# Historical Overview of Maintenance Management Strategies: Development from Breakdown Maintenance to Predictive Maintenance in Accordance with Four Industrial Revolutions

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## Abstract

Every industrial revolution causes changes in technological, socioeconomic and cultural features. Among the technological features belongs also maintenance management. The approach towards equipment maintenance has changed throughout the revolutions from reactive towards predictive. Instead of fixing breakdowns, companies try to predict them and minimalize the risks and costs associated with it.
The main objective of this article is to put the changes in maintenance management strategies in the context of industrial revolutions. Throughout a literature review, the article summarizes the characteristics of each industrial revolution and maintenance management approach together with paradigm shifts that accompanied them. Namely the relation of the first industrial revolution with breakdown maintenance, the second industrial revolution with preventive maintenance, the third industrial revolution with preventive maintenance and finally the fourth industrial revolution with predictive maintenance.

## Keywords
Maintenance management strategy, Industrial revolution, Industry 4.0, predictive maintenance

## 1. Introduction to maintenance

Production machines, equipment and devices will always be liable to wear and the requirement for maintenance. Alongside the advancement of industry goes the improvement of maintenance. As far back as the mankind began making devices that fulfilled their requirements there was the requirement for maintenance. Records of maintenance can be found already in the ancient Egypt. An old Egyptian document, dated 600 b.c. mentions a stoppage of supply of cedar wood required for the maintenance of sacred boat of Amun Ra. (Brugsch-Bey, H. 1881)

The approach towards maintenance has changed throughout the years. It has been transformed from reactive (corrective) actions to ongoing predictive activities with an aim to optimize the time, costs and quality. While nowadays it could be foreseen as a competitive advantage or area, whose improvement may increase profit and bring many benefits, some still consider maintenance as the "necessary evil". In this paper, we identified four key maintenance concepts that correspond to the industrial revolutions.

Nowadays the maintenance management aims to decrease both the unscheduled downtime and scheduled downtime, which both reduce the available time, in combination with optimization of safety, environmental risks and costs. Available time, production quality and performance are the basic key performance indicators (KPI), which combined give the overall equipment effectiveness (OEE) (Legát et al. 2007).

Literature gives many definitions of maintenance. Swedish standard SS-EN 13306 characterize it as a "Combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" (API STD 689 2007 ).
Maintenance management covers all actions including inspection, adjustments, cleaning, lubrication, testing, and replacement of expendable parts, as necessary to maintain the serviceability of the equipment (API RP 8B 2012).

Simeu-Abazi and Sassine state, that “the main purpose of maintenance engineering is to reduce the adverse effects of breakdown and to increase the availability at a lower cost, in order to increase performance and improve the dependability level”(Simeu-Abazi, Z. and Sassine, C. 2001).
Gits (Gits, C.W., 1994)considers modern maintenance as a procedure that is needed by production processes; it is the essential procedure where the input is changed in output and maintenance is an auxiliary procedure that causes the first to the accomplishment of production.

According to Bagadia,(Bagadia, 2006) maintenance implies all measures that assist to save and re-make the required condition of machinery and equipment. They lead to identification and assessment of genuine condition of specialized establishments overall and the consequent technical measures to reestablish every of its capacities in the required quality.
ISO defines maintenance as set of activities performed during the operating life of a structure to ensure it is fit-for-purpose (ISO 19901-7:2013).

## 2. Maintenance management parallel to the industrial revolutions

The term Industrial Revolution was first popularized by English economic historian Arnold Toynbee to describe Britain’s economic growth from 1760 to 1840. Since that, the term has grown on its popularity. Industry revolution is defined as “the comparatively sudden and violent change which launches the industrialized society into being, transforming that society in a way which none of the earlier so-called industrial revolutions ever did” (Coleman, D. C. 1956). The impact of the Industrial revolution concerns technological, socioeconomic and cultural features. Among the impacted technological features belongs also maintenance (Calvert, P. 1970).

### 1.1. Industry 1.0 and Reactive Maintenance

The first industrial revolution is an idea everybody knows as the main industrial revolution and is now taught at schools. It could be compared with the Neolithic Revolution which caused the society to shift from hunters and collectors to agriculture. It was a giant leap towards today's form of society. It started in England and was characterized as a change in the use of energy sources, forms of transport, information transfer and industrialization of production. It was also a crucial period of social, cultural and political changes in individual countries. The symbol of the first industrial revolution was a steam engine invented by James Watt in 1765 (Spear, B. 2008).

