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Digital Transformation in Maintenance Management

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Abstract: The relationship between technology and maintenance is mutually beneficial since technology is continuously improving with consequent substantial advancements in the field of maintenance. Maintenance management may be effectively modernized through digitalization. Developing advanced technologies promotes indeed the possibility of maintaining a competitive and long-term position in this field. Digitalization is consistently transforming organizations by allowing them to use suitable technologies for collecting data automatically. Various equipment and components are nowadays capable of collecting their operating data over an extended period, which may yield a plethora of intriguing insights employing digitalization. However, to achieve effective prediction of any type of failure, maintenance management requires several smart technologies which offer wider applications for digitalization, including artificial intelligence (AI), big data, Internet of Things (IoT), digital twins, novel sensor technologies, data collection and distribution from various smart sensors, and investigating a lot of data utilizing machine/deep learning. Smart sensors facilitate the collection of large amounts of data to be effectively evaluated for enabling maintenance management and decision-making of more complex systems. The focus of this study is to investigate which type of data should have to be digitally collected for effectively implementing predictive maintenance policies. This can be identified by studying the latest trends of digitalization in maintenance management. Moreover, this study aims to elaborate a decision-making model supporting the implementation of maintenance management policies. This will be done by first identifying critical factors for maintenance management and secondly analyzing their mutual relationships in a structured way. In detail, a Fuzzy Cognitive Map (FCM) will be built to model such relations, in order to identify those factors having a greater influence on all the other ones. In this direction, this study may have positive impacts on economic, social, and environmental factors.

Keywords: Digitalisation, Maintenance Management, Data Collection, Decision-Making, FCM.

I. INTRODUCTION

Technology and maintenance are mutually beneficial since the continuous evolution of technology results in significant advancements in the field of maintenance (Karki and Porras, 2021, Roda et al., 2018). One of the primary trends transforming society and industry has been characterized as digitalization (Parviainen et al., 2017), which plays an important part to efficiently modernise maintenance management. Developing innovative technology does pave the way for long-term viability in industry. Digitalization is continuously altering organizations by enabling them to automatically gather data via the use of appropriate technology. Numerous types of equipment and components are now capable of gathering operational data over a long period, which may provide a plethora of interesting insights via digitalization (Karki and Porras, 2021). However, to ensure effective failure prediction, maintenance management needs a variety of smart technologies with broader digitalization applications, including artificial intelligence (AI), big data, the Internet of Things (IoT), digital twins, novel sensor technologies, data collection and distribution from various smart sensors, as well as investigating large amounts of data using machine/deep learning as shown in Figure 1 (Aksa et al., 2021, Isaksson et al., 2018). Authors Lamdasni and Okar (2020), studied that the principles of digitalization and Industry 4.0 can be applied to maintenance, which is a key activity for industries. Data gathering and intelligent systems can aid in failure prediction, maintenance diagnostics, and decision-making (Lamdasni and Okar, 2020). Pech et al. (2021) studied and listed various types of smart sensors that enable the collection of the enormous quantity of data that can be successfully analysed to optimise the maintenance management of complex systems and decision-making.

Digitization has been emerging as one of the most popular trends over the last decade, not only in the manufacturing sector, but also across the board in all aspects of corporate operations including maintenance. The influence of the digital revolution has been compared to the impact of the industrial revolution. The increasing complexity of products, combined with the development of engineering disciplines along with the continuous adoption of technologically smart solutions, are all factors that contributed to the rise of global competitiveness to an unprecedented level, where employing completely new concepts in manufacturing and process upgrading represents a key challenge (Lamdasni and Okar, 2020, Parviainen et al., 2017).

Fig. 1. Technologies connected to Industry 4.0 (Bahrin et al., 2016)

The purpose of this study is to determine what types of data should be gathered digitally to efficiently execute predictive maintenance strategies. This can be determined by reviewing the literature and studying the latest trends of digitalization in maintenance management. This study will also discuss the critical factors of digitalization in maintenance management along with their advantages and limitations. Additionally, this work intends to elaborate a decision-making model to support such strategies of maintenance management. The expected outcome of the study would have the capability to assist maintenance management through the understanding of relations of influence bonding related critical factors with each other, by allowing to monitor equipment health, identify problems, predict and resolve issues long before they occur, and even enhance performance. As a result, this study may have positive impacts on economic, social, and environmental factors, as well as maintenance policies implementation on the whole.

