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Master's Thesis

A Smart Maintenance Management Transformation path: the Pirelli Case Study

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Abstract

The objective of this project is to demonstrate the improvements achievable in the maintenance management of the Pirelli plant through the application of practices and tools belonging to the Industry 4.0 family. The thesis primarily unfolds by exploring the theory related to Maintenance Management. It begins by presenting its foundational pillars and then delves into the theory of maintenance, including a mathematical perspective, introducing the Reliability Theory, and addressing the main maintenance standards that companies must adhere to (ISO 9001 and IATF 16949). The exploration continues by introducing four types of maintenance: Corrective, Preventive, Condition-based, and Predictive. The thesis then covers key strategies in the Maintenance world, including Reliability-Centered Maintenance, starting with its fundamental questions and concluding with its benefits; Total Productive Maintenance, beginning with the 8 pillars of TPM, its benefits, and the OEE indicator; and Smart Maintenance, emphasizing the domains of Industry 4.0 and Sensors. The theoretical part concludes with the analysis of some Maintenance KPIs (Availability, Reliability, and Maintainability Indicators) and presents the functions, implementation, and benefits of CMMS. The subsequent section focuses on the internship conducted at the Pirelli plant in Bollate (MI). It introduces the current situation (AS-IS), the actual project with the results achieved, and concludes with the future initiatives planned by the Maintenance Department. The results obtained affirm the path that European, especially Italian, companies must undertake. Through the adoption of preventive maintenance plans, it has been possible to reduce the MTTR and the downtime of the machinery in question, providing more available time for production.

Contents

List of Figures **vii**

List of Tables **ix**

1 Introduction **11**

2 Maintenance Management **13**

2.1 The Pillars of Maintenance Management 15

2.2 The Reliability Theory 16

2.3 Quality Assessment in the Production Systems: ISO 9000 20

2.3.1 The IATF 16949 Certification 21

3 Typologies of Maintenance **23**

3.1 Corrective Maintenance 24

3.1.1 FMEA and FMECA Methods 25

3.2 Proactive Maintenance 27

3.2.1 Preventive Maintenance 28

3.2.2 Condition-based Maintenance 30

3.2.3 Predictive Maintenance 34

4 Maintenance Strategies **45**

4.1 Reliability-Centered Maintenance 45

4.1.1 The Seven Fundamental Questions of RCM 46

4.1.2 The benefits of Reliability-Centered Maintenance 52

4.2 Total Productive Maintenance 53

4.2.1 The 8 Pillars of Total Productive Maintenance 53

4.2.2 TMP Benefits 55

4.2.3 Steps through implementation of TPM 56

4.2.4 Overall Equipment Effectiveness 58

4.3 Smart Maintenance 59

4.3.1 Industry 4.0 61

4.3.2 Sensors 72

5 Maintenance KPIs **79**

5.1 Availability Indicators 81

5.2 Reliability Indicators . . . 81
5.3 Maintainability Indicators . . . 82

6 The CMMS **85**
6.1 Functions . . . 87
6.2 Implementation of CMMS . . . 88
6.3 Root Causes and Solutions for Poor Implementation of CMMS . . . 89
6.4 Benefits of CMMS . . . 92

7 Case Study: the Pirelli plant **95**
7.1 The AS-IS Situations . . . 95
7.2 The Project and its Results . . . 98
7.3 The Future Initiatives . . . 100

8 Conclusions **103**

Bibliography **108**

List of Figures

2.1 Exemplification of the Subsystems organized in a Manufacturing System [2]. . 13

3.1 The Maintenance Typologies tree 24
3.2 An implementation process of Condition-based Maintenance 34
3.3 Potential failure diagram presenting inspection intervals and predictive maintenance 35
3.4 Predictive Maintenance Workflow 37
3.5 Subdivision of Predictive Maintenance Data-driven Solutions 38
3.6 Prognostics and Health Management 42

4.1 The Bathtub Curve 46
4.2 1st Question of RCM 47
4.3 2nd Question of RCM 48
4.4 3rd Question of RCM 49
4.5 4th Question of RCM 50
4.6 5th Question of RCM 50
4.7 6th Question of RCM 51
4.8 7th Question of RCM 51
4.9 TPM Pillars 54
4.10 TPM implementation steps 56
4.11 The ”Six Big Losses” of OEE 58
4.12 The four dimensions underlying dimensions of Smart Maintenance 61
4.13 The core technologies of Industry 4.0 65
4.14 The RAMI 4.0 Architecture 68
4.15 The role of operators in the evolution of Industry 72

5.1 The three families of Maintenance Indicators 80

6.1 CMMS evolution during last decades 86
6.2 Levels in the implementation of CMMS 88

7.1 The organizational structure of the Pirelli plant 96
7.2 The interventions typologies in the SF machine in April 97
7.3 Example of the BoMs of the SF Machine 98
7.4 Example of the Preventive Plan 99

7.5 The interventions typologies in the SF machine in September 99
7.6 The interventions typologies in the SF machine in October 100
7.7 The value of MTTR during the months 100
7.8 The project contribution into the Smart Maintenance Management path . . . 101

List of Tables

2.1 Advantages and Disadvantages of Repairable and Non-repairable components 18

Chapter 1

Introduction

In the world of manufacturing, the concept of ”Smart” is becoming increasingly prevalent. The term can be attributed to the intelligent use of cutting-edge technologies. The methodology adopted in this thesis involves dividing the body of the text into two parts: the first part includes a substantial amount of theoretical research, utilizing both paper and online materials, to provide a literature base for the project. The second part pertains to the internship carried out at the Pirelli plant, under the supervision of the head of the Industrial Systems Department.

The internship-related topic aims primarily at improving the performance of the Maintenance Department at the Pirelli plant, ensuring a certain level of reliability at a relatively contained cost. The Smart Maintenance Department project on the horizon still has approximately four years of work and investments to update maintenance plans to a predictive level and ultimately implement a Smart Inventory. However, given the limited time frame of the experience at Pirelli, this master's thesis focuses on a preliminary phase compared to the previously presented steps. The goal is to create a corporate Bill of Materials, to be used as an ”enabler,” for example, in identifying critical components used to implement preventive maintenance plans. Once these steps are completed, it is then necessary to assess the impact in numerical terms: on the total interventions performed on the machinery and its MTTR (Mean Time to Repair), extrapolated through company software such as CMMS.

The use of cutting-edge technologies becomes particularly important for European and Italian manufacturing entities, as it allows them to maintain a competitive advantage compared to international competitors. This is crucial because these entities may not have leverage in other competitive advantages that characterize the main competitors in the rest of the world. In particular, actors from Eastern Europe, North America, and Southeast Asia can rely on much lower labor costs, much lower raw material costs, or both simultaneously. For this reason, manufacturing companies must aim for the improvement of their processes, and in this sense, maintenance should be seen not only as a cost but as a guarantee for the correct functioning of the remaining business processes.

The results obtained in this project are encouraging from this perspective. The improvement in the MTTR of the examined machinery, as well as the reduction in the total number of interventions on the machinery, ensuring more available time for production, are objective improvements in maintenance management that optimize available resources. These encouraging results represent only the tip of the iceberg of the entire project, which will lead the Maintenance Department to version 4.0.

Chapter 2

Maintenance Management

Nowadays productive systems, also known as manufacturing systems, form the backbone of modern industrial and economic activities. These systems encompass a wide range of processes, technologies, and methodologies aimed at efficiently transforming raw materials, labor, and capital into finished products or services that meet the needs and demands of consumers. In the contemporary landscape, production systems are not just about making products efficiently; they are a strategic driver of competitive advantage. Companies that can adapt to the contemporary evolving trends and challenges are more likely to succeed in the global marketplace. They comprise several interconnected subsystems that work together to transform inputs into outputs efficiently [1], which, as in Figure 2.1, collaborate to ensure the smooth operation of the overall production process.

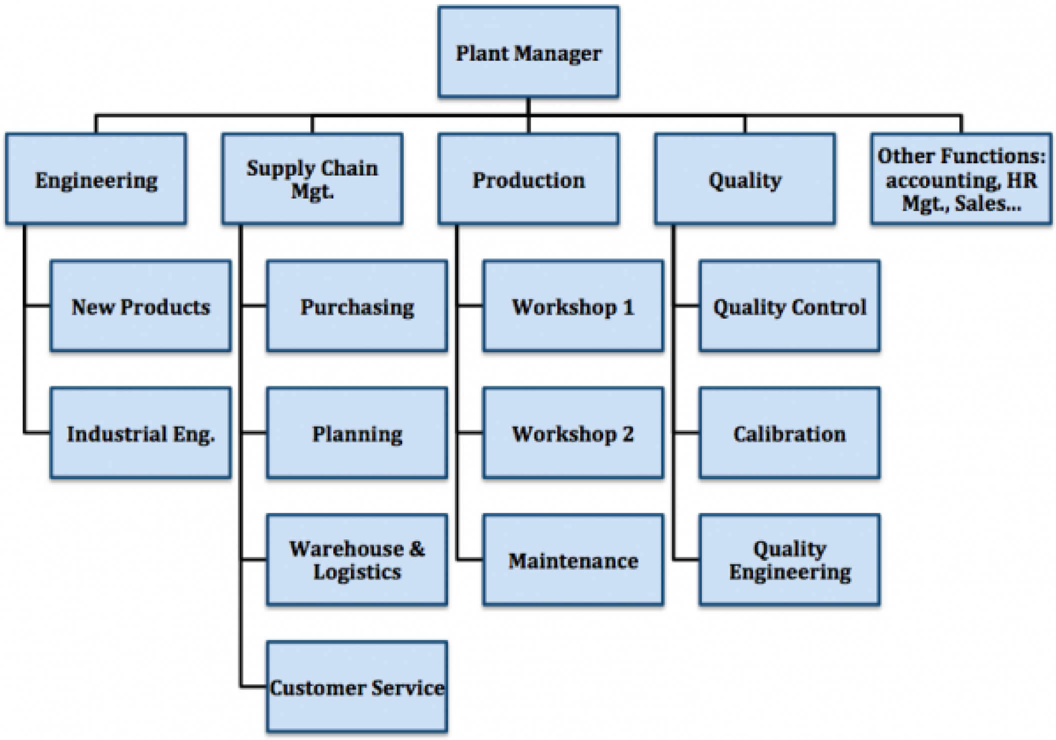


Figure 2.1: Exemplification of the Subsystems organized in a Manufacturing System [2].

Considering the Western manufacturing situation characterized by a higher cost of the workforce compared to the new emerging industrial competitors, it is vital to find solutions to maintain competitiveness. One of the most relevant and helpful aspects could be the exploitation of all the capabilities and potential of the Maintenance Management.

Maintenance management can be defined as: *"All the activities of the management that determine the maintenance objectives or priorities (defined as targets assigned and accepted by the management and the maintenance department), strategies (defined as a management method in order to achieve maintenance purposes), and several improving methods including economical aspects in the organizations"*. [3]

The purposes of Maintenance Management are fundamental within the organization. Essentially they have to ensure the reliability and the availability of the physical assets while minimizing costs. The several duties of the department can be grouped into five macro-responsibilities [4], enlisted below.

1. Maintenance of Existing Equipment
Maintenance of existing equipment is an ongoing process that requires careful planning, execution, and continuous improvement. By proactively addressing maintenance needs, organizations can maximize equipment reliability, extend asset lifespans, and minimize disruptions to operations.

2. Equipment Inspections and Service
Equipment inspection and service are critical components of maintenance management that focus on activities that involve regular checks, assessments, and maintenance tasks to identify and address issues before they lead to equipment failures or safety hazards. The manufacturer will determine the type of (corrective or proactive) action needed and the time interval of intervention.

3. Equipment Installation
Equipment installation pertains to the process of setting up and integrating new machinery, equipment, or systems into an existing facility or production environment. This installation process is a critical step in asset management and maintenance because it lays the foundation for the equipment's performance and reliability throughout its operational life. Proper installation ensures that the equipment operates safely, efficiently, and in accordance with manufacturer specifications and industry standards. It varies from case to case according to the size of the installation and the available workforce, if a massive installation is needed and there is not enough workforce it could be necessary to outsource contractors.

4. Maintenance Store-keeping
Maintenance store-keeping, also known as maintenance store management or spare parts management, refers to the systematic process of acquiring, storing, organizing, and distributing spare parts, materials, and supplies necessary to support maintenance activities within

an organization. Proper maintenance store-keeping is essential to ensure that maintenance tasks can be performed efficiently and that the required components are readily available when needed. In this responsibility, many tasks are involved:

- Record the spare parts for each piece
- Set the inventory level for each part
- Reorder the spare parts to be replaced
- Keep the inventory level as low as possible

5. Craft Administration
It concerns the management and coordination of the manpower who are responsible for performing maintenance tasks on physical assets such as machinery, equipment, facilities, and infrastructure. These craftsmen typically possess specialized skills and expertise in areas like electrical work, plumbing, HVAC (heating, ventilation, and air conditioning), welding, and mechanical repairs. In order to assess the size of the workforce it is necessary to look at the backlog, obviously adjusting it considering the necessity. Craft administration has also the responsibility to handle the tools for the crafts.

2.1 The Pillars of Maintenance Management

Maintenance Management is based on three pillars, which are fundamental in modern organizations to achieve a structured framework able to provide a successful business continuity collaborating with all the departments. They can be developed as:

1. The **Maintenance Engineering Strategies Pillar** comprehends a collection of vital techniques, which can be grouped as follows:

- Reliability-Centered Maintenance (RCM) assumes a pivotal role in both strategic and tactical contexts, aiding in the formulation of maintenance plans that guarantee the desired equipment reliability. (In contrast, Total Productive Maintenance (TPM) primarily concentrates on organizational endeavors at the operational level, aiming to enhance overall equipment effectiveness.)
- Quantitative tools capable of optimizing Maintenance Management policies.
- Tactical, activity-oriented stochastic tools are integrated to model equipment failures, enabling the utilization of additional quantitative methodologies.

This pillar encompasses various operations research and management science techniques that prioritize the optimization of maintenance resource management.

2. The **IT Pillar** would enable supervisors, strategists, and production as well as maintenance personnel to gain access to comprehensive equipment information. This, in turn, would convert this data into actionable insights, facilitating more informed decision-making across the three tiers of business operations.

This system would be developed as the organization's Computerized Maintenance Management System (CMMS). CMMS would facilitate the effective monitoring and control of assets, resulting particularly impactful in situations with a large number of items to maintain and in complex industrial facilities, such as modern production plants. When appropriately configured and integrated with the company's Enterprise Resource Planning (ERP) system, CMMS can evolve into a crucial tool, benefiting all levels of maintenance activities within the company.

An advanced information processing capability, decision support tools, and communication systems, coupled with the synergy between maintenance processes and expert systems, collectively constitute a distributed artificial intelligence environment commonly referred to as e-maintenance. E-maintenance, an evolution of Predictive Maintenance, has the potential to facilitate remote maintenance decision-making, requiring not only information exchange between customers and suppliers but also cooperation and negotiation grounded in the sharing of diverse, complementary, and sometimes conflicting knowledge.

The IT component also encompasses condition monitoring technologies, which, by continually focusing on potential tactical and operational decisions and actions, significantly enhance Maintenance Management efficiency.

3. Last, the **Organizational Pillar** constitutes a cornerstone, particularly when human involvement is a factor in the multitude of decisions pertaining to maintenance and task execution. The methods within this pillar possess the potential to influence all of the maintenance activities. Within this sphere, we encompass all approaches aimed at cultivating competence in relationships.

The purpose of these methods is to guarantee the optimal alignment between diverse activity levels, and various functions within the organization, fostering respect and consideration for both internal and external stakeholders, and promoting seamless interactions in inter-organizational contexts.

2.2 The Reliability Theory

Every final product derived from a modern production system has a useful life and a way in which it can fail. Therefore the term reliability has become widespread and implicit in our way of thinking and living. In addition to the term reliability we can associate the term risk, the reliability theory in fact offers managers of production systems the opportunity to calculate the possibility of risk.

This theory is at the service of the productivity and quality of the previously mentioned systems, not only of their safety.

Linked to this theory are the metrics and concepts presented below, which are fundamental for the theoretical and practical use of Maintenance.

TTF – Time to Failure

Time to Failure, often abbreviated as TTF, is a reliability metric used to quantify the amount of time it takes for a system, component, or device to develop a fault, malfunction, or cease functioning properly.
TTF is particularly important in reliability engineering and maintenance management, as it helps in assessing and predicting the lifespan or operational duration of equipment, products, or systems. In practical terms, Time to Failure can be defined as the elapsed time between the start of operation or deployment of an item and the occurrence of a failure event or the point at which the item can no longer perform its intended function within specified performance criteria.

This random variable can be indicated with f(t) or the probability density function of the τ value (TTF), which represents the precise measurement of the speed with which a generic component breaks at an instant of time t.

From it the following relations:

$$P(\tau \leq T) = \int_{-\infty}^{T} f(x)dx \tag{2.1}$$

$$\int_{-\infty}^{\infty} f(x)dx = 1 \tag{2.2}$$

The 2.1 represents the probability that the random variable takes on a value no greater than T, while the 2.2 represents the normalization condition.

Difference between repairable and non-repairable components

In order to develop the topic further it is necessary to present repairable and non-repairable components, which differ in how they respond to failures.
First, repairable components (ex. vehicles, industrial machinery,..) are those that cannot be economically restored to their original operational state after failure. They typically result in gradual degradation or failure, which can be intermittent or repetitive, thus is possible to trace the root causes. The goal is to minimize the downtime that they experience during maintenance activities and restore the component to service.
Second, non-repairable components (ex. medical equipment) are those that cannot be economically restored to their original operational state after failure. They have a finite lifespan, and their failures a generally irreversible. They are replaced rather than repaired.
The choice between repairable and non-repairable components depends on factors like cost-effectiveness, system design, maintenance capabilities, and the specific application or industry requirements. Both types have their advantages and disadvantages which are compared below:

Table 2.1: Advantages and Disadvantages of Repairable and Non-repairable components

	Repairable components	**Non-Repairable components**
Cost	Lower initial cost Expensive long-term maintenance	Cheaper to replace Higher ongoing replacement cost
Reliability	High reliability	Specific lifespan
Downtime	Reparation downtime	Replacement downtime
Environmental impact	Extended use, more sustainable	More waste

Such distinction is necessary to present the main reliability parameters that describe and model the failure behavior of non-repairable components.

Reliability function

The reliability function, often denoted as R(t), is used to quantify the probability that a component will operate without failure or malfunction for a specified period of time (t).
It is a fundamental function for assessing and improving the reliability and performance of complex systems, contributing to enhanced safety, reduced downtime, and increased customer satisfaction in various industries.
For example it allows to determine the system availability, to program maintenance activities, and to set the service level of the machinery.
Based on 2.1 and 2.2 follow the reliability function:

$$R(t) = \int_{T}^{\infty} f(x)dx = 1 \tag{2.3}$$

Failure Rate

The failure rate, often denoted as λ(t) or μ(t), represents the instantaneous rate at which failures occur in a system or component at a specific moment in time. It is also known as the hazard rate. Mathematically, the failure rate is defined as:

$$\lambda(t) \cdot \Delta t = P(t \leq t + \Delta t) \tag{2.4}$$

Where:
λ(t) is the failure rate at time t;
T represents the time to failure of a component or system;
P(t≤T<t+Δt) is the probability that the component fails within a small time interval Δt starting at time t.
The failure rate, in other terms, provides information about how the probability of failure

changes as time progresses, thus it helps in assessing the reliability and longevity of components. A high failure rate indicates that the component or system is more likely to fail soon, while a low failure rate suggests greater reliability and a lower likelihood of failure in the near future.
In addition, two hypotheses are underlying the reliability model considered:

1. The components can only assume two states: functioning and non-functioning;
2. The transition from one state to another is instantaneous.

Using a practical approach we can derive a further expression, based on the following hypotheses:

1. N number of components put into operation at instant t=0;
2. N_G(t) number of failed components in a generic instant of time t;
3. N_S(t) number of components functioning in t

Indeed the probability of failure represents the probability that a component breaks in a time interval equal to T and it can be denoted as:

$$F(t) = \frac{N_{(G)}(t)}{N} = \frac{N - N_{(S)}(t)}{N} = 1 - R(t) \tag{2.5}$$

MTTF – Mean Time to Failure

Mean Time to Failure (MTTF) is a reliability metric that represents the average amount of time a component is expected to operate reliably before experiencing its first failure. MTTF provides an estimate of the average lifespan of a group of identical components or systems operating under similar conditions. It is often expressed in hours, days, months, or other time units, depending on the context. It can be expressed as:

$$MTTR = \int_0^\infty t \cdot f(t)dt = -\int_0^\infty t \cdot \frac{dR(t)}{dt} \cdot dt \tag{2.6}$$

When some components exhibit a constant failure rate, it means that they have a constant risk of failing over time. In such cases, the MTTF can be calculated as the reciprocal of the failure rate (MTTF=1/λ), where λ is the failure rate. Its use is most appropriate when analyzing systems with constant or relatively low failure rates. For systems with time-dependent failure rates, other metrics like Mean Time Between Failures (MTBF) or survival analysis may be more appropriate. Following the presentation of the reliability parameters for non-repairable components, the time comes to introduce them to repairable components.

MTTR – Mean Time to Repair

The Mean Time To Repair (MTTR) is a metric used to measure the average amount of time it takes to repair a system or component after it has experienced a failure or outage. To present it is necessary to enlist some hypotheses:

1. the repair of the component is allowed;
2. the transition from a state to another is instantaneous;
3. the component is "as good as new".

In addition, we introduce other parameters:

- τ_r repair time random variable;
- g(t) unconditional adjustment rate

thus we obtain the following expression:

$$MTTR = \int_0^\infty x \cdot g(x)dx \tag{2.7}$$

A low MTTR indicates that a component can be repaired quickly, which is often desirable for minimizing downtime and maintaining operational efficiency.

2.3 Quality Assessment in the Production Systems: ISO 9000

Moving on to a more practical domain, modern industries must comply with a series of regulations and standards to guarantee an acceptable level for the consumer. The auditing process in production systems is a systematic and organized examination and evaluation of various aspects of the system's operations, processes, and data to ensure compliance with established standards, security requirements, and best practices.

Auditing helps organizations maintain the integrity, reliability, and security of their production environments.[5]

This process is based on the International Organization for Standardization (ISO), a global alliance comprising 130 national standardization bodies, that strives to advance standardization and foster related endeavors on a global scale. Its primary goal is to facilitate the worldwide exchange of goods and services while promoting collaboration across various domains, including intellectual, scientific, technological, and economic pursuits. Notably, the ISO 9000 series of standards has gained widespread recognition as a foundational benchmark for quality management systems within companies. In essence, these standards define best practices for quality management without prescribing specific methods for companies to achieve them.[6]

The standard ISO 9000 is used to certify the operations of companies, which aims [7] to:

- Improve the company's image
- Improve the productivity
- Growth in bargaining power
- Product quality assurance

During the years the standards were updated, from ISO 9000 family developed several typologies or sub-standards, as:

- **ISO 9001: Quality Management Systems - Requirements**
  ISO 9001 is the most well-known and widely used standard in the ISO 9000 family. It provides specific requirements that organizations must meet to establish an effective quality management system.
- **ISO 9004: Quality Management - Quality of an Organization - Guidance to Achieve Sustainable Success**
  ISO 9004 offers guidance for organizations on achieving sustained success through effective quality management. It provides principles and practices for enhancing overall organizational performance, customer satisfaction, and continuous improvement.

2.3.1 The IATF 16949 Certification

IATF 16949 is a globally recognized quality management system (QMS) standard specifically designed for the automotive industry [8]. It is based on ISO 9001 but includes additional requirements that are specific to automotive manufacturing and supply chain processes. Actually, it has been developed by a group of automotive manufacturers and their respective trade associations that developed and maintained the IATF 16949 standard.
The purpose of IATF 16949 certification is to ensure that automotive companies meet strict quality and safety standards in the design, development, production, installation, and servicing of automotive-related products.

In addition to ISO 9001 requirements, IATF 16949 includes specific automotive industry requirements [9], such as:

- Product safety considerations;
- Specific requirements for product design and development;
- Traceability and product recalls;
- Requirements for monitoring and controlling production and service processes;

- Supplier quality management

IATF 16949 can bring several advantages to automotive companies, including:

- Improved product and process quality;
- Enhanced customer satisfaction;
- Increased competitiveness in the automotive industry;
- Better risk management;
- Improved supply chain performance;
- Global recognition and access to automotive markets.

Chapter 3

Typologies of Maintenance

The automation of industrial facilities represents an approach largely adopted by modern production systems which are involved in an extremely dynamic and modelled environment on top-level standards. These facilities usually require massive amounts of investments and consequently, they need to be exploited at maximum. This is only allowed when a certain level of business continuity is guaranteed, according to the maintenance policies adopted and adequately considering the costs of plant downtime and repairs.

