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INDUSTRY 4.0 ENABLED PREDICTIVE MAINTENANCE OF FACILITIES: A STUDY ON APPLICABILITY, BENEFITS AND CHALLENGES

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ABSTRACT

Maintenance management is an important function under Facilities Management (FM). Industries moved to preventive maintenance models to counteract the inefficiencies of reactive maintenance and further evolved into predictive maintenance (PdM) models. The demand for Industry 4.0 enabled PdM for FM has risen as a result of the industrial revolution and the dynamic nature of the FM functions. Thus, the study aimed to investigate the applicability, benefits, and challenges of applying Industry 4.0 concept for effective PdM in FM. The qualitative research approach was undertaken to accomplish the aim. A comprehensive literature review followed by 15 semi-structured interviews was carried out with experts in the maintenance sector who have Industry 4.0 knowledge. The data was collected from experts in Australia, Qatar, Dubai, Singapore, and Sri Lanka, and analysed through code-based content analysis using NVivo 12. The results demonstrate that there is a huge potential for using Industry 4.0 smart technologies such as big data analytics, Cyber-Physical Systems (CPS), autonomous robots, Cloud Computing, Industrial Internet of Things (IIoT), cybersecurity, Machine Learning (ML), Augmented Reality (AR), Data Mining (DM), system integration, and simulation for PdM under FM. Applying Industry 4.0 concept for effective PdM under FM provides significant benefits such as the deployment of a zero-failure strategy, establishment of machine-to-machine communication and interaction, detection of early anomalies and extended equipment lifetime. Lack of technological knowledge, capital, data management, employees' interest, integration between systems, standardized procedures, and internet access are identified key challenges.

Keywords: *Applicability, Benefits and Challenges; Industry 4.0; Facilities Management (FM); Predictive Maintenance (PdM); Smart Technologies.*

1. INTRODUCTION

Facilities Management (FM) incorporates multiple disciplines to ensure the optimum performance of the built environment in terms of people, process, place and technology (International Facility Management Association, 2009). Due to rapid and large-scale urbanisation, the role of FM along with maintenance management is more effective in emerging countries (Myeda, et al., 2011). Poor, et al., (2019) highlight how maintenance has progressed from reactive to proactive maintenance over three generations. Reactive

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maintenance allows the equipment to run until the failure (Swanson, 2001). Moreover, identifying and correcting the causes of failures that result from the failure occurrence is known as corrective maintenance. (Wang, et al., 2014), where as a Computerized Maintenance Management System (CMMS) is a tool that utilizes an information system with a set of functions to process data and provide informative maintenance-related indicators (Lopes, et al., 2016). Preventive maintenance uses schedules of pre-described frequencies to minimize commonly occurring failures whereas, predictive maintenance (PdM) utilizes time-based information to predict forthcoming failures to avoid unwanted downtime (Matyas, et al., 2017). Compared with other maintenance methods, PdM has some substantial advantages such as, (a) equipment, which needs maintenance is shut down solely before impending failure, (b) minimizes the time spent on equipment maintenance, (c) reducing the cost of maintenance by avoiding disastrous damage, (d) maximizing the availableness of equipment, (e) extending the useful lifetime of equipment and (f) improve occupational and environmental safety and (g) increases the reliability (Bousdekis, et al., 2020). Hence, industries requires real-time monitoring and controlling for the proper execution of maintenance management, which is also beneficial to efficiently regulate and manage maintenance activities (Su, et al., 2011). The present scope of FM solely focuses on the core business activities of the organization to add value to its bottom line by increasing revenue, boosting the company's image, lowering expenses and increasing productivity, whereas, forthcoming advancement in the FM will have the significant impact of future novelty and revolution (Okoro and Musonda, 2019). The demand for Industry 4.0 enabled PdM for FM has risen as a result of the industrial revolution and the dynamic nature of the FM industry. However, there is a lack of a study on how Industry 4.0 can enable PdM in FM. Thus, the study aimed to investigate the applicability, benefits and challenges of applying Industry 4.0 concept for effective PdM in both product and process-based FM. This paper starts with a literature review on Industry 4.0 and its applications to PdM of facilities. Section 3 presents the research methodology. The research findings and discussion are presented in Section 4 followed by conclusions and recommendations.

