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A Feasible Framework for Maintenance Digitalization

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Abstract: The entire industry is changing as a result of new developments in digital technology, and maintenance management is a crucial procedure that may take advantage of the opportunities brought about by industrial digitalization. To support digital innovation in maintenance management, this study intends to meet the cutting-edge necessity of addressing a transformation strategy in industrial contexts. Setting up a customized pathway with adequate methodologies, digitalization tools, and collaboration between the several stakeholders involved in the maintenance environment is the first step in this process. The results of a previous conference contribution, which revealed important digitalization variables in maintenance management, served as the foundation for the research approach herein suggested. We lead a thorough assessment of the literature to categorize the potential benefits and challenges in maintenance digitalization to be assessed in conjunction with the important digitalization aspects previously stated. As a starting point for maintenance management transformation, we offer a feasible framework for maintenance digitalization that businesses operating in a variety of industries can use. As industrial processes and machines have become more sophisticated and complex and as there is a growing desire for more secure, dependable, and safe systems, we see that this transition needs to be tailored to the specific application context.

Keywords: maintenance digitalization; predictive maintenance; Industry 4.0; digital technology

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1. Introduction

Because of the continuous growth of digital technologies and the decrease in technology-related expenses, global organizations are undergoing a significant global transformation [1]. Engineering systems have become increasingly complex over the last few decades as technologies have evolved, and these have become even more critical from the standpoints of reliability and availability [2]. Emerging digital technology developments are transforming the entire industry, and maintenance management is a key area of evolution [3] that could capitalize on the opportunities created by industrial digitalization [4,5]. While manufacturing processes and industrial machines have become more intelligent and complex, global regulations have created a demand for more secure, reliable, and safe systems [6].

Over time, maintenance has evolved from reactive to preventive to condition-based to predictive maintenance, which is also termed Maintenance 4.0 (M4.0) [7], e-Maintenance (e-M) [8], or Digital Maintenance (DM) [8,9], as depicted in Figure 1. DM has gained more prominence in the past decades since it has long been among the key topics of research on digitalization [8]. Despite maintenance tasks being crucial for manufacturing organizations, only a handful are completely digitalized, and diverse barriers may impact the effectiveness of maintenance digitalization [10]. Currently, numerous maintenance operations are still performed manually as maintenance remains one of the most challenging functions of the industry to be digitalized [11]. Despite this evidence, relatively few works of research have delved into the meaning of digitalized maintenance for industries by highlighting both technological and social aspects [4].

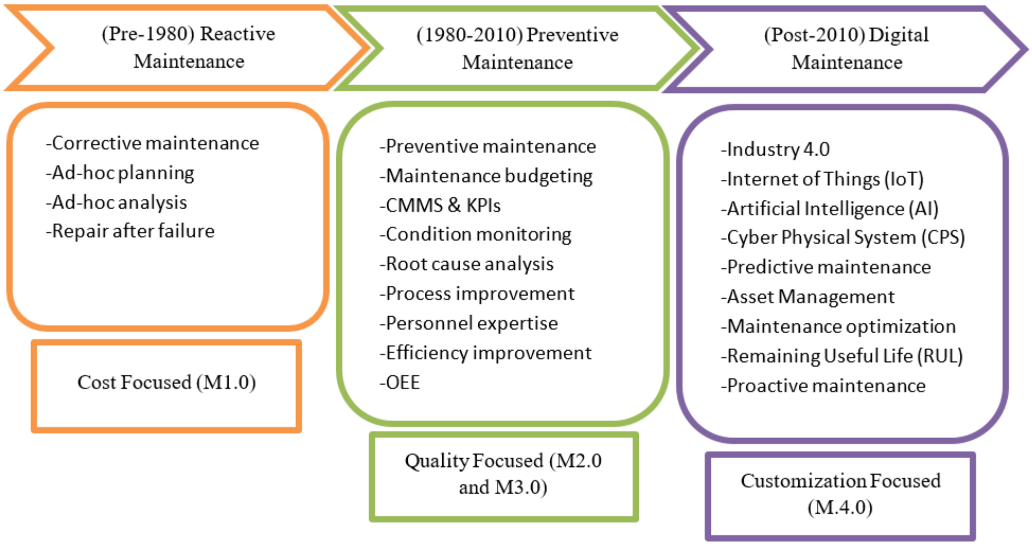

Figure 1. The maintenance journey towards digitalization [7,12].

Maintenance operations employ more than 30% of the total workforce, according to the report by Shin and Prabhu [11]. Obtaining instructions or data from documents, for example, consumes approximately 45% of the time of maintenance professionals. As a result, digitalized maintenance can relieve some of the professionals' workload by simplifying operations and shortening the diagnosis and repair times. Sensor and process data are the foundation of both short and long-term planning, as well as identifying and avoiding breakdowns [13]. Although maintenance is now mostly scheduled on a calendar basis, it is still difficult to use sensor data for planning or optimization. This is caused by difficulties in identifying digital technologies contributing to effective maintenance planning. Furthermore, establishing efficient strategies for improving maintenance schedules through data functions is a complex task [14]. A transformation strategy including methodologies and digitalization tools is required to promote collaboration among the many actors in the maintenance environment [15].

