

Predictive Maintenance Servitisation Pathways

J. Li, J. Milisavljevic-Syed, K. Salonitis

*Sustainable Manufacturing Systems Centre, School of Aerospace, Transport and Manufacturing,
Cranfield University, MK43 0AL, United Kingdom (Tel: +44 (0) 1234 758533; emails:
jiahong.li; jelenams; & k.salonitis@cranfield.ac.uk)*

Abstract: The competition within the manufacturing industry is becoming increasingly intense in the Industry 4.0 era. Some manufacturers are transforming their traditional product-selling business model into product-service combos to gain customer loyalty and new sources of revenue through the so-called manufacturing servitisation. Predictive maintenance (PdM) is a strategy that significantly overlaps with manufacturing servitisation in terms of enabling technologies, including IoT, Big Data, Cloud Computing, etc. PdM is expected to both maximise productivity and minimise maintenance costs. Although much attention has been given to PdM and manufacturing servitisation, previous studies have ignored the synergy of PdM and manufacturing servitisation. This paper highlights the importance and feasibility of implementing PdM servitisation. Additionally, by analysing practical PdM servitisation cases, three PdM servitisation pathways are defined. Finally, the defined pathways are discussed, and future research directions are proposed.

Copyright © 2024 The Authors. This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0/>)

Keywords: Predictive Maintenance, PdM, Servitisation, Manufacturing Servitisation, Industry 4.0

1. INTRODUCTION

Industry 4.0, often referred to as the 4th industry revolution (Lee et al., 2014), typically encompasses the transformation towards automation, digitalisation, and integration of various aspects of manufacturing and industry processes. This transformation is enabled by the incorporation of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), and the interconnection of cyber-physical systems. Such transformation has resulted in increasingly intense competition within the manufacturing industry. For example, manufacturers are expected to produce more customized products (Mourtzis et al., 2022), meet stricter sustainability requirements, and widely apply data technology to enhance manufacturing performance (Lee et al., 2014).

During the transformation process, the manufacturing industry has seen significant changes in the way it operates (Mourtzis et al., 2022). On the one hand, various new methods and/or strategies are applied in manufacturing operations, such as Predictive Maintenance, Digital Twins, Cloud Computing, Augmented Reality and Virtual Reality, to name a few. Among these strategies, predictive maintenance (PdM) is expected to reduce maintenance costs and increase productivity (Zonta et al., 2020). It utilises predictive tools to continuously monitor devices/components states continuously, proactively identifying possible faults (Li et al., 2022). Such predictive knowledge allows for maintenance actions to be taken before faults occur.

Conventionally, enterprises primarily focused on selling products only. In such a business strategy, the relationship between enterprises and customers can be described as a 'one-time purchase' relationship. Servitisation, as business model, in which enterprises attempt to transfer their conventional business model to one that combines both product and service.

In the servitisation business model, enterprises can gain additional value by providing customers with comprehensive services and solutions (Vandermerwe and Rada, 1988). This business model helps improve customer satisfaction and loyalty, thus establishing stronger relationships between enterprises and customers (Luz et al., 2018) and generating additional revenue streams beyond the initial sale of products.

Manufacturing servitisation has been studied intensively, and researchers and enterprises have widely realised and accepted its advantages (Luz et al., 2018). Various manufacturing servitisation business models, structures, and enabling technologies to have been presented and discussed (Chen et al., 2022). However, only a few studies focused on PdM servitisation (Comapre et al., 2019).

PdM servitisation is a topic with significant potential. Firstly, by studying and implementing such an approach, enterprises that have adopted PdM can enhance customer satisfaction and loyalty and generate new revenue sources (Compare et al., 2019). Secondly, researching PdM servitisation would assist enterprises in better understanding the cost-efficiency and return on investment of PdM implementation, thereby aiding in the development of long-term strategies (Wang and Wang, 2018). Lastly, studying PdM servitisation can help justify the initial investment of PdM implementation, as PdM often requires a substantial investment (Comapre et al., 2019).

