A state of the art of predictive maintenance techniques

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Abstract. Nowadays in industry there is a great and increasing demand in resource management, taking into consideration the ever-growing complexity of technical systems. The concept of maintenance is one the most important topics of product development today. As the factories and the industry evolves, the need of proper maintenance plays a major factor in cost and efficiency optimization. In this paper a state of the art of maintenance techniques is presented, predictive maintenance being one of the biggest topics going forward. Predictive maintenance techniques are discussed and presented in detail creating the necessary links with nowadays industry advances: Industry 4.0.

1. Introduction

The present paper aims to deal with the main maintenance concepts, focusing on the principle of predictive maintenance.

The industrial revolution represents one of the most important moments in human history and continues to play an important role in the modern world today. The main areas targeted by the industrial revolution were the technological, socio-economic and cultural ones. Through the changes, it has shaped the modern world in the way it is today, changing the way people live, how they spend their free time and not least how the current political class is organized globally.

Some of the most important technological changes targeted by the industrial revolution are:

- Use of new materials, mainly iron and steel;
- Use of new energy sources, such as coal, steam engine, electricity, oil and internal combustion engines;
- Inventing new machines for the textile industry (eg torsion wheel);
- Organizing the production in the factory type system that we meet today and the division of labour;
- Development of transport and means of communication such as: steam locomotives, steam vessels, airplanes, telegraph, radio;
- Application of scientific principles in industrialization.

All the technological changes have greatly contributed to the use of natural resources and have enabled the mass production of goods [1]. Today, maintenance is an issue of the utmost importance in the industrial environment and beyond. Maintenance performed correctly, regardless of its type, does nothing but improve the working environment and implicitly increase the performances, having a general effect. In the following chapters, maintenance concepts will be dealt with extensively, as well as topical solutions in this field.
2. The maintenance concept
When we talk about products, they represent the centre of interest in companies and factories around the world, therefore a product management plan is needed. It ensures good development and organization of all stages, resources and means involved in the production process.

The idea of maintenance is present from the design stage of a product. It must ensure the proper functioning of the product according to its life. As can be seen in figure 1, according to [2], there are five stages in the life cycle of a product: idea, definition, realization, use, recycling. These five phases can be divided into 3 broad categories:
1. The incipient phase: idea, definition, realization;
2. Middle phase: use;
3. Final phase: recycling.

![Figure 1. The lifecycle of a product.](image)

As time goes on, the medium phase lasts the longest, the product being in the use phase, so it is necessary to maintain it in order to function in optimal parameters.

The maintenance concept is defined by the standard EN 13306, as follows [3]: the combination of all technical, administrative and managerial actions performed during the life cycle of an element to maintain or restore the conditions under which it can perform the required function. In order to perform the maintenance operation, a maintenance management plan is required. Maintenance management is defined as the sum of all the management activities that determine the maintenance objectives, strategies and responsibilities and their implementation by means of maintenance planning, maintenance control and improvement of maintenance activities.

There are therefore several types of maintenance, also defined in standard EN 13306. Figure 2 shows the schematic representation of the maintenance types.

![Figure 2. Types of maintenance according to EN 13306 standard.](image)

Equipment maintenance has evolved over time, from maintenance that was performed only when the elements suffered damage to modern methods, proactive and predictive maintenance, the latter being the most popular today [4]. Maintenance performed only in case of damage has proven to be an inefficient method in time because in many cases alternative failures are observed in the system. This has led to the adoption of the principle of scheduled maintenance where the equipment is subject to a total overhaul whether it has problems.
The disadvantage of the scheduled maintenance method is that it analyses the service life of each element in the system, so some elements are changed even if they have not reached the end of their life cycle. This has led to the evolution towards predictive maintenance.

Figure 2 shows a generalized classification of maintenance types. According to [5], maintenance tasks can be classified into two broad categories:

1. Reactive maintenance - the system is used until breakdowns occur. When a fault occurs, the damaged elements are replaced in order to restore the operating capacity of the system;
2. Proactive maintenance - maintenance actions are planned or take place as a result of tracking indicators. Planning can be done using sensors that announce the early stages of a fault. This type of maintenance aims to maintain the functionality of the system;

Regardless of the type of maintenance applied, the purpose of these activities is to reduce the stops caused by damage as much as possible. To be able to minimize the stops, it is necessary to understand the failure modes and mechanisms. Table 1 presents a comparative analysis of advantages and disadvantages for reactive and proactive maintenance.

