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An overview of Industry 4.0 Applications for Advanced Maintenance Services

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Abstract

Manufacturing today has experienced dynamic changes imposed by social-technical systems that address economic, social and sustainable requirements. Furthermore, the technologies in Industry 4.0 have also brought many smart applications to advance manufacturing to the next level of development. In a focused sense, maintenance plays a key role in manufacturing to create value propositions—extension of equipment useful life and enhancement in overall equipment effectiveness—for stakeholders towards economics and sustainability. In this context, the maintenance services that create the value propositions are not only delivered as after-sales maintenance services but developed to advanced maintenance services embedded into Industry 4.0 applications. To provide a clearer picture of the development, this work aims to review and categorize the maintenance services in three groups—basic services, intermediate services, advanced services—associated with technologies in Industry 4.0 across the life-cycle maintenance service.

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Keywords: Industry 4.0 applications; advanced maintenance services; life-cycle maintenance service

1. Introduction

The technologies (e.g., Industrial Internet of Things (IIoT), wireless sensor networks, big data, cloud computing, cyber physical systems (CPSs)) in Industry 4.0 have brought a wide range of application possibilities in manufacturing towards economics and sustainability: optimization in resource efficiency and effectiveness, and customization in manufacturing [1–4]. The technological advances, such as big data and predictive analytics, also pave the way for

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minimizing waste and resource consumption towards social and environmental sustainability (e.g., energy, water and natural resources) [5].

One of the application areas in manufacturing sector is maintenance that may benefit from the opportunities that emerge with the digital transformation of industrial processes [6]. Therefore, maintenance in Industry 4.0 has radically changed according not only to the technological advances, but also because of the new market dynamics towards economics and sustainability [1,7]. This phenomenon triggers the process of servitization—by which manufacturing companies transform their businesses from product-oriented to product-service oriented businesses—whose opportunities are immense. This phenomenon—known as product-service systems of a comprehensive service package, customer benefit, user integration in service provision [8]—is seen as a key to industrial success and research interests in recent years [9,10]. Therefore, in addition to the technical aspects in maintenance, the aim of this work is to structure maintenance services and discover the integration between them and technologies across the life cycle maintenance service in the context of Industry 4.0.

This work begins with a review of the literature regarding the life cycle maintenance service and technological applications in maintenance in the context of Industry 4.0. The review process analyzes the related review papers on the topic. The subsequent section presents and discusses the current maintenance services structured in different service bundles—basic services, intermediate services, and advanced services—associated with the enabling technologies. The conclusion section ends with a summary and suggestions for future research.

2. Related work

Even though numerous review works contributed into the research summary of maintenance in the context of Industry 4.0, they focused on different topics—life cycle maintenance service, Industry 4.0 applications, servitization—as exemplified in Table 1. However, these topics were not connected to realize their full potential benefits of maintenance in Industry 4.0. Therefore, the review process critically analyzes relevant publications (e.g., books and journal articles), explains and integrates their results together. This process was done by following three steps: (i) search for relevant literature; (ii) evaluate relevant publications; (iii) identify their themes, debates and gaps. Moreover, this review process also captures the latest relevant reports developed by Platform Industry 4.0 as the cornerstone of commercial developments in Industry 4.0.

Table 1. List of review papers

Paper	Title	Research topic	Journal
[1]	Maintenance 4.0 Technologies for Sustainable Manufacturing - an Overview	Industry 4.0 applications in maintenance	IFAC-PapersOnLine
[2]	Maintenance for Sustainability in the Industry 4.0 context: a Scoping Literature Review	Maintenance for sustainability	IFAC-PapersOnLine
[7]	Enabling technology for maintenance in a smart factory: A literature review	Industry 4.0 applications in maintenance	Procedia Computer Science
[10]	Human-centred design in industry 4.0: case study review and opportunities for future research	Human-centred design in industry 4.0	Journal of Intelligent Manufacturing
[11]	Maintenance transformation through Industry 4.0 technologies: A systematic literature review	Industry 4.0 applications in maintenance	Computers in Industry
[12]	Maintenance: Changing Role in Life Cycle Management	Maintenance role in life cycle management	CIRP Annals

In a common perspective, maintenance plays an important role in smoothing manufacturing operations by ensuring production processes remain consistent and efficient and at the same time optimizing and extending the equipment availability. While the efficiency shows how resources—human factors (e.g., number of operators, required skills and workload), energy, gas and water—can be minimized, the effectiveness measures the level of satisfying the customer´s requirements via the set specifications on how the machines and equipment run at their best design capability: quality and operating speed, to name a few.