Despite the potential of PdM servitisation, its feasibility must also be discussed before starting research. As a technology-intensive strategy, PdM usually requires a substantial investment in tangible and intangible assets to implement and operate, such as the Internet of Things (IoT), Machine Learning, Digital Twins (DT), AR/VR, etc. Interestingly, all these technologies are also key enablers of manufacturing servitisation. When examining the related fields of both PdM

and manufacturing servitisation, it becomes evident that there is a significant overlap, indicating a strong interconnection between them. This interconnection is discussed in detail in the following literature review section.

First, this research aims to justify the feasibility of PdM servitisation and highlight the importance and advantages of exploring this topic. To achieve this goal, a literature review is conducted to demonstrate the strong connection between PdM and manufacturing servitisation. The second aim is to define potential PdM servitisation pathways, including their structure, capabilities, enabling technologies, etc. To achieve such an aim, real-world PdM servitisation cases are reviewed and classified. Their business model, structure, and capabilities are presented and discussed. Last, the paper defines the rationale of pathways to distinguish pathways better and help companies to select the most suitable pathway.

2. LITERATURE REVIEW

2.1 Introduction to Predictive Maintenance

Maintenance is essential to the manufacturing industry. Firstly, maintenance costs account for 15 to 60% of the total production cost (Mobley, 2002). In addition, maintenance has a high impact on other essential manufacturing performance indicators, such as productivity, safety, and quality (Zonta et al., 2020). According to Zonta et al. (2020), there has been a significant increase in papers related to PdM published since 2014. In the Industry 4.0 context, PdM gains advantages from data collected from multiple sensors for continuous component state/performance monitoring and remaining useful life estimation (Zonta et al., 2020). It allows the manufacturing industry to optimise their maintenance scheduling based on component state.

2.2 Predictive maintenance implementation goals

This paper explores the PdM implementation goals outlined in previous studies.

Cost reduction

Cost reduction is the primary goal of PdM implementation. As mentioned in the previous section, PdM enables enterprises to estimate the remaining useful life of components. This minimises the requirement for spare parts and maintenance actions, reducing maintenance costs. Therefore, the cost model for the PdM strategy usually depends on the specification of the system/equipment and component RUL (Ran et al., 2019).

Productivity improvement

Productivity improvement is another goal when implementing PdM. It is achieved through device reliability and availability maximisation. Reliability in the maintenance sector refers to the likelihood of a system or equipment maintaining its functional state over a defined period. Availability is expressed as the uptime of a machine or device (Gravette and Barker, 2015). Efforts on such topics can be seen in Daily and Peterson (2017), Gravette and Barker (2015), and Lee et al. (2017).

Maintenance performance optimisation

In practice, more indicators are used to measure the performance of maintenance actions such as safety, product quality, feasibility, etc. Focusing on only one is often insufficient for evaluating the optimal solution. Therefore, multi-objective optimisation approaches promise a more balanced trade-off among various optimisation objectives (Tian et al., 2012). Efforts on such topics can be seen in Sang et al. (2020), Yoon et al. (2017), Liu et al. (2021) and Proto et al. (2020).

2.3 Introduction to manufacturing servitisation

Servitisation is a business model in which enterprises attempt to transfer their conventional product-selling strategy to one that combines product and service. The term "servitisation" first appeared in the late 1980s to early 1990s (Vandermerwe and Rada, 1988) and has seen a significant increase in the number of publications related to it since 2008 (Chen et al., 2022). The aim of this transformation is to gain higher customer satisfaction and sustainable competitive advantages, improve client experiences, build long-term connections, generate new sources of revenue, and boost consumer loyalty (Luz et al., 2018).

The servitisation business model enhances customer satisfaction and loyalty by providing maintenance, repairs, and upgrade services. This approach helps establish stronger connections with clients and generate additional revenue streams. Secondly, manufacturers can distinguish themselves in the competitive market by delivering unique services, thus attracting new customers. Lastly, servitisation enhances efficiency and productivity by continuously analysing data generated from service activities, driving continuous improvements in products and processes (Luz et al., 2018).

