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Predictive Maintenance in Industry 4.0: Current Themes

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Abstract

The Fourth Industrial Revolution (Industry 4.0) has created significant technological growth for manufacturing organizations worldwide, attracting important attention from the research community. Industrial automation and the introduction of smart digital technologies to traditional manufacturing processes has led to a generation of intelligent production methods to engineer smart products. In the last few decades, the term 'maintenance' has evolved with researchers offering various perspectives. The aim of this paper is to identify the issues related to industrial maintenance, uncovering its historical evolution, and providing a perspective for new types of industrial maintenance linked to Industry 4.0.

Keywords: Predictive Maintenance; Industry 4.0; Manufacturing and Production; Intelligent Production; Smart Systems.

1. Introduction

Technological advancements in automation and production have led to the definition of the Fourth Industrial Revolution, creating smart factories that house smart enabling technologies, such as IoT, advanced robotics, 3D printing, and CPS, with the aim of delivering products and services with enhanced quality and reliability. From an organizational perspective, smart equipment and machines play an essential role in increasing profitability and operational efficiency and effectiveness. In the context of competitive global markets, manufacturing and production industries must collaboratively expand their systems, procedures, and facets that are continually being incremented. The unregulated expansion of these constituents allows for developments and expansion in competition. On this basis, difficulties surrounding maintenance, especially when it comes to equipment and machinery, must be explored [1].

Historically, the term 'maintenance' has been linked to culture and reflects an organization's philosophy and concepts. The efficient management of maintenance is crucial for supplemental progress, especially in the age of increased costs related to energy, financial setbacks, diminished turnover, and raw materials, and labor. This paper aims to examine the issues associated to industrial maintenance to uncover its historical evolution and provide perspectives for new types of industrial maintenance linked to the new enabling technologies that are provided by Industry 4.0. To begin, current theorical facets of machinery restoration and maintenance are discussed [2]. Thus, the aim of this paper is twofold. First, it aims to identify the underlying issues tied to industrial maintenance, uncovering its historical evolution and, second, it provides a perspective for new types of industrial maintenance associated to Industry 4.0.

Having presented the research scope, the remainder of this paper is structured as follows: in section 2, the evolution of maintenance is introduced and defined. In section 3, we introduce the utilized research strategies and selection methods that were deemed suitable for this review. In section 4, a discussion about the impact of Industry 4.0 on maintenance strategies is presented. Finally, in section 5, conclusions are drawn and areas for future research are introduced.

2. The Evolution of Maintenance

Extant studies have presented divergent interpretations of the term 'Maintenance' and its purpose. The primary role of maintenance is to reduce the impact of malfunction and to

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expand accessibility at a lower cost and, ultimately, improve performance [1]. Commercial maintenance is a procedure completed during production and is a key stage where input is converted into output and is a peripheral process that allows for the accomplishment of production. Dhillon [3] stated that maintenance relates to all actions that assist in maintaining and simulating the essential state of equipment and machinery. They usher towards the recognition and evaluation of the current disposition of the technical installations as an ensemble and the ensuing technical means to re-establish all its features into the requisite state [1, 3].

One of the diverse approaches in which maintenance is split is when maintenance is carried out after or before failure. Maintenance that is executed before the event of failure intercepts the experience of delay. We can also distinguish between preventative and proactive maintenance, as shown in Fig.1. The first is carried out independent of the status of the device while the second is reliant on the device state. After-fault maintenance is principally performed to restore equipment or a machine to a state where it can still execute its intended purposes [4]. This type of maintenance can also be split into immediate, meaning it is executed instantly after the detection of failure, or moved, meaning it is moved based on instructions.

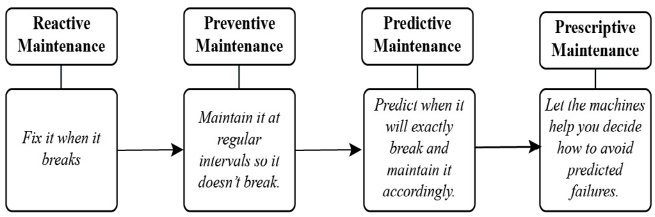

Fig. 1. The Evolution of Maintenance Strategies.