However, in the context of Industry 4.0, the paradigm of manufacturing shifts from not only producing products in an efficient and effective way, but also minimizing material and energy consumption. Life cycle management is becoming a crucial pillar in order to achieve this goal [12]. In this context, the role of maintenance should be integrated in the life cycle management as an essential mean towards fostering long-term competitive, responsible and sustainable performance [13]. Therefore, the view of maintenance services associated with the technologies through the lens of life cycle management is necessary and presented as below:

2.1. Life-cycle maintenance service

Numerous researchers have emphasized the role of maintenance in the life cycle management [12,14,15]. As can be seen in Figure 1, maintenance also focuses on the circular manufacturing in which the aim of maintenance is to maximize the values in use generated by operations across the life cycle—ranging from raw material, production, reuse and disposal—rather than the minimization of maintenance cost [14].

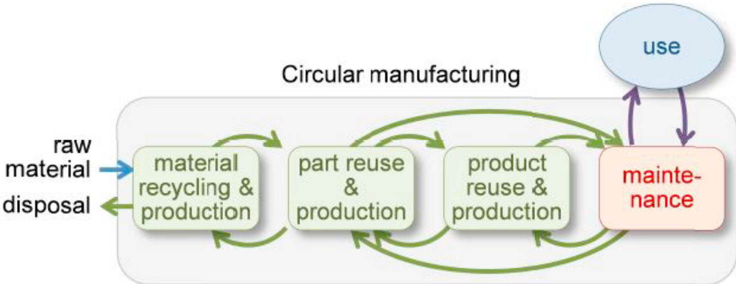

Fig. 1. Concept of maintenance-centred circular manufacturing [14]

The relationship between maintenance and values in use generated by the operations across the life cycle creates a goal conflict between production and maintenance operations. On one hand, production lines are expected to run at the highest possible production ratio, which leads to lack of maintenance activities, accelerating the deterioration of the machines and equipment. On the other hand, the increase or improper schedule in maintenance activities will result in decreasing assets availability and/or lower productivity ratios. Life cycle maintenance management addresses following general phases as described by Figure 2 [12,14–18]:

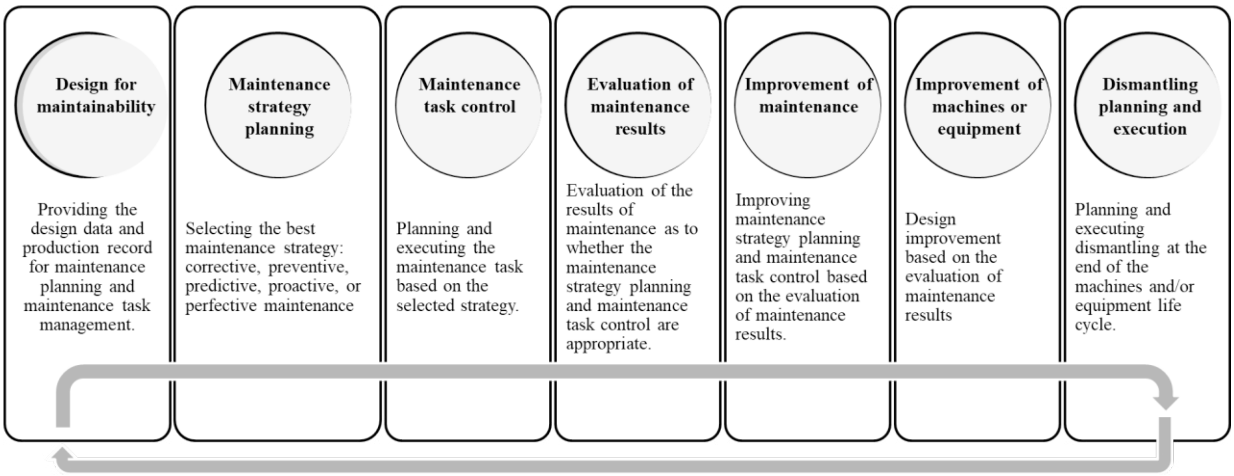

Fig. 2. Life cycle maintenance management, adapted from [16]

The life cycle maintenance management reflects the fact that maintenance is a demanding set of tasks performed on industrial assets [19]. Therefore, outsourcing these maintenance tasks as services deserves attention in the business to business (B2B) strategy [18,19]. This will promote new value propositions which customers are willing to include in their maintenance strategy and asset manufacturers should include in their portfolios—remote maintenance, skills training, diagnosis and upgrading, to name a few—combined with their physical products (e.g., machines and/or equipment) as product-service systems. In context of Industry 4.0, the technologies facilitate the tasks to be done in an efficient and effective way as explained by the following section.