Since the start of the first industrial revolution, there has been a massive increase in labor productivity through the introduction of new ways in agriculture – the introduction of machinery and alternate field cultivation. All this led to the industrialization of the countries – the transformation from the agrarian country into a industrial one (Volek, T., & Novotna, M. 2017).

The revolution hugely affected society (Maciej Dzikuć, Janusz Adamczyk, Arkadiusz Piwowar 2017). The population of England has doubled while the mortality reduced, thanks to the improvement of hygiene, less hunger and improved medical care. Urbanization took place, large urban industrial centres with factories with high chimneys, new roads, railroads, bridges emerged and attracted people from rural areas. At that point in time, Manchester, Liverpool, Birmingham and Glasgow became the most advanced cities.

The most characteristic maintenance form during this period was the breakdown maintenance (also known as “reactive maintenance” or “corrective maintenance”). Break down maintenance is a form of maintenance, where repairs are done only after the breakdown. The aim of it is to put the broken machine back to the regular operational conditions.

The breakdown maintenance has its pros and cons. As pros we could list the fact, that it takes less time and money to do nothing than it does to do something, there is no initial cost, and it requires far less planning. On the other hand, the unpredictable nature of breakdowns leads to shorter asset life, safety issues, inefficient use of time, and can get a lot more expensive. (Christer, A. H., & Whitelaw, J. 1983).

The strategy of "letting the device work until it goes wrong" was the first that humankind naturally applied. On first sight it is the easiest and natural way of maintenance. Machines were rather simple and therefore there was no need for a specialist that would know how to repair it, at the beginning. Even nowadays, reactive maintenance is the most widely used maintenance activity (over 55% according to Bloch and Geitner). Never the less with the increasing complexity of machines, especially after the beginning of the first industrial revolution a new trend started appearing among the industries. (Bloch, H. P., & Geitner, F. K. 1997).

### 1.2. Industry 2.0 and Preventive Maintenance

The Second Industrial Revolution began about one hundred years later in 1870 and was connected to electrification and assembly lines. It resulted in mass production based on division work and electrically powered lines. In 1870 the first large scale assembly line was built up in a slaughterhouse in Cincinnati. Later, the assembly line idea was adopted by Henry Ford for his Model T automobiles factories. Another extraordinary innovation was the light bulb by T. A. Edison in 1879 and transformer, designed by Nicole Tesla (Jonnes, J. 2004).

Work organization was improved by Frederick Taylor, who came up with ways to boost factory profitability up by to a hundred times. His principles of work organization aimed for precise determination of the work process and performance-based wage (Nof, S. Y., Wilhelm, W. E., & Warnecke, H. J. 1997). Other inventions of the second industrial revolution were e.g. dynamite, phone, aircraft and many others. All these inventions and principles are being used till today.

Due to these new inventions, the way of life has changed. Science was suddenly connected to the technology, research results from natural sciences were being applied in industry. This led to the creation of new materials that replaced the natural – man–made fertilizes, dyes and therapeutic substances.  After the invention of the combustion engine, diesel started to be applied and electric motors were produced. Electricity was used to illuminate cities, run trams and to enable communication via telephone.

Sometimes the Second Industrial Revolution is known as the Revolution of the Technical Science. Darwin came with his evolutionary theory. In the material sciences, Newton came up with mechanical origination of nature. Discovery of the microscope made possible to find what one doesn't see with his bare eye. X-rays and radioactivity were found. Max Planck presented quantum theory and Albert Einstein his theory of relativity. Sigmund Freud investigated human personality through the hypothesis of unconsciousness, so-called psychoanalysis (Henderson, W. O. 2013).

The supply of goods began to grow, on the contrary demand fell. Free capital was created, which was necessary for export. States have exported capital to their industrial-building colonies, which on the contrary delivered cheap labour. With this, a struggle began between the Great Powers and the Territorial Colonies, which led to the start of the First World War (Dewey, D. 1959).

With the peak of the second industrial revolution the machines became more complex and production grew rapidly. Breakdowns caused higher and higher expenses and therefore first attempts of preventive maintenance (also known as planned maintenance) appeared. Even Henry Ford recommended preventive maintenance in his FORD MANUAL from 1919. (Ford Motor Company 1919) "Frequently inspect the running gear. See that no unnecessary play exists in either front or rear wheels and that all bolts and nuts are tight. Make a practice of taking care of every repair or adjustment as soon as its necessity is discovered. This attention requires but little time and may avoid delay or possible accident on the road."