II. Literature Review

A. *Digitalization in maintenance management*

The expression Industry 4.0 refers to the fourth industrial revolution marked by the advent of smart factories that are distinguished by their ability to communicate with each other, having been discussed by many scholars. In the fourth industrial revolution, the physical and virtual worlds are integrated to achieve a soft, updated, and intelligent production level through the use of current internet-connected systems, developed manufacturing equipment, and embedded technology. So far, many academics have agreed on the four major milestones that the world has taken on the route to the Fourth Industrial Revolution. The fourth one, referred to as Industry 4.0, first originated as an abbreviation for the worldwide industrial objectives of the German economic system, which has been in place since 2011. There are three connected reasons why Industry 4.0 is being developed and implemented. First and foremost, via digitalization, we have to move away from basic technical-economic links and toward complex networks. Secondly, making use of digital solutions improves the quality of processes, both in terms of products and services. Third, new market models have to be developed. This industrial digital revolution covers the integration of all of the digital technology that we use in our everyday lives, such as smartphones, tablets, and computers.

As manufacturing operations and communication technology advances, and new analytic notions are introduced into the industry, maintenance management has achieved a high degree of precision and an exceptional level of reliability in the large amount of data collected from sensors and robots. Over the recent years, such evolving ideas as Cyber Physical System (CPS), the IoT, and big data have transformed the way in which manufacturing industries are perceived, and have pushed scholars and practitioners to explore new research insights that will doubtlessly influence top management mindsets by opening new avenues for innovation and information capitalization. As already expressed, digitalization has had a significant impact on maintenance activities in industries. Lamdasni and Okar (2020) outlined four stages of maintenance digitization approaches. In the first reactive stage, the utilization of technologies is limited to shorten maintenance reaction time. In the second stage, digital technologies aid in the optimum implementation of the maintenance preventative program. At a predictive maintenance level, intelligent technologies use previous data to forecast conditions, and monitoring present state problems at their starts has become feasible owing to instant data. Furthermore, proactive maintenance is a maintenance plan in which digitalization guarantees criticality analysis and supports in making such critical decisions as equipment end-of-life or investments. Several previous intelligent maintenance systems have been created to facilitate maintenance digitalization. Some of the models studied and summarized by (Lamdasni and Okar, 2020) include the Real-time Intelligent Multiple Fault Diagnostic System (RIMFDS), a platform capable of processing numerous failure analyses as presented by machine sensors, the intelligent predictive decision support system (IPDSS), among others.

Johansson et al. (2019) examined the effect of adopting digital maintenance, such as enhanced information on uncertain conditions, higher capacity, improved maintenance, reduced costs, and increased sustainability. All of these aspects depict a range of economic, environmental, and social advantages. Overall, digitalization is a compelling value-creation strategy that incorporates all automated processes that are coupled with communication and information technology. Several advantages and strong potentials of digitalization have been identified in the literature including quick coordination, more flexibility in manufacturing processes, and reduction of costs (Lamdasni and Okar, 2020). Fig. 2 depicts the maturity model of industry 4.0 concerning digitalization.

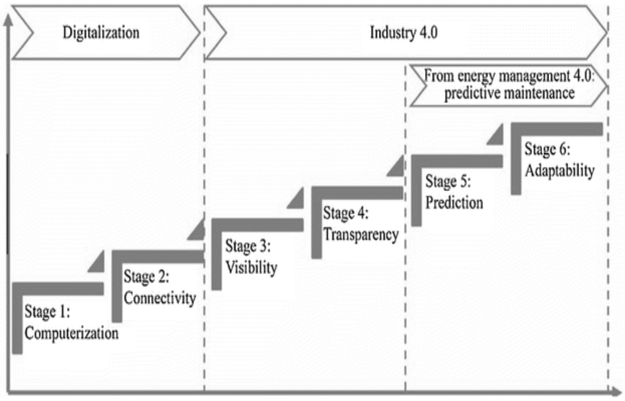

Fig. 2. Industry 4.0 maturity model concerning digitalization adopted from (Rødseth et al., 2017)