This study is a substantial extension of a previous conference paper [16], where we identified various critical factors of digitalization in maintenance management and created a Fuzzy Cognitive Map (FCM) that unveils the indirect effects (IE) and total effects (TE) associated with each critical factor based on relations of influence expressed for pairs of factors. In this study, a qualitative methodology is used to examine the potential benefits of maintenance digitalization along with the challenges, opportunities, and barriers while undergoing the digital transformation of maintenance. By studying and analyzing the potential benefits and challenges, and based on the personnel experience, this study proposes a feasible framework for a digital transformation of maintenance management considering all the previously identified critical factors in [16]. The proposed framework will aid in decision-making to digitalize maintenance systems. Moreover, potential future research directions in maintenance management will be discussed, and recommendations for sustainable maintenance management systems will be provided.

The present paper is organized as follows. Section 2 presents the related literature on maintenance digitalization by analyzing the potential benefits and barriers along with the role of maintenance digitalization. The framework proposed in this study is elaborated on and explained in Section 3, and practical discussions are provided in Section 4 along with future lines of research. Section 5 concludes the study.

2. Literature Review

2.1. Maintenance Digitalization

Maintenance has continuously evolved digitally, however, it is still considered somewhat immature, particularly when compared to other organizational operations [15]. Digitalization may be the best viable solution for maintenance optimizations [9]. Organizations are attempting to incorporate the latest technology (sensors) and spend resources on new skills (training) to increase the production while decreasing the maintenance costs [1]. To such an aim, digital sensors are installed to enable the collection of an enormous quantity of data remotely [17,18], which could be evaluated proficiently to assist in the maintenance planning and decision-making of more complex systems [19–21]. Digital maintenance has emerged from Industry 4.0, which stands on the pillars of Artificial Intelligence (AI), the Internet of Things (IoT), and Cyber-Physical Systems (CPS). It focuses on productive and automated maintenance management via intelligent data gathering, processing, visualizations, and decision-making. Maintenance digitalization was initiated in the 1980s. The terminology condition-based maintenance arose a few decades ago, being regarded as a data-driven and intelligent maintenance approach.

Extensive research is being conducted to identify implementation trends and performance metrics of maintenance task digitization, as well as efforts to adapt to such a transition. However, the goals of this transition are difficult for industrial maintenance decision-makers and professional managers to define and/or agree on. Although the objectives were supposed to be specified, it is unclear how they will be met [1]. As a result, maintenance digitalization should be approached and implemented with caution, as it may serve as an impediment and pose additional challenges [9].

Kans [15] performed interview research by involving maintenance professionals as participants to explore the main difficulties encountered in maintenance for ensuring a steady technological transition. The research aimed to gain a broad understanding of maintenance in the digital era based on technologies, difficulties, and possibilities for a diverse audience. This analysis included technology vendors, sellers of digital maintenance management tools, academicians, and trainers. According to the results, strategic planning, culture, and a lack of expertise are the most significant in technological implementations [15]. Johansson et al. [8] performed a study in collaboration with a computerized railway maintenance development business to determine the maintenance skills for digitalization. The results of the research are outlined in a framework that includes five primary capacities for adopting digitalized maintenance. These capacities are: latest technological advancement, organizational advancement, modification in working practices, regulatory compliance, and cybersecurity. The methodology also examines the consequences of digitized maintenance implementation, which depicts several economic, environmental, and social advantages. Further, Tretten et al. [22] conducted a study to investigate the benefits and growing problems of railway maintenance digitalization from a Situation Awareness approach, and discovered that, while digitalization is intended to increase, Situational Awareness is frequently tested and, in certain cases, hampered. Singh et al. [23] studied the influence of maintenance management techniques on economic, social, and environmental performance. Their work aimed to attain sustainability through the development of a maintenance management theoretical model for a sustainable hydropower plant. Turner et al. [24] outlined the digital maintenance practice for the sustainable circular manufacture of automobile components. The authors discovered it to be a foundation for digital maintenance strategies within the circular economy and Industry 4.0 technology.

2.2. Benefits and Challenges in Maintenance Digitalization

Digital maintenance makes it easier to create, enhance, and use advanced techniques, hence, maximizing their efficacy. Wellsandt et al. [25] cite previous research [26] highlighting the potential of digital maintenance in detecting early equipment behavior anomalies, forecasting the equipment's future health, and developing proactive maintenance plans to eliminate or reduce the impact of predicted failures. The integration of massive amounts of historical and real-time data, as well as analytical skills, has become the bedrock of digital maintenance services. Monitoring, diagnosing, troubleshooting, forecasting, and maximizing capabilities are outcomes of the excellent technological effect, and they contribute to the technological sustainability of such advancements [27]. By digitalization of maintenance and application of relevant technology and software, only mandatory, adequate, and proper maintenance may be conducted via real-time forecasts and diagnostics. This supports sustainable manufacturing [28] by eliminating waste and energy consumption, saving time, and eventually leading to a better environmental outcome. Digital maintenance can drastically reduce failure rates by predicting, diagnosing, and preventing faults early and digitally. It also promotes a safety culture, empowers people to behave responsibly, and guarantees a secure and healthy environment. Table 1 collects and classifies the anticipated advantages of maintenance digitalization [4].

