Editorial for the Special Issue on Sustainable Maintenance 4.0

Letter from the Guest Editors

FOREWORD

It is our great pleasure to introduce this Special Issue on **“Sustainable Maintenance 4.0”** in the *International Journal of Prognostics and Health Management (IJPHM)*. This Special Issue addresses a timely and strategic shift in maintenance engineering and Prognostics and Health Management (PHM): the transition toward maintenance strategies that are not only efficient and reliable, but also environmentally responsible, resource-aware, and socially sustainable.

Global challenges such as climate change, resource depletion, and growing expectations for industrial responsibility call for a transformation of maintenance practices. Although maintenance strongly influences environmental and social performance, these dimensions remain underexplored in current research. Meanwhile, the rise of **Industry 4.0/5.0**—through digitalization, automation, AI, big-data analytics, and predictive maintenance—offers powerful opportunities to enhance sustainability, optimize resource use, reduce waste, and extend asset lifetime. These technologies also support the development of new sustainability-oriented KPIs that go beyond traditional economic indicators.

The contributions collected in this issue illustrate this evolution and provide new insights for both researchers and practitioners.

Scope and Objectives of the Special Issue

The objective of this Special Issue was to gather high-quality research at the intersection of:

- Sustainability and maintenance engineering;
- Lifecycle and environmental assessment;
- Advanced monitoring and prognostics;
- Condition-based and prescriptive maintenance;
- Industry 4.0/5.0 enabling technologies;
- Decision support for resource-efficient operations.

The accepted articles reflect the diversity of current research efforts toward **Sustainable Maintenance 4.0** and jointly highlight the importance of coupling data-driven intelligence, physical modelling, and sustainability considerations.

Overview of the Accepted Papers

Out of all submissions received, six high-quality papers were accepted for publication in this Special Issue. Together, they provide complementary perspectives on sustainability-driven maintenance, ranging from environmental assessments and systematic reviews to monitoring strategies and decision-making frameworks. Below is a summary of each contribution.

The first paper intitled “*Life Cycle Assessment of Aircraft Maintenance: Environmental Implications of Battery Electric Propulsion Systems*” presents an in-depth lifecycle assessment of the maintenance activities associated with future battery-electric aircraft propulsion systems. Beyond quantifying routine inspection and component replacement impacts, the study highlights that battery ageing and repeated battery pack renewals are major contributors to the overall environmental burden. The comparison of present-day and projected 2035 battery technologies clearly shows how improvements in energy density and reliability could drastically reduce maintenance-related emissions. This work demonstrates the importance of embedding **sustainable maintenance principles**—such as lifecycle thinking, design for maintainability, and environmentally aligned PHM policies—into the transition toward electric aviation. It reinforces a key message of **Maintenance 4.0**: sustainability performance must be assessed not only at the operational level but across the entire asset lifecycle.

The second paper intitled “*Time to Replace? A Guide for Sustainable Engine Maintenance Strategies*” examines how different replacement intervals for life-limited engine parts influence environmental, economic, and operational dimensions. By analysing trade-offs between premature replacement (leading to unnecessary material consumption and waste) and delayed replacement (which increases fuel burn due to degraded engine performance), the study highlights the multifaceted nature of **eco-efficient maintenance planning**. The integration of recycling potential and resource criticality (e.g., titanium, nickel, rhenium) adds a valuable perspective on supply-chain resilience and material sustainability. This contribution shows how PHM-supported maintenance strategies can be redefined to balance engine performance, resource consumption, and environmental impact—an important step toward **sustainable engine lifecycle management** and **responsible maintenance decision-making**.

The third paper "*Prescriptive decision-making for sustainable production management: An overall sustainable equipment effectiveness (OSEE) framework using causal AI*" introduces an enhanced decision-support framework that extends the classical OEE indicator to include environmental and social sustainability metrics. With causal AI and Dynamic Bayesian Networks, the approach allows practitioners to understand not only performance outcomes but also the causal pathways linking operational decisions to sustainability results. This provides a powerful tool for **sustainability-informed, prescriptive maintenance and production planning**, allowing users to simulate scenarios and anticipate long-term effects of interventions. By merging digitalization, sustainability assessment, and predictive modeling, the proposed OSEE framework embodies the evolution toward **next-generation maintenance and production systems** that support the vision of **Maintenance 4.0.**

The fourth paper intitled "A*ssessing the sustainability impacts of Industry 4.0 on maintenance policies: A systematic literature review and future research directions* delivers a comprehensive literature review that clarifies how Industry 4.0 technologies influence sustainability within maintenance. While many studies emphasize economic and operational benefits, the authors identify gaps in lifecycle integration, social impact measurement, and the operationalization of circular economy principles in maintenance. The review highlights that digital tools—such as IoT, AI, and digital twins—offer strong foundations for **smarter and more sustainable maintenance practices**, yet are still under-utilized in holistic sustainability frameworks. By outlining future research needs, such as multi-criteria decision-making, lifecycle-based PHM integration, and human-centric maintenance design, this contribution provides a valuable roadmap for advancing **digitally-enabled sustainable maintenance strategies** across diverse industrial sectors.

