sustainability assessment.

Step 5: Collect data from the case study and process it using a data analysis software to evaluate the defined KPIs.

Step 6: Perform quantitative analysis by comparing the maintenance scenarios, identifying trade-offs and synergies to determine their sustainability performance.

Step 7: Interpret the results to provide actionable recommendations. Use these insights to refine the roadmap, ensuring it adapts to evolving technologies and industrial needs.

4. Roadmap illustration on a use case

To validate the practical applicability of the roadmap, we implement it in a **Machinery Fault Simulator (MFS)**, serving as a first case study. Specifically designed for fault simulation and diagnostics, the MFS enables the emulation and analysis of various fault scenarios in rotating machinery, as applied in the use case (figure 3).

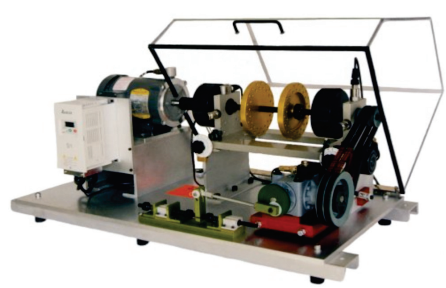

Fig. 3. Spectra-Quest - Machinery Fault Simulator experiment platform. SquestraQuest (SquestraQuest)

It can simulate a wide range of mechanical faults, from bearing defects to gear damage, unbalanced rotors, and shaft misalignments. Its design provides for flexibility, allowing fine control over operational parameters: rotational speed, load, and coupling configurations.

We equipped the MFS with advanced I4.0 technology to enhance its diagnostic capabilities and data collection efficiency. Central to this setup is the Kappa X wireless vibration sensor developed by Sensoteq. the Kappa X sensor is an IoT solution that enables us to monitor the condition of our machine in real time by capturing high-resolution vibration data and transmitting it wirelessly to Analytix, a cloud-based analysis platform. Additionally, the sensor records parameters like speed, acceleration, 3-axis displacement, and temperature. Its low-power design ensures long battery life and minimal maintenance. Figure 4 shows how Kappa X sensor works.

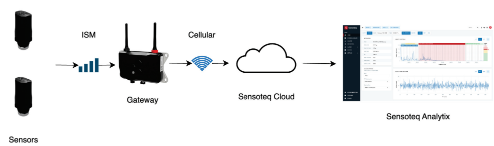

Fig. 4. Kappa X sensor principle. Sensoteq (2019)

Thus, gear and bearing faults will be simulated on the MFS, and fault data acquired through Kappa X sensors will be used to test maintenance scenarios (systematic, condition-based maintenance and predicitive maintenance). Additionally, a life cycle analysis of the Kappa X sensor will be conducted to compare the benefits of these IoT sensors in maintenance with their impact on sustainability and determine the best trade-off. Figure 5 succinctly shows the application of the roadmap to the MFS.

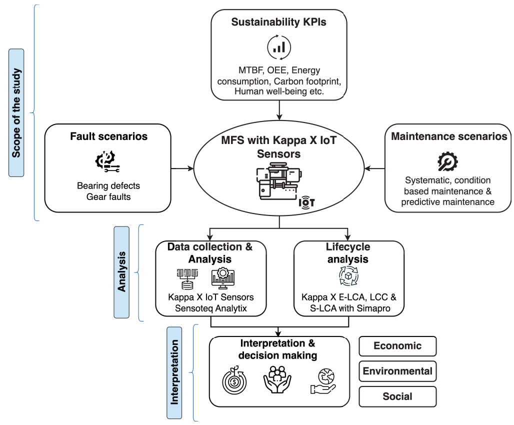

Fig. 5. Roadmap applied to the MFS

5. Conclusion and future works

This work started by addressing the findings from the SLR, which showed gaps in quantifying the lifecycle impacts of I4.0 technologies on maintenance practices. In fact, according to the review, there is a need for frameworks that will account for economic, environmental, and social sustainability dimensions while considering the whole lifecycle of these technologies on maintenance, from their manufacturing to their end-of-life. Additionally, existing research often neglects the negative impacts of these technologies. These insights highlighted the need of developing a holistic evaluation tool to bridge this gap.

With those findings, this study proposed a structured roadmap for integrating and assessing the sustainable impacts of I4.0 technologies in maintenance policies. By adopting a lifecycle perspective, the roadmap balances both the positive and negative impacts of these technologies across economic, environmental, and social dimensions. The roadmap was practically illustrated using the Machinery Fault Simulator (MFS) as a case study, providing a real-world illustration of the roadmap's application.

The key contributions of this work encompass addressing the lifecycle sustainability gaps, introducing a quantifiable methodology for assessing the impacts of I4.0 technologies in maintenance, and emphasizing the strategic importance of maintenance in achieving global sustainability objectives. By focusing on lifecycle considerations, the roadmap ensures that the adoption of these technologies aligns with long-term sustainability goals.

While this study provides valuable insights, it represents an initial step. Future research should focus on applying the proposed roadmap to the MFS in a detailed, quantitative evaluation. This further analysis, in collaboration with Sensoteq, will measure sustainability outcomes, validate the roadmap's effectiveness, and refine its methodology for broader industrial applicability.