2.1. History

Maintenance rates ranging from 15 to 40% of costs have allowed manufacturing leaders to take into consideration issues entangled in maintenance management. Technological developments have progressed maintenance abilities since the start of World War II. However, tools, equipment, and production machines have always been prone to deterioration and the necessity for maintenance is an important issue. Dating back to the first industrial revolution, maintenance was undertaken only when there was a need for it i.e., when equipment no longer worked or stopped altogether. The nature of this maintenance was defined as corrective maintenance. In this instance, parts of equipment became impaired due to the application of tension. Consequently, it is feasible to detect their timespan before damage and, ultimately, it is possible to repair prior to deterioration. In this way, organizations must make an adjustment to their maintenance processes. Errors that arise can lead to delays in shipment and poor customer experiences. However, excessive amounts of maintenance can lead to significant rises in expenditure. Against this background, manufacturers have focused attention on creating maintenance processes that can comprehend the necessity of maintenance prior to failures occurring. In the context of Industry 4.0, maintenance costs are deemed as a value maker. Historically, however, organizations have perceived them as costs that need to be decreased given the tendency to patch-up equipment or machines only when they stop functioning [5].

2.2. Maintenance Types

The historic approach of letting machines or equipment function until they deteriorate is linked to the 1940s and 1950s. Maintenance services were employed for basic tasks, such as lubrication, cleaning, and restoring broken parts. Thus, responsive maintenance only occurs when machines break down i.e., the machines operate and when an error occurs, it instructs the maintenance department to fix it. As a means for extending the duration of equipment, various maintenance processes have been established. Studies [6] have shown how machines and equipment are preserved, with responsive maintenance being the most widely used (56%), followed by precautionary maintenance (33%), and prognostic maintenance (10%). More than 56% of resources and maintenance tasks of a standard manufacturing facility are responsive. The advantages of responsive maintenance are two-fold. First, in the case that a machine or equipment is brand new, we can anticipate slight errors or failures. In cases where the maintenance schedule is solely responsive, we will not misuse labor or sustain budget charges until an error occurs. Given that expenses related to maintenance are zero, this time span is considered a money saver. However, this is not always the case. During periods when organizations are retaining capital and maintenance expenses, they occur much more costs than when employing dissimilar methods to maintenance. Capital outflows are greater given that we anticipate the equipment or machine will give out, consequently curbing its period of functionality, which incurs greater rates of substitution. Further costs linked with the breakdown will surface, resulting in the minor device breaking. These escalated expenses do not arise in the context of active maintenance [6]. The expenses linked with restoration are likely to be greater than usual, given that breakdown will necessitate more large-scale maintenance than if a part of the equipment was not operational until complete malfunction. In the case that the equipment or machine is crucial and needs to be utilized on an ongoing basis, further expenses will be sustained. Given that equipment malfunction is anticipated, there is need for easier supply of spare parts [7].

2.2.1. Preventive Maintenance

The roar of production, post-war, led to innovations in examining and assessing information in addition to product value requirements. The need for precautionary maintenance of machines and equipment, and added stress to diminish costs, resulted in maintenance challenges. The aim of decreased downtime, in addition to demands for expanding devices' lifespan and consistency, steered organizations towards arranging and preparing for maintenance tasks [8].

Preventive maintenance can be described as a task based on a set schedule which identifies, postpones, or lessens the decline of the system or constituent state for the purpose of preserving or lengthening its functionality through administered deterioration to a satisfactory level [9]. Two types of preventive maintenance commonly exist: (1) Machine-based maintenance and (2) Maintenance in interval periods. The first switches components and intervenes with the equipment only when irregularities emerge during its course of use, which makes it more cost-effective. As for maintenance in interval periods, this is shown to be more costly for about 92% of manufacturers when it comes to maintaining equipment components [10].