There remains significant confusion in the field of maintenance management when it comes to the terminology used to describe various types of maintenance, particularly in the industrial sector. This confusion extends not only to Production and Operations Management but also to related literature, acting as a barrier to establishing standardized terminology. It arises due to several factors:

- Misinterpretation or improper dissemination of the adopted names for maintenance types. Often, these names are not adequately explained or understood and may be rooted in local or specific practices.
- The introduction of neologisms, often originating from translations of foreign languages.
- The creation of distinct names for maintenance types by different authors, each influenced by specific contexts.

While the terminology may differ, the underlying concepts must be well comprehended. A rational perspective is necessary to ensure a clear understanding of these concepts, assisting maintenance decision-makers in selecting the most suitable type for a given piece of equipment, installation, or system. Consequently, these definitions have a significant impact on the economic aspects of industrial organizations.

The evolution of maintenance concepts aligns with the expectations of the productive sector and the techniques employed to address emerging maintenance requirements. Presently, there are various philosophies, such as maintaining reliable and available systems, planned shutdowns for maintenance, and the use of sensors and parameter monitoring to determine the optimal timing for maintenance to prevent failures. Additional concepts, like projects aimed at ensuring reliability and maintainability, reinforce proactive maintenance actions,

even during the design phase.
To make informed decisions, it is essential to effectively apply maintenance techniques. Therefore, a thorough understanding of the most suitable maintenance types is imperative. Even when combining two or more maintenance types, it is crucial to have a clear conceptual understanding. Knowing the boundaries between different applications is essential for efficient industrial maintenance planning and management. In reality, both literature and scientific articles continually introduce new terminology and assignments for maintenance types, often with minor variations compared to traditional concepts. However, these variations result in different names, leading to confusion and obscured concepts [10]. Through the scientific literature, it is crucial to find the strategy more suitable for each production system and in this chapter, we will present the most common ones. In this project, the most relevant and important typologies that have been selected by the author are summarized in Figure 3.1.

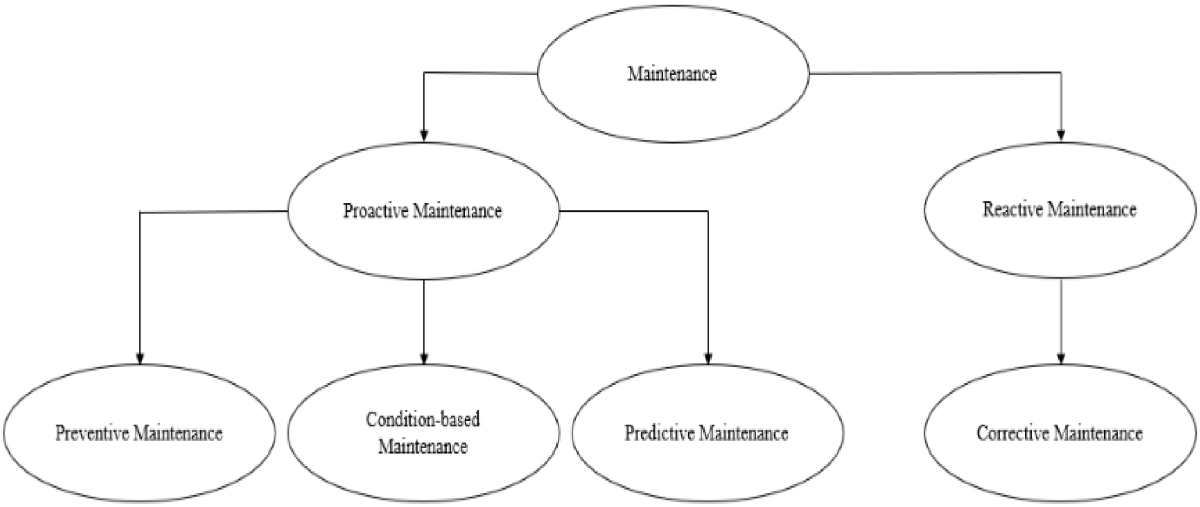


Figure 3.1: The Maintenance Typologies tree

3.1 Corrective Maintenance

In the first part of this chapter will be developed the reactive ramification, which is represented by the so-called Corrective Maintenance.
Corrective Maintenance, also known as breakdown maintenance or run-to-failure maintenance, is a maintenance strategy where equipment and assets are operated until they fail, at which point maintenance activities are initiated to repair or restore them to working condition. The approach of "allowing the device to operate until it malfunctions" was associated with the era leading up to 1945 and, to some extent, persisted into the 1950s. During this time, challenges related to data gathering and analysis, along with strong market demand, influenced this strategy. Maintenance efforts primarily focused on addressing issues like damaged components, as well as basic tasks such as cleaning and lubrication [11]. Over 55% of maintenance and operational activities within an average facility are reactive. The advan-

tages of reactive maintenance can be likened to a double-edged sword. When equipment is brand new, we can anticipate minimal failures, and if the maintenance approach is entirely reactive, we avoid expending labor and capital resources until an issue arises. During this period, maintenance costs effectively amount to zero, resulting in apparent savings.

However capital outlays tend to be higher because we anticipate equipment failures, which, in turn, reduce the equipment's lifespan and necessitate more frequent replacements. Additionally, there are added costs associated with the cascading effects of primary device failures leading to secondary device failures-costs that do not happen in a more proactive maintenance scenario.

When failures do occur, labor costs for repairs are likely to be higher than usual, as the failures often necessitate more extensive and time-consuming repairs than if maintenance had been carried out preemptively. For crucial equipment that must be swiftly restored to operational status, additional expenses are incurred. Lastly, the anticipation of equipment failure often compels organizations to stockpile significant quantities of spare parts, incurring further costs.

In analyzing the corrective approach it is important to identify the key pillars [12] of this methodology, which are enlisted below:

- **Rapid Response**: one of the primary goals of corrective maintenance is to minimize downtime and production losses. Rapid response involves having a well-defined process in place to report, prioritize, and address equipment failures promptly. This may include establishing a 24/7 maintenance team or having clear escalation procedures.
- **Root Cause Analysis**: it's crucial to understand why a failure occurred in the first place. Root cause analysis (RCA) involves investigating the underlying reasons for equipment breakdowns. Identifying the root cause enables organizations to take corrective actions to prevent similar failures in the future;
- **Resource Allocation**: includes having the right tools, spare parts, and skilled personnel available to address equipment failures promptly. Effective resource management can minimize downtime and repair costs.
- **Documentation and Record-Keeping**: is essential for tracking maintenance history, identifying recurring issues, and analyzing trends. Detailed records can help organizations make informed decisions about when to perform preventive maintenance or replace equipment.
- **Feedback Loop**: establish an involvement in maintenance personnel, operators, and other stakeholders. Encourage open communication to share insights about equipment performance and failures, which can lead to better decision-making and process improvements.

3.1.1 FMEA and FMECA Methods

Corrective maintenance focuses on the identification of cause failures from the failure phenomenon. The failure phenomenon contains one or more symptom failures. To fulfill the corrective maintenance, various models [13] have been built to represent the failure mechanisms, the two most adopted are presented below.

Failure Modes and Effects Analysis (FMEA) and Failure Modes, Effects, and Criticality Analysis (FMECA) are methodologies crafted to preemptively uncover potential failure modes in a product or process, thereby evaluating associated risks. Ideally, FMEAs are conducted during the product design or process development phases, although their application to existing products or processes can still yield valuable insights.

Through failure mode analysis, the FMEA team assesses the impact of each potential failure and identifies pivotal single failure points. Furthermore, they may assign a ranking to each failure based on both the criticality of its effects and the likelihood of its occurrence. This method then evolves in the FMECA which is the result of a two-step process:

1. Failure Mode and Effect Analysis (FMEA)
2. Criticality Analysis (CA)

In the FMEA method, risk assessment involves the multiplication of three key components, resulting in a Risk Priority Number (RPN):

- Severity (S): Severity is rated on a scale of 1 to 10, with 10 indicating the highest severity
- Occurrence (O): Occurrence is rated on a scale of 1 to 10, with 10 signifying the highest likelihood of occurrence
- Detection (D): Detection is rated on a scale of 1 to 10, with 10 representing the highest level of detection capability.

The RPN lowest value is 1, while the maximum RPN corresponds to 1000. This index can be used to identify and classify potential failure, giving the maintenance workforce priority.

The FMECA adds also a quantitative tool, the Critical Analysis, which defines the reliability of each item, at a given operating time, identifies the portion of the item's unreliability that can be attributed to each potential failure mode, and rates the probability of loss (or severity) that will result from each failure mode that may occur. Thus it can be calculated criticality for each potential failure mode by obtaining the product of the three factors:

$$\text{Mode Criticality} = \text{Item Unreliability} \times \text{Mode Ratio of Unreliability} \times \text{Probability of Loss} \tag{3.1}$$

Calculate the criticality for each component by obtaining the sum of the criticalities for each failure mode that has been identified for the item (equation 3.2).

$$\text{Component Criticality} = \sum \text{Mode Criticalities} \tag{3.2}$$

The two methodologies produce a series of advantages [14] which can be summarized as:

- Enhances product and process designs, leading to increased reliability, enhanced quality, and augmented safety measures.
- Elevates customer satisfaction, resulting in cost savings, reduced development time and re-design expenses, lower warranty-related expenditures, and minimization of waste and non-value added operations (aligned with Lean Management principles).
- Contributes to the development of control plans, testing requirements, optimal maintenance strategies, reliability growth analysis, and related activities.

The cost-related benefits linked to FMEA primarily stem from the ability to proactively identify failure modes within the process, when addressing them is less costly. Furthermore, financial gains arise from the design improvements facilitated by FMEA, as well as reduced warranty costs and increased sales due to improved customer satisfaction.

3.2 Proactive Maintenance

In this section it will be developed the other branch of the Maintenance typologies: Proactive Maintenance. Nowadays it is regarded as the most innovative and profitable approach, which is represented by three peculiar typologies: Preventive Maintenance, Condition-Based Maintenance, and Predictive Maintenance.
Proactive maintenance is a typology of maintenance where damage is avoided through activities that monitor equipment failures and make minor repairs to restore equipment to its proper condition[15]. These activities reduce the chance of unexpected equipment failures.
The implementation of a proactive typologies into a manufacturing process is performed through four steps [16]:

1. **Planning.** The objective of the planning stage is to fulfill all prerequisites for executing proactive maintenance operations. This stage can be broken down into the following tasks:

    - establishing critical issues
    - identifying root causes and signs
    - creating a pricing model
    - conducting a feasibility assessment

2. **Implementation.** The aim of the implementation phase is to put all prearranged actions into practice to enable proactive maintenance. Upon completing this phase, all specified indicators are continually observed, and proactive services are carried out as necessary. The implementation phase comprises the following tasks:

  - developing monitoring apparatus
  - creating analytical software
  - installing monitoring equipment

3. **Monitoring.** During this phase, active proactive maintenance processes are under constant scrutiny. For instance, the rate of machine failures is closely monitored to gauge the effectiveness of the measures that have been put in place.

4. **Analysing.** In the end, the collected data is analyzed, and a determination regarding the continuation of proactive maintenance is reached. The machine's failure and damage rates must be thoroughly examined. If the predetermined rate is exceeded, adjustments must be made to address new issues, along with their respective indicators, or new indicators for existing problems in the context of machine monitoring.

Starting from this process all the three sub-typologies develop their peculiarities.

3.2.1 Preventive Maintenance

The first typology presented is Preventive Maintenance, which nowadays is the most adopted and developed one considering the manufacturing environment. Preventive maintenance is a systematic approach to maintenance management that involves regularly scheduled inspections, servicing, and repairs of equipment, machinery, or assets to prevent potential issues, breakdowns, or failures. This maintenance strategy typically follows a planned schedule or checklist to ensure that maintenance tasks are performed at specified intervals, based on manufacturer recommendations, industry best practices, or historical performance data. In this classification, assets undergo a consistent maintenance regimen, which includes scheduled activities like examinations, cleansing, lubrication, fine-tuning, and calibration. These tasks are carried out regularly, and their frequency remains relatively stable, aligning with the anticipated lifespan of the components under maintenance. As a result, this approach demands a consistent allocation of both labor and materials. [17]

The pillars of Preventive Maintenance

Further are developed the pillars crucial for the adoption of preventive maintenance [18]. They collectively provide a solid foundation for a robust preventive maintenance program. In fact, when they are well-developed and integrated, they contribute to the overall improvement of the organization's performance. In the list, it is added also the suggestion to achieve such pillar effectively.

The **Experience** is a valuable asset in preventive maintenance. It involves the knowledge and insights gained from past maintenance activities and equipment performance. Experienced maintenance personnel can identify patterns, anticipate issues, and make informed decisions. It can be achieved by:

- Maintaining a skilled and experienced maintenance team.
- Encouraging knowledge sharing and mentorship within the team.

- Reviewing past maintenance records and feedback to learn from experience.
- Using historical data to refine maintenance strategies and improve decision-making.

Coordination and collaboration with other departments within an organization are crucial for the success of preventive maintenance. The smooth functioning of different departments, such as production, procurement, and finance, can have a significant impact on the maintenance program. It can be achieved by:

- Establishing clear communication channels with other departments.
- Collaborating with production to schedule maintenance during planned downtime.
- Working with procurement to ensure the timely availability of spare parts.
- Aligning financial planning with maintenance budgeting to ensure adequate resources.

Scheduling is a foundational aspect of preventive maintenance. It involves planning and organizing maintenance activities, ensuring that they are carried out at the right time, and minimizing disruption to production. It can be achieved by:

- Developing a maintenance calendar with predefined maintenance intervals.
- Utilizing computerized maintenance management systems (CMMS) to automate scheduling and task assignment.
- Considering equipment criticality and operational needs when setting maintenance schedules.
- Prioritizing tasks to maximize efficiency and minimize downtime.

Identifying critical components within your equipment and machinery allows you to prioritize maintenance efforts. Focusing on these components ensures that the most important elements receive the attention they require. It can be achieved by:

- Conducting risk assessments to determine critical components based on their impact on operations.
- Assigning a risk level or criticality rating to each component.
- Implementing condition monitoring and predictive maintenance for critical components.
- Allocating additional resources and attention to critical components, such as more frequent inspections and spare parts inventory.

Advantages of Preventive Maintenance

The advantages of preventive maintenance [19], as outlined subsequently, are crucial for any organization, particularly those that rely on machinery and equipment for their operations.

Reduces Breakdown and Downtime
Preventive maintenance helps identify and address potential issues before they lead to equipment breakdowns. This proactive approach reduces unexpected downtime, which can be costly in terms of lost productivity and revenue.

Less Odd-Time Repair and Reduced Overtime of Crews
By scheduling maintenance during planned downtime, you can avoid odd-time repairs that often require overtime pay for maintenance crews. This not only saves on labor costs but also improves the work-life balance of employees.

Greater Safety of Workers
Regular maintenance checks and repairs can uncover safety hazards and potential risks associated with equipment. Addressing these issues promptly ensures a safer working environment, reducing the likelihood of accidents and injuries.

Lower Maintenance and Repair Costs
Preventive maintenance is generally less expensive than reactive maintenance or emergency repairs. Addressing issues early can prevent them from escalating into major problems that require costly repairs or replacements.

Less Stand-By Equipment and Spare Parts
With well-executed preventive maintenance, the need for backup or stand-by equipment is reduced because the primary equipment is kept in good working condition. Additionally, you can better manage your spare parts inventory, reducing storage costs.

Better Product Quality and Fewer Reworks and Scraps
Consistently maintained equipment operates at peak efficiency, resulting in a more reliable manufacturing process. This can lead to higher product quality, fewer defects, and reduced waste due to rework or scrapped products.

Increases Plant Life
Preventive maintenance ensures that equipment is used optimally and lasts longer. This is especially important for expensive capital assets. Extending the lifespan of your equipment can save you significant capital expenditures in the long run.

3.2.2 Condition-based Maintenance

In the course of examining the proactive typologies, it incurs Condition-Based Maintenance, which signifies a progression from traditional preventive maintenance. This concept first surfaced in the late 1940s within the operations of the Rio Grande Railway Company, with the primary aim of identifying coolant and fuel leaks within a diesel engine's lubricating oil. They achieved remarkable economic success by minimizing engine failures through maintenance actions triggered by any detection of glycol or fuel in the engine oil. The U.S. military, impressed by the effectiveness of enhancing physical asset availability, adopted these methods and also pioneered new ones. Over the 1950s, 1960s, and early 1970s, Condition-Based Maintenance gained traction, leading to the emergence of a dynamic industry encompassing training, products, and services dedicated to CBM technology [20].

In order to define this typology can be helpful to the publication of Butcher [21] which defines

Condition-based Maintenance as “a set of maintenance actions based on real-time or near-real time assessment of equipment condition which is obtained from embedded sensors and/or external tests and measurements are taken by portable equipment.”

The implementation of Condition-based Maintenance

To implement a profitable condition-based approach to a maintenance department it’s useful to follow the steps highlighted by Rastegari [22], which can be presented as:

A. Concept Study. To institute condition-based maintenance, the company must undertake a comprehensive analysis in the early stages of implementation to assess the feasibility of CBM. These aspects fall into three categories: organizational, financial, and technical considerations.

In terms of organizational factors, it is essential to evaluate the organization’s culture and competencies to determine the feasibility of implementing CBM and the suitability of specific technologies. A SWOT analysis and maintenance audits can provide valuable insights into whether adopting CBM is a sound decision. Assessing if CBM can enhance the work environment, reduce unscheduled corrective actions, and boost OEE by minimizing unexpected breakdowns is crucial. Safety concerns, both in terms of environmental safety and personnel safety, must also be considered. The organization must decide whether to develop in-house expertise in condition monitoring or engage external contractors for condition monitoring services. Choosing the right condition-monitoring supplier involves evaluating factors such as the types of technologies offered, ease of access, and long-term support.

In the financial aspect, it is challenging to calculate precise financial figures at this stage. However, it is possible to estimate a list of requirements to assess the cost-effectiveness of implementing CBM. This includes estimating potential investment costs, such as the cost of purchasing condition monitoring equipment and installation, as well as the cost of maintenance and production losses due to breakdowns. These estimates help pre-assess implementation costs and the potential benefits of CBM.

Conducting a criticality analysis and undertaking a maintenance audit prove highly advantageous in evaluating the technical viability of introducing Condition-Based Maintenance. The key considerations involve assessing the familiarity with the failure’s criticality and whether there exist suitable indicators for gauging this criticality. If these aspects align favorably, the next step is to determine the availability of appropriate tools or methodologies for detecting these failures. Furthermore, a crucial element is the capacity to foresee impending failures and implement preventative measures to avert substantial damages while also scheduling maintenance activities in a manner that minimizes disruption to production. This approach ultimately leads to cost savings in maintenance and reduced production losses.

B. Define Responsibilities. To ensure a structured implementation, responsibilities must be defined early in the process. Initially, discussions regarding implementation, development requirements, and the selection of equipment, techniques, and technologies can involve a group of managers and engineers from the maintenance and production departments. As the decision-making phase progresses, responsibilities may shift to smaller groups based on the selected equipment areas and implementation process needs.

C. Selection of Assets. Selecting the right machines or components is a crucial aspect of making the implementation manageable and cost-effective. A criticality analysis of production assets, based on existing data and experience, can guide the selection of objects for implementation. Tools and methods like Reliability-Cantered Maintenance or Failure Modes and Effects Analysis (FMEA) can offer more precision in this stage. The choice between tools and methods depends on the organization's familiarity with these approaches. These tools help structure information and assess asset criticality by identifying assets and their functional specifications and performing failure analysis at various levels.

D. Selection of Techniques and Technologies. After determining which assets to monitor and identifying their potential failure modes, the selection of parameters or failure indicators is essential. These parameters guide the choice of suitable techniques. Factors to consider include the availability of technology for monitoring parameters, the required competence and manpower, and the cost-effectiveness of applying the techniques. Condition-monitoring techniques can range from human senses to measuring systems, and they can be applied online or offline. The choice of technology should align with organizational, financial, and technical considerations, focusing on cost-effective solutions that provide the necessary knowledge and expertise within the organization.

E. Installation. In online technologies, condition-monitoring tools can be installed by condition-monitoring supplier companies. However, certain factors must be decided during the decision-making phase. These factors include sensor positioning, cable routing, unit placement, and database management. Careful selection and placement of measuring points are vital to ensure valuable future analysis. Machine specifications are used to determine the location of bearings and their construction. Decisions on sensor positioning (horizontal, vertical, or axial) and the method of attaching sensors to equipment are important. Cable routing should be designed to minimize cable length, avoid interference with equipment operations, and ensure safety. The unit collecting data should be easily accessible and powered adequately, with connections to the company's Ethernet to transfer data to a database. A computer or laptop can serve as the database, and software products are provided by supplier companies for data collection and analysis.

F. Data Handling. In online condition-monitoring systems, connecting to the company's IT server to collect data in the database can be a challenging part of implementation. Some supplier companies may have limited access to the IT server, necessitating collaborative solutions. Alternatively, 3G modems can be used to collect data in the supplier company's database, although this may limit real-time access to data. Online systems offer the advantage of integrating with the company's maintenance management system, allowing for the creation of maintenance work orders based on CBM system data.

G. Training. Different technologies require distinct training and skills. Personnel responsible for CBM should receive training to become familiar with the condition-monitoring system and data analysis. Advanced skills, such as frequency analysis, may be necessary for more detailed data interpretation. Training can be provided by supplier companies to enhance competence in using their condition-monitoring applications and products.

H. Measurement and Setting Baseline Data. Depending on the technology type, measurements can be conducted either in real-time (online) or manually (offline) using handheld instruments. Measuring data early helps establish baseline data as a reference for equipment conditions. Warning limits can be set based on this baseline data, allowing online technologies to trigger warnings when values deviate from the norm.

I. Data Analysis. The level of data analysis depends on the chosen technology. Some monitoring systems provide direct condition analysis, while others may require more in-depth analysis, such as frequency analysis. In the case of failure detection, various factors, including the time to fault occurrence and subjective factors like unusual noises, can be analyzed. Data analysis should lead to more accurate warning limits and enable maintenance planning at the most appropriate times.

J. Evaluation. The evaluation phase is crucial for determining if the implementation has been carried out effectively and can deliver the desired outcomes. Factors to consider include sensor type, sensor positioning, and success factors like cost and the interval between detecting a failure and fault. It is important to assess whether sensors are sensitive enough for their applications and if adjustments to positioning or additional sensors are needed. The cost-effectiveness of the implementation can be evaluated by comparing initial cost estimates with actual costs. Determining the optimal interval between failure detection and fault occurrence is also a key success factor.

K. Improvement. The results from the evaluation phase serve as a basis for improvement. Technical improvements may involve changing sensor types, sensor positioning, and the number of sensors. The organization should establish a routine monitoring process, specifying what and when to measure while setting more accurate warning limits based on continuous measurements. Overall, continuous improvement is essential for refining the implementation of CBM, increasing competence in data analysis, and ensuring ongoing management support.

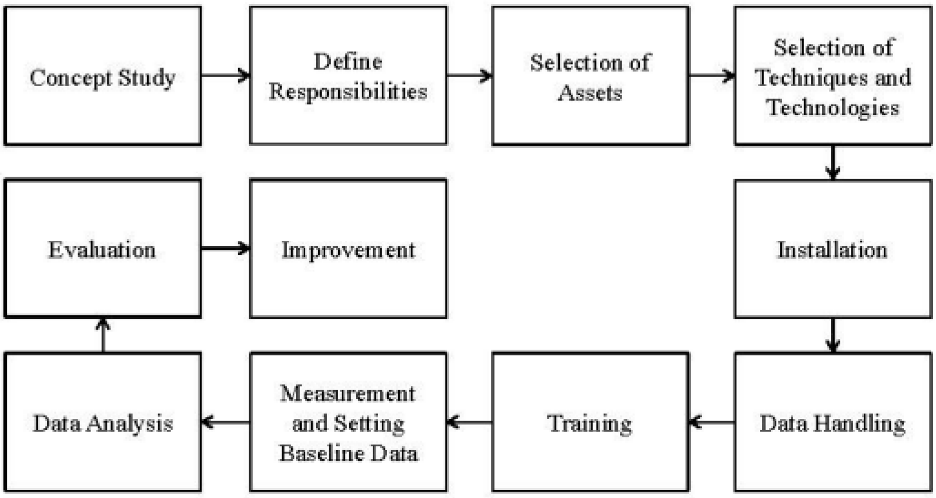


Figure 3.2: An implementation process of Condition-based Maintenance

Benefits of Condition-based Maintenance

In analyzing the positive aspects that the implementation of Condition-based Maintenance brings to the organization, four, in particular, arise from the performance of the maintenance management [23] [24]. Enlisted below:

1. The early detection of potential failures through the application of trend analysis methods and/or qualitative inspections. Subsequent preventive maintenance measures can be implemented based on this information, leading to a decrease in system/component failure rates and an increase in equipment reliability.
2. An accurate awareness of the current system condition and the ability to predict failures with precision. This enables timely shutdowns for repair work that aligns with the manufacturing schedule, ultimately enhancing system availability and minimizing unpredictable breakdowns.
3. The diagnostic capability that not only anticipates component failures but also identifies the root causes of these failures. Employing diagnostic procedures allows for system adjustments to eliminate recognized failure patterns, thereby enhancing the inherent design reliability. Moreover, it facilitates the rapid identification of impending failures, resulting in improved system maintainability, streamlined workload planning, and efficient spare part management.
4. Adaptability when integrated with an adaptive control system, condition-based monitoring can extend the operational lifespan of plant and equipment by mitigating the impact of dynamic failure mechanisms within the system. This, in turn, reduces the likelihood of premature failures and contributes to enhanced system reliability.