2. LITERATURE REVIEW

This section reviews the literature on Industry 4.0, its applications to both product and process-based FM and PdM and benefits and challenges in applying it to PdM of facilities.

2.1 FOURTH INDUSTRIAL REVOLUTION AND ITS APPLICATION TO FM

The Fourth Industrial Revolution (Industry 4.0) is initially raised in Germany to comply with the innovative requirements of the forthcoming industry (Lee, et al., 2014). Unlike the last three industrial revolutions, Industry 4.0 will not be triggered by a single technology (Meissner, et al., 2017). Additive Manufacturing (AM), Big Data Analytics, Autonomous Robots, Cloud Computing, Industrial Internet of Things (IIoT), Cyber Security, Augmented Reality (AR), System Integration and Simulation are considered as nine pillars of Industry 4.0 (Rubmann, et al., 2015). Further, Cyber Physical System (CPS) (Li, et al., 2016), Machine Learning (ML) (Su and Huang, 2018) and Data Mining (DM) (Li, et al., 2016; Su and Huang, 2018) technologies are considered as emerging technologies for the implementation of Industry 4.0.

Industry 4.0 is a fusion of technology, which continuously builds and extends the influence of digitalization in everyday applications, and ensures the function of FM remains sustainable (Okoro and Musonda, 2019). Industry adaptation vs. advancements in FM-related Industry 4.0 practices have created a demand for up-to-date digitized building assets (Stojanovic, et al., 2018). Maintenance management, which is a key area in the FM field, has recently begun to invest in smart technologies to enhance service supply in a novel way (Talamo, et al., 2019). FM is evolving in the Industry 4.0 scenario, as a result of the introduction of new technologies that can boost the capabilities of positions committed to structure management (Nota, et al., 2021). Moreover, the authors highlighted that the adoption of new technologies such as IoT, IIoT, CPS, and Cyber Physical Production System (CPPS) has led to recent advancements in the FM industry.

2.2 APPLICATION OF INDUSTRY 4.0 FOR PDM IN FM

PdM in its early stage utilized measuring, sensing and controlling aspects of machinery to identify whether there have been faced with any significant changes in the physical condition of machinery, whereas now, technological advancements may improve the effectiveness of PdM (Bengtsson and Lundstrom, 2018). The sophisticated sensor infrastructure of Industry 4.0 is enabling the employment of algorithms that evaluate data, predict impending scenarios, and prescribe mitigating steps for production and maintenance operations (Bousdekis, et al., 2021). Further, the authors highlighted that monitoring techniques have changed in recent years as a result of the introduction of Industry 4.0, from visual inspections and manual data processing to high-frequency sensors that generate real-time big data on a variety of techniques like vibration, temperature, and thermography.

2.3 BENEFITS OF APPLYING INDUSTRY 4.0 CONCEPT FOR PDM IN FM

Industry 4.0 boosts PdM capabilities and lays the path for more effective and optimal maintenance operations (Bousdekis, et al., 2020). Numerous benefits gained through the implementation of the Industry 4.0 concept for PdM are listed in Table 1.

Table 1: Benefits of applying Industry 4.0 concept for PdM in FM

Advantages	**References**						
	[1]	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	**[7]**
Ability to determine appropriate intervals for PdM						X	
Enhance production and maintenance processes					X		
Ability to maintain high levels of quality	X			X	X		
Minimize failure and maintenance costs		X	X		X		
Ability to implement a zero-failure strategy		X	X	X	X		
Predictive analytics			X				X
Improve asset status forecasting prognosis		X	X				X
Machine-to-machine communication and interaction			X				
Generate and forecast maintenance-related information		X	X		X		
Facilitate large amounts of real-time and historical data to detect early anomalies		X					
To gain a competitive edge		X					
Extended operating equipment lifetime		X					

Advantages	References						
	[1]	[2]	[3]	[4]	[5]	[6]	[7]
Enhanced safety (Occupants and equipment)		X	X				
Effective use of maintenance resources		X					
Upgraded plant reliability		X					

References: [1] Bengtsson and Lundstrom (2018), [2] Bousdekis, et al. (2020), [3] Li, et al. (2017), [4] Poor, et al. (2019), [5] Sezer, et al. (2018), [6] Spendla, et al.(2017), [7] Kumar and Galar (2018)

2.4 CHALLENGES IN APPLYING INDUSTRY 4.0 CONCEPT FOR PDM IN FM

PdM faces a variety of practical implementation challenges in the complex and dynamic Industry 4.0 environment (Bousdekis, et al., 2020). Table 2 presents various types of challenges of using Industry 4.0 for PdM.