As manufacturers aim to improve equipment efficiency while limiting service interruptions, some rely solely on reactive maintenance which can retain up to 18% through appropriate precautionary maintenance programs. Even though preventive maintenance may not be ideal, the latter offers several benefits compared to responsive maintenance. By using preventive maintenance on machines, it allows for an extension of the lifespan of components. This brings potential savings. Further, preventive maintenance (e.g., filter replacement, lubrication, etc.) typically allows for greater efficiency in relation to equipment or machines [11].

2.2.2. Predictive Maintenance

Predictive maintenance can be defined as estimations that identify potential machine breakdown, allowing for the setback source to be eliminated or maintained, prior to each substantial depreciation of the machine state. Predictive maintenance is quite different from preventive maintenance as it detects maintenance requirements on the present status of the machine, compared to a pre-defined timetable. A well-structured preventive maintenance program eliminates everything but fatal errors. It can be pre-arranged to decrease or exclude the volume of overtime work. It is also probable to decrease inventory and request the essential components. Manufacturers can, therefore, enhance machine operations, save expenses in terms of energy, and surge machinery dependability [12]. A correctly operating predictive maintenance program can lead to 8 to 12% in cost savings [13]. Based on the tools and measurable circumstances, it is achievable to retain 30% to 40% of savings [14].

2.2.3. Prescriptive Maintenance

Prescriptive maintenance has grown in popularity in recent years. It spreads the concept of failure prediction through predicting maintenance methods and recommending a series of actions grounded in historical and incoming real-time information. Prescriptive maintenance strategies are upgraded based on the predicted or observed degradation system and parameters while, in standard time-based maintenance, assessments are purely based on historical information without considering updates [15].

Various sectors have embedded and experienced the accuracy of predictive maintenance. Prescriptive maintenance recommendations allow for the power of machine learning to be applied in a more holistic way in an organization or enterprise's physical operations [16]. Where predictive maintenance allows for delivering data regarding binary decisions, like an option to defer or perform asset maintenance, it suggests a series of options and results from which to choose from. For instance, a production full stop may be circumvented by running a compressor at an inferior pressure or a plant maintains the speed of a machine below a specific threshold, thus delaying the planned downtime for the purpose of overlapping with the delivery of new equipment [17].

Prescriptive maintenance can recognize the requirements of capital expenditure months prior to them being evident to human operators. For instance, prescriptive maintenance tools can be utilized as a digital assessment method in which the outcomes of adding equipment can be digitally generated prior to making an acquisition, which allows for organizations to schedule acquisitions more economically [18].

3. Methodology

To undertake this critical review, we examined academic peer-reviewed publications that delved into maintenance strategies in Industry 4.0 within areas related to manufacturing. An initial unstructured search was completed for the purpose of identifying various approaches and goals in the field of Maintenance 4.0. The objective was to formulate an approach for Industry 4.0 with reference to maintenance. The keywords used for this search included: "Industry 4.0", "Intelligent Production", "Smart Systems", "Manufacturing" and "Predictive Maintenance". This resulted in more than 20,000 publications for the first search and more than 5,000 for the second search. Accordingly, new structured searches were created for each algorithm to create a complete bibliography. Repeated searches were completed, integrating the following keywords: "Maintenance 4.0", "Equipment Maintenance", "and Maintenance Strategy" with each algorithm detected in the previous unstructured searches. Then, we transferred the articles to Mendeley, with a total of 1143 articles being identified. The intent behind this screening was to attain a larger volume of results to the catalog. In terms of cataloging, we opted for the exclusion criteria listed in Table 1. The outcome of these searches produced 31 articles where Predictive Maintenance had been applied. The timespan of identified articles range from 1992 to 2020.

Table 1. Quality assessment criteria.

Section	Description
Criteria 1	Filter looking for period of 30 years, 1991 to 2021.
Criteria 2	Omit dissertations, theses, books, and technical reports.
Criteria 3	Omit documents that are less than 3 pages in length and are not written in English.
Criteria 4	Omit all publications that do not utilize the search terms "internet of things", "smart manufacturing", "intelligent factory", "industry 4.0" or "smart factory", in the title, abstract or keywords.
Criteria 5	Omit all publications that do not tackle monitoring or prediction applied to Industry 4.0, IoT or smart factory as a method, model, or architecture.