3.2.3 Predictive Maintenance

Predictive Maintenance stands as the most advanced form of maintenance available today. It operates as a technique aimed at averting asset failures by scrutinizing production data to recognize trends and forecast potential issues before they arise. The linchpin of this approach lies in amalgamating big data analytics and artificial intelligence to generate insights and identify patterns and irregularities. This method involves a continuous, real-time monitoring system for assets in conjunction with external data, incorporating predictive alerts such as regression analysis, particularly for at least one crucial asset and it can result in an amount of cost savings going from 10% to 30% [25] [26]. The fundamental components of predictive maintenance within the context of Industry 4.0 encompass a suite of elements: sensors, cyber-physical systems, the Internet of Things, big data analysis, cloud computing, networks, artificial intelligence, mobile networks, and Wi-Fi. Furthermore, the roles involved in Maintenance have evolved. Instead of seasoned craftsmen and fatigued inspectors, enterprises now require reliability engineers and data scientists. The data used for predictive maintenance is steadily expanding, with companies amassing information regarding asset conditions, usage, maintenance history, data from related assets relevant to monitored machinery, both internal and external to the company, environmental data, and even more.

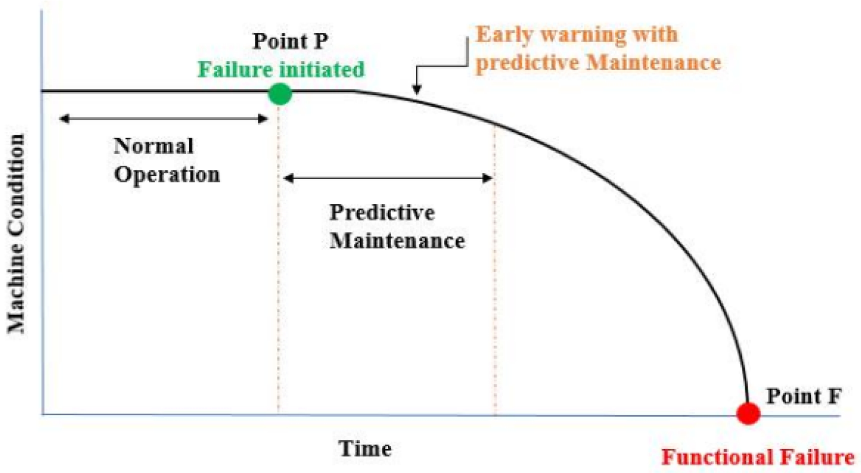


Figure 3.3: Potential failure diagram presenting inspection intervals and predictive maintenance

Predictive Maintenance Workflow

In order to implement a profitable predictive approach it is necessary to follow a series of steps that are fundamental to succeed [27]. As exemplified by Figure it is based on machine Learning and Data Science, which articulate as follows:

Step 1: Understanding the project's needs The initial phase involves grasping the business components and issues inherent in the project, along with the limitations that need to be overcome. During this stage, a comprehensive understanding of the system, relevant equipment, and their operations is imperative for addressing the project's challenges. This encompasses defining the measurable physical quantities, selecting appropriate sensors, and arranging their installation if necessary. Additionally, it's essential to outline a catalog of potential failure types that might be encountered.

Step 2: Data collection, preparation, and understanding
During the Data collection, the equipment's sensors have the capability to gather data and transmit it to the database. This stage focuses on precisely identifying which data to analyze, assessing the quality of available data, and establishing its contextual significance. While during the Data Preparation sub-phase involves tasks such as selecting pertinent data, amalgamating data sets, cleansing and managing missing or erroneous values, identifying and addressing outliers, employing feature engineering to generate new data from existing sources, structuring data suitably, and eliminating unnecessary columns. Data preparation, though time-intensive, typically consumes 70–90% of the entire project duration, being the most crucial stage in the project life-cycle.

Step 3: Data modeling Data modeling is the core of data analysis, taking the prepared data from the prior step (data preparation) as input and delivering the necessary output. It entails selecting the appropriate algorithm based on the type of problem, whether it's classification, regression, or clustering. Testing and fine-tuning various chosen algorithms collectively form a model.

Step 4: Evaluation and Deployment This step comprises two phases:

- **Step 4.1 Model Evaluation** The model needs thorough evaluation, measuring accuracy and relevance, while ensuring a balance between performance and generalization. This means the model must not be biased and should be applicable across different scenarios.

- **Step 4.2 Model Deployment** The evaluated model is finally deployed in the required format and channel, concluding the data-related stage of the predictive maintenance life-cycle. Each phase detailed in the life-cycle should be meticulously executed, as a misstep in one stage can compromise the subsequent steps, potentially wasting all effort. For instance, improper data collection results in lost information, hindering the creation of a representative model.

Step 5: Decision-making In general, the decision-making process aids operators in resolving issues by determining the optimal course of action. A systematic approach assists in making informed decisions with positive impacts on short- and long-term objectives.

- Step 5.1 Problem Identification Recognizing the issue is the first step in making informed decisions. This phase involves developing potential intervention scenarios, including estimated repair times and associated costs.

- Step 5.2 Action Following the identification of potential scenarios, an alternative or a combination is chosen to minimize costs and delays, considering factors like repair days, manpower availability, and spare parts.

Figure 3.4: Predictive Maintenance Workflow

Data-driven solutions to detect failures

The emergence of Machine Learning has prompted the Predictive Maintenance community to employ diverse data-centric approaches in foreseeing potential malfunctions [28]. Machine Learning-based methods offer the advantage of leveraging historical data to discern patterns that pinpoint prevailing defects and extrapolate these patterns to new data. Despite distinct goals, both fault diagnosis and fault prognosis rely on fundamental models to derive predictions. These foundational models can be categorized into classical machine learning and artificial neural network strategies. In contrast to the former, the latter acquires representations in tandem with the classifier, eliminating the necessity for manually curated feature vectors. Below is a partial enumeration of models utilized in Predictive Maintenance.

Traditional machine learning methods

Decision Trees. These non-parametric techniques learn decision rules from input data, starting from a root node and navigating various paths until a leaf node, representing a prediction, is reached. Decision trees have found frequent application in fault diagnosis across multiple scenarios, including refrigerant flow systems, anti-friction bearings, and grid-connected photovoltaic systems. Their swift training pace and rapid predictive capability enable their deployment in real-time problem-solving. The simplicity and diversity of decision tree-based methods facilitate their effective usage in fault prognosis scenarios such as wind turbine engines, lithium-ion batteries, and mechanical equipment.

k-Nearest Neighbours. This algorithm, requiring no training, computes the distance between an arriving instance and all elements in the training set to identify the k closest instances. Classification is based on majority voting among these k instances. Various proposals employing kNN have been introduced for fault diagnosis, often in combination with hierarchical methods or distance and similarity density. Its applications span faults in photovoltaic systems and petrochemical rotating systems.

Support Vector Machine. A supervised method aiming to find a hyperplane optimally separating two classes by maximizing the margin between Support Vectors. SVMs have exhibited positive outcomes across diverse problems, including wind turbines, bearings, chillers, and rotating machinery. Similar to SVM, Support Vector Regression (SVR) addresses regression problems by seeking the hyperplane encompassing the most points, utilized in various Remaining Useful Life (RUL) problems, such as with lithium-ion batteries and bearings.

Artificial neural network-based methods:

Artificial Neural Networks. Comprising input layers, hidden layers, and an output layer, ANNs process each layer's output through a usually nonlinear activation function. Due to their adaptability, these architectures serve in fault detection, identification, and prognosis applications.

Auto-Encoder. AEs aim to learn high-level data representations, compressing input representations through an Encoder and decompressing via a Decoder. Previous research has utilized AEs to extract crucial features for fault diagnosis and prognosis problems. These representations can complement other models or be directly employed in anomaly detection.

Convolutional Neural Networks. CNNs identify local patterns via convolutional operations, amalgamating them to create global representations. While initially effective in structured data like images, CNNs are adaptable to 1D inputs and heterogeneous data. Some studies use CNNs to predict asset degradation over time by analyzing time frames.

Recurrent Neural Networks. Recognizing that machines fail over time, RNNs analyze sequential data, where the current output frames influence future representations alongside subsequent frames. This technique has been applied to various fault diagnosis scenarios, including rotating machinery, chemical processes, and rolling bearings. For prognosis, LSTMs, a variant of RNNs, have been employed in voltage prediction and aircraft engine problems.

Deep Belief Network. DBN employs multiple layers to extract high-level features from data, utilizing Restricted Boltzmann Machines in each layer. DBN is applied in various fault diagnosis problems such as axial pistons and rolling bearings. In fault prognosis, it has been employed in wind turbines and lithium-ion batteries.

Generative Adversarial Networks. Comprising a generator and a discriminator trained in parallel, GANs address the class imbalance by generating data resembling the distribution of the training set. In PdM, GANs serve to generate data akin to the operational set and detect anomalies.

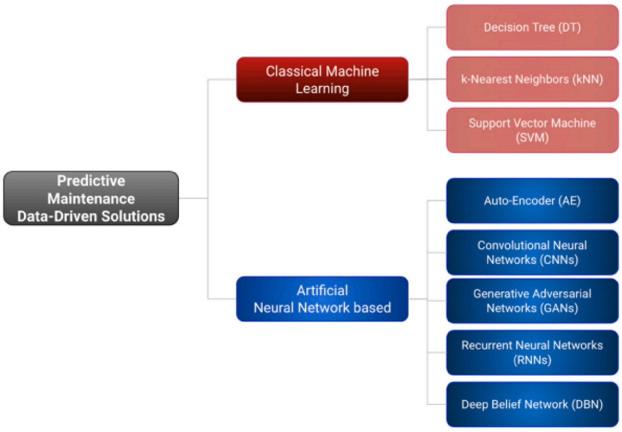


Figure 3.5: Subdivision of Predictive Maintenance Data-driven Solutions

Limits of Predictive Maintenance

As stated by Achouch [29] despite the accessibility of predictive maintenance algorithms, companies seeking advantages from Industry 4.0 must weigh the potential benefits of predictive maintenance against the financial outlay required for procuring essential instruments, software, and expertise. This drawback becomes more critical during the initial phases of predictive maintenance development, especially when there's a lack of actual data concerning normal and abnormal equipment behavior. It's also significant in the case of new systems where operational experience is absent. Such circumstances might lead companies to make heavier investments in predictive maintenance solutions. In various challenges outlined in the literature, four distinct groups are noticeable and warrant consideration: financial and organizational constraints, limitations in data sources, constraints in machine repair activities, and limitations in the deployment of industrial predictive maintenance models.

1. **Financial and Organizational Constraints.** Profit-driven enterprises inevitably weigh the anticipated costs of any fresh investment. Predictive maintenance endeavors, like sensor installation, data retrieval, model preparation and maintenance, and upkeep activities, incur costs for the companies that introduce such predictive maintenance methods. These costs can fluctuate based on multiple factors, such as equipment type and complexity, accompanying sensors, expenses for consultation, installation, and knowledge acquisition, as well as the availability of required expertise either internally or externally. One method to evaluate the potential benefits of introducing predictive maintenance is to create a projected return on investment (ROI). This projection should factor in the value of predictive maintenance outcomes, the payback period, and the associated costs. The financial rationale for implementing predictive maintenance also hinges on the scale and nature of the business where it is introduced.

2. **Limitations in Data Sources.** Having relevant data available is crucial for establishing a production process management model. However, companies seldom possess all the necessary data at the outset of introducing production process management. Post-utilization of existing data, there's a need to identify gaps and address them. Moreover, the quality of existing data sources might not meet the required standards. If only a portion of the data lacks satisfactory quality, this can be rectified during data preparation, provided that there's an adequate number of data points for statistical significance and for successfully isolating critical machine points during defect detection. Challenges arise for companies employing predictive maintenance methods when confidence in the data is compromised, particularly if sensors, controllers, or other data sources provide inaccurate or erroneous measurements. This can lead to erroneous predictions, missed maintenance needs, or false alarms. Another challenge with sensor technology is that currently, sensors typically function offline, without contributing to real-time data. Additionally, sensors are susceptible to downtime, instrument degradation, noise, or outright sensor failure. Consequently, cleaning the data before applying predictive maintenance algorithms becomes crucial to forecast actual scenarios accurately and avoid distorting results.

3. **Constraints in Machine Repair Activities.** Although predicting the remaining lifespan of a component facilitates determining maintenance schedules, actual maintenance faces hurdles related to reliance on human intervention and the absence of self-maintenance. Maintenance effectiveness hinges on the quality of human management and skills, given that current machine components rely on human operators for control and maintenance. Industrial machines primarily operate reactively and follow instructions without questioning them. However, human task planning is based on both data and experience, which the machine could potentially access. Therefore, an intelligent component might propose or initiate actions independently that benefit system health, asset throughput, or product quality. Advancing toward asset autonomy relies on asset awareness and autonomous maintenance. A self-aware asset can assess its conditions based on existing data stored in a predictive maintenance system, identifying critical conditions and autonomously defining maintenance actions. Unlike a central system controlling assets, all necessary information for predictive maintenance decisions, degradation, and prediction models would be distributed and available at a component level. Machines could plan their maintenance programs independently. However, current industrial machines lack this level of self-awareness and self-maintenance.

4. **Limitations in the Deployment of Industrial Predictive Maintenance Models.** Subsequent to the development of intelligent failure prediction models, three challenging steps arise: integration, monitoring, and updating. Integrating the model into the industry poses a challenge as this task is often performed by an IT team distinct from the researchers and developers who created the predictive maintenance models. Establishing an IT infrastructure to maintain data pipelines can be labor-intensive and is typically not factored into project planning. Regarding monitoring, it involves ensuring model updates by incorporating a feedback loop for new incoming data to contribute to learning inputs. Continuously re-training prediction models carries the disadvantage of potentially compromising result reliability. The data's integrity and relevance aren't typically verified in production, permitting the introduction of outliers, which can distort predictions in the long run. Updating the models is essential to prevent conceptual drift affecting machine learning models. To update the prediction models, the company must concurrently modify the code, model, and data. Compared to traditional enterprise software updates, this process of improving predictive maintenance models is notably more intricate.

Prognostics and Health Management

Considering the world of Predictive Maintenance means considering several different kinds of applications. One of them is the Prognostics and Health Management (PHM), which represents a critical process for Predictive Maintenance [30]. It is composed of modules that encompass data collection and processing, fault identification and diagnosis, fault prognosis, and decision support. Each module is briefly described as follows:

- Data acquisition. Involves gathering and storing digital data from sensors or transducers.

- Data processing. Processes acquired data to extract, condense, and select pertinent features and indicators that offer insights into system behavior, anomaly presence, and degradation progression.

- Condition assessment. Focuses on classifying and identifying the system's states, akin to fault detection.

- Diagnostics. Emphasizes detecting, isolating, and recognizing the causes of faults.

- Prognostics. Aims to predict failures before they happen and estimates Remaining Useful Life (RUL).

- Decision support. Primarily recommends the best maintenance actions or alternatives. The decision phase relies on RUL estimates.

- Human-Machine Interface (HMI). This module could integrate into a standard human-machine interface.

The prognosis is executed through various methods, categorized into three primary approaches proposed by the PHM community:

1. **Model-Based Prognostics.** These methods use an analytical model, which comprises a set of differential or algebraic equations derived from classical physical laws. This model represents the dynamic behavior and degradation of systems.

2. **Data-Guided Prognostics.** Methods within this approach aim to translate raw monitoring data into relevant information. They incorporate behavioral models to track the systems' degradation evolution for predicting RUL. These methods involve two phases: an offline phase to comprehend and learn degradation behavior (the learned model) and an online phase to estimate the system's current health state and predict its operational duration before failure. Data-driven approaches utilize diverse data modeling tools, predominantly sourced from artificial intelligence, with neural networks and neuro-fuzzy networks being commonly used.

3. **Hybrid Approach.** This method combines model-based and data-driven approaches to estimate the system's current state and predict RUL. It capitalizes on the advantages of the two preceding approaches while considering their shortcomings.

Figure 3.6: Prognostics and Health Management

The Future of Predictive Maintenance

Advancements in information, communication, and computer technologies (ICT), particularly in the realm of sensor technologies, entity identification and tracking, and localized data storage, alongside signal processing and decision-making, have significantly bolstered Predictive Maintenance. This progress has rendered Predictive Maintenance more robust, applicable, and cost-effective, thereby gaining acceptance across diverse industries. This section provides an overview of research areas that underpin the functioning of Predictive Maintenance:

- **E-maintenance.** The term 'e-maintenance' has been in circulation since the early 2000s and is described as a 'maintenance management concept where assets are monitored and managed via the Internet.' E-maintenance is perceived as a Predictive Maintenance system that offers monitoring and predictive prognostic capabilities. E-maintenance fulfills the essential requirements of predictive intelligence tools to oversee degradation.

- **Remote maintenance and management systems (RMMS).** This field, akin and promising, facilitates the execution of Predictive Maintenance, particularly in remote or hazardous settings. Its initial application can be traced back to 1995. Subsequent applications were proposed for aircraft maintenance, and other instances were developed for monitoring and maintaining machine tools. Additionally, a remote monitoring system was created as part of a process plant's distributed control system (DCS). It has been reported on the remote observation of robots to timely decide on replacements, thereby reducing the cost of unnecessary or premature maintenance, which is at the core of Predictive Maintenance. Nevertheless, it's crucial to note that not all remote maintenance efforts qualify as remote Predictive Maintenance work. For example, a remote sensing programmable automatic service time reminder (PAST-R) alerts the user to perform scheduled service for bearings. However, while this work is conducted remotely, it does not qualify as Predictive Maintenance since maintenance timing isn't based on the actual condition of the bearing that requires maintenance.

Chapter 4

Maintenance Strategies

In this chapter it will be developed the topic of Maintenance Strategies, which are the cornerstone of this management, providing structured approaches to ensure the optimal performance, longevity, and reliability of key assets. Among the myriad of maintenance strategies available, three prominent methodologies stand out: Reliability-Centered Maintenance (RCM), Total Productive Maintenance (TPM), and Smart Maintenance. These strategies represent multifaceted and coexistent approaches, meticulously developed to address the intricate challenges faced by industries today, encompassing a wide spectrum of equipment and technologies. This formal exploration will delve into the fundamental principles, methodologies, and benefits of RCM, TPM, and Smart Maintenance, unveiling their distinct attributes and illustrating their significance as indispensable tools for organizations striving to excel in the contemporary business landscape.

4.1 Reliability-Centered Maintenance

Reflecting on the era of the Industrial Revolution, it has been found that those responsible for designing the novel industrial machinery were also the individuals constructing and operating it. In fact, they maintained a close connection with the physical equipment that resulted from their innovative ingenuity. In the initial stages, practical experience indeed played a pivotal role in shaping the actions related to preventive maintenance. These actions, rooted in firsthand experience, were derived from individuals possessing not only maintenance expertise but also knowledge in design, construction, and operation. As industry and technology advanced, businesses restructured themselves for heightened efficiency and productivity. This restructuring yielded certain advantages and drawbacks, with one of the most pertinent drawbacks being the segregation of roles related to design, construction, and operation into separate organizational entities, resulting in a loss of holistic expertise. To address this shift, reliability engineering emerged during the 1940s and 1950s. Grounded in Reliability Theory, it primarily concentrates on concepts like failure rates and lifespan, which are encapsulated by the "Bathtub Curve" [31].

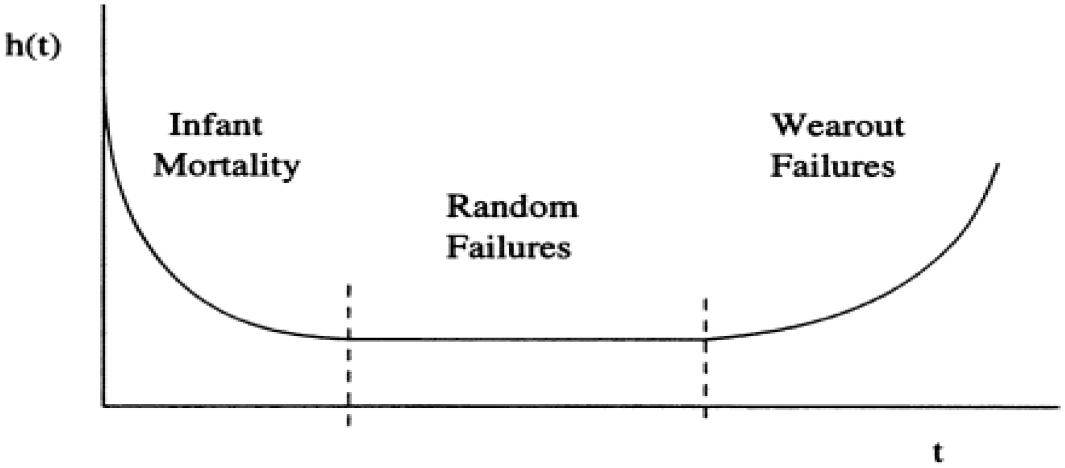


Figure 4.1: The Bathtub Curve

Starting from this background it has been developed the concept of Reliability-Centered Maintenance, which can be defined as:

"A process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating contest".

Reliability-Centered Maintenance originated in the aerospace and aviation industry in the late 1960s and early 1970s. It was initially developed by a team of engineers and researchers at United Airlines under the leadership of Stanley Nowlan and Howard Heap [32]. The primary goal of RCM was to improve the maintenance practices for aircraft, which is still a prominent sector of application.
It quickly gained recognition and adoption in various industries beyond aviation, including manufacturing, energy, and the military. Today, RCM remains a widely used methodology for optimizing maintenance strategies, ensuring the reliability and availability of critical assets, and managing maintenance costs across a wide range of industries worldwide.

4.1.1 The Seven Fundamental Questions of RCM

In order to achieve this, RCM relies on a set of seven fundamental questions, often referred to as the "Seven Questions of RCM" [33, 34]. These questions guide the analysis and decision-making process in RCM and help identify the most appropriate maintenance strategies. Here are the seven questions of RCM:

1. What are the functions and associated performance standards of the asset in its operating context?
2. In what ways can the asset fail to fulfill its functions?
3. What are the consequences of each failure mode?

4. What proactive tasks can be performed to predict or prevent each failure mode?
5. What are the default actions if no proactive tasks are performed?
6. What is the consequence of each failure mode on the operation or mission?
7. What should be done if a suitable proactive task cannot be found?

The initial inquiry pertains to the identification of an asset's functions and its performance standards. Asset functions fall into two distinct categories: Primary Functions and Secondary Functions. Primary Functions represent the core purposes for which the asset was acquired, encompassing attributes like speed, quality, and output. Conversely, Secondary Functions encompass supplementary attributes that enhance user satisfaction, including safety, comfort, control, structural integrity, aesthetics, and efficiency.

Performance standards are defined as the criteria dictating how users expect an asset to perform. They are ascertained through two means: desired performance and inherent capability. Identifying these performance standards is crucial because maintenance efforts aim to restore the asset to its original level of capability, whether it's the designed or built-in capability.