Table 1. Benefits of digitalization in maintenance management [4,9,23].

Factors	Benefits	Description
Economic [4,9,23]	Reduce downtime; Substitute human services by remote services; Minimize labor expenses; Enhance the productivity and effectiveness of maintenance; Boost performance and availability of products; Strengthen competitiveness; Save time.	Making use of resources and information enables early failure detection and prevention, which saves both time and money. Digitalization makes it easier to do distant maintenance tasks, which reduces the need for on-site service technicians, lowers the cost of maintenance, lowers travel expenses, and saves time. Updated equipment, processes, and data aid in tracking, detail analysis, and diagnosis, as well as forecasting and optimization. Lower downtimes and well-maintained systems result in good availability and performance. Increased performance and availability boost competitiveness.
Environmental [4,9,23]	Technological developments and the establishment of efficient tools; Saving time; Minimize wastage; Lessens the carbon footprint; Lower your energy use; Reduced effect on the environment; Create enduring enterprises; lucrative manufacturing.	Only essential, appropriate, and accurate types of maintenance may be used via real-time forecasting and diagnostics by employing the right tools and technology. This saves a lot of time, consumes less energy, and lowers waste. The use of digital tools and less travel reduce carbon footprint, which ultimately promotes favorable environmental effects and aids in successfully and efficiently attaining maintenance objectives. This creates prosperous, long-lasting industries.
Social [4,9,23]	Creating a safety culture and encouraging appropriate behaviors significantly reduces accidents, ensures workplace safety and health, secures data transfer, and mitigates hazards.	By predicting, diagnosing, and minimizing faults proactively and digitally, automated maintenance significantly reduces accidents. This fosters a culture of safety, encourages responsible conduct, and ensures a secure and healthy workplace. Confidentiality reduces risks. A crucial societal necessity in the current context is data and information privacy, which is also guaranteed by the latest technology and tools. This guarantees that digital maintenance will have a good impact on both the environment and society.
Technological [4,9]	Latest developments in efficient maintenance equipment; Switch to remote services from personal on-site services; Beneficial use of data and analytics; Secure data transfer.	The foundation of current maintenance practices has been the extensive use of historical and real-time data combined with analytical capabilities. The maintenance capabilities, such as monitoring, assessing, diagnosing, forecasting, and optimizing, are made easier by the development of new and efficient technologies. This is the result of a favorable technical influence, and in turn, these developments support safe and dependable data transfer, efficient and quick maintenance services, lower operational expenses, etc.
Governance [4,9]	Encouraging safe conduct and a culture of safety; Supporting decision-making; Making strategic planning more effective.	The maintenance service is now more dependable, safe, and efficient thanks to digitalization, which also helps to save costs and boost profitability by reducing downtime and increasing availability. Strategic planning and decision-making are aided by this for organizations.

In addition to its several advantages, several difficulties should be addressed [9], something that raises interesting questions about the components identified as key obstacles towards the digitalization of maintenance [15]. The main issues that emerged in the literature ranged significantly from a lack of business awareness to knowledge gaps and technology anxiety. We have gathered and classified a variety of maintenance digitalization challenges in Table 2. As can be observed, the main difficulties that have been analyzed in the existing literature so far mostly refer to seven areas of management, i.e., strategy, leadership, culture, people, governance, technology, and economy. The first four areas clearly emphasize the important role played by human resources as the main actors involved in the process of digital transformation. Even if a strategy is perfectly formulated, it has to adhere to the actual context and to the level of technological capabilities at which the enterprise is operating. Its implementations strictly rely on the readiness of workers, besides the planning skills of the management. Barriers in the areas of leadership, culture, and people highlight the need for proper training. In certain contexts, this can reveal to be challenging. It indeed requires a proactive and flexible mindset, being quite time demanding, as training processes can be long depending on the level of complexity and initial preparation. Other barriers refer to strict external requirements to be accomplished in terms of data security and, last but not least, the aspect of cost has to be carefully considered. Technological investments should be carefully evaluated in advance to understand if digital transformations can add value to the company and in which time frame. For such an aim, the implementation of such techniques as, for instance, the decision-making tree, may support the evaluation of profitability of investments over a defined period of time.

Table 2. Challenges of digitalization in maintenance management [4,9,15].