4. Impact of Industry 4.0 on Maintenance Strategies

Maintenance strategies are established as an alternative to maintenance or a variation of preventive maintenance types. In simpler terms, Industry 4.0 is the connection between digital and material assets. They are founded on effectiveness and necessitate that each singular asset of a machine or piece of equipment functions to its best ability. This is the reason why many manufacturers have created maintenance strategies when transforming to Industry 4.0 as it enables greater effectiveness and reduced risk of machine or equipment breakdowns or errors. In markets where organizations sell the same or similar products, it is essential to distinguish some aspects of design. Industry 4.0 has pushed manufacturers to be more resourceful and competitive, but this is one reason why some are conducting too many maintenance activities. Nonetheless, frequency of maintenance can be delayed with more detailed data about machine or equipment components [19].

4.1. Maintenance Strategy Design

Maintenance strategies must be sustained through the creation of tactical plans. These plans should also be viable. Further, a maintenance strategy necessitates periodical review given the fluctuating business and changing settings. Thus, the main aspects in the design of a maintenance strategy include: (1) to frame a maintenance strategy a holistic approach is needed, (2) an organized elaboration of maintenance strategy is essential within every case, and (3) besides the maintenance strategy arrangement, an adaptable strategy is necessary for feedback and enhancement to adjust to modifications in relation to maintenance requirements [20]. Moreover, the design of a maintenance strategy should take into account the following considerations: (1) the organization should know the standards of maintenance strategy for the vision of the organization to go hand-in-hand with the effective practices, and (2) when the organization's vision is framed, employees should be encouraged to comprehend the vision and strive for achieving the latter [18,19].

The framework developed by Visser [20], comprises four strategic facets when it comes to maintenance, including: the option of purchasing subcontracted maintenance services or completing maintenance through in-house abilities, structuring the maintenance feature as well as the manner maintenance assignments are planned, identification of maintenance guidelines, and lastly the development of the substructure which will reinforce maintenance within the organization. It is crucial that maintenance goals and methods go hand-in-hand with business objectives which ought to mirror target consumer needs to recognize the performance of the product. The assets must complement the strategic aims and align to an understanding of the function abilities, individuals' participation, maintenance performance requirements, and how rapidly they can be executed. When it comes to maintenance within a factory, the latter examines each feature as well as each digital and physical segment. Against this understanding, there are several types of maintenance that can be categorized into two main clusters, including sub-structural evaluation features and structural evaluation features. The first encompasses maintenance scheduling and regulation systems, human resources, maintenance administration, maintenance plans and models, maintenance adjustments, and maintenance performance quantification. The second includes maintenance amenities, maintenance scope, and maintenance machinery, in addition to vertical integration, Fig. 2 shows this.

The creation of a maintenance strategy incorporates detection mechanisms, part supply, repair processes, part substitutes, and assessment of choices, and relates to framing the best approach for each component, planning a maintenance program for the factory to permit planned and unplanned maintenance tasks to be completed. When designing a maintenance strategy, manufacturers begin by identifying the maintenance aim, however designing them is much more complex than reality. Then, the strategy is prepared for the purpose of attaining the identified objectives at the lowest expenditure. This procedure is valuable in comprehending the foundation for maintenance costs and controlling maintenance spending. The ensuing stages commence with asserting the maintenance philosophy. Following this, it is important to consider the overall maintenance aim. The final step is to measure and assess the maintenance problems and applications, from which, the evaluation and maintenance schedule can be designed. Then, an approach must be shaped for the purpose of incrementing the new applications [21].