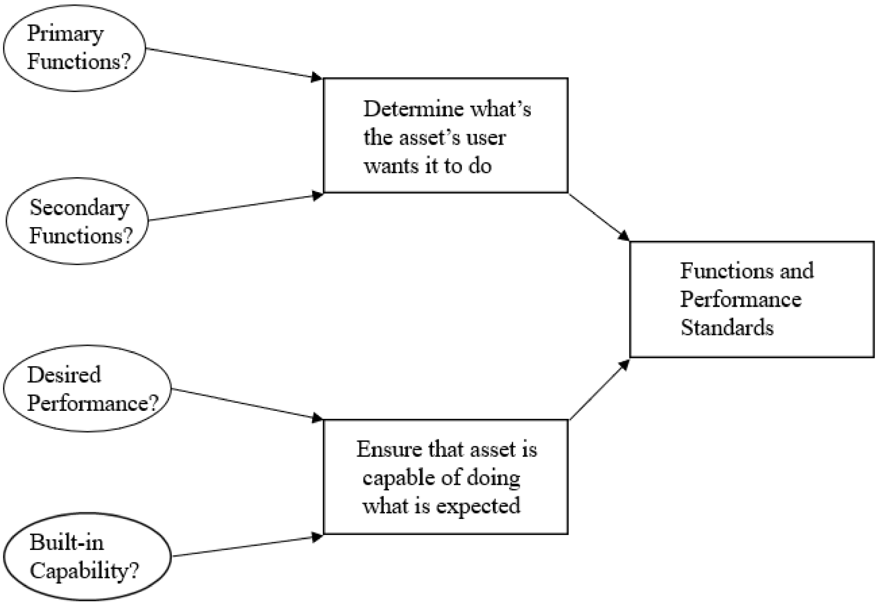


Figure 4.2: 1st Question of RCM

The second query prompts the analyst to contemplate and articulate functional failure. Functional failure is characterized as an asset's inability to perform a function up to the anticipated and acceptable performance standards set by the user. Within the RCM process, it is imperative to specify the conditions under which an asset can be deemed to have reached a failed state. Four different aspects of functional failures are recognized:

- Total failure, which denotes a complete loss of function.
- Partial failure, where the asset functions but falls outside acceptable limits.
- Failures beyond the upper and lower performance standard limits, signifying that the asset fails when it produces components exceeding the upper limit or falling below the lower limit.

Additionally, the operating context of the asset can influence the definition of failure, meaning that the failed state may differ for identical assets depending on their operating conditions. Functional failures are categorized into two groups based on whether the occurrence of failure is evident to the operating crew during their routine tasks: Evident Failure and Hidden Failure. Evident functions are those that become apparent to the operating crew during their regular operations, while hidden functions are discovered when infrequently used equipment is activated or when protective or backup systems fail to operate when required.

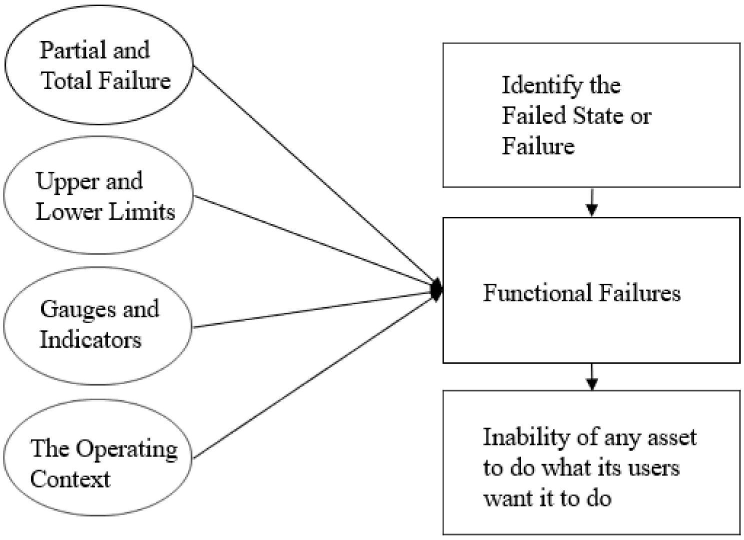


Figure 4.3: 2nd Question of RCM

The third question introduces a pivotal concept in RCM analysis: Failure Modes. Failure modes encompass all events reasonably likely to lead to each failed state. These modes can be classified into three groups: deteriorating capability, increased desired performance, and initial incapability. When documenting failure modes, it's essential to exercise discretion, only recording those that are reasonably expected to occur within the specific context in question. Reasonably likely failure modes include:

- Failures that have previously occurred on the same or similar assets.
- Failure modes are already subject to proactive maintenance routines.
- Other failure modes not yet experienced but deemed plausible possibilities.

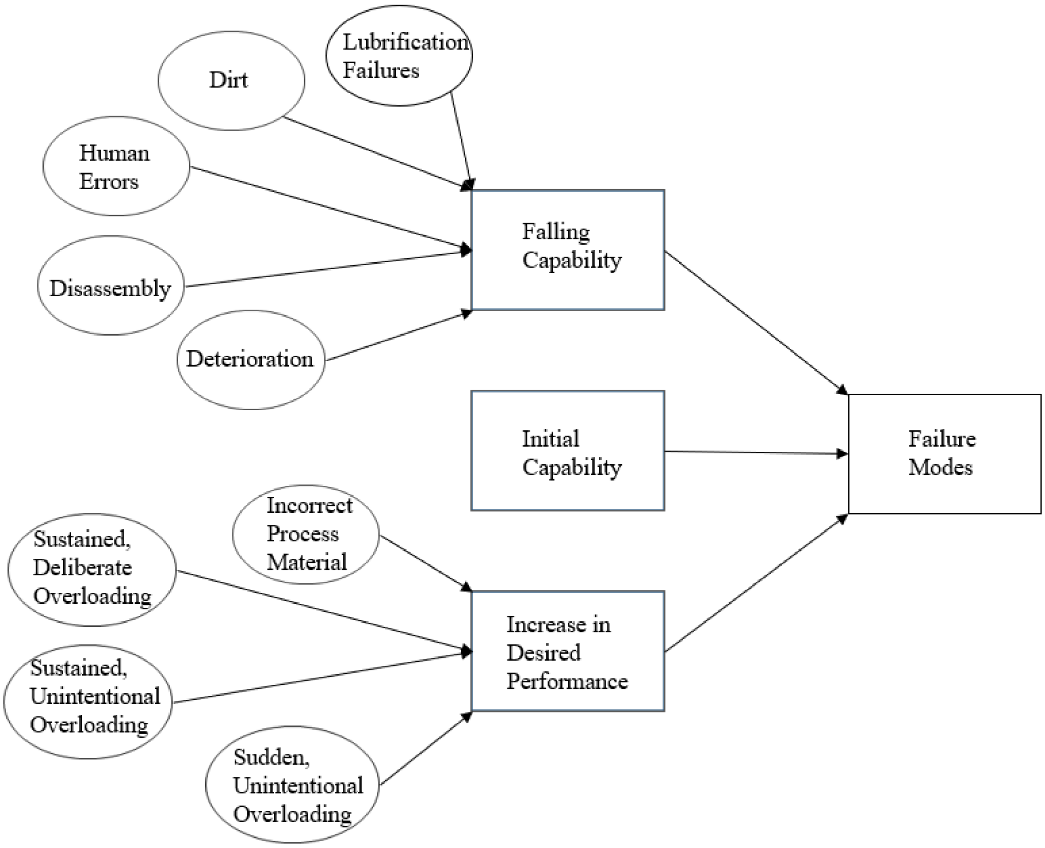


Figure 4.4: 3rd Question of RCM

The fourth question guides the analyst in describing and listing the outcomes when a failure mode occurs. These outcomes are referred to as failure effects. Essential pieces of information to record while describing failure effects include:

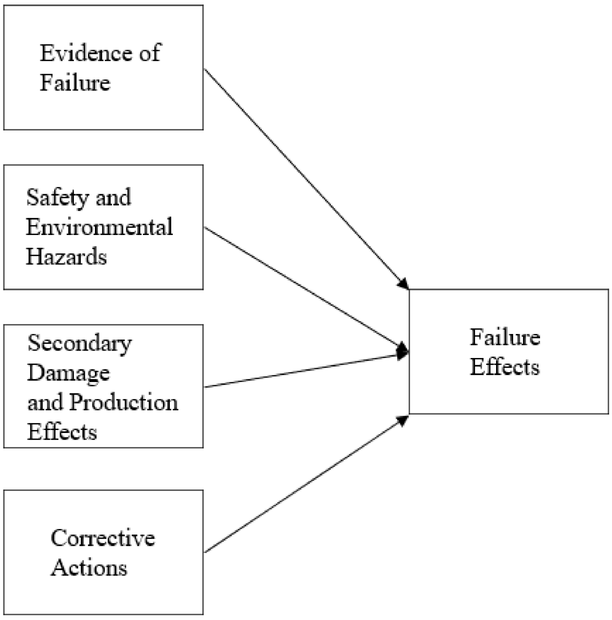


Figure 4.5: 4th Question of RCM

The fifth inquiry enlightens the analyst about the significance of a failure's timing. These are referred to as failure repercussions. They are detailed as follows:

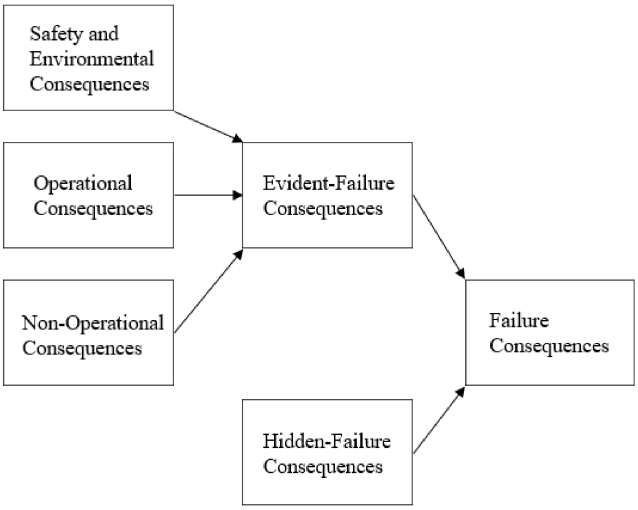


Figure 4.6: 5th Question of RCM

The sixth query offers a forward-looking perspective by enabling the analyst to ascertain actions that could be employed for the prediction or prevention of failure. These actions are referred to as proactive measures. Proactive measures are characterized as actions taken preemptively before a failure event transpires with the aim of averting asset failure. These tasks are categorized into three distinct groups, as outlined below:

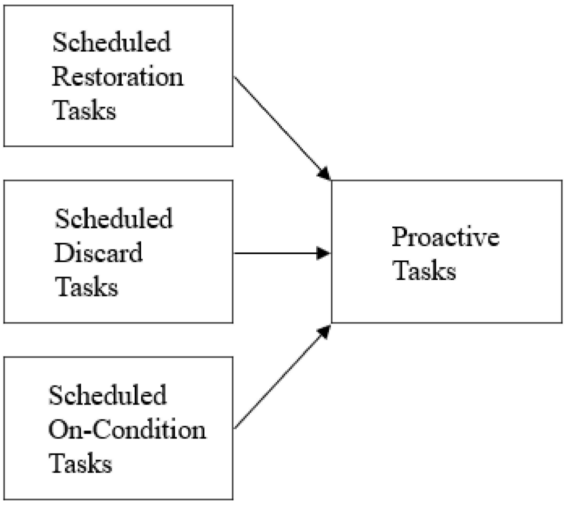


Figure 4.7: 6th Question of RCM

The ultimate query revolves around pinpointing the tasks or actions that should be implemented in cases where a suitable proactive measure cannot be identified. These actions are termed default procedures. Within the RCM framework, three default procedures have been delineated, as delineated below:

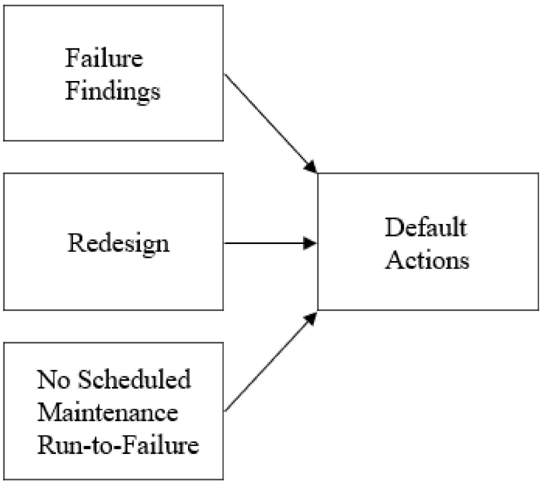


Figure 4.8: 7th Question of RCM

4.1.2 The benefits of Reliability-Centered Maintenance

Analyzing the literature [35] [36] shows how Reliability-Centered Maintenance offers a multitude of benefits for organizations across various industries. Here is a list of some of the key advantages of implementing RCM, along with detailed explanations:

- **Improved Equipment Reliability**: RCM focuses on identifying and mitigating failure modes that could lead to equipment breakdowns. By proactively addressing these issues, organizations can significantly enhance the reliability of their assets. This leads to reduced unplanned downtime and increased availability.
- **Enhanced Safety**: RCM places a strong emphasis on identifying failure modes with safety implications. By addressing these failure modes through preventive maintenance or redesign, RCM helps improve overall safety in the workplace, reducing the risk of accidents and injuries.
- **Better Quality and Productivity**: When equipment operates reliably, it contributes to consistent product or service quality. RCM's proactive approach to maintenance ensures that equipment functions within defined parameters, leading to higher-quality outputs and increased productivity.
- **Cost Savings**: RCM can result in substantial cost savings over time. By preventing catastrophic failures, organizations avoid the high costs associated with emergency repairs, replacement of critical components, and lost production time. RCM also helps optimize maintenance resources, reducing unnecessary tasks and expenditures.
- **Extended Asset Lifespan**: Regular maintenance and early detection of potential issues can extend the lifespan of equipment. This means that organizations can maximize the return on investment (ROI) for their assets and delay the need for costly replacements.
- **Efficient Resource Allocation**: RCM helps organizations allocate maintenance resources more efficiently. Instead of applying a one-size-fits-all approach to maintenance, RCM tailors maintenance tasks to the specific needs and criticality of each asset. This optimizes the use of labor, materials, and time.
- **Continuous Improvement**: RCM is not a one-time activity; it encourages a culture of continuous improvement. Organizations that implement RCM regularly review and update their maintenance strategies, adapting to changing conditions and technology advancements.
- **Improved Decision-Making**: RCM provides a structured framework for making informed maintenance decisions. It requires a thorough analysis of asset performance, failure modes, and consequences, enabling organizations to make data-driven choices regarding maintenance tasks and investments.

4.2 Total Productive Maintenance

In today's fiercely competitive industrial landscape, maximizing productivity, minimizing downtime, and ensuring the highest levels of product quality are paramount for sustainable success. Total Productive Maintenance, or TPM, stands as a powerful philosophy and methodology designed to address these critical challenges and it can be defined as:

"A strategic approach that brings together both production and maintenance activities by combining strong working behaviors, collaboration, and continuous improvement." [37].

The concept of Total Productive Maintenance (TPM) emerged in the 1950s and primarily emphasized preventive maintenance practices. As new machinery was introduced, the primary objective was to implement the preventive maintenance guidelines provided by equipment manufacturers. A strong emphasis was placed on ensuring that equipment operated at its intended specifications without experiencing any breakdowns. Concurrently, a research team was established, which eventually evolved into the Japanese Institute of Plant Management (JIPM).

By the 1960s, TPM shifted its focus towards productive maintenance, reshaping the significance of reliability, maintenance, and economic efficiency in plant design. This shift involved leveraging the wealth of data collected during the 1950s about equipment performance and integrating it into the design, procurement, and construction phases of equipment management. Subsequently, during the 1970s, TPM underwent a transformation, shifting its strategic focus towards achieving efficiency in Preventive Maintenance (PM) by implementing a comprehensive system rooted in respect for individuals and full employee engagement. It was during this period that the term "Total" was incorporated into the concept of Productive Maintenance. By the mid-1970s, the Japanese had begun to disseminate TPM strategies globally, and their achievements in this area were widely acknowledged.

Currently, there is a growing international emphasis on TPM, driven by the objective of maximizing a company's asset utilization. As an illustration, one of the prevailing approaches today is the adoption of Lean Manufacturing principles, which draws inspiration from the Toyota production system.[38]

4.2.1 The 8 Pillars of Total Productive Maintenance

Total Productive Maintenance (TPM) is often structured around a set of key pillars or principles to guide its implementation. These eight pillars of TPM are commonly recognized as follows:

1. **Autonomous Maintenance (AM)**: Involves empowering operators and front-line maintenance personnel to take responsibility for the routine cleaning, inspection, lubrication, and basic maintenance of equipment. The goal is to prevent deterioration and detect issues early, reducing unplanned downtime.
2. **Focused Improvement (FI)**: Encourages continuous improvement efforts to identify

and address the root causes of chronic equipment problems. Cross-functional teams work together to implement solutions that enhance equipment reliability and efficiency.

3. **Planned Maintenance (PM)**: Focuses on developing a structured maintenance plan based on equipment condition and performance data. Planned maintenance activities are conducted proactively to prevent breakdowns and optimize equipment performance.

4. **Quality Maintenance (QM)**: Aims to ensure that equipment is maintained to meet quality standards. Properly maintained equipment helps prevent defects and variations in product quality.

5. **Education and Training (ET)**: Involves providing employees with the necessary skills and knowledge to operate, maintain, and troubleshoot equipment effectively. Well-trained personnel are more capable of contributing to TPM goals.

6. **Safety, Health, and Environment (SHE)**: Prioritizes the safety and well-being of employees and the environment during maintenance and operational activities. Safety practices are an essential part of TPM.

7. **Office TPM**: Extends TPM principles to administrative and office processes. This pillar aims to improve efficiency and reduce waste in non-production areas, such as paperwork, data management, and administrative workflows.

8. **Development Management**: Integrates TPM principles into the design and acquisition of new equipment. The goal is to optimize equipment reliability and maintainability from the outset, reducing future maintenance needs.

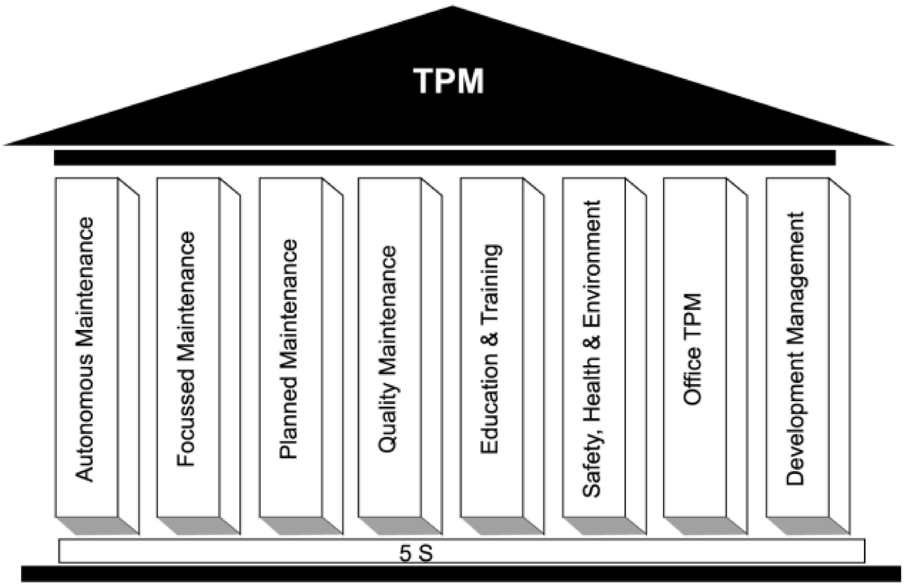


Figure 4.9: TPM Pillars

4.2.2 TMP Benefits

TPM offers a wide range of benefits [37] that extend beyond maintenance and production. It touches on various aspects of the organization, some of which include:

- **Increased Equipment Efficiency**: TPM aims to maximize Overall Equipment Effectiveness (OEE), leading to improved equipment performance, reduced downtime, and increased production capacity.

- **Enhanced Product Quality**: By preventing equipment breakdowns and defects, TPM contributes to higher product quality and consistency, reducing the need for rework or scrap.

- **Reduced Downtime**: TPM's proactive approach to maintenance minimizes unplanned downtime, resulting in higher production availability and better delivery performance.

- **Cost Savings**: TPM reduces maintenance and repair costs by addressing issues before they escalate into major breakdowns. It also lowers energy consumption and reduces the need for spare parts inventory.

- **Improved Safety**: Safety is a fundamental aspect of TPM. By identifying and addressing safety hazards, TPM helps create a safer work environment, reducing accidents and injuries.

- **Employee Involvement**: TPM encourages employee engagement and empowerment, fostering a culture of ownership and continuous improvement. This leads to a motivated workforce and innovative problem-solving.

- **Enhanced Skill Development**: TPM emphasizes training and skill development, ensuring that employees have the knowledge and capabilities to operate and maintain equipment effectively.

- **Better Asset Management**: TPM helps organizations make informed decisions about equipment replacement, refurbishment, or upgrades, optimizing asset management.

- **Increased Equipment Lifespan**: Proper maintenance and care under TPM principles extend the lifespan of equipment and assets, delaying the need for costly replacements.

- **Improved Communication**: TPM encourages cross-functional collaboration and communication, breaking down silos within the organization and promoting knowledge sharing.

- **Competitive Advantage**: Organizations that implement TPM often achieve higher levels of efficiency, quality, and customer satisfaction, which can give them a competitive edge in the market.

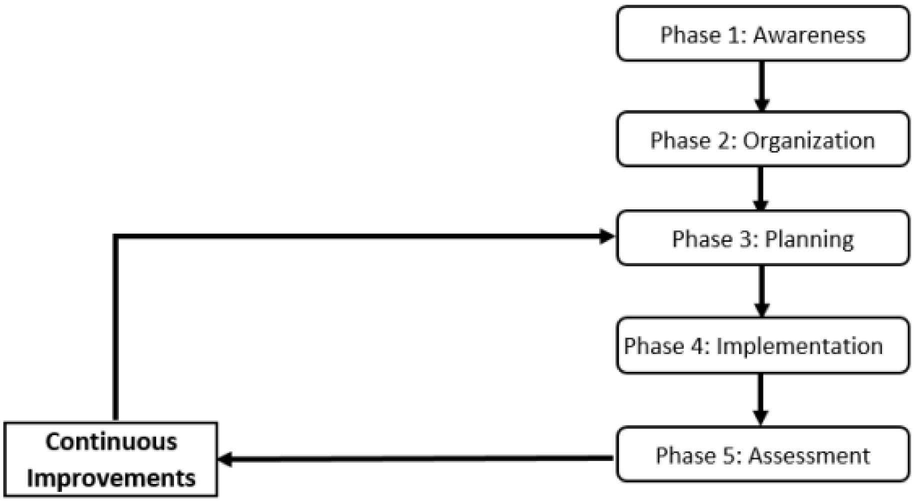


Figure 4.10: TPM implementation steps

- **Environmental Benefits**: TPM's focus on reducing waste and energy consumption contributes to a more environmentally friendly and sustainable operation.
- **Customer Satisfaction**: TPM's emphasis on consistent quality and on-time delivery can lead to higher levels of customer satisfaction and loyalty.
- **Cultural Transformation**: TPM promotes a culture of continuous improvement, where employees are encouraged to take ownership of their work and contribute to the organization's success.
- **Global Recognition**: Organizations that successfully implement TPM may receive recognition and awards, enhancing their reputation in the industry.

4.2.3 Steps through implementation of TPM

TPM can be implemented in any organization, tailored to its size, nature, workforce, level of effort, method of execution, and management approach. Depending on specific implementation requirements, some companies may choose to adopt selected TPM pillars rather than implementing the entire framework.

The selection of tools for TPM implementation [39] is guided by various parameters aimed at achieving desired outcomes. Evaluating overall effectiveness before and after TPM adoption is crucial to monitor progress. The TPM process unfolds in five distinct phases, illustrated in Figure 4.10.

1. Awareness Phase: The primary objective of this phase is to introduce the TPM approach and fundamental concepts to secure commitment and support from all stakeholders for successful TPM practices. It seeks to enhance machine understanding and uncover previously unidentified challenges. Activities within the TPM awareness phase include:

- Removal of unnecessary items and equipment
- Comprehensive cleaning to eliminate dust and dirt
- Participation in TPM meetings, discussions, and workshops
- Visits to companies experienced in TPM implementation, consulting with TPM experts, and arranging in-house TPM training for the management team
- Process engineers analyze the current state of the equipment management system and facilitate staff discussions to identify challenges

2. Organization Phase: The aim of this phase is to establish an organizational structure that plans, promotes, implements, and supports TPM strategies at all organizational levels. During this phase, obstacles hindering access are removed, and hard-to-clean or inspect areas are re-positioned or reconfigured.

3. Planning Phase: This phase requires equipment to be in optimal working condition, and operational conditions must be consistent. Predictable equipment lifespans are established, enabling technicians and operators to schedule routine checks and repairs. This phase initiates the process of determining the appropriate inspection and maintenance frequency. Operators are educated about the cause-and-effect relationship between processes and product quality. Online monitoring of process variables is employed by operators to detect equipment deterioration before it affects product quality. Cleaning, lubrication, and maintenance standards are established to ensure effective cleaning. Ineffective lubrication points are identified, and the procedures are documented for auditing purposes, with continuous monitoring before and after cleaning.