B. *Digitally data collection for maintenance management*

As we enter the Fourth Industrial Revolution which is enabled by Industry 4.0 technologies like machine learning, big data analytics, and virtual reality, we typically have an enormous quantity of data accessible to assist in decision-making and the real-time connection of assets through technologies such as embedded devices, also known as the IoT. In recent years, the major challenge has switched from gathering data to making an intelligent decision about whether the information is practically useful. The importance of having adequate data in the decision-making procedure for maintenance is related to how to use these data and predictive analytics to improve our decisions. New opportunities for data-driven approaches such as predictive analytics, artificial intelligence, and machine learning have arisen as a result of this development, with the potential for significant efficiency improvements (Van Staden, 2021).

Digitally data collection for maintenance management is a strategy that makes use of IoT technology to link maintenance equipment, allowing for remote data collection, information sharing, analysis, and possible productivity and efficiency improvements, in addition to scheduling maintenance tasks. Transforming machine-emitted physical processes like, for example, temperature and vibration into digital signals is what sensors do to gather data. Machine data alone is not enough to make decisions for maintenance, while a reliable IoT architecture is required, allowing widespread sensor data gathering and connecting maintenance equipment to data centres (Curman et al., 2021). Various types of data are being collected digitally, some of the examples are listed in TABLE I.

It is common for the data acquired to contain information about the condition of plant components through inspection devices rather than more routine maintenance tasks, e.g. cleaning, lubrication, and replacement of components. Physical phenomena can be measured throughout time and place to offer diagnostic and prognosis information about the condition of the equipment. Moreover, a list of sensor applications for each kind of equipment and additional information on maintenance digitalization can be studied in various research articles as specified by authors (Al Rashdan and St Germain, 2018).

TABLE I
EXAMPLES OF DIGITALLY DATA COLLECTION

Types of Data	Device/Sensors
Vibration Data	*Accelerometers or Piezoelectric sensors*
Imaging of abnormally hot regions	*Thermography*
Subsurface inspection data	*Ultrasonics*
Materials integrity data	*Resistance*
Viscosity and impurity levels data	*Oil analysis*
Pipe thickness data	*Radiography*

C. *Critical factors for digitalization in maintenance management*

The digital transformation of industries has had a significant impact on maintenance management practices. It is important to identify which organizational capabilities are necessary, as well as how organizations should assess their enthusiasm to begin a digitalization transition for maintenance management. Authors Lamdasni and Okar (2020), conducted a study and identified numerous important critical factors for the successful digital transformation of maintenance management which is categorized under five major concepts including management of information and communication technology, resources for digitalization, organizational development, formation of maintenance strategies, and development of corporate culture as shown in Fig. 3. Further, Johansson et al. (2019) also analysed some more characteristics such as smart technology development, organizational growth, change in working practices, regulatory compliance, and data privacy and security, which are beneficial to be considered for successful adoption of digital maintenance. Moreover, Singh and Gupta (2020) studied and explored fourteen factors of maintenance management through literature study, interviews with maintenance professionals and experts, nominal group method, and idea engineering. Apart from critical factors, three leading constraints to the adoption of maintenance practices in industry have erupted as inadequate management cooperation, absence of overall equipment performance (OEE) assessment, and absence of strategic actions of planning and execution (Singh et al., 2016).