| Maintenance Type | Advantages                                 | Disadvantages                                                                 |
|------------------|-------------------------------------------|-------------------------------------------------------------------------------|
| Reactive         | Low initial costs                         | Unscheduled stops                                                            |
| maintenance      | Easy to implement                         | High associated costs (work over schedule, delivery urgency, manufacturing urgency) |
|                  |                                           | Poorly optimized resources                                                   |
| Proactive        | Increased system reliability              | High initial set-up costs                                                    |
| maintenance      | Minimizing logistical stops               | The cost reduction is not immediate                                           |
|                  | Reduction of non-scheduled stops          |                                                                               |
|                  | Lowers costs (optimizing parts, optimizing work) |                                                                               |
|                  | Maintenance planning                      |                                                                               |
|                  | Optimization of logistic support           |                                                                               |

3. Predictive maintenance nowadays

Predictive maintenance is a relatively new concept that can be framed as a proactive maintenance approach. When speaking about predictive maintenance techniques, conditional predictive maintenance is one of the most used techniques. Conditional predictive maintenance is a strategy where maintenance is performed by observing certain parameters or certain components of the system. The advantage of this method is that the state of the system is presented in real time, based on the parameters followed. Although the systems generally have a well-defined operating curve by the manufacturer, depending on the operating conditions and the working environment it may undergo changes, as a result, damage may occur earlier. At the same time, this method increases the ease with which the faults are detected and especially, their place.

Regarding conditional predictive maintenance, there is a wide range of parameters that can be monitored for predictive maintenance, some of the most important being:

- Vibration analysis - represents the most efficient method for detecting problems in the equipment that perform rotational movements;
- Acoustic analysis - this can detect or monitor cracks in pipes or pipes;
- Lubrication oils analysis - the particles found in the oils used to determine the degree of wear of the components are analysed;
Particle analysis in the working environment - a method generally used in equipment working in a fluid environment;

Corrosive analysis - ultrasound measurements are performed to determine the corrosion in different structures;

Thermal analysis - used especially in the case of mechanical and electrical systems to detect overheating in general.

Performance analysis - an efficient technique to determine operational problems in the system;

Using one or more of the above methods, maintenance solutions for equipment and systems are developed. Therefore, considering that more than 30% of maintenance costs are caused by faulty maintenance planning [6] leading to added costs in the production process, predictive maintenance is a method of increased interest especially when considering industrial environments, where stops can cause large losses.

A new approach to in the predictive maintenance techniques is represented by the usage of 4.0 Industry standards in order to facilitate the processes contained by the predictive maintenance technique. As nowadays the industry is facing difficulties due to the development of technology, the diminution of natural resources, the incidence of wars and natural disasters and at the same time, social issues such as globalization and increasing the retirement age for the labor force, represents difficulties that produce substantial economic effects [7]. In addition to the points listed above, it should be noted that consumers today want a variety and high quality of products, as well as quality services during use.

The vision of Industry 4.0 comes with a massive impact on the current way of working in the industry characterized by a new model of socio-technological interaction. These new smart factories have small, decentralized networks that act autonomously being able to make decisions in different situations and which are interconnected globally with respect to the company, resulting in intelligent products that can be tracked in real time and of whose properties and characteristics are known throughout the production process. The benefits of Industry 4.0 can therefore be used to develop a predictive maintenance strategy using the aforementioned technologies. They provide the premises for the implementation of predictive maintenance strategies, this being achievable with reduced material and human resources.

A brief definition of Industry 4.0 can be considered the one provided by [8] which says that Industry 4.0 represents basically a synergy between Internet of Things, Internet of Services and of course, the industrial process. It should be also noted that Industry 4.0 is shaping not only the manufacturing and maintenance processes, but also the way human-machine interaction take place.

The benefits of predictive maintenance in comparison with scheduled maintenance are strongly highlighted in paper [9]. In comparison with classical maintenance approaches with are at least in the industrial field the main maintenance techniques applied, predictive maintenance promises to lower the increasing failures caused by the incapacity to provide a time estimation for components failure. Regarding predictive maintenance, it can be split in three basic techniques:

- Maintenance based on existing process sensors, which are already equipped;
- Maintenance based on test sensors;
- Maintenance based on test signal technique;

All of the above maintenance techniques aim to provide an improvement in failure analysis, yet they represent different approaches. The first two techniques can be considered as “passive” and the third as “active”, the implementation considering loop responses and real time testing.