No.	Areas	Challenges
1	Strategy	Exactly where to begin the digital revolution; It is uncertain what digital technologies to implement since they are developing so quickly; Additional maintenance strategies are difficult to determine; Impossibility to comprehend industry standards and efficient implementation of methodologies; Inability to link maintenance services to the infrastructure that enables digitalization due to a lack of the proper mentality.
2	Leadership	It is challenging to persuade decision-makers that a system is valuable: despite the maintenance representative understanding, they lack the authority to take it further with the decision makers; Unwillingness to change; The worth of maintenance is not appreciated.
3	Culture	Culture and people are intertwined: there is a lack of receptivity to technological advancement; Organizations are hesitant to adopt digitalization; It is challenging to convince organizations to switch from manual to digitalized maintenance; Technology is feared rather than regarded as a facilitator.
4	People	A lack of proficiency with certain technologies; Changing the mentality of the workforce; A lack of social and technical skills, as well as issues with collaboration and cooperation; A shift in employment duties from operations to control; Technology fear; Older staff or getting older; Difficulty in locating resources with the required expertise on the market; The human experience allows for intelligence in asset health monitoring and guarantees the ability to adjust to changes. Potential human resistance to change.
5	Governance	Rigid attitude toward data security; Bad support structures; Financial and economic obstacles; Strategies determining decisions.
6	Technology	New innovations are required, and the ecosystem is not sufficient; Danger of exposure to the risk of cyberattacks; Risk of losing opportunity with the physical dimension of industrial processes and assets; Fear of having confined technological abilities, like being unable to computerize maintenance activities, being unable to improve big data, and having insufficient remote access because of operational financial constraints; Absence of pervasive standard solutions for advanced technology development; Insufficiency of assurances from current Information Security technology solutions on the full effectiveness in data security.
7	Economy	Apprehension of costs related to digitalization; Financial resources not being available; Limited operating expenses; Operational flaws and technology constraints brought on by constrained operational budgets; Uncertainty regarding the effects on the overall cost of new equipment/technology acquired for digitalization; The inherently challenging nature of calculating the return on investment for the digitalization of maintenance.

2.3. Opportunities for Performance Improvement

Predictive maintenance (PdM) is one of the most frequently mentioned opportunities for digitalizing maintenance management in relation to Industry 4.0. PdM employs real-time monitoring data to accomplish several tasks. Some of them are listed in the following: detecting malfunctions; identifying deviations from typical operational behaviors in industrial operations, machinery, and goods; detecting and characterizing the multifaceted nature of the occurring event; predicting the future condition of the abnormal condition to failure. Prognostics Health Management (PHM) refers to a set of responsibilities that includes detection, diagnosis, and prognostication. PHM is an important aspect of engineering system management in which sensors are used in conjunction with decision-making tools to detect anomalies and diagnose faults [29]. Having the ability to complete these activities accurately allows for the development of effective, on-time, and required maintenance techniques, or the placement of the necessary component in the appropriate location at the appropriate time. This is a huge opportunity because it would maximize manufacturing earnings while minimizing all expenses and losses, particularly asset losses.

According to research by Compare et al. [30] the industry is spending a lot of money to provide itself with the tools needed to deploy PdM. For instance, the Italian industry boosted its spending on R&D and innovation for Industry 4.0 by 15% in 2017, with a sizable portion of the spending going to PdM. Similar spending has been recorded in other nations. This circumstance has led to the creation of several PdM-specific businesses, commercial software, specialist publications, and conferences, etc. The Internet of Things (IoT) is a key component of PdM since it enables the conversion of mechanical movements into the digital signals needed for PdM. IoT continually transmits data from sensors that measure such variables as temperature and vibration and also from other platforms such as machine Programmable Logic Control (PLC), Manufacturing Execution System (MES) terminals, and Computerized Maintenance Management Systems (CMMSs). As highlighted by Wang and Yin [31], several digital technologies in the context of Industry 4.0 have been identified as useful tools, including Smart Factory, Augmented/Virtual Reality (AR/VR), digitalization and virtualization. In this context, the authors cite previous research led by Oesterreich and Teuteberg [32]. The foundation for establishing PdM techniques is provided by these sources of knowledge. Establishing devices and software potentiating connectivity has been the major focus to analyze the health condition of inspected elements.

Occupational health, safety, and environmental issues are some of the areas that are impacted by the commercial implementation of PdM. IoT must be combined with big data and modeling capabilities to fill the gap and achieve the desired purpose of digitalization, which is to enable decision-making for the best possible interaction with real systems [30]. Moreover, Achouch et al. [33] present a thorough review of techniques for smart PdM design in Industry 4.0. Their work recognizes and classifies such aspects as the service life of maintenance and repair work, the difficulties encountered, as well as concepts related to Condition-Based Maintenance (CBM), PHM, and Remaining Useful Life (RUL).