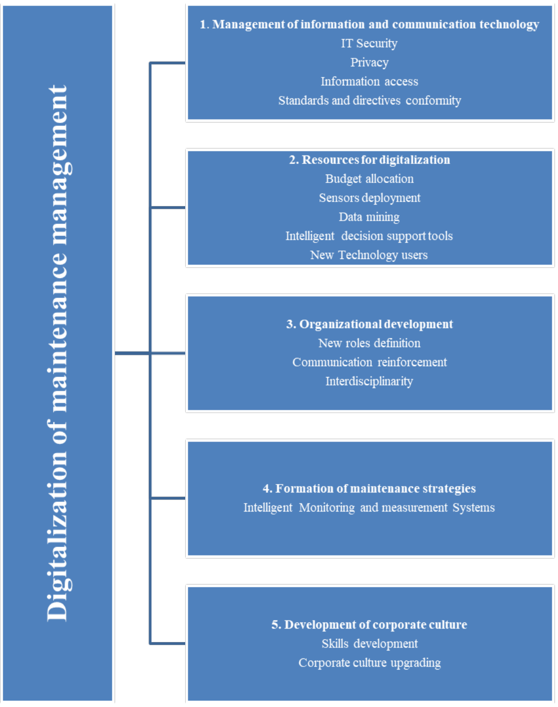

Fig. 3. Critical factors for digitalization of maintenance management

D. *Advantages and limitations of digitalization in maintenance management*

Digital maintenance facilitates the creation, refinement, and application of newer technologies, hence increasing their effectiveness. The integration of massive amounts of historical and real-time data and analytical capabilities has formed the core of digital maintenance services. Maintenance capabilities such as monitoring, diagnosing, troubleshooting, predicting, and optimizing are a result of the good technological impact and contribute to the technological sustainability of these advancements. Only compulsory, sufficient, and proper maintenance can be performed via real-time predictions and diagnostics by digitizing maintenance along with utilizing appropriate tools and technologies. This reduces waste and energy consumption, saves time, and ultimately contributes to a more favourable environmental effect. Digital maintenance significantly reduces failures by anticipating, diagnosing and avoiding breakdowns early and digitally. This fosters a safety culture, enables individuals to act safely, and ensures a safe and healthy workplace. As a result, it assures that digital maintenance positively impacts the environment and society. Karki and Porras (2021) summarized various benefits of digitalization in maintenance management in terms of economic, environmental, social, technological, and governance factors.

Despite the potential advantages, digitization of maintenance also presents various limitations. One of the primary challenges is that not all of the industries possess the required level of skills to undertake digitalization of their maintenance services, mainly due to the inability of comprehending efficient implementation techniques and best practices. Indeed, it can be quite challenging to discover opportunities for creating value and to move the focus away from technology and towards strategic thinking. The most critical factor is the lack of the required proper attitude to change the conventional run-to-failure attitude to one that can perceive and integrate maintenance services to the system that enables digitalization. Quick cost reduction is extremely difficult and does not initially attract all sorts of clients. With constrained operating expenditures, operational problems and technical restrictions are inevitable. As a result, digital abilities are restricted, including the inability to automate maintenance operations, the inability to maximize large data, and inadequate remote monitoring. While it is clear that digitization of maintenance has an influence on sustainability in several ways, determining the precise extent of that influence and how it manifests itself is a significant challenge that requires in-depth and extensive research (Karki and Porras, 2021).

E. *Decision making models supporting maintenance management*

Everyday life is characterised by frequent decision-making, and each of these decisions carries the potential for ambiguity and risk (Van Staden, 2021). Different Multiple-Criteria Decision Making (MCDM) policies and procedures have been suggested in the literature over the past years to select the alternatives that reflect the best compromise under a variety of different assessment criteria. Similar policies have been widely used in a variety of fields, including production, business, energy management, economics, environment, sustainability, supply chain management, tourism, manufacturing systems, materials, safety and risk, operations research, quality, technology, and project management (Ahmed et al., 2021b, Ahmed et al., 2021a). Numerous MCDM approaches have been created and utilized in maintenance management. Among them, for example, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a well-known classical MCDM technique, whose advantages include: clarity, logically understood belief, improved operational efficiency, and the ability to express the efficiency of each alternative by means of a simple mathematical form. As a result, TOPSIS has found widespread application in a wide range of industries (Hung and Chen, 2009, Brentan et al., 2022, De Achieta et al., 2021). Behzadian et al. (2012) presented various MCDM techniques compared or combined with TOPSIS and identified this as an effective method to prioritize maintenance decision making. Singh et al. (2016) adopted TOPSIS in their study to rank the key barriers in maintenance management. Moreover, Alshraideh et al. (2021) used the Fuzzy-TOPSIS decision making model for the selection of the most suitable maintenance contractor under uncertainty by considering the quality of the proposals. In complex decision-making situations, the variables or factors are typically in conflicting proportions, which can provide analysis issues.