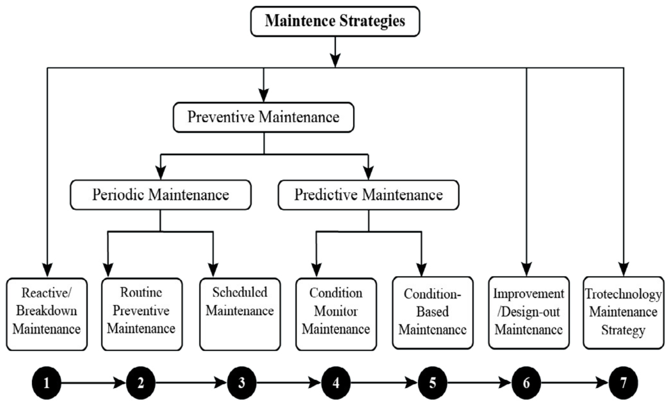

Fig. 2. Maintenance strategies showing ascending order of technology effectiveness.

4.2. Maintenance 4.0

In Industry 4.0 environments, there is a need for supplementary technical abilities from maintenance managers, as they must administer maintenance procedures to oversee the influence that maintenance has on other organizational divisions, business objectives, effectiveness, quality, and security. More assets are committed to the maintenance administration, and this ushers businesses to administer maintenance in a direct approach as well as remotely, as now there is an opportunity to obtain and manage information through software and, more specifically, with minimal expenses. Two new patterns have been recorded, including the capability to evaluate the vast size of information that machines, and assets, generate during their operational lifespan, and the capability of conception of an added value that goes hand-in-hand with the requirements of the organization.

Manufacturing procedures will multiply and become smarter in the ensuing years given the rise of new smart technologies. Through the shift to digital supply chains, the effectiveness will surge, and new business models will be conceived through wireless connectivity and sensors; the manufacture of products will thus be supplemented with distinctive facilities, such as maintenance, or converted into a complete assimilated service. Maintenance will therefore become not just one internal undertaking, but rather a whole facility that can be sold to customers [21].

4.3. Equipment Maintenance

An essential asset in Industry 4.0 environments is equipment. What we imply by the term 'equipment' is the machine, as well as instruments that are crucial for the accomplishment of production procedures. Manufacturers that need to diminish the possibility of unprepared interruption, breakdowns, or errors, must maintain their equipment at the optimal functioning state, as shown in Fig. 3. It is also essential to keep track of undertaken equipment maintenance. Accordingly, the ensuing discussion encompasses some advantages linked to this.

Given that all types of equipment are susceptible to wear and tear, which can lead to malfunction and failure, carrying out regular inspection helps to detect and repair minor problems before they occur. Keeping track of these check-ups and minor maintenance tasks allows for recollection of all safeguarding tasks that the equipment has received, guaranteeing that each piece of equipment can stay in good working order prior to allocating work to it. This allows for specific maintenance programs to be developed – working tasks are divergent for each type of equipment and through the assistance of regular inspections, it is possible to detect and document the variations of each specific equipment, in relation to maintenance mechanics. Ultimately, this aids with the creation of maintenance plans [21, 22].

If equipment is well-maintained, then the likelihood of accidents occurring diminishes; keeping a history of equipment maintenance allows organizations to monitor the condition of equipment [21]. Keeping records regarding responsibility of equipment pieces, given that when dealing with a machine there are often more than one worker handling it, allows organizations to keep records of each worker that allows the detection of who is accountable for each accident, as well as enhancing employees' attention to care for equipment. Similarly, through recording machine related problems and the maintenance performed to fix it, allows organizations to resell the equipment at a higher price, in future.

4.4. Machine Life Extension

To monitor machining technologies, various models possess an assortment of sensors that alert if anything is not functioning correctly, despite its size or extent. Thus, it is essential that someone keeps track of the machinery, as well as its performance. Additionally, there are various tools that can be used to add specific equipment possesses. For instance, thermal imaging, vibration monitoring, audio gauges, as well as other technologies that can assist with gathering data on the equipment for the purpose of having real-time information related to the status and condition of the equipment.