4. Implementation Phase: The TPM council decides to initiate the TPM implementation process by forming a pilot TPM team to gain practical experience within the company. This single team is responsible for executing all TPM activities on a single machine to enhance its performance. The pilot team must determine the best approach for their organization. The key factors in selecting equipment suitable for the pilot TPM strategy include customer importance, capacity constraints, and frequent breakdowns. Experience gained from the pilot project can be leveraged to refine the planning process and identify necessary resources for broader TPM adoption. Additionally, during this phase, workers receive training and guidance in equipment control functions to ensure they are capable of performing basic maintenance tasks and are well-informed about the machines they work with.

5. Evaluation Phase: This phase builds upon the standards and knowledge acquired throughout the preceding implementation phases, enabling operators to independently perform basic maintenance and inspections. The objectives of the evaluation system include:

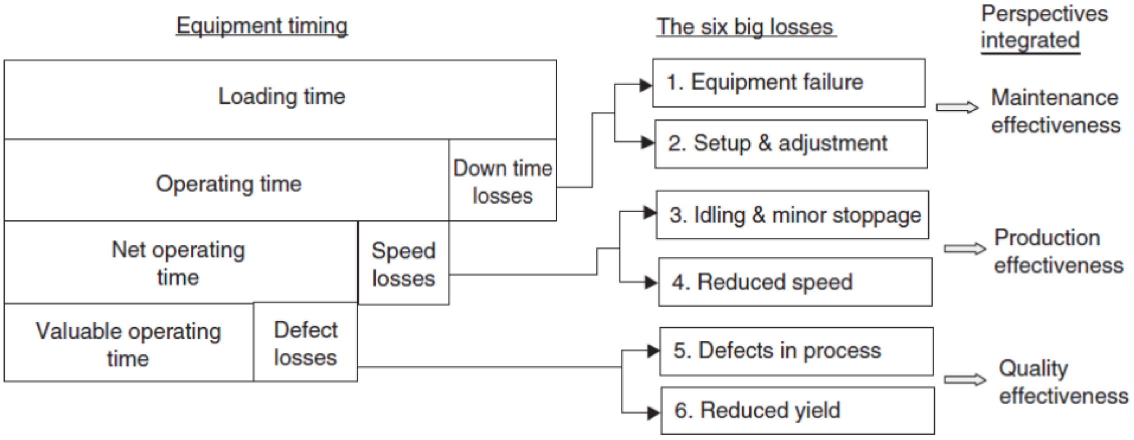


Figure 4.11: The "Six Big Losses" of OEE

- Assessing the progress made in TPM improvement initiatives by comparing it to previous data
- Determining the organization's TPM maturity level
- Identifying areas of strengths and weaknesses in the implementation process
- Integrating TPM improvement initiatives into the enterprise's business plan

Results from this phase are compared to those of earlier stages, and the achievements of the TPM strategy are documented.

4.2.4 Overall Equipment Effectiveness

Measurement plays a crucial role in the ongoing improvement procedures. It is essential to define suitable metrics for the purpose of measurement. As Nakajima [40] suggests, utilizing OEE measurement offers an efficient means of assessing the effectiveness of either an individual machine or a fully integrated manufacturing system. The definition of OEE is illustrated in and detailed below.

$$OEE = A \times Q \times P \tag{4.1}$$

where:

A = Availability rate = $\dfrac{\text{Operating time (h)}}{\text{Loading time (h)}}$

P = Performance efficiency = $\dfrac{\text{Theoretical cycle time (h)} \times \text{Actual output (units)}}{\text{Operating time (h)}}$

Q = Quality rate = $\dfrac{\text{Total production (units)} - \text{Defect amount (units)}}{\text{Total production (units)}}$

Nakajima identified the so-called "Six Big Losses" referring to specific categories of production losses that can significantly impact a machine's or a production line's efficiency, impacting negatively on the three areas of OEE.

1) Equipment Downtime: This loss occurs when machinery is not running due to breakdowns, setup, changeovers, or any unplanned stoppages. Reducing downtime is a key focus of TPM and OEE improvement efforts.

2) Reduced Speed: Also known as ”speed loss,” this refers to instances when a machine is running slower than its optimal speed. It could be due to equipment limitations, sub-optimal settings, or other factors that hinder maximum speed production.

3) Defective Products: This loss occurs when products do not meet quality standards and need to be reworked, scrapped, or discarded. Quality issues can lead to production stoppages and increased costs.

4) Startup and Yield Loss: These losses encompass the time and materials consumed during machine startups, changeovers, and the period until a machine reaches its target production yield. Minimizing these losses is essential for efficiency.

5) Idling and Minor Stops: This category includes short stops or idling periods that are not part of the planned production process. These small disruptions can add up and affect overall equipment effectiveness.

6) Process Defects and Rework: Process defects refer to defects that occur during normal production operations. When products are found to be defective, they may require rework or correction, leading to production delays and inefficiencies.

After analyzing the OEE tool it becomes evident that it represents a valuable metric that offers insights into the causes of time and production losses. Many companies frequently encounter capacity limitations and often consider options like implementing overtime for their existing workforce, hiring additional staff for new shifts, or investing in new production lines to increase production capacity. In the case of such companies, the OEE tool can assist in optimizing the performance of their current capacity. OEE serves as a valuable resource [41] for management to unlock latent capacity, thereby reducing overtime expenses and delaying significant capital investments. It aids in minimizing process variability, shortening changeover times, and enhancing operator efficiency. These are quantifiable advantages that significantly enhance the profitability of production operations and bolster the competitive position of the companies.

4.3 Smart Maintenance

By the end of 2010s, the organizations started to rethink the whole process adopting different enablers belonging to the concept of Industry 4.0. One of these adoptions, Smart maintenance, is defined by Bokrantz [42] as “an organizational design for managing the maintenance of manufacturing plants in environments with pervasive digital technologies" Smart Maintenance consists of four underlying dimensions [43]: data-driven decision-making, human capital resource, internal integration, and external integration, as seen in Figure 4.12.

First, data-driven decision-making is the degree to which decisions are based on data and reflects how maintenance decisions are based on data. This can include automation and augmentation of human decision-making. Owing to technological advancements such as machine learning, a reduction in the price of sensors, and the increasing availability of equipment data, maintenance decisions can be increasingly based on data instead of just experience and intuition.

Second, the human capital resource is defined as unit capacity based on individual knowledge, skills, abilities, and other characteristics that are accessible for unit-relevant performance. In other words, it means the knowledge, skills, abilities, and other characteristics of maintenance employees. Due to technological change, the requirements placed upon maintenance personnel are also changing. In particular, maintenance employees need higher levels of generic skills (such as communication and collaboration), plus specific skills (as in the case of data analytics).

Third, internal integration, the degree to which the maintenance function is part of a unified, intra-organizational whole refers to the cross-functional collaboration between the maintenance function and the rest of the plant organization. It includes such things as the sharing of data, information, and knowledge, and closer synchronization.

Fourth and finally, external integration is defined as the degree to which the maintenance function is part of a unified, inter-organizational Performance indicator for Smart Maintenance. It refers to the establishment of links to external parties, especially networks and strategic partnerships. These links allow for things like equipment data to be shared between parties, allowing the scaling of Machine Learning and consolidation of knowledge resources.

In addition, several contextual factors influence the adoption of Smart Maintenance, and certain of them can facilitate or inhibit its implementation. There are three main categories of context variables: change, investment, and interface. Implementing Smart Maintenance requires substantial change across multiple dimensions of technology, skills, and organization. Such change is influenced by cultural aspects (a data-focused corporate culture for example) and algorithm interpretability, as well as the leadership abilities of maintenance managers. Further, implementation requires investment in both tangible and intangible assets. Tangible assets are obtained primarily through ICT investment (sensors and IT systems, for example), which are relatively cheap. Intangible assets are needed if the technology is to be used effectively. These are obtained primarily through complementary investments (such as the training and education of employees). Such investment is typically much greater than the direct financial cost of the technology itself. Moreover, the success of any type of investment is influenced by the ability to quantify the effects of maintenance in accounting terms. Finally, the contextual factors relating to interfaces primarily influence the establishment of external integration. This includes digital platforms, openness, and IT security.

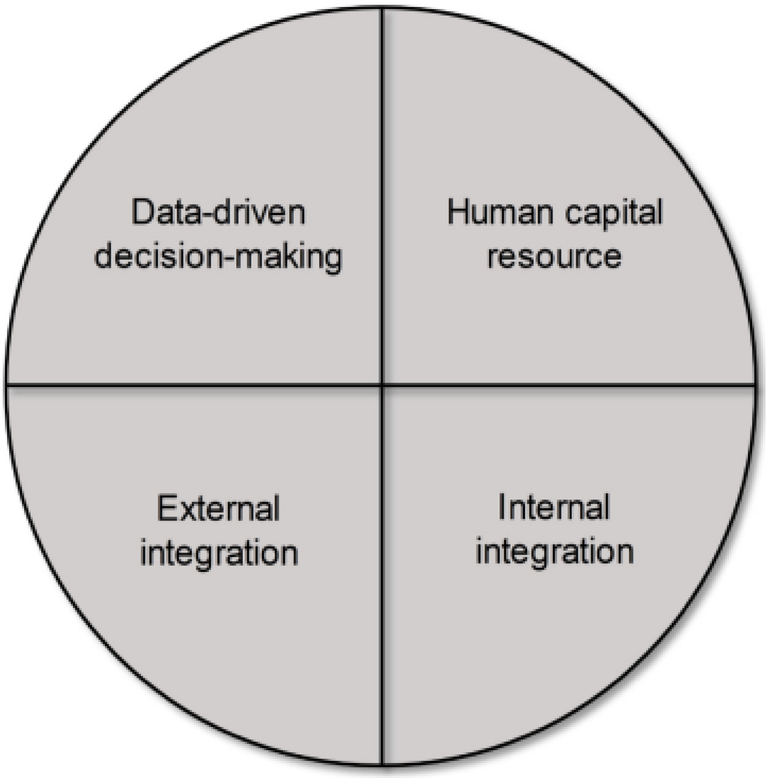


Figure 4.12: The four dimensions underlying dimensions of Smart Maintenance

4.3.1 Industry 4.0

The current (and future) Smart Maintenance strategies and approaches are enabled by the spreading of the disruptive technologies belonging to the family of Industry 4.0. The following sections will scrutinize specific Industry 4.0 technologies such as artificial intelligence, the Internet of Things, big data analytics, and machine learning as well as their historical background.
Industry 4.0, a strategic innovation initiated by the German government in 2011, has garnered global attention in recent years as it represents the most recent iteration of the historical industrial revolutions primarily focused on mechanization [44]. The integration of Cyber-Physical Systems (CPS) technologies like the Industrial Internet of Things (IIoT) and Big Data drives the progression of manufacturing into this 4th industrial revolution. The evolution of Industry 4.0 traces back to the initial three industrial revolutions: the first revolution employed water and steam power for mechanized production, the second introduced electricity and division of labor for mass production, and the third relied on enhanced manufacturing automation via electronics and Information and Communications Technology (ICT). The 4th industrial revolution is fundamentally underpinned by CPS. Within Industry 4.0, three primary components are integrated: vertical integration, end-to-end digital integration, and horizontal integration via value networks.

- Vertical integration amalgamates various sections of an industrial company, including

ICT systems and processes, facilitating real-time communication from product development through different EPR modules to production, logistics, and marketing. This integration ensures seamless communication across all organizational systems, from top-floor operations to shop-floor activities and back.

- End-to-end digital integration interconnects and digitizes the entire product lifecycle, enabling comprehensive product monitoring from conceptual design, through various production stages, logistics, sales, and up to end-of-life phases, ensuring a comprehensive product lineage.
- Horizontal integration allows companies to collaborate with remote offices and external businesses such as suppliers and customers, fostering a fully integrated supply chain and supporting the implementation and maintenance of business strategies, models, and value chains.

The integration layers within Industry 4.0 are made viable through the implementation of IoT and IIoT technologies, transforming industries into smart enterprises. IoT connects physical and intelligent machines and devices, utilizing wired and wireless sensors for data collection and actuators for the manipulation of physical processes. When applied within the industrial sector, this technology is referred to as IIoT, predominantly utilized in the implementation of the vertical integration layer in Industry 4.0.

The Core Technologies of Industry 4.0

The core of Industry 4.0 is represented by the nine composing disruptive technologies which are enlisted below [45]:

1. **Big Data and Analytics**
   The notion of big data pertains to vast, diverse, and intricate datasets that significantly influence a company's strategic decision-making processes. The increasing volume of data and advancements in technology enhance a company's competitive edge by boosting productivity, fostering innovation, and intensifying competition. Decision-makers initiate substantial big data projects to address organizational challenges more effectively, employing monitoring, measurement, and enhanced management techniques. The framework of big data encompasses three primary aspects: data as a tool (resolving conventional value chain issues through existing capabilities), data as an industry (fostering new ventures and developing software systems to handle big data), and data as a strategy (establishing data resources by cultivating innovative business models). Big data analytics involves the analysis of extensive datasets, providing insights into customer preferences, correlation algorithms, trends, and other relevant information. Big data analytics finds applications in various domains, including fault prediction to reduce error probability and proactive harm reduction before significant damages occur. Proficient big data management confers a competitive advantage to firms, benefiting their operations, marketing, and customer experience, among other aspects. The broad

spectrum of technological advancements motivates companies to enhance their talent pool and infrastructure development, propelling them into complex and comprehensive dimensions of their business operations.

In the contemporary landscape, the generation of data from machinery, cloud-based solutions, and business management has escalated, surpassing 1000 Exabytes annually. For instance, in a consumer packaged goods company, a single machine generates 5000 data samples every 33 milliseconds, resulting in 4 trillion samples annually. In this context, the concept of big data plays a pivotal role in the Fourth Industrial Revolution.

2. **Autonomous Robots**

   Industrial robots are pivotal in addressing intricate tasks that are not easily managed by humans within manufacturing industries. In the realm of traditional automation strategies, the complete execution of Just-In-Time (JIT) methodologies and continuous improvements is unattainable without the integration of autonomous robots. Ongoing advancements in industry practices streamline the use of robots, making their utilization less complex and more user-friendly. Diverse human-robot interfaces foster a seamless collaboration between robots and human cognitive abilities. Nonetheless, the role of the operator remains crucial, enabling interaction with the station to execute tasks. Operators provide the necessary information, control the system, and issue instructions to industrial robots.

   The integration of more industrial robots into factory settings is escalating with the onset of Industry 4.0. Robots find applications across various domains such as production, logistics, and distribution activities, remotely controlled by humans through collaborative human-robot partnerships. Companies are introducing new robotics technologies, like the Kuka LBR IIWA, designed to execute delicate tasks in work environments and collaborate with humans. This robot possesses the capability to learn from human colleagues and verify, optimize, and document tasks with the assistance of cloud-based systems.

3. **Simulation**

   Simulation tools serve as invaluable aids in production-related endeavors, fostering a sustainable manufacturing environment. These digital tools, responsible for designing production systems, possess self-configuration capabilities, thereby enabling efficient management of shop-floor operations. In the increasingly competitive business landscape, simulation facilitates adjustments in intricate systems by strategically planning operations and leveraging engineering insights and accurate estimations about the system. Employing simulation models enables dynamic scrutiny of production systems using real-time data, thereby allowing for strategic planning and real-time optimization of operations.

4. **Horizontal and Vertical System Integration**

   Vertical integration pertains to the flexibility and reconfigurability of systems within a factory and the extent of their seamless integration with one another to achieve agility. Horizontal integration focuses on the integration of partners within the supply chains. The industrial network collects Big Data to optimize system performance and transfers this data to the cloud. This coordination mechanism underpins the framework of the smart factory, designing manufacturing systems as self-organized structures that integrate physical objects through smart networks. Additionally, cloud-based systems enable vertical partners to integrate through shared platforms. This integration allows the visualization and tracking of product and process flows by supply chain members.

5. **The Industrial Internet of Things (IIoT)**
   The Industrial Internet of Things (IIoT) represents the next technological revolution, offering computational solutions through cloud-based systems. IIoT's primary task is to connect to the Internet by gathering data from physical objects. The collected data enables computers or higher-level devices to make decisions regarding operations. By using IIoT, business operations become more agile, and integrated, and gain a competitive edge within the supply chain. Therefore, the IIoT capabilities of firms will play a crucial role in the future, primarily associated with operational agility and effective decision-making.

6. **Cloud Computing (CC)**
   Cloud computing (CC) offers various advantages within the information and communication technology paradigm, automating and integrating supply chains, and facilitating management and administration. CC involves the virtualization of resources and services, combining client/server-based systems. It encompasses IT resource pools offering storage and processing capabilities in a virtual system, serving multiple users. Cloud computing is categorized into three models: Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS). Notable examples of cloud systems include Google Drive, offered by Google, Microsoft's Windows Azure, and IBM's BlueCloud.

7. **Additive Manufacturing**
   Additive Manufacturing, also known as 3D Printing, involves the production of customized goods to meet customer requirements. This approach typically uses prototypes and 3D printing methods to produce small batches, minimizing inventory and overproduction. For instance, aerospace companies employ these techniques to reduce aircraft weight and raw material usage, such as titanium. Leading global companies, including Google, Motorola, and Apple, invest in 3D printing to accelerate their smartphone activities. The perceived advantages include reduced lead times, increased production volume, mass customization, and enhanced agility. Additive manufacturing is a process that creates parts from 3D model data, layer by layer (using powder bed, wire-fed systems, or powder-fed systems). This technology enables Just-In-Time (JIT) production due to its flexibility, speed, and adaptability.

8. **Augmented Reality (AR)**
   Augmented reality is an interactive technology that harmonizes the virtual world with users' real-world surroundings. Google introduced the world's first augmented reality glasses, known as Google Glass, while Magic Leap, founded in 2011, adjusts to

the human eye by manipulating the light field angle and depth. Augmented reality enhances human-machine interaction, supports remote control for maintenance tasks, and provides virtual visual inspection. It can be applied in various contexts by combining computer-generated graphics with physical objects. AR provides motion control to users through sensor technology, enabling control over specific tasks.

9. **Cybersecurity**

   Cybersecurity stands as a critical concern that holds the potential to inflict severe damage on the business landscape due to malicious intentions, including terrorist attacks. Hence, it is imperative to employ preemptive measures and defense systems to mitigate the adverse impacts of such incidents. There exist methodologies to counter cyber terror attacks by scrutinizing past occurrences and implementing preventive measures before future attacks ensue. Additionally, the establishment of national defense systems and employee training against cyber threats holds considerable significance. While the implementation of solutions to combat cyber warfare may pose costs to companies, the overall expense is relatively minor compared to the potential detrimental repercussions of cyber-attacks.

Figure 4.13: The core technologies of Industry 4.0

The RAMI 4.0

The Reference Architecture Model for Industry 4.0, known as RAMI 4.0, presents a Service-Oriented architecture framework. This proposal is comprised of a collection of standards, practices, and references. Over the years, it has been developed in collaboration with a significant stakeholder association, the German Electrical and Electronic Manufacturers Association (ZVEI). Notably, in 2020, this initiative became aligned with the IIC (Industrial Internet Consortium), which encapsulates all the American Industrial Internet standards. This alignment further empowered RAMI 4.0, broadening its scope and enhancing its adoption [46]. The model is depicted in a three-dimensional graph that correlates layers, as demonstrated by Figure 4.14. Each dimension and sub-dimension will be detailed in the following subsections [47].

Hierarchy Axis

Based on the International Electrotechnical Commission standards 62264 and 61512, this axis is segmented into hierarchical levels. It categorizes the level at which an asset operates within the system, depending on its condition. Although information exchange between different levels doesn't occur in a traditional cascading manner, it might transpire transversely or even bypass the hierarchical order.

- **Product Level.** This level considers the products themselves, a significant departure from the third industrial generation, acknowledging the final product as part of the system. It's crucial for the manufactured good to interact with the manufacturing process, from early stages like prototyping to later stages such as recycling, ensuring the traceability of the item's lifecycle. An example is a software update made by OTA.

- **Field Device Level.** Infrastructure devices supporting manufacturing operations operate on this level, involving sensors, meters, and scanners. These devices collect data, aiding in decision-making and triggering actions. For instance, a thermometer frequently monitors production temperature, exchanging data with the control level to maintain specified ranges. Interactions often occur between control, station, and work center levels.

- **Control Device Level.** This layer supervises and monitors assets, encompassing human-machine interfaces or SCADA-related devices. It connects the enterprise level by sending and gathering data simultaneously.

- **Station Level.** It represents the core purpose of assets in an industry—used for production. It might relate to modules within a complex system (work center level) or stand alone as a single-piece system. This layer interacts with multiple levels simultaneously.

- **Work Center Level.** Actions here apply to a group of assets sharing a common purpose or collectively dedicated to production. Similar to the station level, it involves multiple inputs and outputs and usually comprises multiple stations.

- **Enterprise Level.** This level handles asset interactions not directly involved in production but in surrounding processes, like orders and administrative activities. It exchanges data with all other levels, gathering more data than it sends, significantly impacting overall business management.

- **Connected World Level.** This level enables factory interactions with the external world, whether suppliers, clients, or subsidiaries. For example, the supply chain could be automatically activated to deliver raw materials or produce elements requested by the production line as needed. It connects to all other layers as required.

Life Cycle and Value Stream Axis
This axis deals with processes or services related to the current status of assets' life cycles. Segmented into four stages:

- Type (Development)
- Type (Maintenance and Usage)
- Instance (Production)
- Instance (Maintenance and Usage)

Type - Development. Relates to the conceptualization phase of a product, involving construction, simulation, or prototyping.
Type - Maintenance and Usage. Pertains to activities like software updates, maintenance cycles, or instruction manuals, focusing on the product, not factory maintenance.
Instance - Production. Refers to the manufacturing action of fabricating the product itself, of primary importance to the factory.
Instance - Maintenance and Usage. Occurs during manufacturing maintenance, covering actions like recycling and servicing.

Layer Axis
Defines asset properties and attributes across six layers, enlisted below:

1. **Asset.** This layer exclusively represents the physical device and security aspects.
2. **Integration.** Transitions assets from the physical to the cyber world through digitalization tools.
3. **Communication.** Manages data exchange and access infrastructure, allowing data flow between devices and manufacturers using various protocols and techniques.
4. **Information.** Contextualizes asset data into the Industry 4.0 language, enabling transitions between layers and interaction across the system.
5. **Functional.** Defines asset capabilities and functions, facilitating comparisons and analysis.

6. **Business.**Aligns assets with specific business processes, being the highest-level layer focused on business and processes.

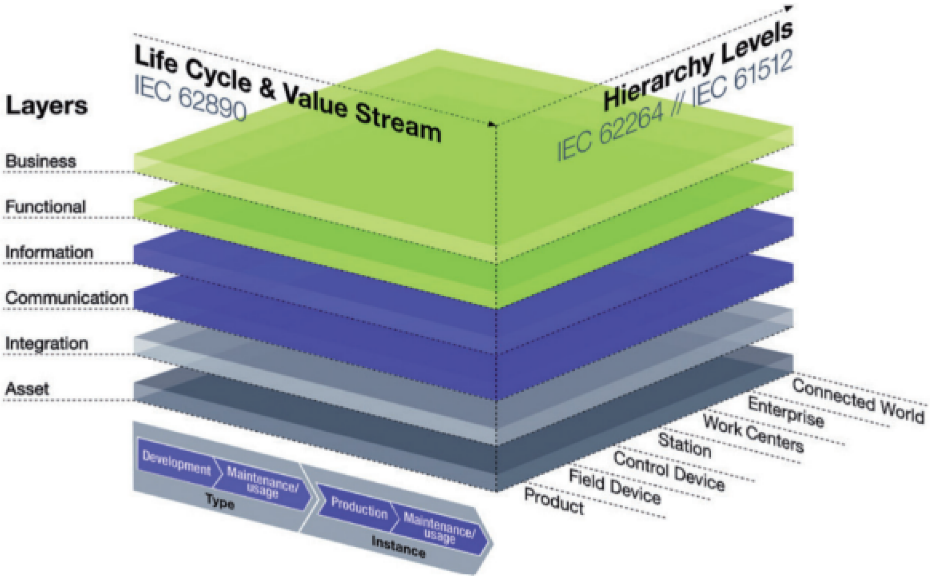


Figure 4.14: The RAMI 4.0 Architecture

The Issues and Challenges of Industry 4.0

Advancements in technology have propelled industrial development from the early integration of mechanical systems to today's highly automated assembly lines, allowing industries to adapt and respond to the dynamic demands of the current market. Challenges such as embedment, predictability, flexibility, and resilience to unforeseen conditions persist in this evolution. Several fundamental challenges and issues [48] emerge during the implementation of Industry 4.0 in current manufacturing industries:

- **Intelligent Decision-Making and Negotiation Mechanism.**Smart manufacturing systems require greater autonomy and social capabilities as vital facets of self-organized systems, whereas existing systems lack sufficient autonomy, with only 3C capabilities.

- **High-Speed IWN Protocols.** Present IWN networks lack the necessary bandwidth for extensive communication and transfer of large data volumes, although they outperform wired networks in manufacturing environments.