Table 2: Challenges in using Industry 4.0 concept for PdM in FM

Challenges	References
Technological challenges	
• Lack of technological knowledge to handle sophisticated computer solutions	[9]
• Ignorance of Industry 4.0 technologies	[5]
• Implementation and adoption challenges	[7]
Investment challenges	
• Lack of capital for investment	[4]
• Uncertain returns from investments	[5]
Data challenges	
• Lack of adequate real-time and historical data	[1]
• Need to manage, store and process voluminous data	[5]
• Unstructured data format	[2]
• Insufficient data processing power	[2]
• Poor data quality	[3]
• Inability to derive information from data	[3], [5]
• Challenge in using production data as a catalyst for Industry 4.0 initiatives	[9]
Employees related challenges	
• Lack of employees towards knowledge upgrades	[1]
• Scarcity of industry 4.0 skilled experts or employees	[4], [11]
• Lack of organizational interest in change	[1], [10]
• Need to invest in data analytics roles	[1]
Integration Challenges	
• Create a synergy between organizational systems and their respective productive teams	[10]
• Lack of integration between systems	[3], [4], [11]
• Enable internal data sharing in the system	[13]

Challenges	References
Standardization Challenges	
• Absence of a well-established uniform standard solution	[5]
Communication Challenges	
• A lack of internet access	[5]
Security Challenges	
• Insecure connectivity protocols	[4]
• Lack of investment to invest in huge security and protection for databases	[6], [8]
• Need for data protection	[4]

References: [1] Bousdekis, et al. (2020), [2] Kiangala and Wang (2018), [3] Li, et al. (2017), [4] Moktadir, et al. (2018), [5] Singh, et al. (2019), [6] Dalenogare, et al. (2018), [7] Frank, et al. (2019), [8] Lezzi, et al. (2018), [9] Moeuf, et al. (2018), [10] Muller, et al. (2018), [11] Oztemel and Gursev (2020), [12] Sung (2018), [13] Xiang, et al., (2018).

3. METHODOLOGY

A comprehensive literature review was conducted to perceive a theory-based knowledge from the research area. Industry 4.0, PdM and FM concepts are reviewed from a broader perspective to elaborate the research problem. The literature review assisted in identifying feasible smart technologies to develop an integration between Industry 4.0 and PdM approach. Hence, in order to achieve the aim, the research necessitates an in-depth expert opinion to be evaluated in a descriptive way. Thus, this research applied semi-structured interviews through qualitative research approach. However, obtaining a large sample of respondents was difficult due to the lack of Industry 4.0 applicability. Hence, 15 experts who had proficiency in the maintenance sector with the knowledge of Industry 4.0 from manufacturing facilities were selected through convenient sampling and interviewed. NVivo software was used in this research to carry out the code-based content analysis.

4. RESEARCH FINDINGS

The semi-structured interviews were conducted with 15 maintenance field experts from Australia, Qatar, Dubai, Singapore and Sri Lankan manufacturing industries, who have Industry 4.0 awareness and knowledge. Experts' profile is given in Table 3.

Table 3: Experts' profile

Code	Designation	Nature of the organization	Experience	Country
R1	Facilities Coordinator	Food Manufacturing	10 Years	Australia
R2	Facilities Engineer	Food Manufacturing	10 Years	Qatar
R3	Head Industry 4.0 Initiative	Stationary Manufacturing	11 Years	Sri Lanka
R4	Plant Engineer	Cement Manufacturing	20 Years	Sri Lanka
R5	Facilities Engineer	Food Manufacturing	09 Years	Dubai
R6	FM Estimation Engineer	Food Manufacturing	08 Years	Qatar
R7	Facilities Engineer	Food Manufacturing	09 Years	Dubai
R8	Mill Manager	Food Manufacturing	20 Years	Sri Lanka

Code	Designation	Nature of the organization	Experience	Country
R9	Senior Reliability Engineer	Tyre Manufacturing	08 Years	Sri Lanka
R10	Facilities Engineer	Food Manufacturing	09 Years	Dubai
R11	Maintenance Manager	Food Manufacturing	12 Years	Singapore
R12	Maintenance Engineer	Food Manufacturing	10 Years	Sri Lanka
R13	Head of Autonomation	Garment Manufacturing	10 Years	Sri Lanka
R14	Engineering Maintenance Manager	Cement Manufacturing	15 Years	Singapore
R15	Senior Factory Engineer	Cement Manufacturing	16 Years	Sri Lanka

Among the respondents, R3 is from a manufacturing firm where Industry 4.0 strategy is developed and their system indicators are clearly defined (Intermediate stage in the Industry 4.0 Ladder). Research findings are discussed below.