Manufacturers encounter specific challenges when adopting servitisation. The essential obstacle involves changing their organisational culture and moving from a product-centric approach to a service-oriented perspective. Furthermore, significant investments in digital technologies and infrastructure, such as IoT, cloud computing, and data analytics, are required to fully reap the benefits of digital servitisation. Additionally, companies may need to focus more on services, which could harm their business (Paschou et al., 2020).

2.4 Predictive maintenance and manufacturing servitisation interactions

Ran et al. (2019) explored research terms strongly related to PdM, which revealed that the terms most associated with PdM include big data, IoT, smart manufacturing, cyber-physical systems (CPS), cloud computing, and machine learning. Zhuo and Song (2021) evaluated research terms strongly related to manufacturing servitisation, and they found that terms most associated with manufacturing servitisation include big data, IoT, smart-service systems, cyber-physical systems, cloud computing, and product-service systems.

There's a notable overlap between PdM and servitization, evident in shared terms like big data, IoT, and cloud computing. Despite PdM and servitization not having been studied together, their interconnectedness is apparent. In this context,

enterprises implementing PdM may require less initial investment to introduce servitisation. In other words, enterprises with PdM may risk losing competitiveness if they do not introduce servitisation. In addition, PdM is a key element for CPS, and servitisation is a key element for the product-service system. Studying PdM servitisation may result in a better understanding of the cyber-physical-product-service systems (CPPSS), which is an important aspect of industry 4.

In addition, Rodrigo et al. (2017) introduced a systematic method for manufacturers to implement servitisation, delineating short-term, mid-term, and long-term goals. Short-term goals include increased cost efficiency, flexibility, and customer retention, achievable through enhancements in operational, project, logistic management, and productivity. Notably, these objectives can be facilitated by implementing PdM, positioning it as a catalyst for servitisation promotion. Thus, companies with PdM integration may exhibit superior servitisation performance. This underscores the strong correlation between PdM and manufacturing servitisation, although further research is warranted in this area.

In summary, the study of PdM servitisation can justify the high initial investment in PdM implementation. Secondly, PdM can serve as an enabler for implementing and promoting manufacturing servitisation. By doing so, manufacturers can attract new customers, generate new revenue, and increase customer satisfaction and loyalty.

3. PREDICTIVE MAINTENANCE SERVITIZATION PATHWAYS

Practical PdM servitisation cases are investigated and analysed, the cases are the project reports or introductions from service providers in the market that are available from open-source databases. In this section, three PdM servitisation pathways are defined based on their business models capabilities, and requirements that have been collected and analysed from the literature review. Such pathways target customers, including machinery, product/component production, assembly, and raw material processing companies within the manufacturing sector.

Pathway 1: Predictive maintenance solution service

The first pathway defined is the PdM Solution Service. In this pathway, companies provide a complete PdM solution to customers. Such a solution includes consultations, such as critical device identification, software for data analysis, predictive modelling, computation, etc., and maintenance strategy analysis. In this pathway, the service provider may also offer IoT solutions associated with the PdM solution to customers (IBM, 2023a; C3.ai, 2023).

In this pathway, customers can mainly benefit from cost reduction, reduced failures, improved asset availability, and reduced operational risks. Customers still perform maintenance actions themselves. To provide a PdM solution service, the provider should be able to identify critical components and devices for different sectors first. Next, the provider should be able to develop suitable PdM models for customers based on their specific needs. Also, the provider should be able to provide optimised maintenance plans based

on the system or device's state. Lastly, some providers may offer their own IoT development plans and devices.