Nonetheless, this type of technology is only effective if a monitor is at hand to oversee when a sensor notices an error or malfunction. Expert technicians and operators, creating the need for human involvement, cannot be replaced in this instance, as there is a requirement for specialist operators to comprehend the issue and an expert technician to recognize how to repair or to notify an expert that is more suitable for repairing the machinery [22]. Here, the team configuration necessitates an individual with liability regarding equipment conservation and upkeep; instructing and authorizing a person to assume this responsibility is vital to the success of precautionary maintenance, if not, it will be set to the side. It should also be noted that each part of a machine is dissimilar, as they all possess complexities and require a timetable to go along with it. Through long periods of time, various tasks will need to be executed, such as replacement of bolts, belts, and seals etc. Thus, instead of waiting for those fragments to induce an error or breakdown, swapping them when they are scheduled is considered most efficient [22].

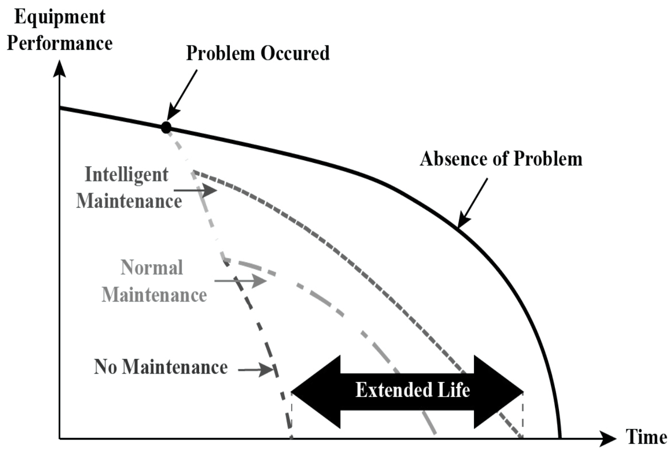

Fig. 3. Role of Maintenance in Equipment Life Extension.

4.5. Subcontracting of Maintenance 4.0

Subcontracting is the outsourcing of non-core tasks or activities to free-up time, personnel, expenses, as well facilities for tasks, in which a business has competitive edge [22]. Companies that possess assets in various fields can contract out marketing, manufacturing, legal, payroll, accounting, data processing or various other facets of their business in order to focus on what they can excel at, therefore decreasing the average unit cost [23]. In this frame of understanding, in previous years, given the costs associated with maintenance, numerous businesses have opted to sub-contract their maintenance procedures with the intent of being more efficient and gaining better results in addition to focusing on the tasks that they excel at. There are various stages of sub-contracting maintenance work, and the ensuing showcases the most important.

The approach of subcontracting the entire maintenance function is used to develop a separate maintenance department or company as it warrants services and dependability when it comes to manufacturing companies. Companies may also subcontract specific skills which is an approach adopted when the business does not need this type of maintenance skills. The subcontracting of work undertaken within scheduled outages or shutdowns is a method that is not cost efficient to not bring additional resources within peak loads [23]. Similarly, subcontracting of a system function or equipment is when businesses choose to sell a guaranteed system function at a specific price considering maintenance and operations.

5. Conclusions

Today, we live in an Industry 4.0 age where competition between manufacturers is complex. New smart technologies, such as IoT, CPS, and cloud storage, create a progressive method for maintenance called 'Predictive Maintenance'. Maintenance is considered an integral activity that organizations strive to develop and improve. When maintenance is improved, breakdown or errors are likely to diminish. Any manufacturer that establishes a maintenance strategy has a competitive edge, given that, if executed correctly, maintenance allows for manufacturing with greater dependability at minimal expense. Within the next few years, there is an expectation that the usage of predictive technologies will expand as there is scarcely any industry that cannot profit from it. The industries that would find Predictive Maintenance of most interest would encompass the ones with expensive and sensitive equipment, a sizable capital, and operational expenditure, as well as inflated danger to human safety. Industries such as manufacturing, oil and gas, aviation, mining, and construction can profit from this. Based on this research, future studies should provide a clearer perspective of steps that should be taken by organizations to begin a conscious transformation to maintenance management. Furthermore, it is essential to mention the connotations of this transformation when it comes to the personnel and to inspect in more detail diagnostics and prognostic algorithms, as well as their implementation in various contexts. In this approach, more pertinent tools should be made accessible for companies wishing to promote maintenance policies within Industry 4.0.

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