Preventive maintenance can be characterized as: Action based on a specific timetable that identifies, avoids or mitigates the decay of component or framework state so in order to maintain or expand its life by means of controlled corruption to an adequate level (Butler, K. L. 1996). There are two essential kinds of preventive maintenance - maintenance in periodic cycles or maintenance dependent on equipment status. Maintenance in periodic cycles anyway seems to be unreasonably costly for about 92% of machine parts. Device-based (proactive) maintenance exchanges parts and interferes with the machine only when deviations begin to show up in its procedure, making it more efficient (Kurkin, O., Kleinová, J., Čechura, T., & Broum, T. 2011).

Preventive maintenance brings less likelihood of breakdowns, fewer downtimes and might be more savvy than reactive. Then again, it builds costs with customary substitutions, there is a requirement for extra parts and planned downtime increases (Poór, P., Šimon, M., & Karková, M. 2016).

As indicated by Bloch and Geitner, (Bloch, H. P., and Geitner, F. K. 1997) by simply spending the necessary resources to carry out the maintenance activities of the designer, the facility's life is extended, and its reliability is increased. In addition to increase reliability, savings are also being made. This savings can be up to 12% on average to 18% of saved costs.

Depending on the current state of maintenance, device reliability and downtimes, many companies dependent on purely reactive maintenance can save much more than 18% by starting the right preventive maintenance program. Although preventive maintenance is not an optimal machine maintenance program, it has several advantages over purely reactive maintenance (Straka et al. 2016). Performing preventive maintenance on the device as designed by the designer will prolong the life of the device. This means saving money. Preventive maintenance (lubrication, filter replacement, etc.) will usually result in higher device efficiency, which will be reflected in savings. Even if we do not prevent the catastrophic scenario, the number of disorders will go down.

### 1.3. Industry 3.0 and Proactive maintenance

With the Third Industrial Revolution, most people have personal experience, whether good or bad. The length of this industrial revolution is the shortest this time, only about a forty-year period from about the end of the Second World War to the late 1980s. The beginning of this revolution dates back to not much of a milestone in human history, the drop of atomic bombs on the Japanese cities of Hiroshima and Nagasaki in August 1945. The use of technology controlled thermonuclear reaction of atomic bombs started a third industrial revolution. Its termination dates back to the early 1990s, by the time of the decentralized merger of thousands, then by millions of people through the Internet using personal computers and mobile phones (Metodická příručka "Člověk a stroj").

The beginning of the Third Industrial Revolution goes back to 1969, when the first programmable logic controller, e.g. PLC, was made (Jensen, M. C. 1993). It is a small industrial computer, a control unit, for real-time automation of processes. For PLC it is characteristic that the program is performed in so-called cycles. The key characteristics of this period were automation, the boom in electronics and information technology. These features were subsequently introduced into production in order to drive machines and automate them (Rosenberg, N. 1963).

The third industrial revolution is most often associated with automation, electronics and the expansion of information technology. Just as the transition from coal and steam to electricity was relatively continuous and logical, the transition from mechanics to automation was more a result of natural evolution than a real revolution.

The Third Industrial Revolution is often referred to as a period of scientific and technological revolution and, as has already been said, the arrival of computers. Its content is the cross-penetration of scientific and technological development into the production process, which leads to innovations up to fourth level (M. Toms 1981) fundamental changes in technology and technology on the basis of new discoveries in automation and cybernetics, energy, research into the atomic and molecular structure of matter in biology, genetics, cosmology (Martin Fassmann 2016) Reactions to fundamental transformations in the productive forces are adequate shifts in marketing and management processes (Peter F. Drucker 1985) especially in the onset of automated control systems not only of production lines, but also of transport and complex machinery and equipment. All this is dramatically reflected in the labour market.

Productive Maintenance (also referred to as PM) started appearing after the second world war. This new approach towards maintenance combines Corrective Maintenance and Preventive Maintenance with a data-driven, analytical approach, and is performed to increase the broadly economic efficiency of production (Aziz, Iftekhar, Sazedul Karim, and M. Hossain 2012). It strives to identify and address the problems that can lead to breakdowns in the first place, such as improper machinery lubrication, misalignment, contamination and other suboptimal conditions.