Pathway 2: Predictive maintenance-enabled service

The second defined pathway is the PdM-Enabled Service. In this pathway, PdM serves as a part of a comprehensive service plan or an enabler for services. These services leverage the capabilities of asset condition monitoring and predicting remaining service life to help customers optimise performance. This optimisation may encompass asset and labour productivity, enhancements in human capital structure, better asset management, safety enhancements, and risk reduction, among other benefits (Siemens, 2023; IBM, 2023b; SAP, 2023; GE, 2023).

To provide PdM-Enabled Services, service providers should possess the capabilities required for offering PdM Solution Services and have a deep understanding of maintenance actions and related work processes, including productivity, safety, and quality. This understanding is essential for identifying potential performance optimisation plans related to maintenance.

Pathway 3: Predictive maintenance service

The last identified pathway is PdM Service. In this pathway, the provider delivers PdM solution services to the customer, conducts asset monitoring and provides maintenance action services. After implementing a PdM system for customers, the provider may monitor local or remote asset and relay fault alerts to the customers. Some providers may also deliver maintenance actions to the customer (ABB, 2023).

Customers can benefit from the advantages of PdM implementation, as well as from more professional maintenance actions and reduced human capital costs. In addition to the capabilities offered through PdM Solution Services, the provider should have a team of maintenance experts to monitor customer asset conditions or perform maintenance actions on their behalf.

4. DISCUSSION OF THE THREE PATHWAYS

This section presents their rationale for distinguishing the three pathways better and helping companies select the most suitable PdM servitisation pathway. Three dimensions are considered for their assessment, namely: "Basic Function", "Additional Functions", and "Cost". Each of the three dimensions includes multiple sub-dimensions. The "Basic Function" and "Additional Functions" benefit each pathway. Besides the sub-dimension types, sub-dimension capability levels are also included to justify their rationale. Sub-dimension capability levels describe the capability of pathways in terms of each dimension.

"Basic Function" refers to the fundamental function for maintenance tasks, including productivity improvement, safety improvement, quality improvement, and functionality. Since the sub-dimensions for "Basic Function" are qualitative in nature, marking scales are employed to quantify them. The marking is based on the description of PdM capabilities in

terms of the sub-dimensions published by researchers. The marking scale is presented in Appendix 1.

“Additional Functions” refers to the functions related to maintenance tasks or enabled by them, including production management improvement, logistic improvement, transparency improvement, and sustainability improvement. The same marking method as in the case of “Basic Function” marking is employed, and the marking scale is also presented in Appendix 2. The two appendices are built based on a literature review. The paper discusses PdM implementation benefits, and the benefit levels descriptions are summarised to mark the basic function and additional function dimensions. The key criteria to be considered when assessing the three pathways are presented in Fig 1.

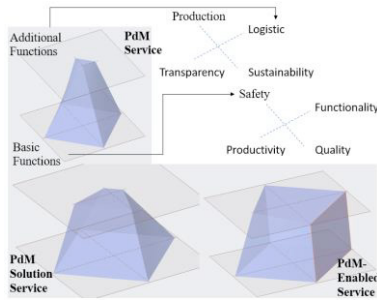


Fig. 1: Pathway rationale

For the sub-dimensions of “Basic function”, both *Predictive Maintenance Solution Service* and *Predictive Maintenance-enabled Service* can achieve Marks 1, 3, and 5. The specific mark achieved depends on the PdM technique applied (experience-based, model-based, data-driven, etc.) (Li et al., 2022). However, real-time decision-making and actions become challenging for the Predictive Maintenance Service Pathway, where devices can be monitored remotely by service providers.

For the sub-dimensions Production Management Improvement and Logistic Management of additional functions, *Predictive Maintenance Solution Service* and *Predictive Maintenance Service* Pathway can only achieve Mark 1 since automated software is not implemented. Regarding transparency and sustainability improvement, the predictive maintenance solution service can achieve Mark 3, but it cannot provide any transparency since service providers collect and store data. Predictive Maintenance-enabled Service can achieve Mark 5 for all sub-dimensions related to additional functions. However, it should be noted that to achieve Mark 5 for Transparency improvement, stakeholders within the value chain must operate their business and production in a fully digitalised way.