2.2. Industry 4.0 applications in maintenance

The application of the technologies in Industry 4.0 is also a criterion to distinguish maintenance from the previous industrial revolutions to Industry 4.0. This differentiation is defined by the level of maturity in maintenance deployment in different aspects—process management, methods and tools for performance measure, IT infrastructure, and people skills—as described by Table 2. Holistic review on possible relevant emerging technological applications of the Industry 4.0 on maintenance is also available [7,11,20–22]: IIoT, big data and analytics (BD), simulation (SIM), cloud computing (CC), system interoperability (SIT), cyber security (CS), virtual reality and augmented reality (VR/AR), autonomous mobile robots (AMR), additive manufacturing (AM). While IIoT is the technology enabling the interconnections of machines via internet for exchanging global or local maintenance and machinery performance data, the big data and analytics enable for data processing towards predictive maintenance that is also supported by the simulation—for prediction and "what-if" scenario analysis—and cloud computing for storage solution and on-demand computing, secured by cyber security. Furthermore, system interoperability facilitates the compatibility of different platforms or machinery languages to be guaranteed. Beyond the technical aspects, human involving maintenance operations is also supported by virtual and augmented reality, autonomous robots working collaboratively alongside with humans, and additive manufacturing for reducing spare parts inventory cost, component assembly cost, and replacing the discontinued parts easily.

Table 2. Maturity levels of maintenance [23]

Capability	Level 1 Visual inspections	Level 2 Instrument inspections	Level 3 Real time monitoring	Level 4 Predictive maintenance in Industry 4.0
Process	- periodic inspection (physical) - checklist - paper recording	- periodic inspection (physical) - instruments - digital recording	- continuous inspection (remote) - sensors - digital recording	- continuous inspection (remote) - sensors and other data - digital recording
Content	- paper based condition data - multiple inspection points	- digital condition data - single inspection points	- digital condition data - multiple inspection points	- digital condition data - multiple inspection points - digital environment data - digital maintenance history
Performance measure	- visual norm verification - paper based trend analyses - prediction by expert opinion	- automatic norm verification - digital trend analyses - prediction by expert opinion	- automatic norm verification - digital trend analyses - monitoring by CM software	- automatic norm verification - digital trend analyses - prediction by statistical software - advanced decision support
IT	- MS Excel/MS Access	- embedded instrument software	- condition monitoring software - condition database	- condition monitoring software - big data platform and network - statistical software
Organization	- experienced craftsmen	- trained inspectors	- reliability engineers	- reliability engineers - data scientists

The connection between the enabling technologies and services in maintenance clarifies the possible applications across the life cycle maintenance service, facilitating the maintenance services segmentation as presented in the following section.

3. Advanced maintenance services across life-cycle

In order to structure the connection between the enabling technologies and advanced maintenance services across life-cycle, Table 3 provides a schematic representation whose rows present the different maintenance processes—that are described by the European Standard EN 17007:2017 [24]—categorized in the different phases during the life-cycle maintenance services of assets.

Table 3. Maintenance service segmentation associated with enabling technologies across the life cycle maintenance service, adapted from [11]

Life cycle	Maintenance processes [24]	Services	IIoT	BD	SIM	CC	SIT	VR/AR	AMR	AM	CS
Design for maintainability	Manage maintenance (strategy and improvement planning, etc.)	Advanced	✓	✓	✓	✓	✓				✓
	Budget maintenance of items	Advanced	✓	✓		✓					
Maintenance strategy planning	Manage data	Intermediate	✓	✓		✓					✓
	Ensure personal health and safety	Basic	✓				✓	✓	✓		✓
	Provide the needed infrastructures	Intermediate				✓	✓				✓
	Provide internal human resources	Intermediate	✓	✓	✓		✓	✓	✓		
	Provide external maintenance services	Intermediate	✓			✓	✓				
Maintenance task control	Deliver the tools, support equipment and information system	Basic	✓			✓				✓	
	Deliver the operational documentation	Basic				✓	✓				✓
	Deliver spare parts	Basic	✓			✓				✓	
Evaluation of maintenance results	Deliver maintenance requirements during items design and modification	Basic	✓		✓		✓				
Improvement of maintenance	Prevent undesirable events by avoiding failures and faults	Advanced	✓	✓	✓		✓				
	Implement preventive and/or corrective actions on the item	Advanced	✓	✓	✓		✓	✓	✓		
	Improve the maintenance results	Intermediate	✓	✓	✓		✓				
Improvement of equipment	Improve the items	Intermediate			✓					✓	
Dismantling planning and execution	Restore the items in required state	Basic	✓				✓	✓	✓		