Productive maintenance brings longer lifespan of equipment, decreased downtime (both planned and unplanned), lower spare parts inventory and is more cost-effective. The big challenge, however is, that it requires, unlike previous maintenance approaches, a large shift of paradigms and organizational changes. Maintenance is integrated into the company strategy and is recognized as improvement worthy. Data starts being collected and, in some cases, real-time monitoring is enabled. Statistical models are applied and new discoveries concerning fatigue are made.

Perhaps the two best-known methods which developed during the period of the third industrial revolution were Total Productive Maintenance (TPM) with origin in Japan and Reliability Centered Maintenance (RCM) with origin in the USA. Let's take a brief look at them.

### 1.3.1. Reliability Centered Maintenance

Reliability-based maintenance is "a procedure to establish maintenance requirements for any physical asset in its operational context." (Moubray, J. 1997) It guarantees that systems keep on doing what their user requires in their present working setting. The reliability-oriented maintenance strategy addresses fundamental issues not secured by other maintenance programs. Perceives that not all machinery in a company has a similar significance that the construction and operation of the equipment are different, and that is more likely to cause a fault for various reasons. It also considers the way that the company does not have a boundless budget and personal assets and should be optimized.

The RCM technique screens the activity of every component and characterizes the outcomes of its failures. The RCM makes a structure of outcomes in decreasing order of severity of individual disorders, to do this, it uses a FMEA analysis. While deciding the outcomes, every one of the activities of the elements of the monitored device must be determined (Šimon, M., & Broum, T. 2018). If the level of risk due to failure cannot be can't be decreased by the chosen maintenance mode, then it is necessary to reconstruct the element. Thus, RCM also deals with the assessment of possible causes of device failures (eg. neglected maintenance, wear, etc.).

RCM prompts an expansion in cost-effectiveness, reliability, machine uptime, and a greater comprehension of the dimension of risk. It is characterized by the specialized standard SAE JA1011 (JA1011, S. A. E. 1999).

### 1.3.2. Total Productive Maintenance (TPM)

TPM was presented by Seichi Nakajima, who during the 60s studied Preventive Maintenance systems in the US and Europe. He worked out his knowledge in a complex system that was given a working name Total Productive Maintenance. In 1971, he brought the framework into Japanese organizations (Nakajima, S. 1988).

- T as Total - participation of all organization employees.
- P as Productive - efficiency of maintenance and production equipment, constantly improving.
- M as Maintenance - of machinery and equipment in good technical condition.

Total productive maintenance is equipped to connecting all staff in the workshop to exercises that minimize downtime, limit accidents and occurrences. The TPM is about beating the conventional division of people into workers working on the machine, and "workers who fix it". It depends on the way that the worker who deals with the machine gets the opportunity to initially catch the anomalies in his work and sources of future equipment failure. Motto of TPM is: "Protect your machine and take care of it with your own hands." (Legat, V. 2013) Thus, the greatest diagnostic and maintenance activities in TPM are exchanged from the traditional support straightforwardly to the production workers - the production sections (Petr Baron et al.). It usually starts with enhancing the work environment, cleaning machines and checking their condition (Broum, T., & Kleinová, J. 2018) Besides, the operator figures out how to "understand his machine", to figure out how to carry on as his "very own". Notwithstanding maintainers and operators, different professions, for example, technical preparation of production are involved in TPM (Ahmed, S., Hj. Hassan, M., & Taha, Z. 2005).

The move in thinking must be done mainly in optimizing (Orosz T., 2017) the "man-machine" relationship, where the operator performs not just the job, but additionally the job of active maintenance co-worker (Poór, P., Kamaryt, T., & Simon, M. 2015). It is significant that the whole framework is secured by dynamic management support for TPM implementation projects and the collaboration of technical staff throughout the organization (Waeyenbergh, G., & Pintelon, L. 2002). It is an enterprise-wide system k that incorporates preventive maintenance. The TPM depends on the help of item maintenance by little gathering activities (production groups). The TPM is applicable wherever where production (operation, equipment) is based on technological service (operators). TPM objectives are (Islam, S. 2011):

- zero downtime,
- zero errors,
- zero disturbances (Baluch, N. H., Abdullah, C. S., & Mohtar, S. 2012).

The premise of the TPM theory is, from one viewpoint, to expand the effectiveness of machinery and to decrease maintenance expenses and misfortunes because of downtimes, then again, based on great correspondence between the operator and the maintainer.

### 1.4. Industry 4.0 and Predictive Maintenance

Curiously, the first three industrial revolutions happened first and, afterwards they have been named. With the Fourth industrial revolution, it's not the same case. The revolution is still happening, and we already realized it (Hořánek, V. Basl J.: 2018). The changes are happening faster due to the interconnection of the world.