Cost refers to the cost of pathway implementation and operation. Based on Achouch et al. (2022), Table 1 presents the sub-dimensions included in the Cost dimension.

Where C_H is the required hardware cost for implementing pathways, for a defined production system, the required hardware for adapting three pathways is the same. Therefore, $C_{H1} = C_{H2} = C_{H3} = C_h$. C_S is the required software cost for

implementing pathways; since *Predictive Maintenance-enabled Service* allows customers to have different additional functions compared to other pathways, the required types/functions of software also increase. After investigating the prices of several types of software in the market, the authors assume that $C_{S2} = 1.5C_s$ to $3C_s$. However, service providers own and operate the required software in the Predictive Maintenance Service pathway. Therefore, $C_{S3} = 0$. For the same reason, it is assumed that $C_{T2} = 1.5C_t$ to $3C_t$ and $C_{T3} = 0$.

Table1: Cost dimension

Sub-dimension s	Cost		
	Pathway		
	Predictive maintenance solution service	Predictive maintenance-enabled service	Predictive maintenance service
Hardware C_H	$C_{H1} = C_h$	$C_{H2} = C_h$	$C_{H3} = C_h$
Software C_S	$C_{S1} = C_s$	$C_{S2} = 1.5C_s$ to $3C_s$	$C_{S3} = 0$
Training C_T	$C_{T1} = C_t$	$C_{T2} = 1.5C_t$ to $3C_t$	$C_{T3} = 0$
Labour and repair (per year) C_{LR}	$C_{LR1} = C_{lr}$	$C_{LR2} = C_{lr}$	$C_{LR3} = 0$
Service C_{SR}	$C_{SR1} = C_{sr}$	$C_{SR2} = C_{sr}$	$C_{SR3} = C_{sr} + nx$

C_{LR} is the cost for labour and repair every year; for a defined production system, the required cost for labour and repair every year for pathways is the same. However, in the *Predictive Maintenance Service* pathway, service providers conduct maintenance actions. Therefore, the three required consultancy pathways are the same; however, an additional fee for maintenance operation service is required for the Predictive Maintenance Service pathway. Therefore, $C_{SR1} = C_{SR2} = C_{sr}$ and $C_{SR3} = C_{sr} + nx$. Where n is the number of years of service use and x is the additional maintenance operation service fee yearly. The cost model for pathways is presented in Fig 2.

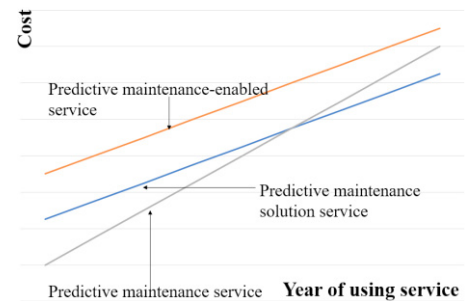


Fig. 2: Pathway cost model schematic illustration

Predictive Maintenance-enabled Services require the most initial investment. However, as the number of years of use increases, the total cost of Predictive Maintenance Services will exceed that of other pathways. This is because Predictive

Maintenance Services require an additional fee for maintenance operations.

5. DISCUSSION AND CONCLUSIONS

Three PdM servitisation pathways are defined in this paper: PdM Solution Service, PdM-Enabled Service, and PdM Service. While these pathways' business models, requirements, and capabilities differ, their core business logic remains consistent—providing PdM implementation and operation-related solutions to help customers reduce maintenance costs, optimise processes, and enhance human capital performance. The rationale for the defined pathways is presented, including basic functions, additional functions, and cost. The PdM Service pathway can achieve the least basic functions, while the PdM-Enabled Service can achieve the most additional functions. Regarding cost, PdM-Enabled Service requires the most initial investment, but PdM Service is the most expensive in the long term.