2.4. Sustainable Maintenance Digitalization

As highlighted by such authors as Franciosi et al. [34], sustainable Key Performance Indicators (KPIs) have to be integrated into the maintenance decision-making process. This would help to upgrade the traditional maintenance vision through the formalization of new maintenance processes including sustainability-related aspects. To achieve long-term sustainable maintenance and equipment life-cycle management, the advanced technologies of Maintenance 4.0 have proven to be essential. Maintenance 4.0 can indeed break the trade-offs of traditional maintenance strategies by allowing businesses to maximize the useful life of their equipment. It simultaneously supports avoiding downtime, enhancing safety and security, reducing the whole consumption of energy and resource, and being cost-effective [35].

The Maintenance 4.0 idea integrates digital technology to provide authentic access to an extensive volume of data [36] on the availability and state of equipment, as well as to present positions of a specific facility. This is crucial in terms of controlling the life cycle of technological infrastructure and overcoming the difficulties of sustainable maintenance. It enhances the visibility of data about the actual state of a physical item throughout its life cycle and allows the support team to take the necessary steps to prolong its lifetime. Additionally, the reliability of the judgments can be improved by basing maintenance choices on data rather than merely on people’s experience. As a result, the efficacy of continuing maintenance operations increases, as well as the efficiency of the associated human and material resources. When transformed into indicators, these data allow for the monitoring of machine components and, as a result, the comparison of values [37]. In such a way, any deviation can be easily detected and generate alerts, continuously improving decision-making, intelligent and sustainable industrial operations, and the creation of new business value [38].

An examination of the literature reveals that implementing data-driven maintenance approaches opens up a wide range of new prospects for enhancing maintenance procedures about all aspects of sustainability while increasing the efficiency and stability standards [39]. Over the years, as previously emphasized, maintenance has been regarded as a low-automation, low-digital task that adds little value. However, the emergence of smart techniques and approaches for evaluating huge amounts of data has opened up new prospects for improvement. The availability, dependability, and effectiveness of employing technological objects can be optimized, and difficulties in the execution of sustainable growth can be better addressed [7].

3. Proposed Framework for Maintenance Digitalization

We have extensively examined the potential benefits of maintenance digitalization along with the main challenges and opportunities to be focused on while undergoing digital transformation. In this section, we are going to propose a feasible framework for the digital transformation of maintenance management, synthesized in Figure 2. The proposed framework includes all the critical factors identified in Ref. [16], our previous work, and it aims to aid in decision-making for a smooth digital transformation of sustainable maintenance management in Industry 4.0. For the sake of clarity, critical factors are recalled in Table 3.

Table 3. Critical factors of maintenance management published in Ref. [16].

ID	Factors	Influence
CF_1	Management commitment and support	M
CF_2	Smart technology development	L
CF_3	Organizational growth	M
CF_4	Development of skilled and empowered workforce	M
CF_5	Resources required for digitalization	L
CF_6	Maintenance strategy development	M
CF_7	Corporate culture	L
CF_8	Change in working practices	M
CF_9	Effective and efficient maintenance system	M
CF_{10}	Regulatory compliance	M
CF_{11}	Safety and health awareness	H
CF_{12}	Data privacy and security	M
CF_{13}	Sustainable performance improvement	H

The last column of Table 3 displays the related degree of influence that has been formalized by synthesizing the opinions provided by an expert in the field of digitalization processes and maintenance management for a real manufacturing company operating in the food sector. We specify that these evaluations are herein shown to exemplify the procedure at a practical level, as they can be changed and/or adapted according to the particular business context under analysis. Specifically, evaluations reflect the influence that each factor has on all the other factors, and are described according to a linguistic scale (H = high influence, M = medium influence, L = low influence). These results were obtained in Ref. [16] by applying the AI-based technique known as Fuzzy Cognitive Map and served as input of the framework. The FCM-based approach manipulates judgments of preference provided by the expert when comparing critical factors in pairs. Now we will discuss the potential directions in the domain of maintenance management by providing practical recommendations for a sustainable digitalized maintenance management system.