- **Manufacturing-Specific Big Data and Analytics.** Ensuring the quality and integrity of recorded data from manufacturing systems poses a challenge. The diverse annotations of data entities and the integration of various data repositories with different semantics for advanced analytics present an increasing challenge.

- **System Modeling and Analysis.** To minimize dynamical equations and derive appropriate control models in system modeling, it's crucial to model systems as self-organized manufacturing systems. Ongoing research focuses on complex systems.

- **Cybersecurity.** The increased connectivity and use of standard communication protocols in Industry 4.0 elevate the necessity to safeguard critical industrial systems, manufacturing lines, and system data from cyber threats.
- **Modularized and Flexible Physical Artifacts.** For product processing, equipment for machining or testing should be grouped and collaboratively operated for distributed decision-making. Hence, there's a need to develop modularized and intelligent conveying units capable of dynamically reconfiguring production routes.
- **Investment Issues.** Investment remains a general challenge for most new technology-based initiatives in manufacturing. Significant financial investment, especially for Small and Medium-sized Enterprises (SMEs), is necessary for the initial implementation of Industry 4.0. Implementing all the pillars of Industry 4.0 requires a substantial industry investment.

Operator 4.0

Another application belonging to the family of Smart Maintenance can be considered the evolution of the role of the workforce in the industries. In fact, referring to Operator 4.0 highlights the enhancement of machines which extends the cognitive capabilities of a person's perception of the environment. This is facilitated by wearable tech, sensors, and virtual reality gear, allowing operators to access crucial data that wouldn't otherwise be readily available in real-time:

- Augmented and virtual reality tech. These tools process digital information, reducing human errors and lessening the reliance on an operator's memory. They create a digitally replicated presence, reducing risks.
- Intelligent personal assistants, big data, and social network agents. Incorporating AI into human-machine interfaces enables voice, language, and vision recognition software for human-like task performance. This connects operators to smart devices' communication and machine learning methods for decision-making support.

Despite significant technological progress and the gradual introduction of Industry 4.0 into company operations, human involvement in production is and will always be vital and irreplaceable. The concept of Balanced Automation Systems is evolving from the subordinate roles of people to machines and process control into a research question and technological development. This fact emphasizes the need for human-machine cooperation to enhance job satisfaction, product quality, and cost minimization simultaneously. The typology of Operator 4.0 [49], consists of several categories aimed at improving operators' roles in the ongoing technological revolution:

- **Super-Strength Operator.** Utilizes exoskeletons for physical interaction.
- **Collaborative Operator.** Engages collaborative robots for physical interaction.

- **Virtual Operator.** Utilizes virtual reality for cognitive interaction.
- **Augmented Operator.** Engages augmented reality for cognitive interaction.
- **Smarter Operator.** Employs intelligent personal assistants for cognitive interaction.
- **Social Operator.** Utilizes social networks for cognitive interaction.
- **Analytical Operator.** Engages big data analytics for cognitive interaction.
- **Healthy Operator.** Utilizes wearable trackers for physical and cognitive interaction.

1. **Enhanced Strength Operator - operator utilizes exoskeletons**
   Powered Exoskeletons represent a mobile, lightweight, and flexible biomechanical system that can mitigate the trade-offs between manual and automated operations within production systems. These Exoskeletons enable limb movement and bolster strength and endurance. Over the long term, powered exoskeletons could enhance the sustainability of factories, especially considering an increasing proportion of elderly workers. These powered exoskeletons foster cooperation between humans and technology, simplifying tasks and alleviating physical stress. In essence, they offer additional protection, support, and strength to operators, thereby contributing to the social sustainability of the workforce. This improvement stems from enhancing the ergonomics of manual operations and elevating productivity and work quality by bolstering an operator's workload-handling capabilities.

2. **Collaborative Operator - operator employs collaborative robots**
   Collaborative Robots, a form of industrial robots, proficiently execute a variety of repetitive and non-ergonomic tasks. These robots are designed to collaborate with operators, utilizing safety measures and intuitive interaction technologies. Their operation allows interaction in shared spaces with human counterparts without necessitating traditional safety barriers. This can result in the recuperation of shop-floor space typically occupied by safety barriers.

   Moreover, these robots significantly increase operator productivity and job satisfaction by assisting in more effective task accomplishment and relieving them from tedious, non-ergonomic, and vulnerable tasks. Consequently, these technologies enhance shop-floor safety and productivity. These robots are easier to teach new tasks, without requiring programming by specialists.

3. **Virtual Operator - operator engages virtual reality**
   Virtual Reality represents a computer-generated simulation replicating a design, assembly, or manufacturing environment. This technology offers an amalgamation of interactive reality and sophisticated simulations of practical scenarios.

   Virtual Reality contributes to optimized decision-making and operator training. For instance, part models can be transformed into interactive virtual simulations to train operators in complex assembly tasks during the product assembly stage. This technology proves beneficial during production maintenance by aiding operators in assembling new parts or following new maintenance procedures.

4. **Augmented Operator - operator utilizes augmented reality**
   Augmented Reality represents a technology that enriches the real-world surroundings of the operator with digital information and media overlaid in real-time within their field of view. Augmented reality serves as a pivotal technology for improving the transmission of information from the digital realm to the physical domain of the operator. This technology brings real-time support to the operator, acting as a digital assistance system that reduces human errors. It creates a novel human-machine interface for manufacturing IT applications and assets, providing real-time feedback to enhance decision-making.

5. **Smarter Operator - operator employs an intelligent personal assistant**
   A Smarter Personal Assistant, whether a software agent or artificial intelligence, is designed to aid the operator in interacting with information systems and executing tasks in human-like interactions. Notably, it offers voice-interaction technology, enabling hands-free completion of specific tasks. This assistant offers several advantages to the operator, such as searching and retrieving data from a digital library, reading instructions during task performance, setting reminders for actions, interfacing with devices and machines via voice commands, and providing effective problem-solving tips.

6. **Social Operator - operator utilizes social networks**
   Enterprise Social Networking Services focus on employing mobile and social collaborative methods to connect shop floor operators with factory resources. This connectivity creates a network between operators and smart devices to share and create information for decision-making support. Social networking among operators empowers the workforce, expedites idea generation, and facilitates problem-solving by bringing together the right individuals. The ultimate goal of enterprise social networking is to facilitate communication between operators and machines to achieve production goals. Machines and production systems can share reports about actual production, preventive measures, production plans, and other non-time-critical information to enhance operators' knowledge about processes. Furthermore, operators can receive reminders about essential schedules via social network posts, minimizing constant notifications.

7. **Analytical Operator - operator utilizes big data analytics**
   Big Data Analytics involves collecting, organizing, and analyzing large volumes of data to obtain valuable insights and predict events. This analytics process assists operators in making more accurate predictions, understanding factory performance, providing real-time alerts based on predictive fault detection, and improving quality, thus enhancing efficiency. Real-time analysis and predictions enable the issuance of warnings about potentially hazardous situations to individual operators. The abundance of data, facilitated by inexpensive sensors and Industrial IoT, will lead to more powerful and applicable solutions in the future, resulting in more accurate data models for analytical operators.

8. **Healthy Operator - operator uses wearable trackers**
   Wearable trackers are devices that monitor human activity, heart rate, and other health-

related parameters, including GPS functionality. Although their implementation in the industry may take time, these devices illustrate their potential. Personal and workforce analytics from these wearable devices can avert immediate safety threats and quality issues by monitoring health-related metrics and notifying decision-makers. Additionally, they can improve internal logistics by determining the closest operator to an urgent task. These devices can detect increased heart rates due to stressful conditions or sudden movements, aiding in preventing workplace stress and accidents. Data privacy is a critical concern with Health-Monitoring Operator solutions. It poses challenges in two perspectives: processing data in real-time without storing personal data but sending notifications, or storing data for analysis, raising privacy concerns.

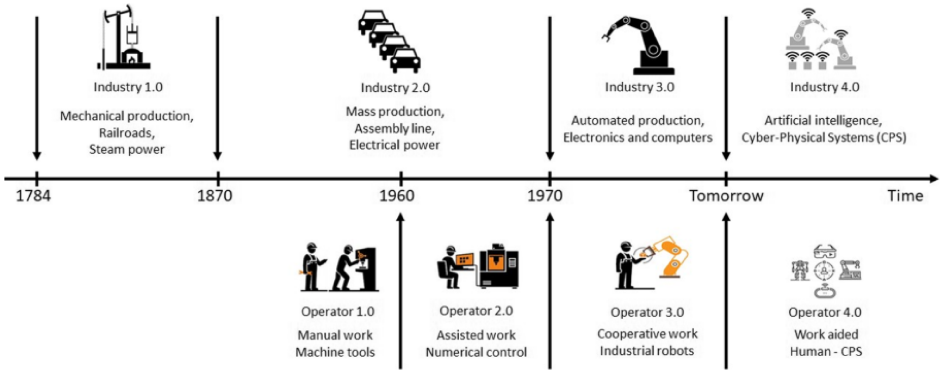


Figure 4.15: The role of operators in the evolution of Industry

4.3.2 Sensors

Industrial sensors constitute a pivotal component within the domain of modern manufacturing and production systems, serving as the sensory infrastructure responsible for capturing, analyzing, and interpreting crucial data in industrial settings. This section it will analyze the continuous evolution of sensor technologies and their integration with advanced systems such as the Internet of Things (IoT) and artificial intelligence, industrial sensors have become integral in facilitating automation, predictive maintenance, and quality control.

Industrial Sensors

In order to develop this crucial topic it is necessary to present the most common typologies of sensors adopted in the industrial environment, which represents the physical asset of smart sensors. Sensors can be categorized according to the type of quantity they measure, their operating principle, and the output magnitude. Among others, mechanical, electrical, thermal, and optical sensors belong to the first or third group, while contact and proximity sensors belong to the second. Sensors also vary in their sensitivity to the quantity to be detected, their responsiveness to the slightest distinguishable stimulus amidst background noise, their compact size to avoid disrupting measurements, accuracy (which combines insensitivity to irrelevant quantities and noise immunity), and the measurement range.

Mechanical Sensors

Mechanical sensors are classified because both the input and output quantities are mostly mechanical. They are categorized based on their operating principles: contact sensors, elastic sensors, mass (or inertial) sensors, thermal sensors, and hydropneumatic sensors.

- **Contact sensors** detect displacement, such as linkages and gears.
- **Elastic sensors** are named for the deformation of the elastic element caused by the input quantity, whether it is a force or pressure, resulting in displacement. Examples include Bourbon springs used in pressure gauges. An inertial or mass sensor, like a pendulum, is affected by gravity's acceleration. Thermal sensors, measuring temperature changes through expansion or increased pressure, include bimetallic and liquid thermometers. Hydropneumatic sensors utilize contact between two fluids, one liquid and one gaseous, measuring the variation in fluid flow when encountering an obstacle. The Pitot tube in wind tunnels is an example used to measure air current speed.

Temperature Sensors

Temperature sensors measure air temperature or the surface temperature of liquids and solids. They often act as transducers, converting temperature into an electrical magnitude. They differ in contact (thermocouples and resistance temperature detectors (RTDs)) or non-contact temperature sensors.

- The **thermocouple** utilizes the Seebeck effect, generating electricity when a circuit formed from conductive or semiconductive metallic materials experiences a temperature difference. A thermocouple consists of two metallic conductors joined at a "hot junction" where the measurement is taken and connected at the other ends to an electrical terminal called a "cold junction," linked to the measuring instrument. Opening the circuit, if the cold junction maintains a constant temperature, the hot junction will produce an electric voltage. Thermocouples are used for high-temperature measurements, commonly found in industrial settings despite potential systematic errors.
- The **resistance temperature detector (RTD)** relies on the resistance of metals, typically involving platinum wires within insulating support and a protective sheath. As the temperature increases, the metal's electrical resistance also increases, which the sensor detects. RTDs are widely used and are known for their detection precision and immunity to noise.
- **Non-contact temperature sensors**, such as infrared sensors, measure temperature through the infrared radiation emitted by the target. An infrared temperature sensor contains a lens directing radiation towards a receiver, converting it into an electrical signal and then into temperature. These sensors are suitable for moving measurements or conditions where direct object contact is not feasible. Beyond pyrometers and infrared thermometers used in industrial process monitoring, advanced temperature sensors include infrared thermal cameras. These cameras digitally process images, detecting the thermal distribution across an area, processing a matrix of points, and wireless data loggers collecting temperature measurements in real-time at specific intervals.

Proximity Sensors

Proximity sensors, and electrical devices, detect objects (especially metallic ones) nearby, whether in contact or at a distance. The range within which they detect is called the ”sensing range.” They are categorized as:

- Inductive proximity sensors leverage electromagnetic induction, inducing a current generated when the magnetic field changes within a closed circuit.
- Capacitive proximity sensors take their name from the capacitor, an electrical component comprising two plates, each charged with opposite polarity, storing potential energy in an electric field. Simplifying, the two plates generate an electric field: if one plate serves as the sensor, the nearby object becomes the other plate. The resulting current change alters the distance between the plates, a distance that can be detected and measured. Measurement accuracy improves when the target object is flat and parallel to the sensor.
- Magnetic proximity sensors detect the field generated by a magnet positioned on the object being measured. They are commonly used for security purposes, such as positioning a magnet on a window or door frame, with a Reed switch sensor. The Reed switch is comprised of two separate ferromagnetic blades, partly overlapping, enclosed in a glass bulb. In the presence of a magnetic field, these blades tend to attract and close the circuit. When the door opens, the circuit breaks, triggering the alarm. Other magnetic proximity sensors, as transducers, operate with the Hall effect, producing a difference in electrical voltage when a conductor carrying an electric current is subjected to a magnetic field.
- Ultrasonic proximity sensors employ sound waves with frequencies above 20,000 Hz, beyond the human ear’s audible range, to measure the distance from a specific target, detecting its presence or absence. The sensor emits an ultrasonic wave at a specific frequency towards the target and measures the time for the echo to return, calculating the distance.
- Optical proximity sensors, or photoelectric sensors, measure the beam of light reflected by the object to be detected. Typically, an infrared light beam is used to avoid confusion with other ambient light sources.

Inductive Sensors

Inductive sensors use electromagnetic induction, generating induced current when the magnetic field changes in a closed circuit. For example, the magnetic field varies in the presence of a ferromagnetic material: in this case, reluctance, which opposes the flow of an electromagnet, decreases. This change is measurable by the proximity sensor, which can calculate the presence and/or distance from the target object. However, for this type of operation, the object must be ferromagnetic. Apart from proximity, there are also inductive displacement sensors: among the most used is the LVDT, Linear Differential Variable Transformer.

Optical Sensors

Optical sensors, more precisely transducers, detect light rays and convert them into electronic signals. An optical sensor generally comprises a light source (e.g., LED) and a receiver (e.g., photodiode). The measurement occurs when the object interrupts or reflects the emitted light. As seen, optical proximity sensors usually employ an infrared light beam. Among the most common optical sensors are photocells or photodetectors, which vary based on the object's position concerning the emitter and receiver: between (barrier system), in front (retroreflective system), or facing the receiver (direct reflection system). In special cases, to transmit light from the emitter to the receiver, optical fibers replace classic photoelectric components. Other optical sensors include photodiodes, phototransistors, arrays of photodiodes, photoresistors, and Position Sensitive Diodes (PSD). Optical sensors also underpin photoplethysmography (PPG), measuring changes in blood vessel size to calculate heart rate via a smartwatch.

Motion Sensors

Motion sensors, also known as volumetric detectors or radar, detect the presence of individuals in the environments they are installed. They are classified as classic or "curtain" motion sensors, which work as barriers to trigger an alarm when crossed. These are akin to proximity sensors. Common types include Passive Infrared (PIR) sensors, which detect objects by measuring their infrared rays. Specifically, PIR functions as a detector, recognizing sudden temperature changes caused by a person or object entering the monitored area compared to the established "standard" temperature. Using multiple sensors within the same PIR.

Sensor Measurement Parameters

As important as analyzing the different typologies of sensors is identifying the parameters useful to gather information. This understanding can be derived from either historical data records or product specifications. Subsequently, these parameter specifics must be transformed into the requisite performance criteria for sensor systems. Various crucial performance benchmarks for sensor systems encompass [50]:

- **Measurement Range**: denoting the lowest and highest values within the sensor's capability to detect. The system's measuring span ought to exceed the actual range of what's being measured.
- **Dynamic Range**: quantifies the ratio between the largest detectable output fluctuation and the smallest distinguishable output variation, usually articulated in dB. This aspect significantly influences a sensor's capacity to respond to both substantial and minute amplitude changes in signals.
- **Accuracy**: denotes the proximity between the measurement and the accurate value of the measured quantity. Often represented as the error between the measurement and the true value.
- **Sensitivity**: generally, the proportion between a minor alteration in output and a minor modification in input, usually a unit adjustment in input. Sensitivity mirrors

the gradient of the calibration curve. While it may remain consistent across all inputs, it can also vary across different input segments.

- **Repeatability**: signifies the consistency between outcomes from successive measurements of the same quantity under identical measurement conditions.
- **Resolution**: the smallest input change necessary to elicit a noticeable change in the output. The sensor's precision is specified by the unit of the measured parameter or as a percentage of the measured parameter's range.
- **Frequency Response**: the output-to-input ratio of a sensor concerning frequency, often indicated in dB. It encompasses the sensor's capability to function effectively within a range of frequencies and showcases cutoff frequencies at the lower and upper limits.
- **Hysteresis**: the divergence in a sensor's output when approached from different input directions.
- **Linearity**: measures the maximum deviation of the output function from an ideal straight line.
- **Response Time**: denotes the duration a sensor necessitates to react to a given input, signifying the system's responsiveness to changes in the measured parameter.
- **Stabilization Time**: the duration required for a sensor to achieve a stable output upon exposure to a constant input.
- **Sampling Rate**: the number of samples taken from a continuous signal within a specific time unit, establishing a discrete signal.

Smart sensors

The evolution of Industry 4.0 technologies has been a pivotal driving force in the transformation of conventional manufacturing processes, introducing a paradigm shift in the production landscape. Central to this transformation are smart sensors, which have emerged as a cornerstone in the realization of efficient, responsive, and interconnected industrial systems. These sensors, empowered by the integration of Industry 4.0 technologies, offer enhanced capabilities and functionalities, adapting the existing sensor infrastructure to meet the demands of modern manufacturing.

Industry 4.0 signifies a fusion of digital technologies and physical systems, orchestrating a revolution in manufacturing, characterized by the utilization of cyber-physical systems, the Internet of Things (IoT), cloud computing, and data analytics. Within this framework, smart sensors play a critical role as the conduits for data collection and transmission in real-time, providing essential insights into the operational processes of machinery, equipment, and the overall manufacturing environment.

The adaptation of existing sensors in the context of Industry 4.0 technologies represents a significant leap toward intelligent manufacturing. By infusing traditional sensors with smart capabilities such as connectivity, data processing, and autonomous decision-making, industries can achieve heightened efficiency, predictive maintenance, and agility in responding to dynamic production requirements. Smart sensors offer a range of improvements, from real-time monitoring and control to the predictive analysis of equipment performance and the optimization of manufacturing processes.

Smart sensors are integral components of the Internet of Things (IoT) that transform real-world input into predefined functions, processing this data before transmitting it to a digital data stream for further communication to a central gateway.

These advanced sensors are highly accurate, aiding in the automated and error-free collection of diverse data, particularly for monitoring and regulating systems across a wide array of applications [51]. In the context of Industry 4.0, smart sensors possess distinct attributes such as the capability for self-diagnosis by monitoring and interpreting signals, offering features like self-detection, intelligent calibration, digital sensor data, remote sensing, and configuration abilities.

Notably, smart sensors significantly reduce the need for human intervention and management control in various operational systems, simplifying tasks, ensuring operational isolation in challenging industrial settings, and interpreting data in a logical manner through computerized systems. With their ability to enhance work productivity and perform self-diagnostics, smart sensors find utility in multiple applications within industries, significantly impacting manufacturing efficiency and performance.

They are instrumental in monitoring and enhancing equipment and system performance, leading to reduced waste and better management of production processes, contributing to economic growth in various industries. These sensors facilitate the generation and aggregation of data from diverse devices and systems, ensuring seamless connectivity across industrial facilities, and aiding in the enhancement of information flow and the prediction of machinery failure.

One of the key advantages of smart sensors lies in their ability to expedite the flow of real-time information, enabling prompt adjustments that boost production output and profitability by increasing transparency and information flow. The application of smart sensors in the industry extends advantages like heightened productivity, efficient resource management, seamless integration of production processes, and the automation of various production elements. Furthermore, they are pivotal in identifying and resolving technical issues before they escalate, providing relevant, up-to-date information pertinent to production and business processes, and increasing efficiency to achieve mass production while reducing assembly costs.

Chapter 5

Maintenance KPIs

Maintenance can effectively manage maintenance activities and track their success, organizations rely thanks to a set of key performance metrics. These metrics serve as vital tools for assessing the efficiency and effectiveness of maintenance processes, helping to identify areas for improvement, allocate resources judiciously, and ultimately enhance overall operational performance. In this era of data-driven decision-making, maintenance metrics provide valuable insights that enable organizations to align their strategies with their maintenance objectives and to make informed choices regarding resource allocation and asset management. Understanding and utilizing these key performance metrics is crucial for organizations looking to optimize their maintenance processes, reduce operational risks, and maximize the return on investment from their assets. By systematically monitoring and analyzing these metrics, organizations can make informed decisions and strategic adjustments that lead to enhanced operational efficiency and a competitive advantage in today's dynamic business environment.[52]

In the contemporary economic landscape, Key Performance Indicators (KPIs) hold significant importance in the management of businesses. They serve the crucial purpose of discerning vital data from the less pertinent, simplifying intricate subject matter, and fostering transparency. Numerous scholars have affirmed that KPIs serve as the foundation for the analysis and enhancement of processes, along with the establishment of benchmarks. Furthermore, KPIs serve the following functions:

- Facilitating planning across diverse domains, such as strategy and budgeting.
- Providing the prerequisites for goal setting and overseeing their execution.
- Serving as a foundational element for decision-making within a company.
- Offering incentives, primarily to top management but also to employees.

They can be classified [53] [54] as:

- Leading indicators are metrics that provide insights into activities and factors that have a significant impact on future performance. They are leading in the sense that they signal potential changes or improvements before the actual performance outcomes are realized. Organizations use leading indicators to proactively manage and influence their future results.

- Lagging indicators are metrics that assess the results of past activities. They are often used to measure the historical performance of an organization. While they provide a view of what has already happened, they are less useful for immediate course correction.
- Diagnostic Metric is a KPI that does not fall into the categories of leading or lagging indicators but rather acts as a signal for the health of processes or activities. For instance, the number of client meetings per week by sales representatives might be a leading indicator of Sales Revenue (a weaker indicator or outcome). ”Successful completion of complex repairs during the initial visit” can serve as a leading indicator of ”Customer satisfaction.” Leading indicators are highly valuable metrics as they reveal predictive and insightful causal relationships within the business processes, guiding actionable steps for process improvement. Therefore, crafting effective leading KPIs is crucial for the success of any business organization, enabling it to adapt swiftly to changes and remain prepared for forthcoming transformations. However, identifying leading indicators can be a challenging task that often requires months for data collection, definition and rule establishment, metric preferences, and feedback facilitation, among other factors.

The Maintenance Indicators can be grouped into three main families: the Availability Indicators, the Reliability Indicators, and the Maintainability Indicators.

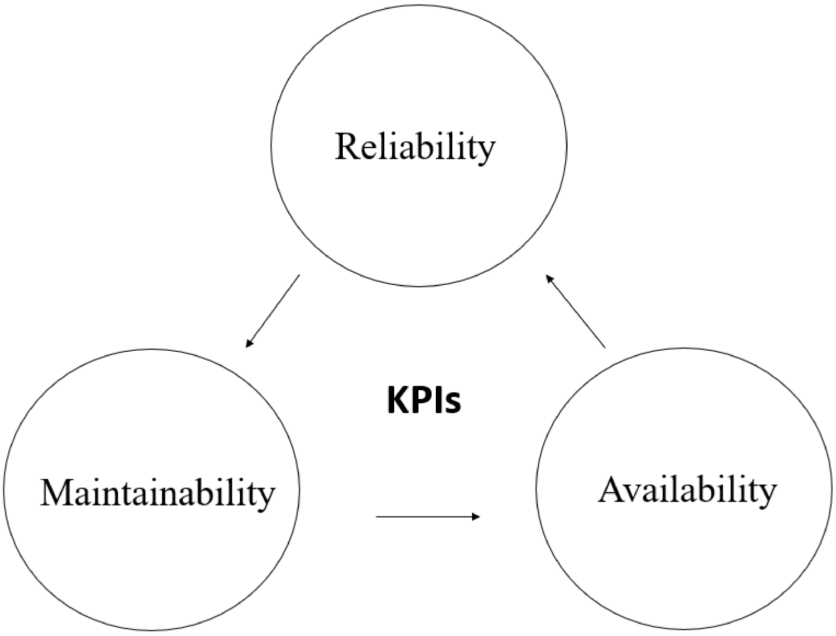


Figure 5.1: The three families of Maintenance Indicators

5.1 Availability Indicators

The Availability Indicators give an indication of how much the machine is made available for production; a distinction can be made between time dedicated to prevention and time dedicated to correction. The main indicators belonging to this family are listed below.