4.1 CURRENT MAINTENANCE PRACTICES USED FOR FM

To identify the existing industry practices in the maintenance field, respondents were asked to mention the maintenance practices followed in their current organization. Respondents' responses are summarized in Figure 1.

Name	Files	References
Current Maintenance Approaches	15	102
Computerized Maintenance Management System	15	15
Condition Based Maintenance (CBM)	12	12
Corrective Maintenance	15	15
Lean Maintenance	2	2
Predictive Maintenance (PdM)	15	15
Preventive Maintenance	15	15
Reactive Maintenance	15	15
Reliability Centred Maintenance (RCM)	8	8
Total Productive Maintenance (TPM)	5	5

Figure 1: Currently utilized maintenance approaches in FM

According to the analysis, it was evident that reactive maintenance, corrective maintenance, preventive maintenance, PdM and Computerized Maintenance Management System (CMMS) are prominently used maintenance approaches. Respondents also mentioned that CBM and PdM terms and approaches are interchangeably used in the maintenance field. However, all respondents have highlighted that the PdM approach is not well-established in the industry at the moment. However, the applicability of PdM for FM is acknowledged through currently utilizing PdM techniques and by recognizing its intended benefits for each organization through respondents' responses. According to the analysis, the most commonly used PdM techniques are oil analysis, thermographic analysis and visual inspection. Moreover, vibration analysis is also cited by most of the respondents. Only a few respondents are utilizing ultra-sonic analysis. A proactive approach like PdM is beneficial for the operations of the industries in numerous ways. According to respondents' opinion, most industries are trying to implement the PdM approach to reduce their cost burdens. Next significance is given by the respondents to avoid or reduce downtimes. Further, respondents highlighted that there is a high opportunity for identifying the maintenance requirement accurately. Each and every organization and its maintenance managers are getting benefited from the PdM approach.

Asian maintenance experts are satisfied with current maintenance approaches. After COVID-19, Gulf industries are becoming more interested in smart maintenance solutions with less human interaction, whilst the majority of Australian (Oceania) companies are still using excel-aided preventive maintenance programs. On the other hand, maintenance management approaches evolve from time to time in a way to fulfil arising maintenance requirements. However, there are many issues in executing the current maintenance approaches. R1, R3 and R10 stated that the complex and unpredictable nature of maintenance is "*generic and inevitable in the maintenance field*". R5 and R8 highlighted that "*PdM will determine the future of the industries*". Still, they highlighted that a proper PdM is not possible without the foundation of correlation techniques or smart technologies. All experts answered in a similar way to "*computerize or digitalize the maintenance management process*" to carry out effective PdM in FM.

4.2 INDUSTRY 4.0 AND ITS SIGNIFICANCE TO CARRYOUT PDM IN FM

This section focuses on the expert's awareness and knowledge of Industry 4.0. All fifteen respondents were well aware of Industry 4.0. "Automation", "integration" and "smart machinery, people and resources" are the keywords used by the respondents for defining Industry 4.0. Other than these words, respondents gave prominent focus to the word "real-time data". Considering the feedback received from respondents, Industry 4.0 can be defined as:

> "*An industrial transformation or a digital transformation, which can be considered as an expensive solution to overcome existing gaps in the industries by enabling automation through advanced technology, simulating, scheduling, integrating smart machinery, people and process, monitoring, controlling machines and equipment by real-time data collected through wireless connectivity and sensors".*

4.2.1 Need for a Novel Maintenance Approach in Facilities Maintenance

Industries are gradually recognizing the value of the facilities maintenance. However, the current level of maintenance is not adequate to address all the maintenance requirements of the industries. Respondents' responses to identify whether there is an actual need for a novel maintenance approach in the facilities maintenance are summarized in Figure 2.