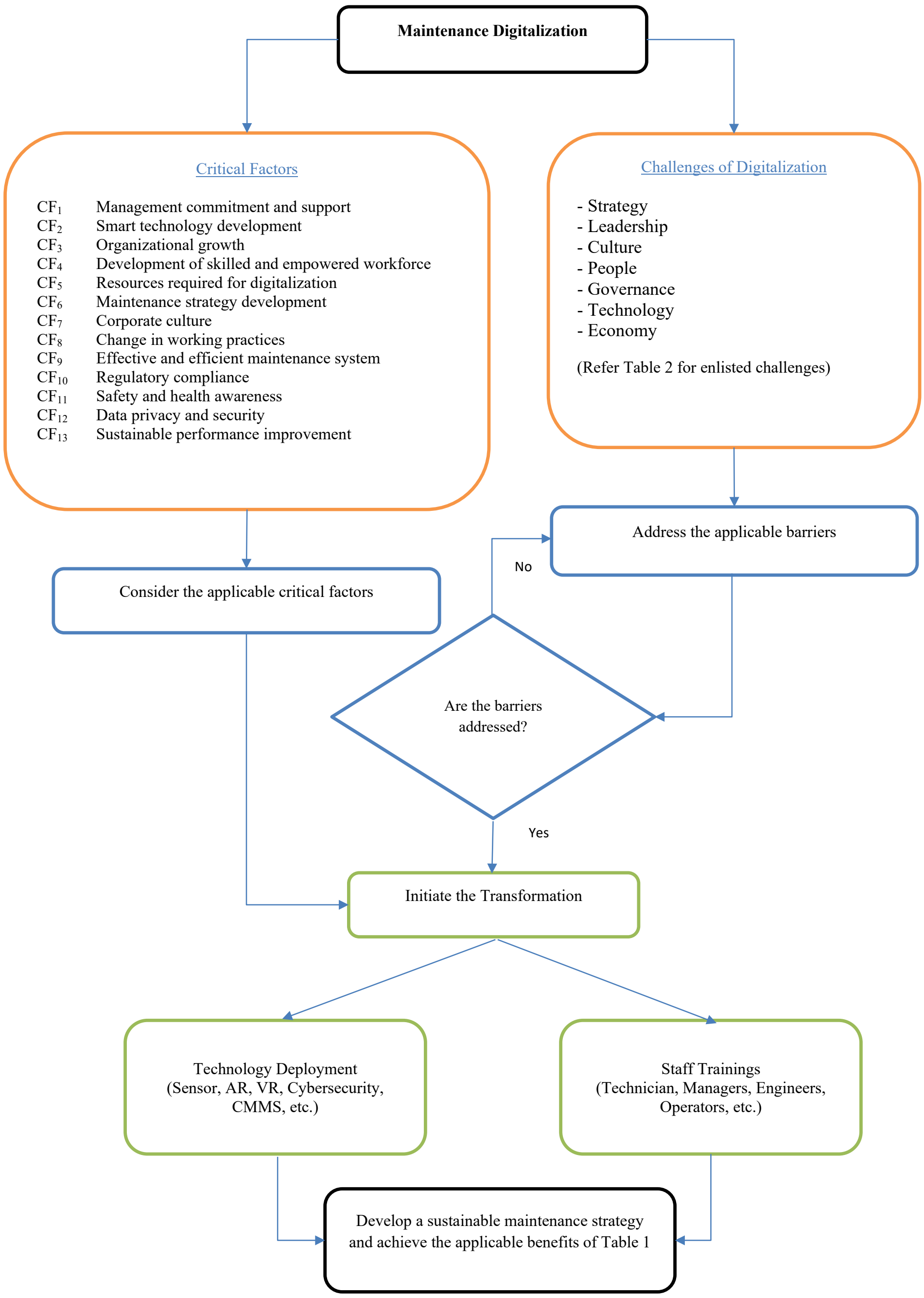

Figure 2. Feasible framework for maintenance digitalization.

As can be observed in Figure 2, the feasible framework takes into account the preliminary evaluation of critical factors and related challenges perceived as difficulties in implementing maintenance digitalization. These elements have to be selected as 'applicable' and, as already specified, they have to be assessed with relation to the specific organizational environment and operating sector of reference. This makes this framework customizable, with the possibility to be adopted by any company as a guideline to build up best practices. It is important to specify that critical factors have to be taken into account and addressed before initiating the transformation, e.g., suitable training programs aiming at enhancing human skills must be established, sufficient resources need to be available to be invested, and so on. This is because a company should achieve an adequate level of readiness before undertaking transformation. We herein reproduce the FCM we built in our previous work to prioritize the critical factors in the food manufacturing sector (Figure 3).

The Mental Modeler software was used to obtain the map reproduced in Figure 3, which displays 125 connections among 13 factors, i.e., about 9.6 connections per factor. The map graphically reports the evaluations of influence attributed to pairs of factors, which are represented in terms of arrows.In such a way, it is possible to visually appreciate the intensity of connections related to each critical factor analyzed in Table 3. Not only is this intensity related to the number of arrows departing from (and arriving at) a specific factor, but also to the arrows' thickness. It is indeed possible to observe as more condensed connections and thicker arrows involve factors C_{11} and C_{13}. These are the factors with an associated higher global evaluation of influence, as explained next.