BD % based on OEE
It's the ratio between the time the machine remained faulty (F) compared to the time programmed for production (TPP) expressed in minutes. In order to improve the value has to diminish.

$$\text{BD\% on OEE} = \frac{\text{F}}{\text{TPP}}$$

BD % based on Time Available for Production
It's the ratio between the time the machine remained faulty (F) compared to the time available for production (TAP) expressed in %. Must be a value less than or equal to the BD% on the OEE indicator.

$$\text{BD\% on Availability} = \frac{\text{F}}{\text{TAP}}$$

PM % based on Time Available for Production
It's the ratio between the time the machine has remained stopped due to preventive maintenance activities (PM) compared to the time available for production (TAP) expressed in %.

$$\text{PM\% on Availability} = \frac{\text{PM}}{\text{TAP}}$$

Operational Availability - OA
It is the ratio between the time available for production (TAP) net of downtime due to maintenance activities (MADT) and the available time itself, expressed in %.

$$\text{OA} = \frac{\text{(TAP-MADT)}}{\text{TAP}}$$

5.2 Reliability Indicators

The Reliability Indicators measure the ability of equipment or systems to consistently perform their intended functions without failures or breakdowns. It assesses the likelihood of failure over a specified period.
In order to proceed with the development of these KPIs it's necessary to define four different events:

1. T1 - Opening Downtime: the operator declares the beginning of the downtime on the PCS.

2. T2 - Opening Intervention: the maintainer as soon as he intervenes on the machine logs on the PCS.
3. T3 - Closing Intervention: the maintainer as soon as he ends the intervention logs out on the PCS.
4. T4 - Closing Downtime: it is automatically finished with the first piece counted by the machine.

BreakDown Maintenance Number - BDMN
It represents the count of faults where maintenance has intervened to resolve them. The correct value is independent of the correct behavior of the maintainer who must log in.
BDMN = CountBD(T2)

Mean Time Between Failure - MTBF
It is the average time between two subsequent failures. It is calculated as the ratio of the scheduled production time net of failures (TAP - F), divided by the number of failures minus one (BDN - 1), expressed in minutes. From a continuous improvement perspective, the value must increase.

MTBF = $\frac{\text{(TAP-F)}}{\text{BD-1}}$

5.3 Maintainability Indicators

The Maintainability Indicators assess how easily and efficiently equipment or systems can be repaired or maintained. It measures the time, resources, and effort required to restore the equipment to operational status after a breakdown or failure.

Mean Down Time - MDT
It's the average duration of total failures. It is calculated as the ratio between the total time of failures (T4 - T1) divided by the number of them (BDN), expressed in minutes, and with a view to continuous improvement it must tend to decrease.

MDT= $\frac{\sum(T4-T1)}{\text{BDN}}$

Mean Down Time Maintenance - MDTM
It is the average duration of faults repaired by maintenance workers. Analytically it is calculated as the ratio between the total time of faults (T4-T1) repaired by maintenance divided by the number of them (BDMN), expressed in minutes.

MDTM= $\frac{\sum(T4-T1)}{\text{BDMN}}$

Mean Time To Repair - MTTR
It's the average duration of a failure repaired by the maintenance department. It is calculated as the

sum of the Time To Repair (TTR) of each failure divided by the number of maintenance interventions (BDMN), expressed in minutes.

MDT= $\frac{\sum(TTR)}{\text{BDMN}}$

Chapter 6

The CMMS

Maintenance management within extensive industrial operations is intricate and exerts a significant influence on the profitability of a company's earnings. Consequently, it appears that effective maintenance management is nearly unattainable without the backing of a computer-based system. To attain streamlined maintenance management necessitates access to technical, financial, and historical information related to both the equipment and the company's infrastructure. This is effectively accomplished through the utilization of a Computerized Maintenance Management System (CMMS). Maintenance management entails numerous activities aimed at defining maintenance objectives, strategies, and responsibilities, and executing them through processes such as maintenance planning, control, and supervision, all while enhancing the organizational structure, including its economic aspects.
CMMS can be defined as a specialized software application or integrated suite of tools designed to streamline and optimize the management of maintenance activities within an organization. CMMS solutions are used across various industries to efficiently plan, schedule, track, and analyze maintenance tasks and resources, with the primary goal of enhancing asset reliability, minimizing downtime, and extending the lifespan of equipment and facilities. It serves as a central hub for managing all aspects of maintenance operations, from asset tracking and scheduling to resource allocation and performance analysis [55].

The historical development and progression of Computerized Maintenance Management Systems (CMMS) span several decades [56], marked by significant innovations and advancements. Below, we provide an overview of the major milestones in the evolution of CMMS:

- Before the 1980s CMMS originated in the creation of computerized systems designed to manage maintenance data. During this era, early computer systems were harnessed for the storage and retrieval of maintenance-related information. These systems primarily focused on overseeing inventory control, work order management, and the tracking of equipment. They played a pivotal role in transitioning organizations from manual record-keeping to the adoption of digital databases.
- The 1980s witnessed the emergence of specialized CMMS software applications. These platforms were engineered to handle more intricate maintenance functions, including the scheduling and tracking of preventive maintenance activities. The proliferation of computer technology and the increased affordability of computing equipment contributed to the widespread adoption of CMMS solutions.
- From 1990s ushered in a period of rapid expansion for CMMS. Software interfaces became more user-friendly, and they featured enhanced reporting and analytical capabilities. Integration between CMMS and other enterprise systems, such as Enterprise Resource Planning (ERP)

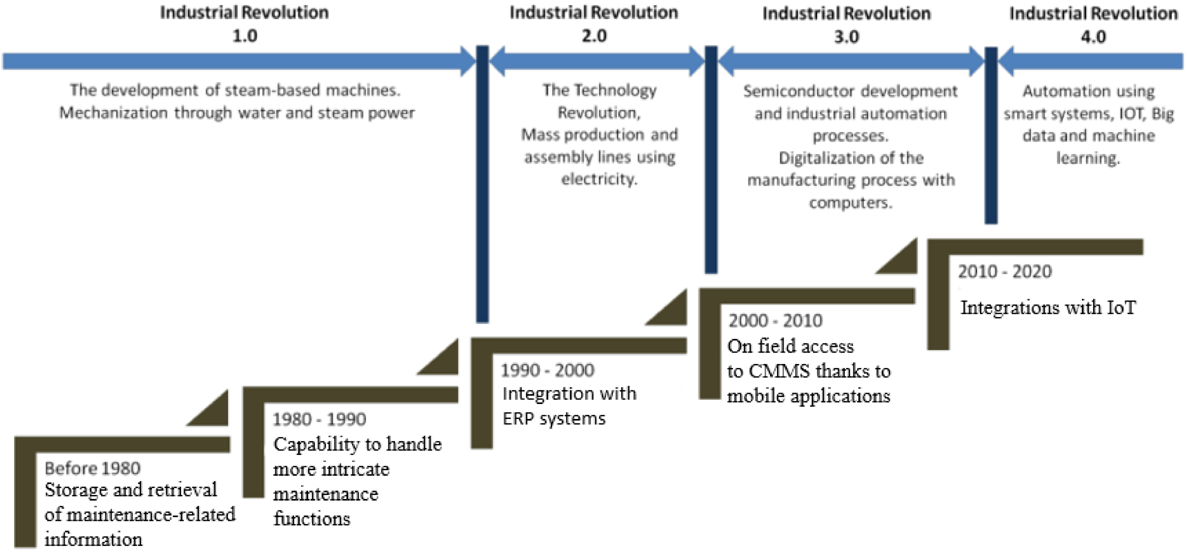


Figure 6.1: CMMS evolution during last decades

software, gained prominence, enabling seamless coordination between maintenance operations and other facets of business management.

- During the 2000s, web-based and cloud-based CMMS solutions gained traction, providing improved accessibility and fostering collaboration among maintenance teams. The prevalence of mobile applications tailored for CMMS use allowed maintenance personnel to access and update maintenance data while in the field, significantly enhancing operational efficiency.
- While from the 2010s it has witnessed the convergence of CMMS with Internet of Things (IoT) technology. This integration enabled real-time monitoring of equipment and assets, paving the way for predictive maintenance strategies. CMMS software evolved to encompass advanced analytics and reporting functionalities, empowering organizations to make data-driven decisions and optimize their maintenance operations.
- Nowadays CMMS continues to evolve, now incorporating cutting-edge technologies like Artificial Intelligence (AI) and Machine Learning (ML) to support predictive maintenance and optimize asset performance.

6.1 Functions

The functions of a Computerized Maintenance Management System (CMMS) typically consist of several modules that work together to facilitate effective maintenance management. The structure of a CMMS can vary depending on the software provider and the specific needs of an organization. Customization options are often available to adapt the CMMS to the unique requirements of different industries and businesses. However, the majority of this software presents the same modules [57] (enlisted below), which can be considered necessary to provide a minimum level of dependability to the CMMS.

1. **User Interface**, which is composed of a dashboard, the main screen where users log in and access various CMMS functionalities, a navigation Menu that provides access to different modules and features within the CMMS, and the user profiles that allows administrators to manage user roles, permissions, and access levels.
2. The **Asset Management** build on two main domains: the Asset Registry which stores detailed information about all equipment, machinery, and facilities, including specifications, maintenance history, and location, and Asset Hierarchy which organizes assets into a hierarchical structure, such as systems, subsystems, and individual components.
3. **Work Order Management** has the role of allowing users to create, assign, and prioritize maintenance tasks, monitor the status of work orders from creation to completion, and store a record of all work orders for historical analysis.
4. **Preventive Maintenance Scheduling** which enables the creation and scheduling of routine maintenance tasks based on time intervals, usage, or condition-based triggers, contains detailed instructions and checklists for each preventive maintenance task and provides a visual overview of scheduled PM activities.
5. **Inventory and Parts Management** that manages spare parts, consumables, and materials, including stock levels, reorder points, and usage tracking, and at the same time stores information about suppliers and tracks procurement activities.
6. **Maintenance Records and Documentation** whose role is to record details of maintenance activities, including date, time, and personnel involved. It stores inspection results and compliance documentation and it manages manuals, schematics, and other maintenance-related documents.
7. The**Resource Allocation** has the responsibility of managing maintenance personnel, their schedules, and skills as well as the responsibility of tracking the availability and condition of tools and equipment needed for maintenance tasks.
8. **Reporting and Analytics** whose main duties are generating customizable reports and analytics on maintenance performance, costs, and asset health and displaying important metrics for maintenance management, as KPIs.
9. **Integration with Other Systems**, For example, interfaces with other enterprise systems, such as ERP or IoT platforms, for data exchange and coordination or Mobile Access which provides mobile applications for field personnel to access CMMS data and update work orders in real-time.
10. **Compliance and Safety** which helps organizations adhere to industry-specific regulations and safety standards and helps organizations to comply with safety protocols and ensures their enforcement during maintenance activities (ex. POWRA)

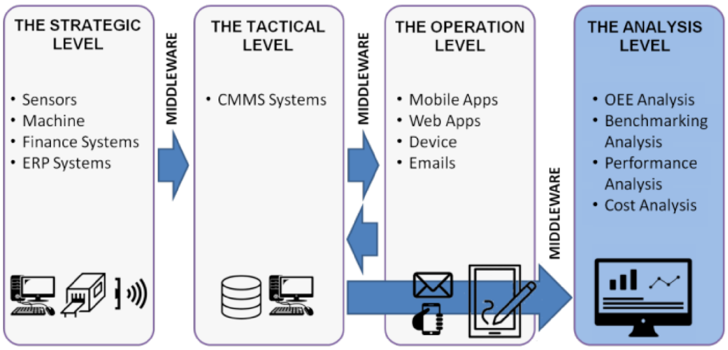


Figure 6.2: Levels in the implementation of CMMS

11. **Help Desk** that provides support for CMMS users, including technical assistance and issue resolution, and offers training materials and resources to educate users on CMMS functionalities.

6.2 Implementation of CMMS

CMMS plays a pivotal role in business operations, aligning with the concepts outlined by Márquez [58] who categorizes business activities into three distinct levels:

1. The Strategic Level

2. The Technical Level

3. The Operational Level

These levels can be described as follows:
The Strategic Level aligns maintenance management objectives with broader business goals. It involves strategic planning to establish critical targets that support current operations. Building connections with other systems, such as electronics, devices, or Enterprise Resource Planning (ERP) systems, holds significant importance at this stage.
At the Tactical Level, the allocation of predefined maintenance resources is determined. Detailed maintenance requirements, as well as planning and scheduling of resources, are defined. CMMS, functioning as a maintenance management system, stores all planning-related data in its database. It facilitates scheduling, planning, and resource allocation, encompassing workforce and spare parts management.
The Operational Level ensures that maintenance tasks adhere to the established planning, encompassing task categories, schedules, procedures, and tools. Work assignments are distributed among the relevant staff members. Additionally, maintenance data should be incorporated into the CMMS database, ensuring updates upon task completion.
However, to meet the requirements of Industry 4.0, there is an additional component known as "The Analysis Level." In this stage, all collected information undergoes "Big Data" analysis based on predefined parameters. This analysis serves as a response to maintenance operations, facilitating further adjustments and task planning. Mathematical and statistical calculation methods are employed in this process, and the results of the analysis are presented in the form of graphical representations, tables, or percentages.

6.3 Root Causes and Solutions for Poor Implementation of CMMS

Successfully implementing a Computerized Maintenance Management System (CMMS) within an industrial environment remains a challenging endeavor, marked by various complexities and potential setbacks. Despite the notable advantages and promise that CMMS holds, its effective adoption often encounters numerous obstacles, leading to sub-optimal outcomes. The roots of poor implementation are multifaceted and demand a careful analysis to understand and overcome these challenges. In the landscape of industrial operations, the introduction and integration of CMMS face hurdles that significantly affect its successful deployment. Factors contributing to these challenges include [59]:

1. Organization's lack of preparation
Numerous instances of CMMS implementation failures stem from inadequacies within the maintenance organization, often ill-prepared to assimilate a complex computer system. Essential for any organization contemplating CMMS adoption is to ascertain their stage of maintenance evolution. Prior to integrating a CMMS, the maintenance strategy should have transitioned from a reactive stance to, at minimum, a proactive approach. A well-structured preventive strategy must be firmly in place and actively adhered to throughout the organization. A well-defined workflow delineating each facet of this strategy forms the fundamental groundwork for implementing the CMMS. It acts as a tool that not only adds significant value to all departments but also culminates in a measurable added value for the company.

2. CMMS as a supportive tool for maintenance strategy
A common misconception regarding the role of a CMMS is that it embodies the maintenance strategy itself, rather than serving as a supportive tool for an organization's existing maintenance strategy. This misinterpretation often leads to improper utilization of the available system modules. The misguided belief that a CMMS alone can shift an organization's maintenance approach from reactive to proactive results in under-utilization. This misuse, coupled with inadequate data implementation, leads to the CMMS being reduced to a mere "work order system." Worst-case scenarios entail experienced maintenance personnel channeling their efforts into the CMMS, consequently impeding maintenance performance due to the lack of time devoted to previously well-understood maintenance essentials, essential for maintaining operational standards.

3. Insufficient IT infrastructure
The often underestimated, yet crucial, step in CMMS or EAM system implementation is the organization's IT infrastructure. To seamlessly integrate a "new" tool, the infrastructure's speed and capacity become paramount. High-speed internet connectivity is imperative to swiftly and reliably exchange data, especially with the prevalence of "cloud-based" CMMS and EAM systems. Additionally, an efficient and fast intranet plays a pivotal role in keeping documents updated, secure, and accessible across the organization. Inadequate infrastructure results in interruptions and hindrances for system users in their daily tasks. This, in turn, prompts individuals to revert to local databases (e.g., MS Office) out of frustration, thereby undermining the benefits of a CMMS. Furthermore, inadequate printing capability poses a technical hindrance, necessitating comprehensive planning to enable seamless printing of work packages, an aspect that significantly impacts the productivity of the planning department, particularly for larger CMMS platforms like SAP and Oracle EAM.

4. Inability to convey CMMS benefits to management
The failure to effectively communicate the benefits of CMMS to senior management and sustain their support throughout the often extended implementation duration presents a substantial challenge. Unrealistically short milestones and the subsequent exceeding of deadlines can lead to the erosion of critical senior management support. A lack of clear communication regarding the benefits and the

establishment of realistic time frames further contribute to this issue. Effective return on investment must be clearly communicated, emphasizing the lengthy implementation duration in tandem with the management's recognition of the genuine benefits of maintenance tools.

5. Neglecting a well-designed change management process

The implementation challenge of CMMS or EAM systems often encounters resistance from maintenance craftsmen and supervisors. The underlying problem typically stems from change management rather than technical CMMS issues. Often, implementations focus primarily on technical aspects such as PM Plans, codifications, and user training, inadvertently overlooking or delaying the human aspect. Consequently, this results in poor implementation due to underused or unreliable data entered into the system. The challenge in change management lies in underestimating resistance to change and managing unrealistic expectations about the positive changes anticipated from the CMMS or EAM system.

2.6. Insufficient allocation of resources

A frequently underestimated aspect of CMMS or EAM system implementation is the substantial number of hours and effort required. Collating and formatting the necessary data for system upload requires a significant effort. Additionally, system roll-out demands continual follow-up to ensure adherence to defined processes and the gradual elimination of parallel systems. Often, companies strive to rely solely on in-house resources, which proves unrealistic given the considerable man-hours and effort necessary.

However, it is possible to identify the best practices that are useful to avoid the possible reasons for the failure of the implementation of the CMMS. Below each point explain how to cope with each risk.

1. Organizational Readiness Assessment

It is natural for an organization to aspire to implement state-of-the-art tools when adopting new processes. However, an essential preliminary step before introducing a new "tool," such as a CMMS or EAM System, involves assessing the organization's current status in the context of the "evolution of Maintenance Strategies." To mitigate potential biases, it is advisable to conduct this assessment with the involvement of an external entity. Assessments carried out by internal resources with long-standing interpersonal relationships often yield overly favorable results. The organization's management must be cognizant that the successful implementation of a CMMS, aimed at enhancing maintenance and yielding increased profits through added value, hinges on the presence of a well-structured maintenance strategy with a proactive approach. If the assessment reveals a misalignment in this aspect, it becomes imperative to redirect efforts toward establishing this foundation, a pivotal initial step in preparing the organization for CMMS adoption. Neglecting this foundational step substantially increases the likelihood of failure.

2. CMMS as a Supportive Tool for Maintenance Strategy

Organization management and personnel need to comprehend that a CMMS does not constitute a maintenance strategy in itself but functions as an indispensable tool for enhancing maintenance management. A clear understanding of the CMMS's role within the maintenance strategy framework will delineate the specific information the system should generate to support the strategy. This understanding will guide the determination of necessary inputs, encompassing data requirements, structural configurations, and workflow processes that the system must support. Collaboration between craftspeople, maintenance leaders, operators, and operational leadership is vital in achieving substantial improvements in the overall operational process. The ultimate goal is the success of the entire operations and the tangible outcome is sustained and profitable business continuity. The CMMS serves as a common platform that facilitates the implementation of the strategy across various departments within the organization. This enables swift and efficient communication, culminating in numerous organizational benefits:

- Enhanced planning and scheduling
- Reduced time for spare parts and tool assembly
- Lowered stock levels
- Overall increase in productivity

3. Adequate IT Infrastructure
For the seamless integration of the CMMS or EAM system, the organization's IT infrastructure must meet specific criteria. This includes ensuring that the internet connection, intranet, and printing environment are well-prepared to ensure system performance remains seamless, rapid, and reliable. Third-party software solutions for printing work order packages, along with associated documents, can be considered. Some providers can even assist in implementing the server structure, ensuring the continuous printing of updated documents, such as safety documents, when work orders are initiated. An appropriate printing solution further ensures automatic printing of all components within work packages, thereby streamlining the process.

4. Communicating CMMS Benefits to Senior Management
A well-implemented CMMS promises numerous benefits for the organization. However, the most significant added value that must be conveyed to senior management is the CMMS's capacity to transform data into actionable information for problem analysis and solution identification. This transformation facilitates performance enhancement by mitigating hidden costs, as elucidated in the "Iceberg Model." It encompasses the ability to calculate key metrics like MTBF, MTTR, and OEE, producing "Top Ten" reports that empower maintenance managers to swiftly address problem areas and optimize resource allocation. This represents the real potency of the CMMS. While the substantial benefits of the CMMS in reducing hidden costs are undeniable, they can sometimes be challenging to predict precisely. Nonetheless, it is well-documented that a correctly implemented CMMS leads to a 5-10% reduction in direct maintenance costs within three years. This reduction is primarily driven by significant improvements in planning, leading to improved workforce utilization, and inventory control, which includes stock level management. Consequently, the return on investment for a properly implemented CMMS or EAM system often materializes in less than one year. Senior management must recognize the often protracted implementation timeline and pledge unwavering support throughout the entire duration.

5. The Imperative of a Well-Designed Change Management Process
The natural inclination to fear change presents a challenge, and the only effective approach to surmount these human barriers is through the development of a meticulously planned change management process. This process necessitates transparent and inclusive communication with all employees, starting from the earliest phases of implementation. It is crucial for every employee, from craftsmen to managers, to understand the overarching vision, the implementation process steps, and the milestones to be achieved. Critical aspects to be addressed and communicated across all organizational departments encompass:

- Clearly defined roles and responsibilities
- Well-defined guidelines
- The necessity for cross-departmental collaboration
- Acknowledging that resistance to change is natural and providing opportunities for information sharing and addressing concerns
- Managing realistic expectations about changes and anticipated benefits

6. Resource Adequacy
During the budget development phase, careful consideration must be given to manpower concerns, and adequate contingencies should be in place. Depending on the estimated total man-hours required and the readiness of the organization, the implementation team should comprise a combination of:

- CMMS supplier personnel
- Key users (in-house staff temporarily released for the project duration)
- Internal staff temporarily reassigned from regular duties
- Experienced contractors

Engaging external personnel allows the management to temporarily relieve their staff, thus avoiding part-time involvement that might hinder the project's progress. An effective CMMS implementation necessitates the full-time dedication of knowledgeable and experienced personnel. A dedicated full-time project implementation team, augmented by external support, is crucial in expediting the transition to system ownership by future users as soon as possible after the project's initiation. Many organizations have successfully identified ”key users” who undergo workshops to understand the system's advantages, utility, and organizational benefits. These key users are selected based on several characteristics:

- Openness to new techniques
- Representativeness across different areas of the organization
- Strong social connections within the organization
- Leadership skills

6.4 Benefits of CMMS

In contemporary maintenance management systems, computerized systems have become an integral component. Manual maintenance systems cannot match the precision, efficiency, speed, sophistication, and processing capabilities of computer technology. Modern computer technology has made it feasible to develop and oversee maintenance as a pivotal business driver, thanks to its ability to handle information and analysis requirements effectively, it has made it possible to achieve some crucial benefits [60].

The primary benefits when implementing such a component include:

1. Enhanced control over resources (maintenance personnel, spare parts, equipment, etc.).
2. Improved cost management and audit ability.
3. Capacity to schedule intricate and dynamic workloads.
4. Integration with other business systems.
5. Augmented reliability of physical assets through the application of a well-structured maintenance program.

Simultaneously, Schultz [61] also mentions two principal goals of a CMMS. The first goal is to manage and control work in a meaningful manner, while the second entails devising a proactive maintenance plan. Furthermore, Langan [62] asserts that CMMS and other software have expanded the role of maintenance to a ”preventive level,” bolstering its credibility in the eyes of management. Peters underscores that a CMMS equips maintenance processes with system tools and an information framework to integrate best practices, positioning maintenance as a pivotal component of the overall operation. In addition, Callahan [63] also identifies the following as the primary benefits of a CMMS:

1. Diminished frequency of equipment breakdowns, thereby enhancing overall plant productivity and profitability.
2. Shifting the focus from reactive to proactive maintenance.
3. Reducing long-term maintenance expenses.
4. Elevating total maintenance department control through improved organization and activity tracking.
5. Enhancing communication between the maintenance department and other plant functions.
6. Statistically predicting equipment failures through performance analysis.
7. Simplifying failure rate and root cause analyses with graphical representations of complex equipment and its parts.
8. Maintaining records to aid in achieving ISO or other industrial certifications and ensuring compliance with safety, health, and environmental regulations imposed by the government and related organizations.
9. Providing management with more comprehensive reports by maintaining maintenance history files and generating backlog reports for corrective and planned maintenance tasks.