The first contribution of this paper is justifying the interrelation between PdM and manufacturing servitisation. The two terms share several overlapping technologies, and PdM can be an enabler of manufacturing servitisation. The second contribution is defining three PdM servitisation pathways, which allow an understanding of the existing forms of PdM servitisation. The last contribution is defining the rationale of pathways, which allows manufacturers to select the most suitable pathway based on their situations.

This paper underscores the advantages and feasibility of studying PdM servitisation. Utilising practical PdM servitisation cases, the authors have defined three pathways related to PdM implementation and operation: PdM Solution Service, PdM-Enabled Service, and PdM Service. In addition, this research defines the rationale of each pathway.

In the future, the authors aim to establish a rule-based method for companies to assess the optimal pathway, which involves considering three defined dimensions. In addition, the authors recommend that future studies focus on establishing new PdM servitisation pathways based on the distinctive features of PdM and manufacturing servitisation and developing frameworks for pathway implementation.

REFERENCE

- ABB. (2023.) "ABB Ability™ Monitoring Service." Accessed:20092023. <https://tinyurl.com/yrk4zwpr>.
- Achouch, M., Dimitrova, M., Ziane, K., Sattarpanah Karganroudi, S., Dhoui, R., Ibrahim, H., & Adda, M. (2022). On predictive maintenance in industry 4.0: Overview, models, and challenges. *Applied Sciences*, 12(16), 8081.
- C3.ai (2023) "Launch AI-Powered Predictive Maintenance In Weeks." Accessed 08102023. <https://tinyurl.com/ms97j8px>.
- Chen, Y., Wu, Z., Yi, W., Wang, B., Yao, J., Pei, Z., & Chen, J. (2022). Bibliometric Method for Manufacturing Servitization: A Review and Future Research Directions. *Sustainability*, 14(14), 8743.
- Çınar, Z. M., Abdussalam Nuhu, A., Zeeshan, Q., Korhan, O., Asmael, M., & Safaei, B. (2020). Machine learning in predictive maintenance towards sustainable smart manufacturing in industry 4.0. *Sustainability*, 12(19), 8211.
- Compare, M., Bellani, L., & Zio, E. (2019). Optimal allocation of prognostics and health management capabilities to improve the reliability of a power transmission network. *Reliability Engineering & System Safety*, 184, 164-180.
- Daily, J., & Peterson, J. (2017). Predictive maintenance: How big data analysis can improve maintenance. *Supply Chain Integration Challenges in Commercial Aerospace: A Comprehensive Perspective on the Aviation Value Chain*, 267-278.
- GE. "Asset Performance Management (APM) Software." <https://tinyurl.com/47dy98jp>
- Görür, O. C., Yu, X., & Sivrikaya, F. (2021). Integrating predictive maintenance in adaptive process scheduling for a safe and efficient industrial process. *Applied Sciences*, 11(11), 5042.
- Gravette, M. A., & Barker, K. (2015). Achieved availability importance measure for enhancing reliability-centered maintenance decisions. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, 229(1), 62-72.
- He, Y., Gu, C., Chen, Z., & Han, X. (2017). Integrated predictive maintenance strategy for manufacturing systems by combining quality control and mission reliability analysis. *International Journal of Production Research*, 55(19), 5841-5862.
- Hribernik, K., von Stietencron, M., Bousdekis, A., Bredehorst, B., Mentzas, G., & Thoben, K.-D. (2018). Towards a unified predictive maintenance system-a use case in production logistics in aeronautics. *Procedia Manufacturing*, 16, 131-138.
- IBM (2023). "Predictive maintenance with IBM Maximo Application Suite." Accessed 01102023. <https://tinyurl.com/yd9nzmw4>
- (2023b). "IBM Maximo Application Suite." Accessed 081023. <https://www.ibm.com/products/maximo>.
- Irawan, C. A., Ouelhadj, D., Jones, D., Stålhane, M., & Sperstad, I. B. (2017). Optimisation of maintenance routing and scheduling for offshore wind farms. *European Journal of Operational Research*, 256(1), 76-89.
- Kryvinska, N., Kaczor, S., Strauss, C., & Gregus, M. (2014). *Servitization strategies and product-service-systems*. Paper presented at the 2014 IEEE world congress on services.
- Lee, C., Cao, Y., & Ng, K. H. (2017). Big data analytics for predictive maintenance strategies. In *Supply Chain Management in the Big Data Era* (pp. 50-74): IGI Global.
- Lee, J., Bagheri, B., & Kao, H.-A. (2014). *Recent advances and trends of cyber-physical systems and big data analytics in industrial informatics*. Paper presented at the International proceeding of int conference on industrial informatics.
- Li, J., Schaefer, D., & Milisavljevic-Syed, J. (2022). A decision-based framework for predictive maintenance technique selection in industry 4.0. *Procedia CIRP*, 107, 77-82.
- Lu, B., Chen, Z., & Zhao, X. (2021). Data-driven dynamic predictive maintenance for a manufacturing system with quality deterioration and online sensors. *Reliability Engineering & System Safety*, 212, 107628.
- Luz Martín - Peña, M., Díaz - Garrido, E., & Sánchez - López, J. M. (2018). The digitalization and servitization of manufacturing: A review on digital business models. *Strategic Change*, 27(2), 91-99.
- Mobley, R. K. (2002). *An introduction to predictive maintenance*: Elsevier.
- Mourtzis, D., Angelopoulos, J., & Panopoulos, N. (2022). A Literature Review of the Challenges and Opportunities of the Transition from Industry 4.0 to Society 5.0. *Energies*, 15(17), 6276.
- Paschou, T., Rapaccini, M., Adrodegari, F., & Saccani, N. (2020). Digital servitization in manufacturing: A systematic literature