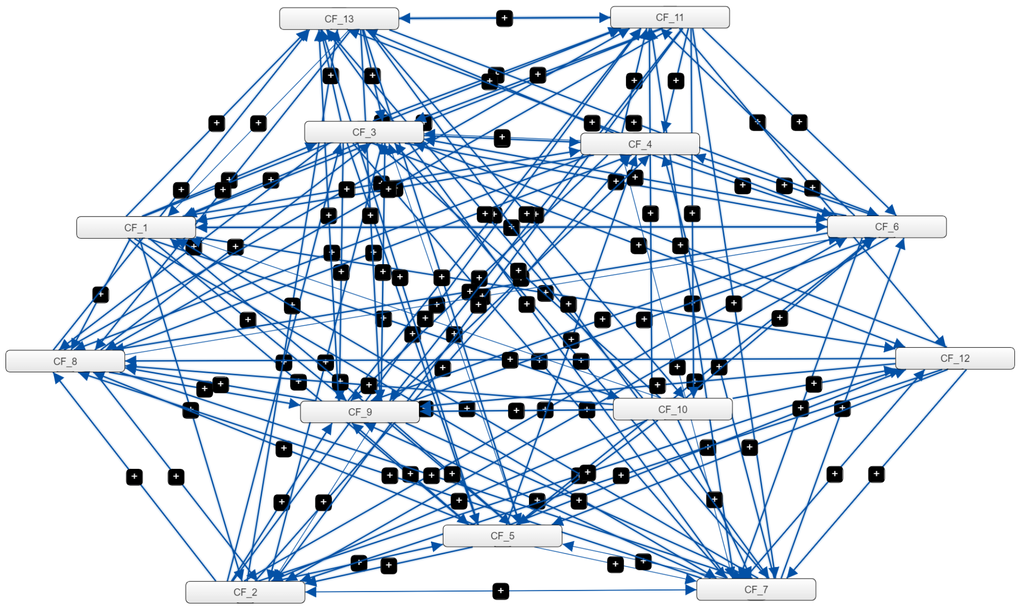

Figure 3. FCM displaying relationships among critical factors (update of Ref. [16]).

The results obtained in Ref. [16] are part of the input data for the implementation of our framework. They demonstrated that safety and health awareness and sustainable performance improvement are key issues to be taken into account. They are followed by the other following factors: management commitment and support; organizational growth; development of the skilled and empowered workforce; maintenance strategy development; change in working practices; effective and efficient maintenance system; regulatory compliance; data privacy and security. We can also notice as, for that specific sector and according to the interviewed expert, other factors had attributed a lower degree of influence, resulting in an overall lower impact. These factors are smart technology development, resources required for digitalization, and corporate culture. Such a contextual evaluation has to incorporate a plan to address all the relevant challenges detailed in Table 2 about the main organizational dimensions. It is important to proceed by analyzing those dimensions of barriers that would be mainly affected if problems involved those critical factors with associated higher evaluations of influence. For example, in our case, it is immediate to notice as critical factors CF_{11} (safety and health awareness) and CF_{13} (sustainable performance improvement) are mostly connected to digitalization challenges such as strategy, people, and technology. These are the aspects that need to be addressed with priority before initiating the transformation. Furthermore, developing a FCM within each of the main areas explored in Table 2 could be a potential procedure object of future research. This would aim to indicate the most critical aspects for each area and, consequently, the most critical areas. Otherwise, the prioritization can be carried out according to the personal perception of the management. This has to be chosen according to the preferred procedure that the company will decide to implement. Initiating the transformation surely includes achieving the initially planned training objectives and incorporating the required technologies. Such an integration results in the development of a sustainable maintenance strategy tailored to the specific company for which it is recommended to periodically review results. Specifically, the level of achievement of the benefits collected in Table 1 should be measured and monitored. Benefits should be evaluated as '*applicable*' based on specific company needs, even if we do not recommend to herein restrict this aspect. The reason is that not even previously planned objectives may be unexpectedly achieved, resulting in a global enhancement of the level of performance for the company. The proposed framework can be integrated into the company documentation as a formal management procedure.

Summing up, we herein formalize the steps to be followed for implementing the proposed feasible framework within any real business context:

- **Step 1**: First contextual analysis of the company, aimed at identifying the actual potential for maintenance digitalization. This step will require a careful preliminary assessment of the characteristics involving the specific business context where the implementation of the framework is desired. The output of this step is two-fold. First, a detailed preliminary report describing the relevant aspects of the critical factors listed in Table 3 has to be formalized. Second, a maintenance expert (or a decision-making team) has to be elicited and relationships of influence bounding critical factors have to be assessed via FCM, as suggested in Ref. [16];
- **Step 2**: The procedure proposed in our framework is initialized by using as input data the evaluations of influence related to critical factors derived from the previous step. Once the most influential factors are highlighted, it is now necessary to check the existence of any of the barriers (the challenges of digitalization) reported in Table 2. It is also important to understand the intensity of these barriers and how they will be practically addressed;
- **Step 3**: In consideration of the applicable critical factors, all the existing barriers need to be suitably addressed by means of the actions identified during the previous step. This aspect has to be sorted out before initiating the transformation. We must specify that this step involves an iterative procedure, as all the barriers need to be carefully scrutinized, evaluated according to the company environment and fully taken into account before proceeding to the next step;
- **Step 4**: Once all the barriers have been satisfactorily addressed and the transformation has been initiated within the company, suitable technology deployment along with effective actions of staff training have to be put in place to support the company in determining a long-term maintenance strategy;
- **Step 5**: The sustainable maintenance strategy previously mentioned has to be herein formalized and implemented to achieve objectives reported in Table 1. This step involves the formalization of continuous monitoring and control activities, aimed at periodically checking the effectiveness of the strategy over a defined time horizon. The final goal is also to record improvements in business results, something that can be done using a suitable set of performance indicators.