To mitigate this problem, extending traditional models to fuzzy logic has been effectively implemented in a range of industrial applications (Palczewski and Sałabun, 2019). In the context of the present research, studying the relations of dependence bounding the identified critical factors with each other may serve to highlight those factors that can be regarded as most influential for the optimization of the whole maintenance management process. This goal can be effectively achieved by building a decision-making model based on the use of Fuzzy Cognitive Maps (FCMs) (Kosko,1986) as showed in previous works (Carpitella and Izquierdo, 2022, Carpitella et al., 2021), both dealing with the field of risk management.

III. RESULTS AND DISCUSSION

As we are living in the digital era, technology is rapidly changing with the massive advancement of smart technologies which enables more effective and efficient maintenance management. The role of digitalization in maintenance management in industry is discussed and such maintenance capabilities as monitoring, diagnosing, predicting, troubleshooting, and optimizing are all identified as potential benefits of digitalization. This study identified various critical factors necessary for digitalization of maintenance management including management of information and communication technology, resources, organizational growth, smart technology development, formation of maintenance strategy, corporate culture, change in working practices, regulatory compliance, data privacy, and security, and so on, as re-elaborated in TABLE 2. Digitally data collection through smart technology is also discussed in this study. Further, the study highlighted potential advantages and limitations during the transition towards digitalization of maintenance management. Hence, it has been found that the digitalization of maintenance management is collectively beneficial to perform timely maintenance and prevent failures beforehand.

TABLE II
CRITICAL FACTORS OF MAINTENANCE MANAGEMENT

No.	Critical factors of maintenance management
CF_1	*Management commitment and support*
CF_2	*Smart technology development*
CF_3	*Organizational growth*
CF_4	*Development of skilled and empowered workforce*
CF_5	*Resources required for digitalization*
CF_6	*Maintenance strategy development*
CF_7	*Corporate culture*
CF_8	*Change in working practices*
CF_9	*Effective and efficient maintenance system*
CF_10	*Regulatory compliance*
CF_11	*Safety and health awareness*
CF_12	*Data privacy and security*
CF_13	*Sustainable performance improvement*

Moreover, the study also discussed some decision-making approaches commonly applied in the field of maintenance management aiming at enabling maintenance personnel to make appropriate decisions and perform maintenance activities on a priority basis.

As stated in the previous section, the critical factors of maintenance management formalised in TABLE 2 are going to be further analysed in order to identify the most influential aspects on the basis of relations of influence. TABLE 3 reports relations that have been collected during various brainstorming sessions with an expert in the field of digitalisation processes and maintenance management. Evaluations have been expressed in the form of linguistic variables, which have successively been translated to fuzzy numbers in order to build the FCM displayed in Fig. 4. The map has been built with the Mental Modeler software. For further details, readers are encouraged to read the previously referenced works (Carpitella and Izquierdo, 2022, Carpitella et al., 2021), where the FCM tool was proposed to deal with other engineering field, and whose results led to the elaboration of relevant managerial procedures.

As it is possible to observe, TABLE 3 reports the indirect effects (IE) and total effects (TE) associated to each critical factor on the basis of relations of influence expressed for pairs of factors. Linguistic evaluations have been attributed as very low (VL), low (L), medium (M), high (H), very high (VH). The evaluation procedure is extremely flexible since evaluations can be adapted according to the particular business context of reference. Elements associated with higher TE values express conditions of major influence, in other terms their effective management could have positive effects on all the other elements taken into account.

FCM of Fig. 4 shows 125 connections among 13 elements, corresponding to circa 9.6 connections per element. Critical factors CF_11 and CF_13 have been associated with total effects expressing linguistic evaluations of high influence. This means that such aspects as "safety and health awareness" and "sustainable performance improvement" are key issues to be taken into account when designing and implementing digital transformations involving maintenance management processes. Other aspects have associated medium total effects while, according to the opinions expressed by the interviewed expert, critical factors CF_2, CF_5, CF_7 can be considered as being the less influent ones, having associated lower total effects. Smart technology development, resource required for digitalization and corporate culture are certainly important issues within the field of analysis. However, in terms of prioritisation of relevant aspects, the FCM tool suggests us to focus more on other factors, something that may positively impact also less influent factors. This is clear as, for instance, the implementation and the optimization of effective and efficient maintenance systems (CF_9) definitely contribute to the definition of novel smart developments (CF_2) for the whole maintenance function, and so on.