The fifth paper "*Cost and environmental assessment of tool replacement strategies under imperfect wear monitoring in Ti6Al4V milling*" explores how different tool replacement strategies—fixed interval, condition-based, and imperfect monitoring—affect environmental impacts, cost, and production reliability. Using realistic degradation models and Monte Carlo simulation, the paper demonstrates that even imperfect condition monitoring can significantly reduce tool waste, scrap generation, and energy consumption. This reinforces the idea that **PHM-enabled maintenance**, even at non-ideal technological maturity, can deliver immediate sustainability gains in manufacturing operations. By connecting wear mechanisms, process stability, carbon footprint, and resource efficiency, the study illustrates how digital diagnostics can support **sustainable and high-performance machining practices**, contributing to cleaner and more efficient industrial processes.

And finally, the sixth paper—*Impacts of sensor degradation on measurement uncertainty in prognostics and maintenance decision-making: State of the art and challenges*— provides a detailed and comprehensive review of how sensor degradation affects data reliability, prognostics accuracy, and maintenance decision-making. The article maps a wide range of degradation mechanisms and explains their influence on uncertainty growth, model robustness, filtering instability, and remaining useful life (RUL) estimation accuracy. It highlights that many existing predictive maintenance models overlook the progressive deterioration of sensing systems, which can lead to suboptimal or incorrect decisions. By identifying key research challenges—such as adaptive calibration, degradation-aware filtering, and resilient prognostics models—the study emphasizes the need for **trustworthy, uncertainty-aware digital maintenance systems**. This is a fundamental requirement for achieving **reliable and sustainable Maintenance 4.0 frameworks** in real-world industrial contexts.

Key Insights and Emerging Trends

Across the six contributions accepted in this Special Issue, several cross-cutting insights and converging trends clearly emerge, illustrating how maintenance is evolving toward more sustainable, intelligent, and lifecycle-oriented paradigms:

- Lifecycle thinking is becoming essential for maintenance strategy design.
- Environmental and resource impacts must be integrated into maintenance planning, not treated separately.
- Digital technologies (IoT, AI, predictive analytics) play a pivotal role in enabling Sustainable Maintenance 4.0.
- Uncertainty management, especially stemming from sensor degradation, is central for reliable prognostics.
- Circularity and material efficiency (remanufacturing, recycling) are gaining prominence.
- Human-centric considerations, though still underrepresented, are increasingly recognized as key components of sustainability.

These trends collectively illustrate a paradigm shift: maintenance is no longer only a cost-driven activity but a **strategic contributor to decarbonization, resilience, and industrial sustainability**.

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Conclusion

We hope that this Special Issue will stimulate further research on **Sustainable Maintenance 4.0**, inspire new methodologies, and foster collaboration between academia and industry. The selected papers demonstrate that integrating sustainability into maintenance engineering is not only feasible but essential for the future of industrial systems.

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References

Rahn, A., Wolf, J.-A., Dauer, R., Meissner, R., Pohya, A. A., & Wende, G. (2025). Life Cycle Assessment of Aircraft Maintenance: Environmental Implications of Battery Electric Propulsion Systems. *International Journal of Prognostics and Health Management. Vol.16 No. 4, 2025.*

Oestreicher, A., Hoff, T., Pohya, A. A., & Wende, G. (2025). Time to Replace? A Guide for Sustainable Engine Maintenance Strategies. *International Journal of Prognostics and Health Management. Vol.16 No. 4, 2025.*

Madreiter, T., & Ansari, F. (2025). Prescriptive Decision-Making for Sustainable Production Management: An Overall Sustainable Equipment Effectiveness (OSEE) Framework Using Causal AI. *International Journal of Prognostics and Health Management. Vol.16 No. 4, 2025.*

Diop, M. M., Danjou, C., Ponchet Durupt, A., Baouch, Y., & Boudaoud, N. (2025). Assessing the Sustainability Impacts of Industry 4.0 on Maintenance Policies: A Systematic Literature Review and Future Research Directions. *International Journal of Prognostics and Health Management. Vol.16 No. 4, 2025.*

Colantonio, L., Moroncini, G., Sénéchal, O., Dehombreux, P., Ducobu, F., & Equeter, L. (2025). Cost and Environmental Assessment of Tool Replacement Strategies Under Imperfect Wear Monitoring in Ti6Al4V Milling. *International Journal of Prognostics and Health Management. Vol.16 No. 4, 2025.*

Thai, T.-T. N., Do, P., Iung, B., & Gardoni, P. (2025). Impacts of Sensor Degradation on Measurement Uncertainty in Prognostics and Maintenance Decision-making. *International Journal of Prognostics and Health Management. Vol.16 No. 4, 2025.*