Considering that the vast majority of industrial processes are conducted using electrical and mechanical systems, paper [10] proposes an overview over predictive maintenance techniques used for performance enhancements. The main topics considered are electrical motors performance and bearing failures, these being the most common problems. The study concentrates on two case studies carried on a 75-hp blower motor and a 200-hp air compressor motor in an active plant. Results and conclusions were gathered from both experiments, confirming a misalignment in blower motor shaft and a performance loss and a degradation for the compressor motor due to small periods of overload.
Grall, Antoine, et al. [11] propose a method of predictive maintenance used for systems that are subject to continuous deterioration. The paper aims to treat two main points, as follows:

- Creating a structure for implementing conditional predictive maintenance and determining a mathematical model of cost analysis from the way the faults appear;
- Demonstrate that long-term maintenance costs can be substantially reduced by using such an approach.

A random model is used to simulate the continuous deterioration of the system. It can simulate an aging in the case of mechanical models, the evolution of defective products in the case of a production line, the level of corrosion / erosion in the case of structures. The chosen model offers a cost efficiency considering the time required to perform maintenance for an indefinite period. It aims to make a minimum estimation of the costs considering the level of wear and the appropriate moment for stopping the equipment. As maintenance based on continuous parameter monitoring performs better than other maintenance methods, the mathematical model presented must be able to prevent random occurrences. The solution is outlined around two main ideas:

- Determining the maintenance method for the system concerned according to the evolution of the damage (implementation of the strategies of preventive maintenance, corrective maintenance or the use of the system regardless of the degree of damage);
- Determining and establishing the data for the next inspection;

The simulations performed offer a wide range of solutions for determining the maintenance mode or the use of the equipment until an imminent failure to obtain the desired result: the efficiency of the maintenance costs.

An innovative approach is also taken by Wang, Jinjiang, et al. [12] who propose a predictive maintenance system that is based on a new cloud architecture that uses a mobile client instead of the classic server-client architecture. This approach aims to increase the flexibility and adaptability of the system, reduce the volume of raw data that is transmitted and improve the response time to the dynamic changes that occur in the monitored systems. This approach is not without problems, some of the points that remain open are: automatic maintenance planning, energy management, management of data analysis and transmission, data storage, large-scale system implementation. To address some of these issues, as mentioned from the outset, this solution proposes using mobile agents to distribute tasks in the cloud.

The mobile agent is a method derived from the field of study of artificial intelligence that aims to divide the tasks and their parallel execution. Agents are represented by software programs that migrate within the network. The main features of a mobile agent are autonomy, intelligence, adaptability, which makes this approach suitable for cloud architecture. Such an implementation makes the distribution of computing power more efficient, reduces the amount of data transmitted and allows the modification and adaptation of algorithms running on equipment, thus increasing their versatility.

For system testing, six AC motors were used, five of them having different defects, and one being used as a standard. Using mobile agents, software programs are sent to be run and to purchase different parameters, according to predictive maintenance methodology. The data is then processed with specific algorithms, after which a characteristic of the monitored equipment is obtained. The results confirmed the efficiency of the system and provided relevant data on the condition of the analysed engines compared to the standard engine.

In the paper [13], the authors propose a method of predictive maintenance that is performed with a monitoring system subject to errors. For data generation, it is considered a system subject to continuous degradation which is modelled using Markov chains. This method provides the means for performing an efficient simulation to track the evolution of the main topic of this paper: correlating the efficiency of data analysis and acquisition equipment with reducing costs in predictive maintenance compared to other maintenance methods.

For a robust evaluation of the proposed system, the analysis is performed on 2000 simulated elements, and the costs of procurement equipment used in predictive maintenance are also considered. Of course, depending on the quality of the sensors and the cost of repairing the damage, predictive
maintenance may or may not be the best option. When the simulation parameters are changed and the quality of the sensors used for the acquisition decreases, the efficiency of the predictive maintenance decreases considerably, being below the preventive maintenance. This can be solved only by using sensors and modules for the acquisition and interpretation of qualitative data and also by implementing filters for the acquired data.

The results of this simulation reinforce the idea of adopting predictive maintenance systems, which improve maintenance costs, even when the cost of analytical equipment is taken as long as the sensors and the acquisition systems provide qualitative data.

Ullah, Irfan, et al. [14] propose a predictive maintenance solution through thermography using ML (Machine Learning) techniques. This type of anomaly occurs mainly in power equipment, where imperfect contacts, corrosion, imperfect insulation, etc. causes overheating of the equipment. The use of thermography is a non-invasive method that can monitor the equipment in operation. The analysis is done on a total of 150 photos, which are determined around 300 points of interest. Then using ML techniques, the points of interest in the photos are classified as defects or functioning in parameters.