review and research agenda. *Industrial Marketing Management*, 89, 278-292.

- Proto, S., Di Corso, E., Apiletti, D., Cagliero, L., Cerquitelli, T., Malnati, G., & Mazzocchi, D. (2020). REDTag: a predictive maintenance framework for parcel delivery services. *IEEE Access*, 8, 14953-14964.
- Ran, Y., Zhou, X., Lin, P., Wen, Y., & Deng, R. (2019). A survey of predictive maintenance: Systems, purposes and approaches. *arXiv preprint arXiv:1912.07383*.
- Rødseth, H., & Schjølberg, P. (2016). *Data-driven predictive maintenance for green manufacturing*. Paper presented at the 6th International Workshop of Advanced Manufacturing and Automation.
- Saez, M., Maturana, F., Barton, K., & Tilbury, D. (2017). *Anomaly detection and productivity analysis for cyber-physical systems in manufacturing*. Paper presented at the 2017 13th IEEE Conference on Automation Science and Engineering (CASE).
- Sang, G. M., Xu, L., de Vrieze, P., Bai, Y., & Pan, F. (2020). *Predictive maintenance in industry 4.0*. Paper presented at the Proceedings of the 10th International Conference on Information Systems and Technologies.
- SAP (2023) "SAP Asset Performance Management." Accessed 07102023. <https://www.sap.com/uk/products/scm/apm.html>.
- SIEMENS (2023). "Measurement Intelligence for process industries #makessense." Accessed 07102023. <https://tinyurl.com/48yee9jp>.
- Tian, Z., Lin, D., & Wu, B. (2012). Condition based maintenance optimization considering multiple objectives. *Journal of Intelligent Manufacturing*, 23, 333-340.
- Tiddens, W., Braaksma, J., & Tinga, T. (2022). Exploring predictive maintenance applications in industry. *Journal of Quality in Maintenance Engineering*, 28(1), 68-85.
- Turnbull, A., & Carroll, J. (2021). Cost benefit of implementing advanced monitoring and predictive maintenance strategies for offshore wind farms. *Energies*, 14(16), 4922.
- Vandermerwe, S., & Rada, J. (1988). Servitization of business: adding value by adding services. *European management journal*, 6(4), 314-324.
- Wang, K., & Wang, Y. (2018). How AI affects the future predictive maintenance: a primer of deep learning. In *Advanced Manufacturing and Automation VII 7* (pp. 1-9). Springer Singapore.
- Yoon, J. T., Youn, B. D., Yoo, M., & Kim, Y. (2017). A newly formulated resilience measure that considers false alarms. *Reliability Engineering & System Safety*, 167, 417-427.
- Zhou, C., & Song, W. (2021). Digitalization as a way forward: A bibliometric analysis of 20 Years of servitization research. *Journal of Cleaner Production*, 300, 126943.
- Zonta, T., Da Costa, C. A., da Rosa Righi, R., de Lima, M. J., da Trindade, E. S., & Li, G. P. (2020). Predictive maintenance in the Industry 4.0: A systematic literature review. *Computers & Industrial Engineering*, 150, 10688