These advancements will ensure that the roadmap evolves into a robust, practical tool, capable of guiding industries in adopting sustainable maintenance practices.

Acknowledgement

This research is funded by the French government as part of a joint PhD between université de technologie de Compiègne and Polytechnique Montréal. Their support has been essential for the completion of this work.

References

Almeida, J. C., B. Ribeiro, and A. Cardoso (2023). A human-centric approach to aid in assessing maintenance from the sustainable manufacturing perspective. In *Procedia Comput. Sci.*, Volume 220, pp. 600–607. Elsevier B.V.

Chabane, B., D. Komljenovic, and G. Abdul-Nour (2023). Converging on human-centred industry, resilient processes, and sustainable outcomes in asset management frameworks. *Environment Systems and Decisions 43*, 663–679.

Ertz, M. and F. Gasteau (2023, 6). Role of smart technologies for implementing industry 4.0 environment in product lifetime extension towards circular economy: A qualitative research. *HELIYON 9*.

Franciosi, C., B. Iung, S. Miranda, and S. Riemma (2018). Maintenance for Sustainability in the Industry 4.0 context: a Scoping Literature Review. Volume 51, pp. 903–908. Elsevier B.V.

Franciosi, C., A. Voisin, S. Miranda, and B. Iung (2020). Integration of i4.0 technologies with maintenance processes: what are the effects on sustainable manufacturing? In *University of Salerno*, Volume 53, pp. 1–6.

Jena, M. C., S. K. Mishra, and H. S. Moharana (2024). Integration of industry 4.0 with reliability centered maintenance to enhance sustainable manufacturing. *Environmental Progress and Sustainable Energy 43*.

Mabaso, M., R. Peach, and L. Pretorius (2024). Determining maintenance 4.0 readiness: A case study of a south african food manufacturing company. In *PICMET - Portland Int. Conf. Manag. Eng. Technol.: Technol. Manag. Artif. Intell. Era, Proc.* Institute of Electrical and Electronics Engineers Inc.

Madreiter, T., B. Trajanoski, A. Martinetti, and F. Ansari (2024). Sustainable maintenance: What are the key technology drivers for ensuring positive impacts of manufacturing industries? In *IFAC-PapersOnLine*, Volume 58, pp. 616–621. Elsevier B.V.

Munsamy, M. and A. Telukdarie (2018). Application of industry 4.0 towards achieving business sustainability. In *IEEE Int. Conf. Ind. Eng. Eng. Manage.*, Volume 2019-December, pp. 844–848. IEEE Computer Society.

Narkhede, G., S. Mahajan, R. Narkhede, and T. Chaudhari (2024, 3). Significance of industry 4.0 technologies in major work functions of manufacturing for sustainable development of small and medium-sized enterprises. *Business Strategy and Development 7*.

Orosnjak, M., M. Jocanovic, M. Cavic, V. Karanovic, and M. Pencic (2021, 9). Industrial maintenance 4(.0) horizon europe: Consequences of the iron curtain and energy-based maintenance. *Journal of Cleaner Production 314*.

Patalas-Maliszewska, J. and H. Losyk (2022, 12). An approach to maintenance sustainability level assessment integrated with industry 4.0 technologies using fuzzy-topsis: A real case study. *Advances in Production Engineering & Management 17*, 455–468.

Samadhiya, A., R. Agrawal, S. Luthra, A. Kumar, J. A. Garza-Reyes, and D. K. Srivastava (2023, 4). Total productive maintenance and industry 4.0 in a sustainability context: exploring the mediating effect of circular economy. *International Journal OF Logistics Management 34*, 818–846.

Saraswat, P. and R. Agrawal (2023). Artificial intelligence as key enabler for sustainable maintenance in the manufacturing industry: Scope & challenges. *Evergreen 10*, 2490–2497.

Sensoteq (2019). Hmi user guide.

SquestraQuest. User operating manual for machinery fault simulator.

Sénéchal, O. and D. Trentesaux (2019, 7). A framework to help decision makers to be environmentally aware during the maintenance of cyber physical systems. *Environmental Impact Assessment Review 77*, 11–22.

Tomasoni, G., F. Marciano, E. Stefana, and P. Cocca (2024, 1). Assessing the sustainability impact of improving secondary steel production: Lessons learned from an italian plant. *Environmental and Climate Technologies 28*, 32–44.

Turner, C., O. Okorie, C. Emmanouilidis, and J. Oyekan (2020). A digital maintenance practice framework for circular production of automotive parts. In *University of Surrey*, Volume 53, pp. 19–24.

Vrignat, P., F. Kratz, and M. Avila (2022). Sustainable manufacturing, maintenance policies, prognostics and health management: A literature review. *Reliability Engineering and System Safety 218*.

Waghanna, P., A. Reddy, S. Deshpande, S. Chavan, V. R. Jaiswal, and V. Naranje (2024). Effects of adopting industry 4.0 on a manufacturing plant. In *Int. Conf. Reliab., Infocom Technol. Optim. (Trends Future Dir.), ICRITO*. IEEE Inc.