This method is possible using an infrared thermographic camera. It captures and filters the infrared light component and thus provides images on the thermal profile of the equipment being tracked. As in the deterioration of the electrical equipment the main effect of the aging of the cables is represented by an increase of the resistance, the thermographic analysis with infrared can offer relevant information in the study of the equipment for the implementation of the practices of predictive maintenance. Regarding the maintenance applied to electrical equipment, it is generally neglected, using the strategy of use until failure and applying the corrective maintenance when the equipment requires it.

Using the means of Industry 4.0, Cachada, Ana, et al. [15] propose an innovative predictive maintenance structure based on OSA-CBM (Open System Architecture for Condition Based Monitoring) architecture. The OSA-CBM structure consists of six steps in comparison to the structure proposed in this paper which consists of only four steps, as follows:

1. Data acquisition - is based on automatic, semi-automatic and manual data acquisition methods.
   This is done using IoT (Internet of Things) and HMI (Human Machine Interface) technologies;
2. Offline data analysis - this step is based on the use of several technologies such as machine learning, cloud technology and advanced data analysis technology to make new monitoring rules and procedures. Depending on the type of method and algorithms chosen, results with different degrees of efficiency are obtained;
3. Dynamic monitoring - it is composed of two subassemblies: the visualization subassembly and the early damage subassembly;
4. The module for decisions and support - when it is necessary to carry out tasks or interventions, the information is sent to the module for decisions and support through an organizing tool;

The solution comes with improvements in comparison with OSA-CBM technique which makes usage of the Industry 4.0 and cloud techniques in order to create an enhanced predictive maintenance system.

Implementing predictive maintenance on an industrial basis represented by Industry 4.0 [16], changes the processes in comparison with classical maintenance. One of the main problems is represented by the overwhelming amount of data which is acquired and must be processed accordingly [17]. This leads to big data paradigm, which must be treated using data management methods.

Data management processes have been around for a long time, yet new techniques are developed in order to adapt to data environment changes. Data management processes aim to provide a standard procedure for data analysis in order to evaluate and propose a solution based on analyzed data [18]. There are of course many data processes available [19], each suited to different data management necessity, some of the most important ones being:

- Cross Industry Standard Process for data Mining (CRISP-DM) process model;
- Sample, Explore, Modify, Model and Access (SEMMA) process model;
- Team Data Science Process (TDSP) methodology;
The first two models are around for about two decades, but the changes in the industrial processes data analysis shaped around the new industries asked the necessity for new data management processed, thus newer methods like TDSP emerged.

Figure 3 presents an intelligent predictive maintenance system framework implemented with Industry 4.0 means [20].

![Figure 3. Predictive maintenance in Industry 4.0 framework.](image)

All of the above methods represent a novel approach in terms of predictive maintenance techniques. As expected, the predictive maintenance started to become the standard in maintenance techniques due to the multitude of benefits. With the new technological advances and the 4.0 Industry movement, the factories and machines started to become more advanced and connected. This opened the way for real time parameter monitoring which is the founding pillar in the predictive maintenance. The speed and ease wherewith the data is now acquired and sent is something that must be taken advantage of. With new innovations, like Internet of Things and Internet of Services new challenges appear, data management and processing being one of them [21].

4. Conclusions

This paper starts with the beginning of the industrial revolution and briefly presents the industrial evolution, but also its problems and changes over time. Initially seen as a means of eliminating humans from the field of work, technology has transformed the world into what it is today.

Since the beginning of technological upgrades, the efficiency of systems and means of production has been a priority to increase production and reduce costs. The maintenance of the equipment was a problem that raised a major interest, being a broad topic on which continuous research was carried out. Today, evolution allows the creation of intelligent and autonomous maintenance systems, which have analysis capabilities far beyond those of human personnel.

The main subject of the present paper is predictive maintenance - an intelligent way of monitoring the parameters of the equipment in real time in order to determine the possibility of damage. Further, the concept of predictive maintenance in Industry 4.0 is presented and how the synergy between these two revolutionary methods can generate more efficiency. Moreover, data management processes are presented in order to deal with data acquired in order to implement predictive maintenance system.

The study of the current solutions offers an overview of the research and discoveries in this field. There are presented several predictive maintenance solutions implemented in different environments that have different systems analysis methods, use different algorithms, but which have a common purpose: to determine the possible breakthroughs in advance in order to be able to plan a maintenance strategy so that the efficiency to be as high as possible.

Therefore, intelligent maintenance started to gain weight in applied maintenance methods due to the long term benefits it provides. Even if the implementation of Industry 4.0 may be yet in an
incipient phase, the value added by the means offered by it can provide a starting point for intelligent maintenance systems and methods which are superior to the old maintenance practices.

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