The columns shown as marked indicate the potential applications of the technologies in maintenance associated with service value propositions [11]. These service value propositions are categorized in three groups [9,25]: the basic services, the intermediate services, and the advanced services. The basic services represent the services provided at the point where the manufacturing asset in involved in recovering equipment from failure (a traditional reactive service), focusing maintenance activities to ensure the effectiveness. The intermediate services provide values in use to the customer by minimizing the disruption due to maintenance failures at the customer site, exploiting equipment competences to assure state and condition of equipment. Lastly, the advanced services deliver highest values in use by collaboratively improving and optimizing the equipment towards better performance for the customer so that the customer is supported to achieve their evolving goals in an efficient and effective way. This requires the provider stretches its manufacturing enterprise to take on activities that are usually internal to the customer site. This context brings new value propositions in maintenance that change the relationship between the provider and its customer, which is facilitated by the technologies in Industry 4.0. The relationship is shifted from selling the machine and/or equipment alone to the customer—as a product-oriented provider—to share the responsibility (e.g., risk and revenue sharing agreement) between the provider and customer—as advanced services—towards the improvement and optimization of the equipment for better performance, achieving both the customer business objectives and the provider's new product-service value delivery.

In the life cycle maintenance service, the provider can offer advanced services by being involved in the very early stage of design for maintainability—that includes strategic management for maintenance and budget—for the customer. This can possibly lead to customer support agreement and/or possible risk and revenue sharing contract among the provider and the customer. In this context, one of the enabling technologies is SIT in which the different operating systems in both the provider and customer can seamlessly integrate and work with each other. Besides, CC not only enables both the provider and customer share data storage for the maintenance and budget management in design for maintainability, but also manages data and provides the needed infrastructures—cloud storage and computing power—as external maintenance services in maintenance strategy planning. While the delivery of tools, information, operational documentation and spare parts in maintenance task control is considered as basic services, asset manufacturer can also offer valuable advanced services to the customer by providing solutions to prevent undesirable events, failures and faults towards maintenance improvement. The implementation of these technologies associated to the concept of advanced services reveals potential for designing and implementing novel, flexible pricing or revenue models for the system of products and services, resulting in data-driven business models developing into knowledge-driven models [8]. These models are also called as value-based services that realize revenue mechanisms illustrated by Figure 3:

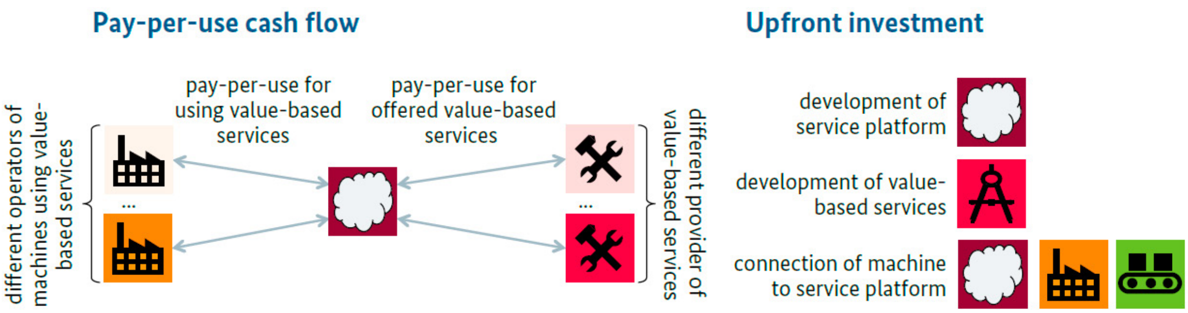

Fig. 3. Principal revenue mechanisms [26]

Various value propositions are possible including adequate gain and risk sharing models. This amount of value stream will depend on the number of connected machines, the amount of usage data and connection over time, and the use of platform for basic to advanced analytic capabilities [26]. Although the different services in maintenance can be realized with the support of technologies in the context of Industry 4.0, the methodology for designing the advanced services in industries and research alike is not complete. This requires a new methodology that enables the asset manufacturer to design and deliver the product-service value propositions to its customers and stakeholders—as a human-centered approach—beyond its original product (e.g., equipment and/or machines) [10].

4. Discussion and conclusion

The maintenance services that are categorized in three groups—basic services, intermediate services, and advanced services—associated with enabling technologies across the life cycle maintenance service indicate the business opportunities for the provider—who provides products in the form of machines and/or equipment—to offer its new product-service value propositions to its customers and stakeholders. This approach will not only enhance the provider competitiveness and new business value propositions, but also will help to achieve the customer business objectives towards economics and sustainability. The future research should develop a new methodology that supports businesses to design and deliver the product-service value propositions associated with enabling technologies—to realize full potentials in Industry 4.0—across the life cycle maintenance service.

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