IV. CONCLUSION

Digitalization enables to perform remote maintenance activities, which results in cheaper maintenance costs and time savings for all the involved stakeholders. The use of technology and data assists in promptly detecting and preventing failures. Nowadays, maintenance services are based on the analysis of large amounts of past and real-time data, as well as the use of advanced analytics tools. Novel and efficient technologies have arisen, allowing the facilitation of such maintenance functions as monitoring, diagnosing, troubleshooting, predicting, and optimizing. This is the result of effective technical influence and, in exchange, these developments encourage secure and dependable data transfer, effective and fast maintenance operation, decreased operational expenses, and so on. Maintaining current equipment processes and data allows better monitoring operations, more accurate diagnosis, troubleshooting, prediction and optimization.

Greater availability and performance capabilities are ensured by reducing unscheduled downtime and maintaining equipment in good condition. This increases customer confidence in the company's capacity to compete on the global stage. Through the use of the appropriate types of technologies and tools, only the necessary, adequate, and right types of maintenance can be performed, allowing for real-time prediction and diagnostics to take place. As a result, waste can be minimized, energy consumption reduced, and time saved. Digitalization in maintenance adds significant value to the reduction of incidents by predicting, diagnosing, and avoiding failures as early as possible. Safety culture is established, and a safe conduct is empowered, resulting in a safe and healthy work environment for everybody. Confidence in an enhanced maintenance potential reduces dangers. In addition, the latest devices and technologies assure information and communication security, which is currently regarded as a critical societal requirement. This guarantees that digital maintenance positively impacts the environment and society. With digitization, maintenance services become more dependable, secure, and efficient, allowing equipment to operate at optimum capacity. It helps to decrease shutdowns and boost uptime, as well as lower total costs and increase profitability, something that strengthens decision-making and strategic planning inside the company. All of this ultimately contributes to good environmental effects, leading to develop sustainable businesses with substantial profits.

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Appendix A. TABLE III CONNECTION MATRIX

	CF_1	CF_2	CF_3	CF_4	CF_5	CF_6	CF_7	CF_8	CF_9	CF_10	CF_11	CF_12	CF_13	IE	TE
CF_1	0	VH	H	VH	M	H	H	VH	VH	M	VH	H	H	M	M
CF_2	0	0	VH	VH	H	H	L	VH	VH	0	H	M	H	L	L
CF_3	M	VH	0	H	H	H	H	H	H	0	H	M	H	M	M
CF_4	H	0	L	0	0	M	VL	H	H	0	VH	0	H	VL	M
CF_5	VH	H	L	M	0	VH	L	H	VH	0	0	M	H	L	L
CF_6	H	M	M	M	0	0	H	VH	VH	0	H	0	VH	M	M
CF_7	H	L	H	H	L	H	0	H	H	0	H	H	H	L	L
CF_8	0	M	H	H	0	L	M	0	M	0	VH	0	H	L	M
CF_9	0	L	H	H	H	VH	M	H	0	0	H	0	VH	L	M
CF_10	VL	VH	H	0	M	H	H	M	H	0	VH	VH	VH	VL	M
CF_11	VH	H	H	VH	0	H	H	VH	H	M	0	M	VH	M	H
CF_12	0	M	M	0	M	0	M	M	M	0	0	0	0	M	M
CF_13	VL	0	H	0	H	VH	H	H	VH	M	VH	0	0	VL	H
IE	VL	L	L	M	L	L	VL	M	M	M	H	M	H		

Appendix B. FIG. 4. FCM DISPLAYING RELATIONSHIPS AMONG CRITICAL FACTORS FOR DIGITALIZATION OF MAINTENANCE MANAGEMENT