Appendix1: Basic function marking

Basic Functions				
Sub-dimensions		Marks		
		1	3	5
Function			Retraining the device to a functional state	
Productivity	Fuzzy state prediction enables device state inspection, fault estimation, and prevention of unexpected shutdowns before job completion (Tiddens et al., 2020).	Accurate fault prediction is achieved, enabling the accurate prediction of remaining useful life for parts. (Saez et al., 2018).	Accurate fault prediction is achieved, and possible faults can be detected and predicted in real-time (Daily and Peterson, 2016).	
Quality	Product quality is improved, and any uninspected tool or device defect is minimized before completing a specific job (Tiddens et al., 2020).	Product quality is further improved, and uninspected tool or device defects are predicted and resolved in advance (He et al., 2017).	Product quality is improved to the greatest extent, as uninspected tool or device defects are predicted and resolved in advance. (Lu et al., 2021).	
Safety	The device is anticipated to operate normally until a specific job is completed, aiming to enhance safety (Compare et al., 2019).	Safety for the operator, device, and customer is further enhanced with the expectation of normal device operation (Yoon et al., 2017).	Theoretically, any potential safety risk is predicted in real-time and resolved in advance (Görür et al., 2021).	

Appendix2: Additional function marking

Additional Functions				
Sub-dimensions		Marks		
		1	3	5
Production	The production plan will not be affected since device shutdown can be avoided before a specific job is finished (Tiddens et al., 2020).	Production plans are automatically conducted by production management software using device operation data (Lee et al., 2017).	Management software automatically conducts production plans using real-time device data. If stakeholders change, plans can be instantly re-optimized (Einabadi et al., 2019).	
Logistic	The raw material and spare part purchase plan, as well as the product delivery plan, can be optimized (Irawan et al., 2017).	Software automatically optimizes raw material and spare part purchase, storage plans, and product delivery plans (Hribernik et al., 2018).	The raw material and spare part purchase and storage plan, as well as the production delivery plan, are automatically optimized by software based on real-time device operation data. (Proto et al., 2020).	
Sustainability		The waste of energy and raw materials is reduced since the productivity and product yield are improved (Çınar et al., 2020)	The waste of energy and raw materials is reduced to the largest extent since the productivity and product yield are improved to the largest extent (Rødseth et al., 2016)	
Transparency		Any stakeholder is allowed to access the production, purchase storage plan, and delivery plan (Sang et al., 2020)	Any stakeholder is allowed to access and work on the production, purchase storage plan, and delivery plan in real-time (Rødseth et al., 2016)	



DSPACE

<https://dspace.org/>

Predictive maintenance servitisation pathways

Li, Jiahong; Milisavljevic-Syed, Jelena; Salonitis, Konstantinos

2024

Elsevier

<https://doi.org/10.1016/j.ifacol.2024.08.142>

Li J, Milisavljevic-Syed J, Salonitis K. (2024) Predictive maintenance servitisation pathways. IFAC-PapersOnLine, Volume 58, Issue 8, pp. 329-334