Chapter 7

Case Study: the Pirelli plant

After disseminating various academic topics related to maintenance, it is time to delve into the heart of this thesis project. The following will present the activities carried out as well as the results obtained. It will be noted how the chapters leading up to this point were necessary to introduce this, as those topics were encountered during this journey aimed at transforming maintenance management.
The realization of this project was made possible thanks to an internship within the Industrial Systems Department, specifically in the Maintenance Department, at the Pirelli factory in Bollate (Milan). The goal of the Maintenance Department, where the project of this master's thesis is embedded, is to elevate maintenance management to a higher level, referred to as the Smart Maintenance Management level, to bring about a series of fundamental advantages for achieving the plant's objectives.
These interconnected objectives as cost efficiency, safety, and compliance with rules or business continuity are embedded in the role of the Maintenance Department of each manufacturing company. This preamble is needed to indicate the main steps that will be presented and developed in the next sections. The sections are:

- The AS-IS situation
- The Project and its Results
- The Future Initiatives

In parallel with this project, it has been performed also an audit process with a consultant of the IATF 16949 standards, which represents the customers and visits the plant to assess the level of compliance to the standard that wants to maintain an acceptable level of performance within the manufacturing industries. The different departments of the plant have to submit the way they organize their work, in which manner tasks are planned and performed, which are the future objectives and perspectives. In response, the consultant of the IATF 16949 makes suggestions and highlights practices that need to be improved to continue to maintain the seal of approval IATF 16949. Focusing in particular on the Maintenance team has been useful to recap precisely the level of accomplishment of the various initiatives and to show external stakeholders how things are performed within this department, something similar to what is going to be presented below, the project.

7.1 The AS-IS Situations

First of all, it is necessary to present the plant, the factory, indeed, part of the Pirelli galaxy, is mainly involved in manufacturing bicycle tires and also conducts finishing processes for tires intended for high-performance cars. The plant is structured as indicated in Figure 7.1 according to a typical pattern of horizontal organization division. The various machines comprising the plant can be divided into three categories based on their role in tire production:

- semi-finishing
- finishing
- curing

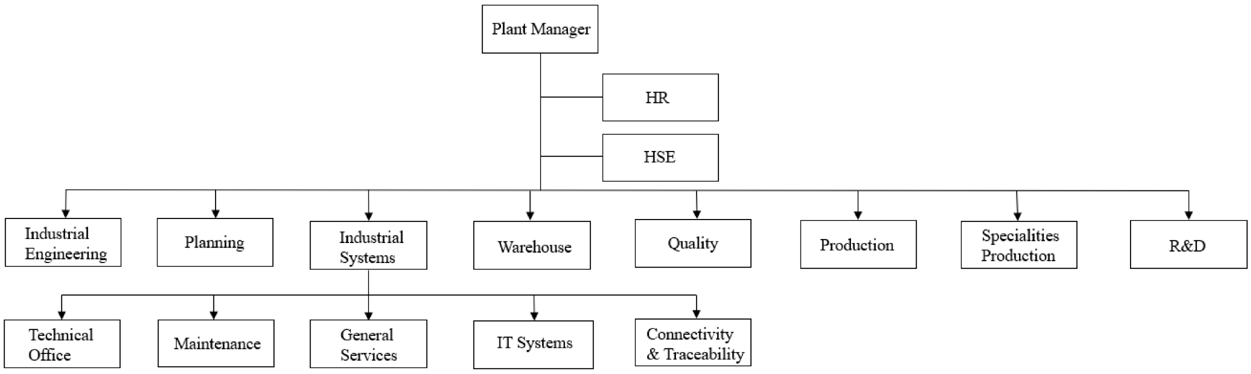


Figure 7.1: The organizational structure of the Pirelli plant

The machines in the plant dedicated to bicycle tire production are newly manufactured and installed; in fact, the change in the plant's production type occurred in 2021. Therefore, there is still a lack of basic know-how on these machines to implement strategies aligned with the company's target.
Focusing on how the Maintenance Department performs each failure will be helpful in the continuation of the project explanation.
The Maintenance Department supervises five teams of maintainers, composed of three people with mechanical and electrical competencies. The teams rotate to cover three turns per day, on seven working days. They are available to intervene and fix the failure that occurs, thanks to the communication allowed by the CMMS. A common exemplification of the management of every call coming from the operator could be the following:

1. The failure occurs
2. The operator notices the failure and communicates through the PLC and then the CMMS to the maintainer's office opening a ticket
3. According to the availability of the maintainers, the worker arrives at the machine that is not working and assesses safety, the so-called POWRA (Point Of Working Risk Assessment). The POWRA aims at assuring the safety of the workers, indeed they have to answer several questions with a tick on yes or no
4. If the safety is guaranteed the maintainers can perform the intervention to restore the working condition of the machine. Otherwise, safety conditions must first be restored before any intervention can take place. The kind of intervention depends on the typology of the failure which can be of two types: electrical, which requires a lot of time to be identified but the intervention is really fast and standardized or mechanical, which contrary is easily detectable but requires longer time of intervention

5. When the maintainer has completed the task, it describes the intervention on the CMMS, to get knowledge about causes and to keep track of the materials and components used from the warehouse

6. Then the machine is considered as working from the first piece produced

The project specifically focused on a machine belonging to the semi-finishing sector; therefore, it will be referred to as the SF Machine. The SF Machine is positioned upstream of the tire packaging process, which has not yet undergone the vulcanization process. The cutting machine and automatic joint in question aim to produce plies that will be subsequently used as reinforcement inside the tire casing. In fact, through a cutting and joining process, it is possible to produce, starting from a roll of calendared fabric, rolls of textile fabric with a variable fabric angle according to the specified setup.
The mentioned machinery features, in the loading and entry station, a roll of calendared textile material, that is, fabric coated with rubber material produced in a calendar. The fabric produced at the end of the production flow will be one of the semi-finished products used in the machinery that carries out the subsequent process, namely, the packaging process. The packaging machines, following a well-defined sequence, subsequently assemble the so-called "green tire", which is the tire assembled with various semi-finished products but not yet subjected to the vulcanization process.
Before explaining the activities carried out during the project, it is necessary to present the situation of the machine at the beginning of the project in terms of knowledge about the machine and intervention management.
The SF Machine did not have a company's bill of materials: there was the one provided by the German manufacturing company, divided into various files, without a properly unified structure. There was no collection of critical components in the machine, nor of the electrical system that allows the machine to operate, work safely, and keep track of data.
In the SF Machine were performed only corrective maintenance interventions, or work orders for temporary solutions (it can be associated with corrective ones) which is a request that outlines specific tasks or activities to address an immediate issue or problem with a piece of equipment, machinery, or a facility. The emphasis here is on implementing a temporary fix or solution to keep the operation running until a more permanent solution can be applied during scheduled maintenance or a planned shutdown. As shown in Figure 7.2, which shows the total amount of interventions in the SF Machine, there was a predominance of corrective interventions with an absolute lack of preventive ones, resulting in an MTTR of 49 minutes (as shown in Figure 7.7).

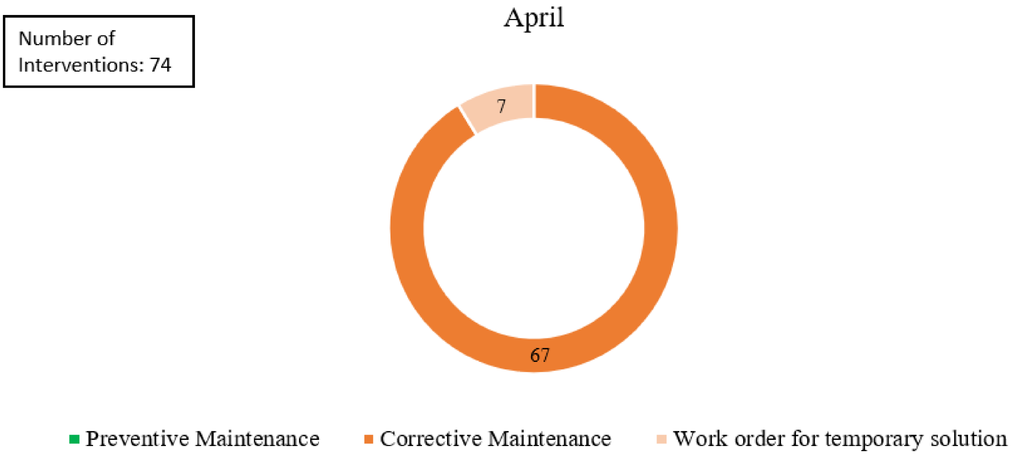


Figure 7.2: The interventions typologies in the SF machine in April

7.2 The Project and its Results

After reviewing the situation at the beginning of the project, it is time to present which tasks have been carried out during this period and what results have been achieved. The goal of the Maintenance Department is to achieve an advanced Smart Maintenance Management approach, and in the six months during which this project has taken place, there has been a contribution to this ongoing journey that will continue in the coming years. This contribution, concerning the SF Machine, starts from the basics, as highlighted in the previous paragraph regarding the initial situation of the machinery.

The first task in this journey is probably the most important, namely the drafting of the company's Bill of Materials (BoMs), creating a file that includes all components branched from the larger assembly to the more specific, as follows:

- Machine
- Assembly
- Sub-assembly
- Component
- Sub-component

It also includes a description of the singular component, the manufacturer, the manufacturer's code, an image, and the quantity. All these features will be useful to allow the maintainer to easily identify the precise point of intervention. This activity is necessary to have a deep understanding of the machinery, useful for making subsequent decisions. It serves as an "enabler" for the next steps, as well as allowing the plant to "standardize" components, which will positively impact the management of spare parts and the warehouse, enabling an overview that reduces warehouse outcomes.

The drafting of the Bill of Materials (BoMs) allows identifying the critical components of a machine. Components can be defined as critical when they possess at least one of these characteristics:

1. High cost to be replaced
2. Long supply time
3. Being essential to allow the machine to operate at full capacity.

In Figure 7.3 it is possible to have an example of the BoMs produced during the project, where the critical component selected is represented by the Electric Cylinder.

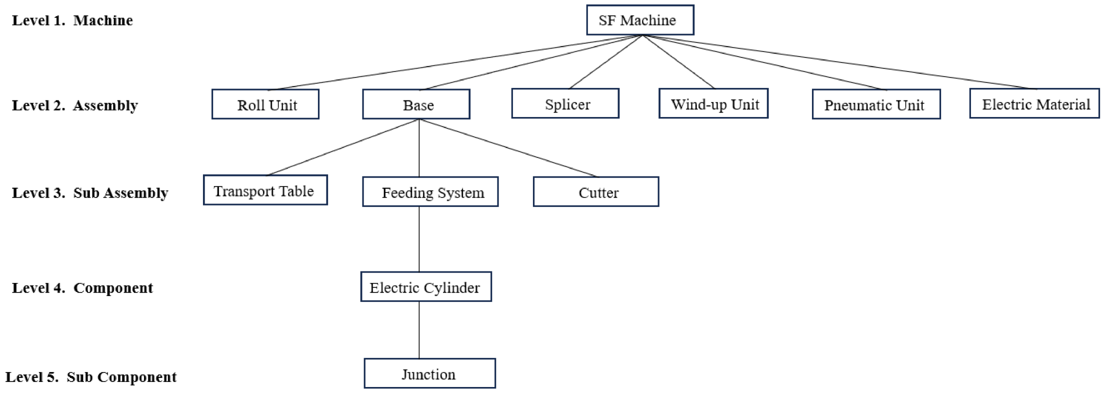
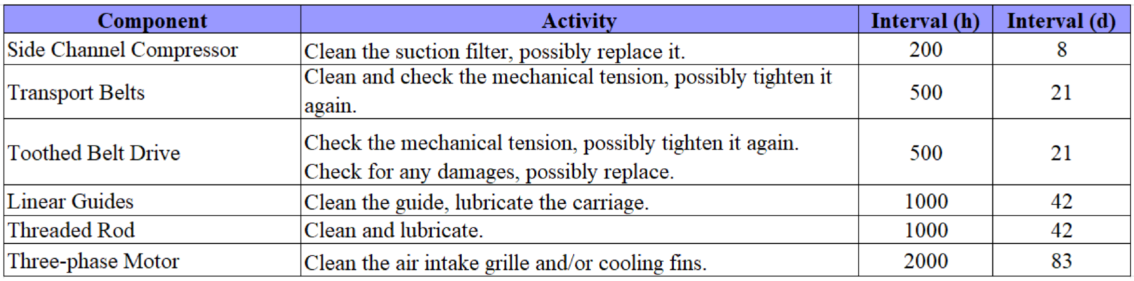


Figure 7.3: Example of the BoMs of the SF Machine

After identifying the critical components, preventive maintenance plans can be drawn up, using the various functionalities offered by the CMMS. The implementation of a preventive maintenance plan involves deciding the time frame for periodic intervention on the component, as exemplified by Figure 7.4, which depends on a series of factors:

- supplier indications (which also provide the type of action to be taken)
- the know-how of the maintenance department
- the needs of other company departments
- any machine downtime availability



Component	Activity	Interval (h)	Interval (d)
Side Channel Compressor	Clean the suction filter, possibly replace it.	200	8
Transport Belts	Clean and check the mechanical tension, possibly tighten it again.	500	21
Toothed Belt Drive	Check the mechanical tension, possibly tighten it again. Check for any damages, possibly replace.	500	21
Linear Guides	Clean the guide, lubricate the carriage.	1000	42
Threaded Rod	Clean and lubricate.	1000	42
Three-phase Motor	Clean the air intake grille and/or cooling fins.	2000	83

Figure 7.4: Example of the Preventive Plan

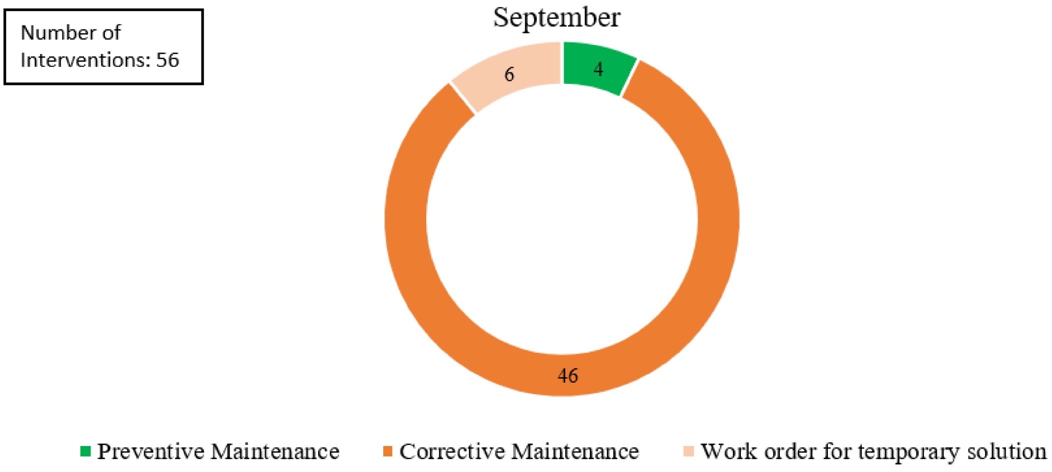


Figure 7.5: The interventions typologies in the SF machine in September

It is necessary to delve into the fact that supplier indications are usually considered too conservative, thus, it is not realistic to adopt the proposed measures in the plant's reality. For example, interventions that the manufacturer suggests should occur daily, weekly, or monthly are incorporated into a macro-intervention with a frequency of two months. Moreover, any interventions scheduled semi-annually, annually, or even over several years are usually planned when there is a machine downtime, typically in August.

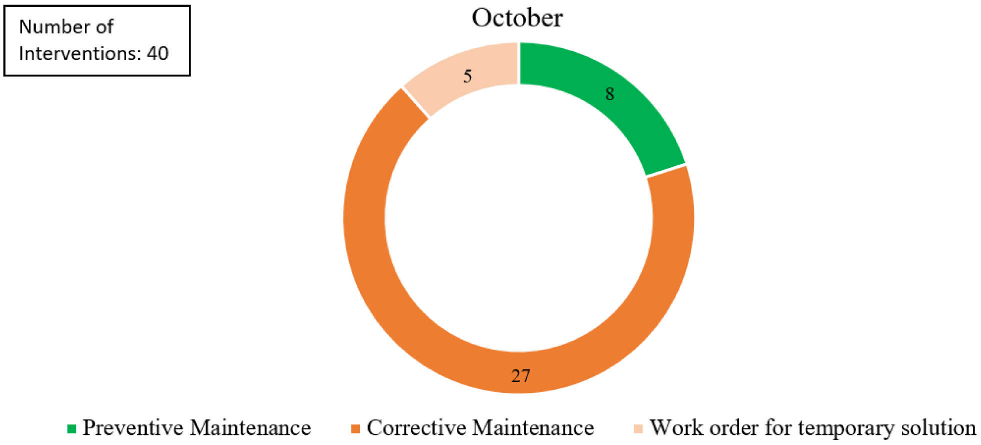


Figure 7.6: The interventions typologies in the SF machine in October

As the implementation of preventive maintenance plans progressed, the percentage of scheduled interventions in the SF Machine increased, therefore reducing the corrective interventions, as shown in Figure 7.5 and Figure 7.6. Furthermore, there has been a decrease in the total number of interventions month by month. All of this had a drastic impact on reducing the Mean Time To Repair (MTTR) of the machinery, decreasing from 49 minutes, as seen in Figure 7.7, to 40, down to 25 minutes. (Data collected on the usefulness of the scheduled maintenance system are also collected through the CMMS, which is the reference tool in Smart Maintenance.)

The decrease in MTTR marks the achievement of the set objectives. This allows the plant to have more time available for production, avoids unexpected downtime (ensuring business continuity), and reduces costs. This fact easily demonstrates the convenience of adopting this kind of approach to handle maintenance, indeed the most effective gain derives from the reduction to zero of the logistic time necessary for the maintainer to arrive at the machine and eventually the time to go in the warehouse to bring the necessary spare parts.

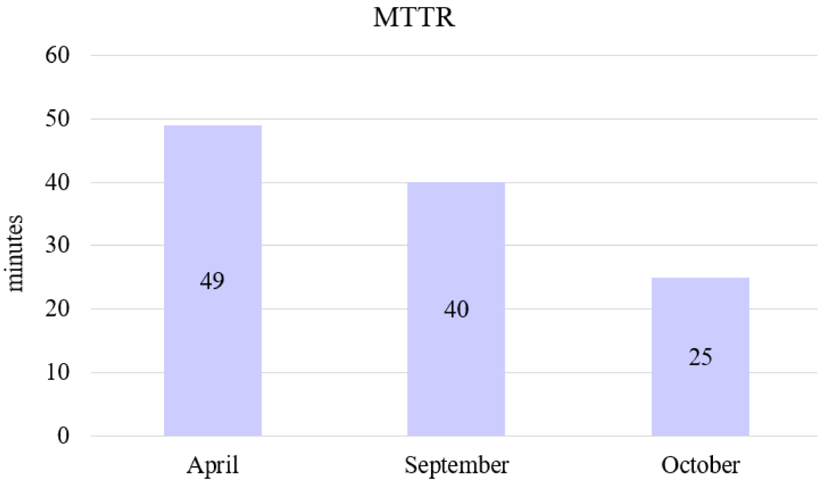


Figure 7.7: The value of MTTR during the months

7.3 The Future Initiatives

To achieve the goal of implementing a Smart Maintenance Management system in the Pirelli plant, there are still various steps to be taken. First of all, it is necessary to apply preventive maintenance to all machinery, after which predictive maintenance systems can be introduced. The latter represents the forefront of maintenance and relies on technologies belonging to the Industry 4.0 family.

Among the solutions that offer the opportunity to fully exploit the advantages of predictive maintenance are next-generation smart sensors, which represent the cutting edge in measurement technology. Alternatively, existing sensors can be ”upgraded” to version 4.0 by connecting them to the Industrial Internet of Things (IIoT). These two types of smart sensors are gathered by the way they collect information. For example, in a hydraulic cylinder where a piston moves from one side to the other, compressing air each time, the sensor measures the time it takes for the piston to complete a full movement. When this time exceeds the tolerance threshold, the sensor sends an alert to the system, and an intervention is carried out. This example is not casual, as, during the internship period, the first smart sensors were applied to a hydraulic cylinder of the SF Machine. However, it was not possible to collect data on it due to the limited duration of the internship.

When predictive maintenance reaches 100% utilization, it can permanently replace preventive maintenance. Until then, a mix of all three types (corrective, preventive, and predictive) must be used simultaneously, as shown in Figure 7.8. The total availability of predictive monitoring, however, will not allow the maintenance department to work without recording and performing corrective maintenance interventions. This can be explained, first of all, by the need to be able to operate even in the case of an ”emergency” and especially by the fact that the maintainer is still a stochastic resource, so it cannot be ruled out that unforeseen interventions may occur.

In conclusion, this technological advancement will also have an impact on the management of spare parts and the warehouse. The goal is to automate the warehouse through the use of laser-guided vehicles (LGV) and allow it, through automated guided vehicles (AGV), to support the maintainer in his intervention, for example, by autonomously providing the exact spare part needed.

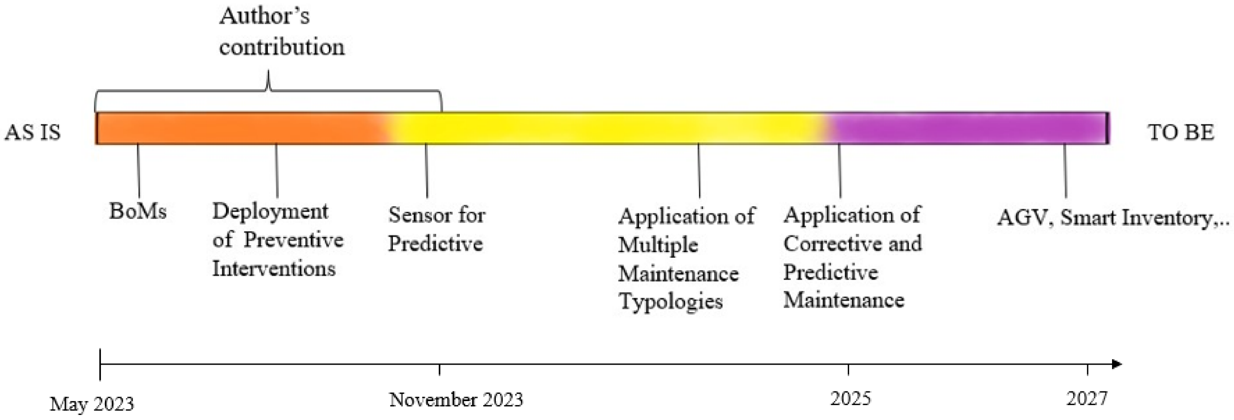


Figure 7.8: The project contribution into the Smart Maintenance Management path

Chapter 8

Conclusions

The thesis project, as seen, did not have the opportunity to witness and contribute fully to the completion of the Smart Maintenance path. The optimal result will be evident in approximately 3 or 4 years. However, it is possible to draw positive conclusions from the results obtained during this internship.

First, the objective of this master's thesis is to demonstrate the effectiveness of the improvements made to maintenance management through the use of new available technologies. By drafting the company's Bill of Materials, it was possible to proceed with the implementation of a preventive plan for the SF machine, also having the opportunity to measure its effects. These effects proved satisfactory as, over the months (particularly from April to September and October), a significant decrease in the total number of interventions required on the machinery was recorded with an increase in preventive interventions. This is also reflected in the MTTR (Mean Time To Repair) of the machinery, which was reduced from 49 minutes in April to 25 minutes in October.

These results have positive effects on company performance. By reducing the total number of interventions, there is an increase in available production time, enhancing the plant's production capacity in terms of the number of pieces. Furthermore, the reduction in sudden machine stops ensures business continuity, providing reliable times and circumstances for the implementation of corporate strategies. The decrease in interventions and the individual duration of each intervention through the implementation of preventive maintenance plans thus helps reduce costs related to sudden machine stops and overall production process slowdowns. All of this, combined with subsequent interventions that will be implemented shortly, from predictive maintenance to Smart Inventory, requires planning and investments that will bring immediate benefits in terms of cost.

The cost of the Maintenance Department is always one of the most closely monitored aspects of corporate management. Since it does not directly add value to the product, efforts are made to minimize its expenses. In case of necessity, it is often one of the first branches of the company to be downsized. However, as demonstrated by this project, proper planning and the use of cutting-edge technologies within the scope of Industry 4.0 would allow the Maintenance Department to become a virtuous tool in the hands of the company. Moreover, considering the current state of the Western industry, especially in Europe, where there is a high cost of labor and raw materials compared to emerging countries, staying competitive requires excelling in cost and waste reduction.

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