4. Discussions and Future Trends

We have extensively discussed the significance of existing technologies and their informed adoption in optimizing maintenance systems for maximum machine utilization and optimal results. We have formalized various benefits from the existing literature in terms of economic, technological, social, governance, and environmental aspects of maintenance digitalization. While achieving these benefits, industries can develop a sustainable maintenance system for increased productivity by preventing failures in advance. In addition to the benefits of maintenance digitalization, interesting evidence regards the elements identified as the main challenges, namely, strategy, leadership, culture, people, governance, technology, and economy, which are perceived as barriers that can sabotage the process of digital maintenance transformation. In this paper, we proposed a feasible framework of maintenance digitalization focusing on the critical factors identified and prioritized in a previous work [16] and considering the potential barriers to developing a sustainable digital maintenance management transformation. Further, the proposed framework provides specific directions to initiate a digital transformation of maintenance management. We emphasized that once the potential barriers are identified, these must be addressed before moving toward the digital transformation of maintenance management. The foundation of the proposed framework is represented by the preliminary development of an FCM, an AI-based technique aimed at assessing, within a set of decision-making elements, those to be considered with priority when leading the whole analysis. In our case, with relation to the food manufacturing sector taken as a target example, the most critical factors referred to safety and health awareness and sustainable performance improvement. The challenges and benefits discussed in the present research have to be analyzed and monitored accordingly, by considering the specific dimensions classified in Tables 1 and 2. We may conclude as barriers related to strategy, that people and technology should be addressed with priority and connected with the achievement of environmental, social, and technological aspects, among others.

Digitalization in maintenance contributes significantly to failure prevention, and improving maintenance capability reduces risks. Modern equipment and technology ensure data and communication security, which is now regarded as a critical societal requirement. This ensures that digital infrastructure is maintained in a way that benefits both the environment and the society. Digitalization makes maintenance services more reliable, safe, and efficient, allowing machines to perform to their full potential. It helps to reduce downtime and increase availability, as well as lower the overall expenses and increase the profits, which supports internal decision-making and strategy development. All of these accomplishments have a positive impact on the environment and promote the growth of profitable and sustainable businesses.

The creation of data-gathering procedures and the supply of thorough processing techniques, analyses, and applications should be a significant contribution to dealing with the new data analytical maintenance difficulties brought on by internet-connected technologies. It is essential to perform further studies on the audit trail gathering of maintenance data so that, for example, future systems can support "Human in the loop" interactions, the last one being a relevant topic of research currently discussed in the literature [40]. The feasible framework proposed in this research is a generalized framework and can be taken as an idea for initializing maintenance management transformation, while modifications may be needed to achieve the desired results. Future lines of research related to the application of this framework may be extended from the maintenance field towards other important industrial management areas, for example, inventory management aimed at improving core supply chain operations, a relevant topic highlighted in Ref. [41]. Applications should ideally be customized according to the specific nature of manufactured products, e.g., multi-stage products [42,43], and/or re-workable products [44]. Lastly, given the flexibility of our approach, the developed framework may be updated and tailored to contexts that are not strictly related to the industrial environment, also in integration with machine-learning-based techniques [45] at the stage of critical factors' prioritization, or to improve sustainability aspects in such crucial fields as mobility projects [46].

5. Conclusions

Using current technologies and developing technical skills is critical for optimizing engineering processes while retaining human expertise. In the digital age, the value of human capital may account for up to 80% of a company's resources. However, it is critical that employees evolve alongside innovation and effectively prepare to face the future. Companies should begin the shift as soon as possible in order to be a part of the change rather than passively waiting for it to happen.

Knowing why and how to implement changes is the subject of organizational change, which affects people on personal, corporate, and social levels. The emphasis must be on understanding the benefits of digitalization and overcoming anxiety by emphasizing the benefits for both the business and the individual employee. Plans for digitalization and IT governance are tools for achieving this transition. It is difficult to pioneer new technological solutions. It is recognized that those who dare to move quickly during a corporate transition may gain a competitive advantage. As a result, developing a compelling business case and having the financial resources to accelerate digitalization may pay off.

In this paper, we have implemented a feasible framework by using critical factors formalized in a previous study and integrating the need of addressing the related challenges that emerged in the literature according to specific company needs. This framework is flexible and can be used as a guideline within any operational sector, by tailoring it based on the specific business reality.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
AR	Augmented Reality
CBM	Condition-Based Maintenance
CMMS	Computerized Maintenance Management System
CPS	Cyber Physical System
DM	Digital Maintenance
e-M	e-Maintenance
FCM	Fuzzy Cognitive Maps
IoT	Internet of Things
KPI	Key Performance Indicator
M4.0	Maintenance 4.0
MES	Manufacturing Execution System
OEE	Overall Equipment Effectiveness
PdM	Predictive Maintenance
PHM	Prognostics Health Management
PLC	Programmable Logic Control
RUL	Remaining Useful Life
VR	Virtual Reality

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