Name	Files	References
Need for a novel maintenance approach in Facilities	13	13
To achieve greater added values	2	2
Requirement for a change or proactive approach	5	5
Increasing criticality in managing assets	6	6

Figure 2: Need for a novel maintenance approach in facilities maintenance

Thirteen respondents mentioned that there is an actual need for a novel maintenance approach. On other hand, two respondents argued that there is no need for a novel maintenance approach. Supporting this, R1 stated, "*There is no term is validated as a novel maintenance approach. New maintenance concepts and practices are using the same existing approaches to optimize available maintenance practices. Concepts are same, approaches are getting smarter and trying to define more combination, optimization and monitoring ways.*". Further, R4 presented his reason as, "*There is no need for a new maintenance approach for facilities maintenance. Anyhow, modification* *in the traditional maintenance approaches along with smart technologies is appreciated.*".

4.2.2 Importance to Switch toward the New Industrial Paradigm

The opinion of all respondents about the significance or importance to switch toward a new industrial paradigm is summarized in Figure 3.

Name	Files	References
Importance to Switch Towards New Industrial Paradigm	15	17
Achieving sustainability	1	1
Competitive advantage	7	7
Enhancing collaborative smart work environment	2	2
Globalization	1	1
Inevitable or mandatory requirement	2	2
Reduced costs	1	1
Supply the demand for real-time insights	3	3

Figure 3: Importance to switch toward a new industrial paradigm

R3 and R4 highlighted their answer with a real-life example of "KODAK". KODAK failed to retain its market as it fails to give importance to digital technology. Likewise, R10 mentioned that "*Failing to adopt Industry 4.0 smart technologies will force firms to lag, as their activities will not be sufficiently smart to compete with other industries*".

4.3 APPLICABILITY OF SMART TECHNOLOGIES TO IMPLEMENT INDUSTRY 4.0 ENABLED PDM IN FM

Possible applications of smart technologies to enable effective PdM in FM were collected from industry experts and presented in Table 4.

Table 4: Possible application of smart technologies to enable effective PdM in FM

Smart Technologies	Possible Applications
AM	Printing 3D spare parts
Big Data Analytics	Assessing the health of machines and predicting breakdowns
CPS	Inducing self-aware and self-adaptive abilities of machines
Autonomous robots	Performing critical maintenance activities in human restricted areas
Cloud computing	Processing, analysing, and storing maintenance data
IIoT	Predicting future failure events
Cyber security	Providing data protection against cyber-attacks
ML	Facilitating both supervised and unsupervised ML to predict failures
AR	Visualizing machine's physical conditions
DM	Extracting hidden patterns, trends and relationships from data
System integration	Automating communication cooperation and standardized procedures regarding PdM
Simulation	Developing a virtual model using real-time data

R11 highlighted that "Industries which are now practicing Industry 3.0 are more curious about Industry 4.0 implementation". Further, above-identified all possible applications of smart technologies can be successfully utilized to enable effective PdM in FM.

4.4 BENEFITS OF APPLYING INDUSTRY 4.0 TO PDM

Respondents identified the advantages of applying Industry 4.0 to PdM in FM and the identified benefits are presented in Figure 4.

Name	Files	References
Derivable Advantages	15	224
Ability to determine appropriate intervals for PdM	15	15
Ability to implement a zero-failure strategy	14	14
Ability to provide high quality of maintenance	15	15
Detecting early anomalies (Real-time and historical data)	15	15
Effective use of maintenance resources	15	15
Enhance maintenance processes	15	15
Enhanced safety (Occupants and equipment)	15	15
Extended operating equipment lifetime	15	15
Generate and forecast maintenance related information	15	15
Improve asset status forecasting prognosis	15	15
Machine-to-machine communication and interaction	15	15
Minimize failure and maintenance costs	15	15
Predictive analytics	15	15
To gain a competitive edge	15	15
Upgraded plant reliability	15	15

Figure 4: Advantages of applying Industry 4.0 to PdM

All experts agreed that determining appropriate intervals for PdM, enhancing maintenance, predictive analysis and high levels of quality, asset forecasting prognosis, machine-to-machine communication and interaction, detection of early anomalies, extended operating lifetime, safety, effective use of maintenance resources, upgraded plant reliability, gaining competitive advantage and minimizing failure and maintenance cost as some of the benefits that can be gained from Industry 4.0 application for PdM in FM. Except R1, all experts agreed on the benefit of the "ability to deploy a zero-failure strategy". R1 stated that a "*zero-failure strategy cannot be achieved*". However, "*implementing a zero-failure strategy is possible with appropriate strategic planning and implementation of maintenance activities*" stated R9.