The following period of the Industrial Revolution is the development of the Internet. The Internet has basically existed since 1962, yet in 1987 the expression "Web" was made. Its commercialization occurred just in the year 1994. From that point on, it very well may be said that the Internet enters into all regions of human action. Since the late 1990s there has been a gigantic increment in Internet clients, which presently comes to around billions (Smith, B. L. 2001).

### 1.5. Predictive Maintenance

Predictive maintenance (nowadays also called PdM 4.0) is now the highest form of maintenance as of today. It is a method of preventing asset failure by analyzing production data to identify patterns and predict issues before they happen (Kmec, Valenčík, Gombár, Karková, Vagaská 2016). The key to this is a combination of big data analytics and artificial intelligence in order to create insights and detect patterns and anomalies. It includes continuous real-time monitoring of assets in combination with external data (e.g. environmental data, usage, etc.) with alerts based on predictive techniques such as regression analysis, for at least one important asset (Orosz et al., 2015).

The basic components of predictive maintenance in the context of industry 4.0 are: Sensors, Cyber-Physical Systems, Internet of Things, Big Data, Cloud computing, Networks and Artificial Intelligence, Mobile networks, WIFI. Also, the job titles involved in Maintenance changed. Instead of experienced craftsmen and drained inspectors, businesses must employ reliability engineers and data scientists (Mihalov, Pietrikova, Balaz, Mados, Adam 2018). The data used for predictive maintenance are growing in count, as the companies collect data about the condition of assets, usage of assets, maintenance history, data from other assets that are relative to the work of monitored machine, both from inside and outside of the company (e.g. assets of our suppliers), environmental data and others.

Some of the key critical success factors for the predictive maintenance implementation are budget, culture, technological solutions, availability of data, data security and others. A well-functioning predictive maintenance program can mean savings of 8% to 12%. Depending on the equipment and material conditions, it is possible to save 30% to 40% (US Department of energy 2010).

The following savings resulting from the use of predictive maintenance are:
• Return on investment: 10 times
• Reduction of maintenance costs: 25% to 30%
• Troubleshooting: 70% to 75%
• Reduction of downtime: 35% to 45%
• Increased production: 20% to 25% (Bloch, H. P., and Geitner, F. K. 1997).
But the start of predictive maintenance is not cheap. A large part of the equipment requires a cost of more than € 30,000. Staff training also requires additional funding.

Table 1. Correlation of Industrial Revolution and Maintenance (Coleman, Damodaran, Chandramouli, Deuel, 2017)

| **Industry revolution** | **Industry 1.0** | **Industry 2.0** | **Industry 3.0** | **Industry 4.0** |
|---|---|---|---|---|
| Characteristics of the industrial revolution | Mechanization, steam power, weaving loom | Mass production, assembly lines, electrical energy | Automation, computers, electronics | Cyber Physical Systems, IoT, networks, cloud, BDA |
| **Type of maintenance** | **Reactive maintenance** | **Planned maintenance** | **Productive maintenance** | **Predictive maintenance** |
| Inspection | Visual inspection | Instrumental inspection | Sensor monitoring | Predictive analysis |
| OEE | <50% | 50-75% | 75-90% | >90% |
| Maintenance team reinforcement | Trained craftsmen | Inspectors | Reliability engineers | Data scientists |

## 3. Conclusion

Based on the presented facts, we can clearly see a correlation between the industrial revolutions and machinery maintenance. From the earliest ones (corrective maintenance), during times of first industrial revolution and introduction of steam machines, through planned maintenance during the era of Ford automobile cars. Here, Henry Ford recommended preventive maintenance in his FORD MANUAL to his customers. With the 3rd generation of industrial revolution automation and computerization are the main phenomena. This has resulted in the use of productive maintenance –Total Productive Maintenance or Reliability Centered Maintenance, with the great help of beginning automation and computerization. Concept of relatively new Industry 4.0 fully used the advantage of cyber systems, cloud storage or Internet of Things resulting in the most advanced form of maintenance "Predictive Maintenance". As seen in the table at the end of the article, there is also an inverse correlation between the level of Maintenance and its "factor" OEE. The more developed maintenance, the higher the Overall Effectivity of Equipment is. This "model" is only the beginning of our research and we will continue to develop this topic of Predictive Maintenance and its place in Industry 4.0.

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## Biographies

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