4.5 CHALLENGES IN APPLYING INDUSTRY 4.0 TO PDM

All respondents identified challenges for the application of Industry 4.0 to PdM in FM. Respondents' opinions towards each type of challenge are discussed below.

Technology-related challenges

Industry 4.0 is a digital transformation, which requires the support of smart technologies. R1 stated that "*switching into new technology-based systems is always a challenge in its earlier phases of implementation*". Industries must overcome these technological challenges to achieve intended Industry 4.0 benefits.

Investment related challenges

Investment challenges are very common in the industries. Industrial transformation requires a high initial cost. R11 highlighted that "*large manufacturing firms are hesitant to invest due to unknown risks in investments, where medium scale manufacturing firms face limited capital concerns when investing.*"

Data related challenges

Data plays a significant role in the fourth industrial revolution. Initially, it is difficult to collect, manage, process and analyse data. Industries must overcome these data challenges to derive the actual benefits of the implementation. However, all respondents mentioned that "*smart technologies have solutions for all identified data challenges. These data-related challenges just an initial implementation challenge"*.

Employees related challenges

Employees are always resistant to change. Industrial changes are growing concerns for employees. R1, R3, R4, R5, R9 and R13 highlighted the fact that, inducing employees' willingness toward new changes or implementations is always challenging.

Integration related challenges

Industries might face integration challenges while transforming the current industry into smart. Industries have to change the existing system to smart systems gradually. However, there is a need to maintain both old and new systems parallelly. R7 stated that *"upgrading an automated system into a smart system is not a complex one. But there is a challenge in identifying the integration requirements of the systems"*.

Standardization related challenges

Standardizing the application of smart technologies will ensure their interoperability, compatibility and security along with the industrial processes. R4 mentioned that "*Standardization challenges are common in industries. Still, there is less to be concerned about standardization because conformance requirements for all industries are revised continuously*".

Communication related challenges

The Industry 4.0 concept relies on data communication by which all real-time decisions are taken. Communication challenges affects the Industry 4.0 implementation.

Security related challenges

Currently, industries are relying on computerized systems to carry out their business processes. R4 mentioned that "*Cyber-attacks are inevitable in technological advancements*". Further, R8 stated that "*Cyber security is constantly developing as cybercriminals are finding new ways to exploit loopholes*". Before investing in smart technology-based industrial platforms, industries must assure the security of their data.

5. CONCLUSIONS AND RECOMMENDATIONS

FM input appears to be essential in the forthcoming industry. With the introduction of the Industry 4.0 idea, the use of complicated machines and equipment in the contemporary industry has rapidly increased. Maintenance practitioners in the FM industry are currently facing difficulties in managing assets due to their increasing critical nature. Thus, the FM industry foresees a proactive maintenance approach rather than a reactive maintenance approach. Therefore, maintenance practitioners in the FM industry are now realizing the significance of Industry 4.0 to carry out effective PdM under FM. Feasible applications of each smart technology such as AM, Big Data Analytics, cloud computing, CPS, IIoT, cyber security, autonomous robots, ML, AR, DM, system integration and simulation are gathered. Nowadays, every spare part comes with an embedded system that allows the spare part manufacturer to gather and evaluate real-time data on behalf of the client in exchange for a fee. Rather than investing money on external monitoring systems, maintenance professionals can avail the potentials of Industry 4.0 concept and smart technologies. Application of Industry 4.0 smart technologies can facilitate machine-to-machine communication and interaction to improve the self-aware, self-predictable, self-maintainable, self-diagnosis, and self-adaptive abilities of machines and equipment. Utilizing smart technologies for PdM upgrades plant reliability, extends operating equipment lifetime, enhances safety for occupants and equipment and facilitates FMs with effective use of maintenance resources. Still, there are technology, investment, data, employees, integration, standardization, communication and security-related challenges in applying the Industry 4.0 concept for carrying out effective PdM under FM, which needs proper solutions. Maintenance practitioners involved in FM can apply the findings of this study on Industry 4.0 smart technologies for PdM to enhance the overall effectiveness of the maintenance process.

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